

**Conservation implications of Rainbow trout (*Oncorhynchus mykiss*) invasions in the upper Blyde River system, South Africa**

**By**

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# **Conservation implications of Rainbow trout (*Oncorhynchus mykiss*) invasions in the upper Blyde River system, South Africa.**

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## Declaration

I, the undersigned, hereby declare that this thesis, which I hereby submit for the degree of Doctor of Philosophy (Zoology) at the University of Pretoria, is my own work and has not previously been submitted by myself or anyone else for a degree at this or any other tertiary institution.

Signature: 

Date: 05/02/2023

## **Disclaimer**

This thesis consists of a series of chapters that have been prepared as stand-alone manuscripts for subsequent submission for publication purposes. Consequently, unavoidable overlaps and/or repetitions may occur between chapters.



## General Abstract

Salmonids (trout and salmon) have a long history worldwide of introduction into areas outside their native ranges for angling and aquaculture. In South Africa, for more than a century several salmonid species have been widely introduced into lakes and rivers in the country to create and enhance sport-fishing opportunities. These include species such as *Oncorhynchus mykiss*, *Oncorhynchus kisutch*, *Oncorhynchus tshawytscha*, *Salmo salar*, *Salmo trutta* and *Salvelinus fontinalis*. Management of these salmonid species is often difficult because they are conflict-generating invasive species that have major negative environmental impacts, but also have socio-economic benefits. This thesis investigated the nature, extent, and impact of rainbow trout, *Oncorhynchus mykiss* (Walbaum, 1792) on indigenous congeners within the Upper Blyde River catchment in northern South Africa. The study envisaged to gain a better understanding of factors that have allowed rainbow trout to be a successful invader and also to gain insights into its invasion rate and conservation implications within South Africa.

The first component of the study applied the spread debt concept (an aspect of invasion debt) to highlight the potential increase in the area invaded by *O. mykiss* over time in Mpumalanga Province, South Africa. It specifically, assessed the extent of the invasion, identified areas that are climatically suitable for establishment but are still invasion-free, and evaluated how its potential invasive range may be affected by climate change scenarios. The total river length that was predicted as suitable for *O. mykiss* under current climate was *ca.* 3500 km in an extension of *ca.* 15,000 km. Current occupancy (river length predicted as suitable with known rainbow trout occurrence records) was *ca.* 1220 km (35%) and the invasion debt was estimated as 65%. While these data infer a large invasion debt, they are confounded by a lack of knowledge on sampling effort and verified true absence and should therefore be recognised as an over estimation. In addition, the extent of the suitable area varied under different climate change scenarios where it was projected to decrease under

Representative Concentration Pathway (RCP) 4.5 scenarios and increase under the RCP 8.5 scenarios. This demonstrates some of the difficulties of quantifying the potential future extent and impacts of biological invasions and how the invasion debt concept can be applied to provide an important link between invasion biology, management, and policy.

The second component of the study assessed how *O. mykiss* invasions in the upper Blyde River have affected the community structure and function of indigenous species by evaluating the composition, relative abundance, and community structure in invaded and uninvaded river sections. There were significant differences in composition and abundance between fish communities that could be attributed to *O. mykiss* invasion and variation in habitats. Populations of indigenous species that historically occurred throughout the upper catchment, such as *Enteromius treurensis*, were greatly reduced and fragmented in the presence of *O. mykiss*. However, instream migration barriers such as waterfalls have prevented upstream migration of *O. mykiss*, and these invasion-free areas have remnant populations of native fishes that appear to be largely intact. This finding is consistent with other studies that have shown that introduced alien predatory fish can have a significant effect on fish communities and highlighted the need to prevent human-facilitated introductions in biodiversity-sensitive areas, such as mountain headwater streams, that are inhabited by endemic and range-restricted minnows.

The third component assessed trophic interrelationships of fish communities in invaded and uninvaded river reaches within the upper Blyde River catchment. It specifically evaluated the hypothesis that *O. mykiss* invasion is likely to lead to a decrease in the trophic functional diversity through predation and that indigenous fish will shift their trophic niche to either minimise competition with, or avoid predation, by *O. mykiss*. Fish communities in uninvaded areas utilised fewer and similar food sources and occupied lower trophic levels, than fish communities in invaded areas. *Oncorhynchus mykiss* fed mainly on invertebrates and at trophic

levels similar to and or lower than indigenous fishes. This suggests that their current impact on indigenous fish communities is mainly through competition for resources. The study posit that *O. mykiss* invasions reduced the abundance of indigenous fishes and thereby reduced predation pressure on aquatic invertebrates, with a knock-on effect on the trophic interrelationships among fish assemblages. These findings are consistent with other studies in South Africa that have shown that the impacts of *O. mykiss* invasion can lead to a decline and fragmentation of indigenous species populations and niche shifts.

The last component of the thesis provided as assessment of the risks associated with the six trout species that are known to occur in South Africa using the recently developed Risk Analysis Framework for Alien Taxa (RAAT). The RAAT framework offered a simple, objective, and transparent process of identifying risk associated with the introduction of alien species in South Africa and the development of appropriate management strategies. Four species (*O. mykiss*, *O. kisutch*, *O. tshawytscha*, and *S. trutta*) were considered to have a high risk of invasion because they are already present in South Africa and have a high potential to cause moderate to major impacts. *Salmo salar* and *Salvelinus fontinalis* were classified as low risk because they are not present in the country and are known to cause minor to moderate impacts in their invasive range globally. The recommendations from the risk analyses largely support the current management interventions as prescribed by the NEM:BA A&IS Regulations. The two key recommendations from the risk analyses are that *O. mykiss* and *S. trutta* should be included on the NEM:BA A&IS list of regulated species, and that National Management Plans should be developed for each trout species that is known to be present in South Africa. The tenet of these management plans should be to preserve the benefits while limiting the negative impacts. This can be achieved by managing trout by area, where utilisation is allowed in areas where trout have naturalised and/or were historically stocked while preventing introductions into new areas. There is also a need for a broader consultative

process when these management plans are been developed to minimise contestations around the proposed management plans.

**Keywords:** climate change; community structure and function; *Enteromius treurensis*; invasion debt; risk analysis; Treur River; trophic interrelationships; trout.

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## Table of Contents

|                                                                                                                                                                                                                          |     |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Declaration.....                                                                                                                                                                                                         | ii  |
| Disclaimer .....                                                                                                                                                                                                         | iii |
| General Abstract .....                                                                                                                                                                                                   | iv  |
| List of figures .....                                                                                                                                                                                                    | xi  |
| List of Tables .....                                                                                                                                                                                                     | xiv |
| Chapter 1: General introduction.....                                                                                                                                                                                     | 1   |
| Problem statement and rationale .....                                                                                                                                                                                    | 8   |
| Objectives.....                                                                                                                                                                                                          | 10  |
| Study approach.....                                                                                                                                                                                                      | 14  |
| Thesis outline .....                                                                                                                                                                                                     | 16  |
| References .....                                                                                                                                                                                                         | 17  |
| Chapter 2: The legacy of over a century of introductions: spread debt of rainbow trout<br>( <i>Oncorhynchus mykiss</i> ) in Mpumalanga Province, South Africa <sup>1</sup> .....                                         | 31  |
| Abstract .....                                                                                                                                                                                                           | 31  |
| Introduction .....                                                                                                                                                                                                       | 32  |
| Methods .....                                                                                                                                                                                                            | 34  |
| Results .....                                                                                                                                                                                                            | 41  |
| Discussion .....                                                                                                                                                                                                         | 45  |
| References .....                                                                                                                                                                                                         | 50  |
| Appendices .....                                                                                                                                                                                                         | 59  |
| Chapter 3: The effect of rainbow trout ( <i>Oncorhynchus mykiss</i> ) invasions on native fish<br>communities in the subtropical Blyde River, Mpumalanga province, South Africa .....                                    | 75  |
| Abstract .....                                                                                                                                                                                                           | 75  |
| Introduction .....                                                                                                                                                                                                       | 76  |
| Materials and methods .....                                                                                                                                                                                              | 78  |
| Results .....                                                                                                                                                                                                            | 82  |
| Discussion .....                                                                                                                                                                                                         | 88  |
| References .....                                                                                                                                                                                                         | 93  |
| Appendices .....                                                                                                                                                                                                         | 99  |
| Chapter 4: Niche expansion by indigenous fish species following the introduction of rainbow<br>trout ( <i>Oncorhynchus mykiss</i> ) in a subtropical river system, upper Blyde River, South Africa <sup>3</sup><br>..... | 102 |
| Abstract .....                                                                                                                                                                                                           | 102 |

|                                                                                             |     |
|---------------------------------------------------------------------------------------------|-----|
| Materials and methods .....                                                                 | 105 |
| Results .....                                                                               | 112 |
| Discussion .....                                                                            | 118 |
| References .....                                                                            | 122 |
| Appendices .....                                                                            | 133 |
| Chapter 5: The potential risk associated with invasive salmonid species in South Africa.... | 136 |
| Abstract .....                                                                              | 136 |
| Introduction .....                                                                          | 137 |
| Material and Methods.....                                                                   | 140 |
| Results .....                                                                               | 143 |
| Discussion .....                                                                            | 148 |
| References .....                                                                            | 156 |
| Appendices- Risk analysis reports .....                                                     | 169 |
| Appendix 5.1: Coho salmon ( <i>Oncorhynchus kisutch</i> ) .....                             | 169 |
| Appendix 5.2: Rainbow trout ( <i>Oncorhynchus mykiss</i> ) .....                            | 186 |
| Appendix 5.3: Chinook salmon ( <i>Oncorhynchus tshawytscha</i> ) .....                      | 204 |
| Appendix 5.4: Atlantic salmon ( <i>Salmo salar</i> ).....                                   | 220 |
| Appendix 5.5: Brown trout ( <i>Salmo trutta</i> ).....                                      | 236 |
| Appendix 5.6: Brook trout ( <i>Salvelinus fontinalis</i> ) .....                            | 255 |
| Chapter 6: General discussion .....                                                         | 271 |
| References .....                                                                            | 289 |

## List of figures

### Chapter 1

**Figure 1.1:** A map of the study area showing the location of sites sampled. Sites invaded by rainbow trout (*Oncorhynchus mykiss*) (●) and sites free of invasion (○) in the Blyde and Treur rivers in Mpumalanga Province, South Africa. Insert map of South Africa (top left)..... 10

### Chapter 2

**Figure 2.1:** The predicted distributional range of rainbow trout (*Oncorhynchus mykiss*) across five Water Management Areas (Komati, Mfolozi, Olifants, Vaal and Tugela) in Mpumalanga Province, South Africa. Areas with suitable conditions are indicated by blue, current distribution (occupancy) of rainbow trout in yellow, and protected conservation areas in green. Insert the maps of Africa (top left) and South Africa (bottom left).....41

**Figure 2.2:** Projected changes in the extent of areas that were predicted as climatically suitable for rainbow trout (*Oncorhynchus mykiss*) in Mpumalanga Province, South Africa between 2050 and 2070 based on two Representative Concentration Pathways (RCP 4.5 and 8.5) scenarios: a) RCP 4.5 (2050), b) RCP 4.5 (2070), c) RCP 8.5 (2050), and d) RCP 8.5 (2070).....44

### Chapter 3

**Figure 3.1:** A map showing (A) the distribution of native and threatened fish species (*Enteromius treurensis*, *Enteromius brevipinnis* and *Labeobarbus nelspruitensis*) in relation to the presence of *Oncorhynchus mykiss*; and (B) surveyed sites with the invasive rainbow trout (*Oncorhynchus mykiss*) (●) and sites free of invasion (○) in the upper catchment of Blyde and Treur Rivers in Mpumalanga Province, South Africa.



Trout occupancy refers to areas where trout is known to occur, based on a consultative stakeholder mapping process done by the Department of Forestry, Fisheries and the Environment, and the South African National Biodiversity Institute. Data sources for the distribution of native fish species were obtained from IUCN (International Union for Conservation of Nature) 2007a, 2007b, 2007c.....79

**Figure 3.2:** A non-metric multidimensional scaling (nMDS) showing sampling sites similarity based on species composition in the invaded and uninvaded sections of Blyde River and the uninvaded Treur River in Mpumalanga province, South Africa. The dashed circles indicate similarity (60%) between and among sites evaluated using an agglomerative hierarchical cluster analysis (using group-average linking) based on a Bray-Curtis similarity matrix..... 86

**Figure 3.3:** Canonical correspondence analysis showing the relationship between species composition and environmental variables among the invaded and uninvaded sections of Blyde River and the uninvaded Treur River in Mpumalanga Province, South Africa. A. ura = *Amphilius uranoscopus*, C. pre = *Chiloglanis pretoriae*, E. ano = *Enteromius anoplus*, E. lin = *Enteromius lineomaculatus*, E. tre = *Enteromius treurensis*, L. mar = *Labeobarbus marequensis*, L. nel = *Labeobarbus nelspruitensis*, O. myk = *Oncorhynchus mykiss*, T. spa = *Tilapia sparrmanii*. Alt = Altitude and Invst = Invasion status which refers to the presence or absence of *O. mykiss*.....87

## Chapter 4

**Figure 4.1:** A map showing the location of sites sampled. Sites invaded by rainbow trout (*Oncorhynchus mykiss*) (●) and sites free of invasion (o) in the Blyde and Treur Rivers in Mpumalanga Province, South Africa.....106

**Figure 4.2:** Centroid positions, and estimates of niche size and overlap using sample size-corrected standard ellipse areas (SEAc) of fish species sampled from sites invaded by rainbow trout (*Oncorhynchus mykiss*) on the Blyde River (b, e) and sites free of invasion both the Blyde River (a, d) and Treur rivers (c, f).  
.....116

**Figure 4.3:** The magnitude and direction of change in centroid positions of *Enteromius treurensis* and *Amphilius uranoscopus* across invaded and uninvaded sites on the Blyde and Treur rivers in Mpumalanga Province, South Africa.....118

## Chapter 5

**Figure 5.1:** The native and global introduction ranges of salmonids species (*Oncorhynchus*, *Salmo*, and *Salvelinus* spp). Source: Muhlfeld et al. (2019), <https://doi.org/10.47886/9781934874547>.....144

## List of Tables

### Chapter 2

**Table 2.1:** Bioclimatic variables and their percentage contribution to model performance for predicted distributional range of rainbow trout (*Oncorhynchus mykiss*) under current and future (2050 and 2070) climatic conditions in Mpumalanga Province, South Africa. Two Representative Concentration Pathways (RCPs) scenarios (RCP 4.5 and RCP 8.5) were used to build the future climate change models.....42

**Table 2.2:** The extent of river length that is predicted as suitable for rainbow trout (*Oncorhynchus mykiss*) under current and future (2050 and 2070) climatic conditions in Mpumalanga Province, South Africa. Two Representative Concentration Pathways (RCPs) scenarios (RCP 4.5 and RCP 8.5) were used to build the future climate change models.....44

### Chapter 3

**Table 3.1:** Sampling sites and their geographic coordinates (sites 1-11) where surveys were undertaken on the Blyde and Treur Rivers in Mpumalanga province, South Africa. Invasion status was defined as either invaded when rainbow trout (*Oncorhynchus mykiss*) was present or uninvaded when it was absent.....80

**Table 3.2:** Composition and abundance of fish communities in Blyde and Treur rivers in Mpumalanga Province, South Africa. Numbers outside parentheses indicate total number of individuals with standard deviation collected using electrofishing (n= 436) and those in parentheses using fyke nets (n = 174).....84

**Table 3.3:** Water quality parameters recorded at sites where fish surveys were undertaken in the Blyde and Treur rivers in Mpumalanga Province, South Africa.....89

## Chapter 4

**Table 4.1:** Sampling sites on the Blyde and Treur rivers in Mpumalanga Province, South Africa and their associated rainbow trout (*Oncorhynchus mykiss*) invasion status, geographic coordinates, and elevation.....107

**Table 4.2:** The composition and abundance (by numbers) of invertebrate and fish taxa sampled from sites invaded by rainbow trout (*Oncorhynchus mykiss*) on the Blyde River and sites free of invasion both the Blyde River and Treur rivers. The numbers of fish outside parentheses indicate the total number of individuals collected using electrofishing and those in parentheses using fyke nets.....113

**Table 4.3:** Proportion (% of isotopic value) of food sources utilised by rainbow trout (*Oncorhynchus mykiss*) and indigenous fish species in the catchments of the Blyde and Treur rivers, Mpumalanga Province, South Africa.  $\pm$  denotes standard deviation...114

## Chapter 5

**Table 5.1:** A summary of the risk analyses for six trout species that are known to be invasive or have been introduced in South Africa.....147

## Chapter 1: General introduction

Alien freshwater fish species have a long history of being introduced into areas outside their natural range by humans mainly to meet societal needs such as provision of food, ornamentation, and biological control (Cambray 2003a; Ellender et al. 2014; Weyl et al. 2020; Bernery et al. 2022). The introductions began in the 19<sup>th</sup> Century and the rates of introduction increased in the early 20th Century mainly due to increased global trade and connectivity (Turbelin et al. 2017; Seebens et al. 2017). These introductions were initially driven by acclimatisation societies during the colonial era when Europeans settled in several countries globally and such societies advocated for the introduction of species that were familiar and representative of European countries (Hey 1926; Lever et al. 2011). It was believed that such introductions were for a good cause because at the time the practice was considered to enhance biodiversity, improve livelihoods and recreation (Hey 1926). For example, the societies were responsible for several fish introductions in Australia (García-Díaz et al. 2018), Europe (Gherardi et al. 2009), New Zealand (McDowall 1994), and the USA (Lever et al. 2011). This pathway is now of minor importance because of the global recognition of impacts of alien fish introductions and most countries have implemented interventions to limit new introductions (Blackburn et al. 2014; Hawkins et al. 2015). However, some pathways such as aquaculture, angling, and ornamental trade are still active and of major importance in the introduction of alien fish species globally (Ellender et al. 2014; Ellender and Weyl 2014; Turbelin et al. 2017). These pathways collectively account for 89% of global introduction events of alien fishes where most introductions are predominantly from aquaculture (42%), ornamental trade (17%), release of bait for angling (14%), biological control (9%), and stocking for fisheries (7%) (Bernery et al. 2022).

The overall global distribution of these alien species was also affected by the production quantity and value of the species in aquaculture which determined their demand (Little et al. 2016; Bush et al. 2019). The recent FAO global aquaculture production statistics indicated that there are over 600 species farmed globally since introductions intensified in the 1900s (Naylor et al. 2021). Among these species, the freshwater fishes with the highest production quantity in 2017 were carps, barbels and other cyprinids which accounted for a quarter of global aquaculture production quantity at a value of \$250 billion (Cai et al. 2019; Naylor et al. 2021). The most popular group of species farmed in 127 countries are tilapias and other cichlids with a contribution of 5.25 % in world aquaculture by quantity and a value of 4.42 % (Cai et al. 2019). Salmons, trouts and smelts were reported to be number three under the high value group (8.94 %) and number 9 (3.11%) under world aquaculture by quantity (Cai et al. 2019). The most traded species within this group are Atlantic salmon (*Salmo salar*, 68 %), rainbow trout (*Oncorhynchus mykiss*, 23 %), and coho salmon (*Oncorhynchus kisutch*, 5.2 %) (Cai et al. 2019).

### **The global distribution of trout**

Trout is a common name for several freshwater fish species from three genera within the family Salmonidae (Cuvier 1816) comprising *Oncorhynchus* Suckley, 1861, *Salmo* Linnaeus, 1758 and *Salvelinus* Richardson, 1836. Several trout species have been introduced globally to areas outside their natural ranges to enhance angling opportunities and aquaculture (Cambray 2003b; Crawford and Muir 2008; Stanković et al. 2015). The global spread of most species of trout was facilitated by the construction of hatcheries that enabled the stocking of propagules and improved transport and storage systems (e.g., air travel and refrigeration) that enabled fast and efficient transportation of alien fishes over long distances and in short periods to different areas around the world (Cambray 2003b; Crawford and Muir 2008). In addition, most introductions were successful because there was a pre-selection of suitable receiving environments similar

to the species' native ranges. For example, the cutthroat trout (*Oncorhynchus clarkii*), native to Alaska and British Columbia in North America, is one of the most distributed trout species but their introduction into the Great Lakes, Northwest Territories, Alberta, and Saskatchewan was not successful (Hubbs and Lagler 1958; Epifanio 2000). In Africa, the documented introduction of cutthroat trout was in Morocco and North Africa (Welcomme 1988). Other species of trout that were successfully introduced into Africa includes brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) (Crawford and Muir 2008). The native range of *S. trutta* includes parts of Europe along the Atlantic, North, White and Baltic Sea Basins (from Spain to Chosha Bay in Russia), Asia and the Atlas Mountains in North Africa (Picker and Griffiths 2011; McIntosh et al. 2012; Weyl et al. 2017; Froese and Pauly 2021). In Africa, the brown trout was initially introduced to South Africa from Scotland in 1890, where it was subsequently introduced into neighbouring countries such as Swaziland (1915), Lesotho (most likely between 1907 and 1914), Zimbabwe (1907), Tanzania (1934) and even the sub-Antarctic Marion Island (1964) (de Moor and Bruton 1988; Weyl et al. 2017). Other introductions of the brown trout in sub-Saharan Africa occurred in Kenya from England in 1905, Madagascar from France in 1926 and Ethiopia from Kenya in 1967 (Weyl et al. 2017).

*Oncorhynchus mykiss* is among one of the most widely introduced fish species for sport fishing globally (Cambray 2003b). It is native to the northwest Pacific coast of North America and has spread and established populations in all continents, except Antarctica (Crawford and Muir 2008). It has been introduced in more than 80 countries globally and has established feral populations throughout its introduced range (Cambray 2003b). As an angling species, *O. mykiss* was one of the anglers' favourites that fast-tracked its distribution globally (Cambray 2003b). The demand of *O. mykiss* for fly fishing was high globally because it was mainly the first choice for wealthy individuals (Welcomme 1988). One of the first introductions of rainbow trout occurred in New Zealand in 1877 from the USA and currently, almost all

introduced populations have naturalised (Welcomme 1988; McDowall 1994). In Africa, this species was first introduced into South Africa for recreational fisheries (de Moor and Bruton 1988; Crawford and Muir 2008). South Africa then served as a bridgehead for introductions into neighbouring countries and beyond such as Swaziland, Zimbabwe, and Kenya (Crawford and Muir 2008). In Kenya, introductions occurred in the Athi-Galana-Sabaki watershed and in Zimbabwe, it was introduced in the eastern highlands where thriving populations are currently found (Kadye et al. 2013; Weyl et al. 2020). Introductions of *O. mykiss* into the other parts of the continent such as Malawi, Madagascar, Morocco, and Tanzania were done from Great Britain, France, and Scotland for recreational establishment in the mountain streams (Welcomme 1988).

### **Rainbow trout introduction in South Africa**

In South Africa, *O. mykiss* was first introduced in 1897 in the Western Cape Province, where the first hatchery was built for the sole purpose of its breeding and introduction across the country (McCafferty et al. 2012). Its distribution was initially supported by government agencies that encouraged the spread of alien angling fish species in the country to maintain recreational fisheries (Skelton and Davies 1986; McCafferty et al. 2012). Currently, *O. mykiss* has a much wider distributional range than most other angling species introduced into South Africa, with populations occurring in most of the headwater rivers in KwaZulu-Natal, north-eastern Free State, Mpumalanga, Limpopo, Western and Eastern Cape Provinces (Picker and Griffiths 2011). Subsequently, the focus of government organisations has been to limit the introduction and dispersal of *O. mykiss* into areas that are currently free of invasion because of the impacts of trout on native biodiversity (de Moor and Bruton 1988; Ellender et al. 2014). Currently, *O. mykiss* has established populations in the mountain streams and upland reservoirs in over 80% of the major drainage basins in the country (Weyl et al. 2020).

### **Impacts of trout**



### *Negative environmental impacts*

In its introduced range, *O. mykiss* has been implicated in causing major impacts on indigenous fauna and ecosystems mainly through competition and predation (Drenner and Hambright 2002; Simon and Townsend 2003; McDowall 2006; Fausch 2007), modifying aquatic-terrestrial linkages (e.g., Epanchin et al. 2010; Jackson et al. 2016), altering food-web structure (Flecker and Townsend 1994), and disrupting nutrient cycles (Schindler et al. 2001; Eby et al. 2006). In South Africa, there is, however, limited information on the impacts of *O. mykiss* invasions (Zengeya et al. 2020; van Wilgen et al. 2022). The few available studies have shown that *O. mykiss* can cause a decline, and in some cases local extirpation of indigenous invertebrates, frogs, and fishes (Karssing et al. 2012; Rivers-Moore et al. 2013; Shelton et al. 2015a; Jackson et al. 2016; Marr et al. 2017; Weyl et al. 2020).

### *Competition*

Evidence from across the invaded range including Australia, eastern North America, Japan, Peru, and South Africa show that *O. mykiss* competes with native fauna for habitat and food resources (Rosenthal 1980; Crowl et al. 1992; Fausch 1988; Taniguchi et al. 2000; Ellender 2013; Jackson et al. 2016; Marr et al. 2017). In South Africa, *O. mykiss* have been implicated in the decline in abundance of river minnows in several mountain headwater catchments such as Breede River (Shelton et al. 2015a) and Blyde River (Maimela et al. 2021). For example, in the Keiskamma River in the Eastern Cape Province, South Africa, the border barb (*Pseudobarbus trevelyani*) was reported to be absent in the catchments with trout, indicating competition for habitat (Ellender 2013). Similar patterns were observed in the uKhahlamba Drakensberg Park in Kwa-Zulu Natal Province, South Africa where the Natal cascade frog tadpoles were absent in trout-invaded river sections but occurred in invasion free river sections (Karssing et al. 2012). Similar patterns were also observed elsewhere in other countries, such as Zimbabwe (Kadye et al. 2013) and Japan (Kitano et al. 1993; Urabe and Nakano 1998).

where trout displaced native species from their preferred habitat. In addition, trout invasions by both *O. mykiss* and *S. trutta* have been shown to modify aquatic-terrestrial food-web linkages by competing for resources with indigenous riparian consumers such as spiders in several river systems such as the Keiskamma, Thukela, and the uMngeni (Jackson et al. 2016).

### *Predation*

*Oncorhynchus mykiss* is mainly carnivorous and has been reported to reduce indigenous fish populations in its introduced range through predation (Crowl et al. 1992; Lintermans 2000; Dunham et al. 2004; Kitano 2004; McDowall 2006; McIntosh et al. 2010; Young et al. 2010; Habit et al. 2010; Marr et al. 2017). In South Africa, *O. mykiss* has led to a decline and in some cases local extirpation of native invertebrates, frogs, and fish (Weyl et al. 2020). For example, *O. mykiss* has caused a decline in abundance of populations of native river minnows such as Cape galaxias (*Galaxias zebratus*), Breede River redbfin (*Pseudobarbus burchelli*) and Cape kurper (*Sandelia capensis*) (Woodford and Impson 2004; Shelton et al. 2015a), Maloti minnow (*Pseudobarbus quathlambae*) (Jubb 1966; de Moor and Bruton 1988), endangered border barb (*Amatolacypris trevelyani*) (Ellender 2013), and the critically endangered Treur River barb (*Enteromius treurensis*) (Maimela et al. 2021). The presence of *O. mykiss* has also been implicated in the decline of several amphibian species such as Natal ghost frog (*Hadromophryne natalensis*) (Karssing 2010; Karssing et al. 2012) and the Cederberg ghost frog (*Heleophryne depressa*) (Avidon et al. 2018). In addition, *O. mykiss* invasions have induced trophic cascades by releasing some herbivorous invertebrates from predation, leading to an increase in grazing pressure and lower algal biomass at invaded sites (Shelton et al. 2015b).

### *Hybridisation*

When *O. mykiss* is introduced in river systems with indigenous salmonid species that it can hybridize with, it has the potential to extirpate indigenous fish population (Weigel et al. 2003;

Young 2009). The integrity of indigenous salmonid species was compromised after *O. mykiss* was introduced in the USA and some species such as the Alvord cutthroat (*Oncorhynchus clarkii*) has been reported to be extinct because of hybridisation with the introduced rainbow trout (Fuller et al. 2023). Other studies in the western USA have also reported that introgressive hybridisation with *O. mykiss* has often resulted in the loss of the diversity of indigenous cutthroat trout (Allendorf and Leary 1988; Weigel et al. 2003; Young 2009). The indigenous species that have been reported to hybridize with *O. mykiss* in its introduced range are mostly salmonids, however, in South Africa, there are no indigenous salmonid species prone to hybridisation with *O. mykiss* and this impact mechanism is not of concern in the country (Skelton 2001).

#### *Transmission of disease*

*Oncorhynchus mykiss* has been shown to carry whirling disease myxosporean parasite *Myxobolus cerebralis* and Enterococcus-like bacterium (Carson et al. 1993; Bartholomew and Reno 2002; Bartholomew et al. 2005). However, these diseases are of minimal concern in South Africa, since they are salmonid-specific diseases (Carson et al. 1993; Bartholomew et al. 2005) and therefore unlikely to have adverse effects on native fishes in South Africa. In addition, to date, all the diseases/parasites listed by FAO (2012) which commonly infect *O. mykiss* have not been found in South African salmonids (despite regular testing of imported ova and cultured adults for Viral Haemorrhagic Septicaemia and Infectious Haemopoietic Necrosis) (Anchor Environmental Consulting 2012).

#### *Negative socio-economic impact*

There are no documented negative socio-economic impacts of *O. mykiss* in South Africa. Although there were limited number of studies that have been done to assess the negative socio-economic impact of alien species globally and in South Africa (Zengeya and Wilson 2020). For example, the recently developed Socio-Economic Impact Classification of Alien Taxa

(SEICAT, Bacher et al. 2018) has only been applied to a few taxa such as gastropods and mammals in South Africa, and amphibians, marine fishes and acacia trees globally (Bacher et al. 2018; Galanidi et al. 2018; Jansen and Kumschick 2022).

### *Positive impacts*

There are no environmental benefits documented for *O. mykiss* in South Africa. *Oncorhynchus mykiss* does, however, have high socio-economic value because it is utilised in aquaculture and recreational fisheries (McCafferty et al. 2012). There are several studies that have assessed the economic benefits derived from *O. mykiss* such as recreational fishery, tourism, and aquaculture (Britz et al. 2009; Anchor Environmental Consultanting 2010; Britz and Venter 2016; Du-Preez and Lee 2010; McCafferty et al. 2012). Trout farming (primarily *O. mykiss*) is regarded as the second-largest aquaculture sector in terms of production in South Africa (Britz and Venter 2016). These studies strengthen the evidence base for quantifying the benefits derived from introduced fish species, but there were done using different methods and at small scales (e.g., towns, and discrete catchments), and the results still have to be extrapolated to larger scales (e.g., national). This could be achieved by using recently developed frameworks such as the Environmental Impact Classification of Alien Taxa Plus (EICAT+) (Vimercati et al. 2022) that enables the classification of positive impacts of alien taxa on native biodiversity.

### **Problem statement and rationale**

The negative impacts of *O. mykiss* in South Africa were first realised through observations and this raised the critical need for studies to evaluate the extent of their impact in the receiving systems (Cambray 2003b). The lack of literature on the impacts of *O. mykiss* on indigenous fish species may have also been one of the factors that resulted in prolonged debates on the management of trout species because of anecdotal evidence (Ellender et al. 2014). On the other hand, it was known that *O. mykiss*-related activities alleviated poverty by providing

employment opportunities for local communities (Du-preez and Lee 2010). This did not only make the implementation of *O. mykiss* control measures difficult but caused conflicts between stakeholders as unbiased practices to conserve indigenous fish species in the country could not be realised (Zengeya et al. 2017). The current study, therefore, adds to the few studies that assess the impacts of the invasive predatory *O. mykiss* in the headwater streams in South Africa. The study identifies areas prone to invasion, the extent of the distribution of *O. mykiss* and its impacts on the indigenous fish species with the aim to assist policy-makers in formulating science-driven applicable and effective control measures.

### **Study area**

The study area includes one of the main rivers in Mpumalanga Province, the Blyde River, and its tributary the Treur River (Raven 2004; Figure 1.1). They are both situated in the northern part of the Great Drakensburg Escarpment which forms part of the few habitats that harbour the range-restricted river minnows in South Africa (Raven 2004). The area is characterised by grassland vegetation that is interspaced by Afromontane forests, rocky substrate, shallow and deep pools, and cool to moderate temperatures which provide suitable climate and habitat for the establishment of trout species (Raven 2004). The Blyde River is one of the major perennial tributaries of the Olifants River that contributes to most of its water supply annually (de Koning and de Beer 2013). The Blyde River has a catchment area of approximately 2.842 km<sup>2</sup>, flowing north-wards through the small town of Pilgrim's Rest situated in the Kruger Lowveld region of Mpumalanga Province (de Koning and de Beer 2013). The lowveld stretch of the river flows through agricultural and wildlife farmlands where the water is used mainly for agricultural, industrial, and domestic purposes (Raven 2004). The Blyde River receive higher rainfall (with a mean annual precipitation of >1000 mm) than other sub-catchments of the Olifants River basin (Raven 2004). The region receives rainfalls during summer (October to February), with >74% of the rain falling between November and February (Raven 2004).

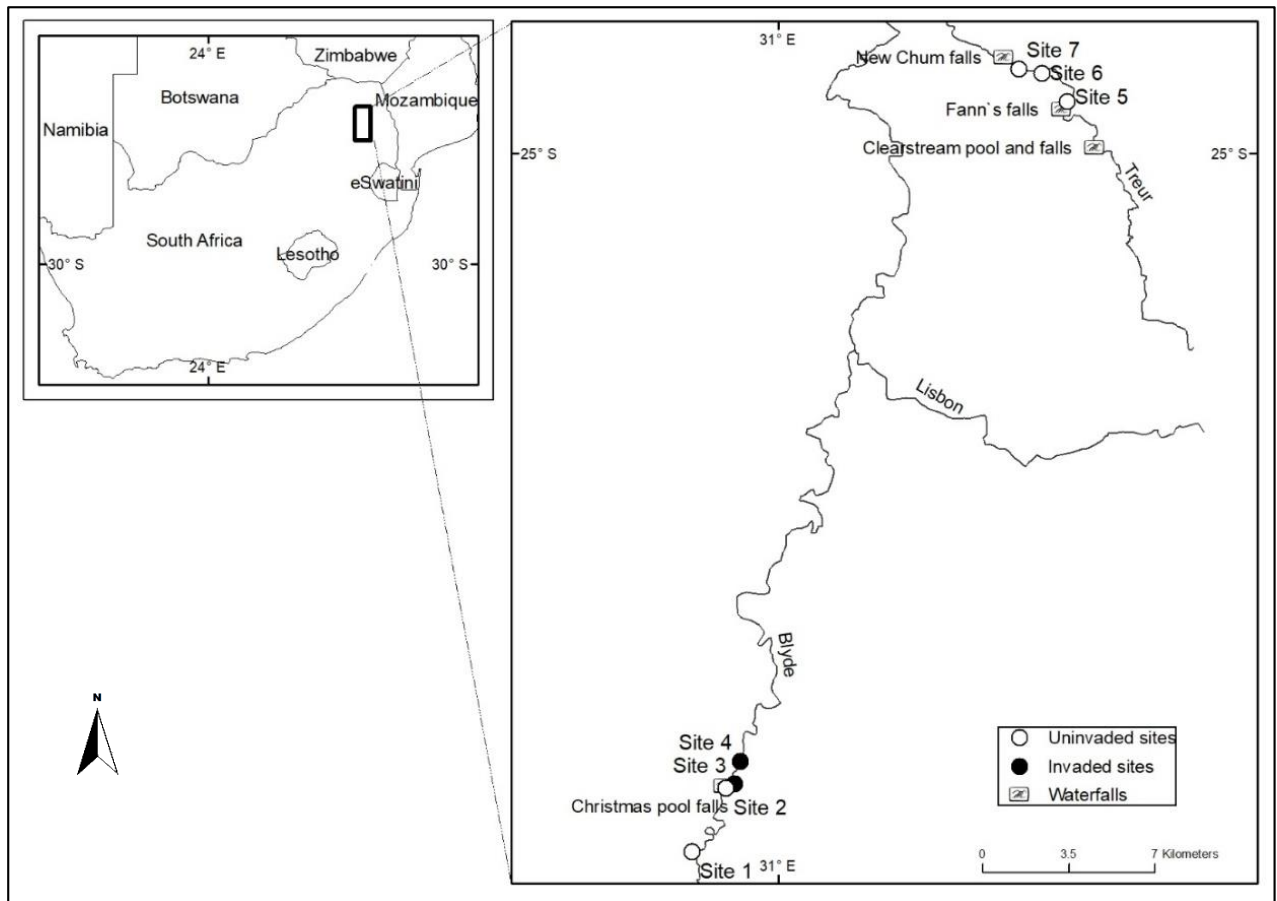


**Figure 1.1:** A map of the study area showing the location of sites sampled. Sites invaded by rainbow trout (*Oncorhynchus mykiss*) (●) and sites free of invasion (○) in the Blyde and Treur rivers in Mpumalanga Province, South Africa. Insert map of South Africa (Top left).

## Objectives

The general objective of the present study was to evaluate the current and future extent of *O. mykiss* invasions in the upper Blyde River catchment and to determine its impacts on indigenous species composition and structure. The specific aims were to: 1) assess the nature and extent of *O. mykiss* invasion and project how current and future climatic scenarios are likely to affect its potential invasive range; 2) determine the impacts of *O. mykiss* invasion on indigenous fish species composition, relative abundance and community structure; 3) and

assess trophic interrelationship between *O. mykiss* and the indigenous fish species to determine if *O. mykiss* invasion has altered community structure and function, such as trophic functional diversity and trophic niche size of indigenous fish species; 4) to evaluate the risk associated with the introduction of other salmonids species in South Africa; and 5) provide some recommendations for the management and mitigation measures to prevent future introductions, and minimise impacts associated with *O. mykiss* populations that are already present in the country.

### **Research questions and predictions**

Given the above background, objectives and aims of the present study, the following research questions (and their associated predictions) were addressed:

- 1) Does the current distribution of rainbow trout extend to all climatically-suitable habitats in Mpumalanga Province, South Africa, and will climate change limit or expand its potential distribution in the province? It is predicted that *O. mykiss* has a low invasion debt because sustained and widespread stocking in pre-selected suitable receiving environments has allowed it to establish in most of the areas that it has been introduced, but climate change is likely to lead to a range constriction because of increasing temperatures (Isaak et al. 2010; McCafferty et al. 2012; Comte et al. 2013; Rivers-Moore et al. 2019);
- 2) How does the invasion of *O. mykiss* affect species composition, distribution and community structure of indigenous fish species in the upper Blyde River catchment? It is predicted that the presence of *O. mykiss* would create differences in species composition and community structure, such as a decline and fragmentation of indigenous fish species populations, in invaded river sections (McIntosh et al. 2010; Shelton et al. 2015a; Weyl et al. 2020); and

- 3) Has *O. mykiss* invasion in the upper Blyde River catchment led to an increase in the trophic functional diversity of indigenous fish species through trophic dispersion and niche shift? It is predicted that *O. mykiss* invasion would lead to an increase in trophic functional diversity of indigenous fish species through trophic dispersion and that indigenous fish will shift their niche width (i.e., the variety of food items utilised by a species) and position (i.e., type of food resources utilised) to minimise competition with, or avoid predation, by *O. mykiss* (Potgieter 2014; Shelton et al. 2015b, 2017); and
- 4) What are the risks associated with the introduced salmonids in South Africa and those that could potentially be introduced? It is predicted that the risk associated with the invasion of salmonids in South Africa will be high because their known impacts in their global invasive range are severe (Shelton et al. 2015b, 2017).

### **Research hypotheses**

Given the above research questions (and their associated predictions), the following research hypotheses were tested in the four data chapters in this study:

#### *Hypotheses 1 (Chapter 2)*

Null hypotheses ( $H_0$ ):

- I. There is no invasion debt for *O. mykiss* in Mpumalanga Province, South Africa;  
and
- II. Climate change due to increasing temperatures will not affect the current extent of *O. mykiss* in the province.

Alternative hypotheses ( $H_a$ ):

- I. There will be low invasion debt for *O. mykiss* in the province because sustained and widespread stocking in pre-selected suitable receiving environments has allowed it to establish in most of the areas that it has been introduced; and



- II. Climate change due to increasing temperatures is likely to lead to range constriction of *O. mykiss* invasive range in the province.

*Hypothesis 2 (Chapter 3)*

H<sub>0</sub>:

- I. The invasion of *O. mykiss* will have no impact on the community structure and distribution of indigenous fish species in the Blyde River in Mpumalanga Province.

H<sub>a</sub>:

- I. The invasion of *O. mykiss* will likely lead to a decline and fragmentation of indigenous fish species populations, in invaded river sections of the upper Blyde River catchment.

*Hypothesis 3 (Chapter 4)*

H<sub>0</sub>:

- I. *Oncorhynchus mykiss* invasion is likely to have no impact on the trophic functional diversity and of indigenous fish species in the upper Blyde catchment.

H<sub>a</sub>:

- I. *Oncorhynchus mykiss* invasion is likely to lead to an increase in the trophic functional diversity through trophic dispersion, and that indigenous fish will shift their niche width and niche position in order to either minimise competition with, or avoid predation, by *O. mykiss*.

*Hypothesis 4 (Chapter 5)*

H<sub>0</sub>:

- I. There are no risks associated with introduced and potentially to be introduced salmonid species in South Africa.

H<sub>a</sub>:

- II. There are risks associated with introduced and potentially to be introduced salmonid species in South Africa.

### **Study approach**

The present study evaluated the current extent of *O. mykiss* invasion in Mpumalanga Province, South Africa and assessed how this may be affected by climate change in future. This was achieved through use of Species Distribution Modeling (SDM) in Maxent (Phillips et al. 2006) to predict the potential suitable area for *O. mykiss* in Mpumalanga Province. Occurrence records from both indigenous and introduced ranges were used to predict climatically-suitable areas where *O. mykiss* is likely to establish populations in the province. Most of the occurrence data were obtained from the Global Biodiversity Information Facility (GBIF; <http://www.gbif.org>), and from the South African Institute for Aquatic Biodiversity (SAIAB) and South African National Biodiversity Institute (SANBI). The bioclimatic variables used for environmental projections were obtained from Worldclim (<http://www.worldclim.org>). The output models were used to estimate the current invasion debt of *O. mykiss* in Mpumalanga Province using the approach by Rouget et al. (2016). Future environmental variables were used to predict the potential impact of climate change on the current distribution of *O. mykiss* under Representative Concentration Pathway (RCP) climate scenarios 4.5 and 8.5 that have been applied to other taxa (Shechonge et al. 2019), but not on *O. mykiss*. This component of the study was directed at estimating the spread of *O. mykiss* since its introduction over a century ago and assess if there are still potential suitable areas that are free of invasion.

The potential impact of *O. mykiss* on indigenous fish species composition and distribution was evaluated through a fish survey in the invaded and uninvaded catchments of the Blyde River and its tributary, the Treur River, as the control river. Other possible factors such as environmental variables that may potentially affect the community structure and

distribution of indigenous fish species along the two rivers were evaluated. The interactive impact of the two factors is likely to result in fragmented indigenous fish species communities and reduced populations due to increased competition on habitat use and environmental conditions that limit the occurrence of some fish species. The prediction in this part of the study was that native species distribution is limited to the catchments where *O. mykiss* does not occur, and the environmental conditions either enable or limit the occurrence of the indigenous fish species that form the community structure of the river.

The subsequent part of the study was aimed at assessing the feeding behaviour of indigenous fish species in relation to the invasive *O. mykiss* as a top predator. Most South African rivers where *O. mykiss* occurs, have no indigenous fish species with similar or comparative traits (Cambray 2003b), which suggest that the occurrence of the invasive piscivore is likely to alter the food web structure of the system. The main objective of this part of the study was to evaluate if the invasion of *O. mykiss* has affected the niche position and size of the indigenous fish species through predation and/or competition for food resources. This was conducted through the use of two complimentary methods, stable isotope and stomach content analyses (Lombard et al. 2018). The combined use of the two approaches provides an overview of recently consumed food resources and the diet of the species over time (Kadye and Booth 2012).

The final component of the study analysed the risks associated with the introduction of *O. mykiss* in South Africa using the recently developed Risk Analysis Framework for Alien Taxa (RAAT) (Kumschick et al. 2018, 2020a, 2020b). The risk analysis for *O. mykiss* in South Africa consisted of four components: risk identification, risk assessment; risk management and risk communication. Risk identification - biological invasions present various risks that can be broadly grouped in terms of species, pathways, and areas (Kumschick et al. 2020a). In this study, the risks associated with biological invasions from *O. mykiss* were identified in terms of

species. Risk assessment - this step evaluated the likelihood of *O. mykiss* being introduced, establishing and spreading in South Africa, and the consequences (negative impacts) thereof. Risk management - this step included the evaluation of the best management options for *O. mykiss* populations that are known to be present in South Africa to mitigate spread and impacts while allowing utilisation. Risk communication – this included the collation and summary of the complete background information of the RAAT framework process to make recommendations for management, regulations, and stakeholder engagement with relevant stakeholders.

### **Thesis outline**

This thesis comprises of six chapters, a general introduction (Chapter 1), four data chapters (Chapters 2, 3, 4, and 5), and a general discussion (Chapter 6). Chapter 1 provides an overview of *O. mykiss* as an introduced invasive species and its impacts on indigenous fish species globally. It highlights the documented impacts of *O. mykiss* in South Africa and elsewhere, and provides a problem statement and the rationale behind the study. Chapter 2 investigated the current extent of the distribution of *O. mykiss* in Mpumalanga Province and estimated the potential suitable river length that is not invaded a century after introduction. It further evaluated the potential impact of climate change on the distribution of *O. mykiss* under future climatic scenarios. Chapter 3 evaluated the possible impacts of the invasive *O. mykiss* and environmental variables on the distribution of indigenous fish species in the Blyde River in Mpumalanga Province, South Africa.

Chapter 4 focused on the trophic relations between the introduced and invasive *O. mykiss* and indigenous fish species in the Blyde River. It investigated the possible impacts of *O. mykiss* on niche position and size of indigenous species using stable isotope and stomach content analyses. Chapter 5 assessed the risks associated with the introduction of *O. mykiss* in

South Africa using the recently developed Risk Analysis Framework for Alien Taxa (RAAT). The RAAT framework offers a simple, objective, and transparent process of identifying risk associated with the introduction of alien species and it also allows for the comparative analysis across different regions and taxonomic groups. This allows for science based risk analysis process to inform on the development of appropriate management strategies for *O. mykiss* in South Africa. The general discussion (Chapter 6) concludes the study by highlighting the overall findings of the four data chapters. It provides insights into the current status of *O. mykiss* in the Blyde River catchments, potential and observed impacts and provides some management recommendations and mitigation measures to prevent future introductions, and minimise impacts associated with *O. mykiss* populations that are already present in the country.

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## Chapter 2: The legacy of over a century of introductions: spread debt of rainbow trout (*Oncorhynchus mykiss*) in Mpumalanga Province, South Africa<sup>1</sup>

### Abstract

For over a century, rainbow trout (*Oncorhynchus mykiss*) has been widely introduced into lakes and rivers in South Africa to create and enhance sport-fishing opportunities. Despite its long history of introduction, naturalised populations of rainbow trout are still localised to a few areas with suitable habitats and climate. This study assessed the spread debt of rainbow trout in Mpumalanga Province, South Africa to highlight areas with known introductions, the extent of the invasion, and to identify areas that are suitable for establishment but are still invasion-free. The total river length that was predicted as suitable for rainbow trout under current climate was *ca.* 3500 km in an extension of *ca.* 15,000 km. Current occupancy (river length predicted as suitable with known rainbow trout occurrence records) was *ca.* 1220 km (35%) and the invasion debt was therefore estimated as 65%. While these data infer a large invasion debt, they are confounded by a lack of knowledge on sampling effort and verified true absence and should therefore be recognised as an over estimation. In addition, the extent of the suitable area varied under different climate change scenarios where it was projected to decrease under RCP 4.5 and increase under the RCP 8.5 scenarios. This study demonstrates some of the difficulties of quantifying the potential future extent and impacts of biological invasions and how the invasion debt concept can be applied to provide an important link between invasion biology, management, and policy.

**Keywords:** Biological invasions, climate change, conservation, species distribution modelling (SDM), spread.

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## Introduction

Biological invasions are a threat to biodiversity, ecosystems and the services they provide, human livelihoods and health (IPBES, 2019). One of the major challenges in managing biological invasions is the difficulty in quantifying their potential future extent and impacts (McGeoch et al., 2010; Richardson & Pyšek, 2012; Pereira et al., 2013). This is especially a concern when the number of new introductions has rapidly increased over the last two centuries due to increasing global connectivity (Seebens et al., 2018). The high proportion of recently introduced alien species whose future impacts are difficult to predict is likely to lead to an increase in challenges associated with biological invasions, an important aspect of a phenomenon known as “invasion debt” (Essl et al., 2011; Rouget et al., 2016). Invasion debt consists of 1) introduction debt (i.e., the number of new alien species that will be introduced to a region if no action is taken); 2) establishment debt (i.e., the number of alien species that will become invasive in future); 3) spread debt (i.e., the increase in area invaded by invasive species over time); and 4) impact debt (i.e., the increase in impacts due to the invasion over time) (Rouget et al., 2016).

The invasion debt concept is widely applied to provide an important link between biological invasions, management, and policy. For example, establishment debt can be used to identify new invasions that have implications in the development of post-border biosecurity and implementation measures to prevent the spread of potential invasive species (see Seebens et al., 2018). Spread debt can be used to identify additional areas that are likely to be invaded, and management implications include the identification of priority areas for control, the identification of areas where spread reduction methods are required, and spatial planning of the management of biological invasions (e.g., Khosa et al., 2019; Padayachee et al., 2019). There are few studies that have investigated some aspects of invasion debt in South Africa, such as establishment debt (e.g., Novoa et al., 2015; Faulkner et al., 2016; Walker et al., 2017), spread

of single species (e.g., Moore et al., 2011), and only one study has investigated all four components of invasion debt (Rouget et al., 2016).

Trout is a common name for several freshwater fish species from three genera within the family Salmonidae (Cuvier, 1816) which are *Oncorhynchus* Suckley, 1861, *Salmo* Linnaeus, 1758 and *Salvelinus* Richardson, 1836. Several trout species have been globally introduced to areas outside their natural ranges to enhance angling opportunities and for aquaculture (Cambray, 2003; Crawford & Muir, 2008; Stanković et al., 2015). In South Africa, there are four trout species that have been introduced and these include *Oncorhynchus mykiss* (Walbaum, 1792) (rainbow trout), *Salmo salar* Linnaeus, 1758 (Atlantic salmon), *Salmo trutta* Linnaeus, 1758 (brown trout), and *Salvelinus fontinalis* (Mitchill, 1815) (brook trout) (Ellender et al., 2014; Marr et al., 2017). The introductions of Atlantic salmon and brook trout were not successful, probably due to lack of suitable habitats, but brown and rainbow trout have naturalised in several mountain headwater streams in the country (Ellender et al., 2014; Weyl et al., 2017). This can be attributed to sustained and widespread stocking for sport fishing, initially by government agencies and later by angling societies and private individuals, and a pre-selection of suitable receiving environments that are similar to the species' native ranges (de Moor & Bruton, 1998; Ellender et al., 2014)

For cold water species such as trout, climate change events such as global warming are likely to decrease habitat availability through range constriction of suitable areas (Isaak et al., 2010; Comte et al., 2013). The invasibility of a given area is partly influenced by climatic suitability of the recipient habitat to the invader (Lim et al., 2018; Shelton et al., 2018). Climate change can therefore be a critical factor in determining the potential range of rainbow trout. Climate change has been implicated in changes to precipitation patterns, intensity and an increase in the frequency and magnitude of extreme events such as droughts and flooding (Bates et al., 2008). Changes in precipitation and water temperature influence the availability

of surface water, habitats, and food resources (Lowe-McConnell, 2000), which in turn, affect the abundance, composition, distribution, productivity, and phenology of aquatic species (e.g., Bates et al., 2008, Argent & Kimmel, 2013; Comte et al., 2013; Junker et al., 2015).

The main objectives of this study were to predict the extent of rainbow trout invasions in the river systems in Mpumalanga Province, South Africa, and project how current and future climatic scenarios are likely to affect its potential invasive range. Rainbow trout was introduced into local streams and rivers in the province as early as 1910 and it is currently known to occur in several upland areas of the province where it supports aquaculture and sport fishing (McCafferty et al., 2012). Despite its long history of introduction, naturalised populations of trout are still localised to a few areas with suitable habitats and climate. In other areas water temperatures are only suitable during certain periods of the year and populations need to be maintained through stocking (Rivers-Moore et al., 2019). We hypothesised that rainbow trout has a low invasion debt because sustained and widespread stocking in pre-selected suitable receiving environments has allowed it to establish in most of the areas that it has been introduced, but climate change is likely to lead to a range constriction because of increasing temperatures.

## **Methods**

### *Species distribution modelling (SDM)*

Current and future suitable areas for rainbow trout were predicted using species distribution modelling (SDM) with Maxent based on climatic variables (Phillips et al., 2017). Maxent uses the association between environmental variables and species occurrence data to predict areas that are climatically suitable (Phillips et al., 2006). The approach has been widely applied to predict species distribution of freshwater fish (e.g., Zengeya et al., 2013; Lübcker et al., 2014; Zengeya et al., 2015; Khosa et al., 2019), and in a range of biological disciplines such as

ecology and evolutionary biology (e.g., Kearney & Porter, 2009; Elith & Leathwick, 2009; Guisan et al., 2014), impacts of climate change (e.g., Wiens et al., 2009), and biological invasions in general (e.g., Townsend & Vieglais, 2001, Broennimann & Guisan, 2008).

#### *Current bioclimatic data*

The environmental variables used to train the SDM consisted of 19 widely used bioclimatic variables (<https://www.worldclim.org/version> 2.1) downloaded at a spatial resolution of 30 arc seconds. The bioclimatic variables represent annual forecast (e.g., annual mean temperature and annual precipitation, seasonality, mean temperature of the warmest month, mean temperature of the warmest quarter and precipitation of the wettest quarter), and extreme environmental variables (e.g., temperature of the coldest and warmest month and precipitation of the wet and dry quarters). The selection of variables used to train the model can influence model performance and various methods have been used to pre-select variables (Elith et al., 2011; Zengeya et al., 2015). The current study used an iterative process to evaluate the influence of bioclimatic variable selection on model performance (Zengeya et al., 2015). The first approach took advantage of the in-built regularisation in Maxent that deals with the selection of bioclimatic variables (regulating some to zero). This process has been shown to perform well and is considered to out-perform other pre-selection procedures (Elith et al., 2011). A Spearman correlation analysis was then used to check for correlated variables ( $> 0.8$ ) (Dormann et al., 2012). Variable contribution to model performance was then checked by jack-knife analysis for each pair of correlated variables. The second approach only used variables that were pre-selected using correlation and jack-knife analysis. However, the in-built regularisation method outperformed the preselection procedure, and it was therefore used for proximal variable selection.

#### *Species data*

Occurrence data for rainbow trout were obtained from the GBIF: Global Biodiversity Information Facility

(<https://www.gbif.org/occurrence/download?q=Oncorhynchus%20mykiss>, accessed 13 July 2021), South African Institute of Aquatic Biodiversity (SAIAB), and Mpumalanga Tourism and Parks Agency (MTPA). The occurrence records were obtained from both native and introduced ranges of rainbow trout in order to achieve a better estimation of the species realised niche. The occurrence records were also checked for duplicates and inaccurate coordinates (e.g., some records were not properly geo referenced and were on sea instead of inland freshwater systems). In addition, records that had no geographic coordinates were also removed. This decreased the number of occurrence points in the final dataset from 120,707 to 15,917 records (see Appendix 1). The occurrence records were however, biased towards the native range. To prevent over representation of the associated environmental conditions in the native range, a preliminary analysis was undertaken to check for autocorrelation. This was achieved by spatially rarefying the occurrence data at 1°, 2°, 3°, 4°, and 5° using the SDM-toolbox in ArcGIS (Brown, 2014). The best model performance was obtained with data spatial rarefied to 1° (972 records), and this spatial resolution was then used to run the final models.

### *Model building*

Several modelling standards have been proposed that recommend the use of multiple techniques when modelling species distributions (e.g., Araujo et al., 2019). However, single statistical methods such as Maxent might be more appropriate when simple models are used. A Maxent model with only hinge features selected has been shown to outperform other more complex models when modelling the distributions of alien species (Elith et al., 2010). In addition, the performance of consensus models built from multiple approaches varies and it is still unclear on whether these consensus models perform better than the individual models they comprise (Hao et al., 2019). Therefore, in this study a single statistical approach (Maxent) was



used to model species distribution. Models were optimised using the following parameters: 1) a maximum number of 500 iterations; 2) a regularization multiplier of 1; 3) convergence threshold of 0.00001; 4) only hinge features selected. Clamping was selected to ensure that the models are not predicting into areas that had dissimilar environments to the selected background localities (Merow et al., 2013).

Maxent uses presence-only data and background localities to project potential suitable areas (Merow et al., 2013). The extent of this background is known to influence model performance, where a broad background can cause over-estimates and a constrained background can cause under-estimates (Van Der Wal et al., 2009). In the current study, the background was limited to areas with similar climate to known occurrence records of rainbow trout in both its native and introduced ranges. This was undertaken by overlaying the Köppen-Geiger climate classification system with the known distribution, following Thompson et al. (2011). Köppen-Geiger polygons indicate areas with similar climates and a given climate zone was included as part of the background if it contained an occurrence record within the range of rainbow trout using ArcMap® 10.4 (ArcGIS™; ESRI®, Redlands, CA, U.S.A.). By selecting the entire climatic zone, an intermediate background size was obtained, compensating for areas in the introduced ranges that had few occurrence records (Van Der Wal et al., 2009). Each model was then calibrated with 10000 pseudo-absence points randomly from the defined background (Phillips & Dudik, 2008). Model evaluation was done using cross validation, where occurrence records were randomly partitioned into a calibration set (70% of all records) and a testing set (30%) using k-fold partitioning (Phillips et al., 2006). This involved splitting the occurrences records into 10 replicate folds and each fold was then used in turn for test data. A consensus map was then created as an average of the 10 iterations. Several different methods have been used to select thresholds of occurrence, and the choice of an appropriate method is dependent on type of data that is available and questions the study intends to address (Pearson,

2007, Liu et al., 2016). In this study model output was set to logistic format and an equal training sensitivity and specificity threshold rule was applied where areas with a probability  $\geq 0.5$  were taken as climatically suitable and those below were taken as not suitable. Rainbow trout is a cold-water species that has a restricted range in South Africa where it occurs only in areas that experience low water temperatures (10-20 °C) (Rivers- Moore et al., 2019; Weyl et al., 2020). A high threshold value (0.5) was therefore chosen to minimise the risk of identifying unsuitable sites by identifying only areas with highest suitability (Pearce & Ferrier, 2000; Pearson, 2007).

#### *Model evaluation*

The performance of the model was assessed using a receiver operating characteristic curve (ROC) which measures the discrimination ability (between presence and background) of the models where values  $\leq 0.5$  indicate random predictions and values between 0.8 and 1.0 indicate acceptable predictions (Swets, 1988). Model performance was assessed as fair (when AUC values were between 0.8 and 0.9), good (0.9 - 0.95) and excellent ( $> 0.95$ ), following Thuiller et al. (2006). Although the AUC statistic has widely been used to validate niche models (Philips et al., 2006; Elith et al., 2011), it is not necessarily an appropriate measure for presence-only model evaluation (Boyce et al., 2002). Consequently, model performance was further assessed using the Continuous Boyce Index (CBI) (Boyce et al., 2002). The CBI evaluates the ability of habitat suitability models to predict the presence of a species in a given area. It is continuous, and values may range from -1 to 1, with negative values indicating models that predict worse than random, and the positive values indicating models that are consistent with presence distribution in the evaluation dataset.

### *Climate change*

Climate change models were built using projected climate data for 30 years (2050: 2041-2060) and 50 years (2070: 2061-2080) that were obtained from recent climate projections by the IPCC Fifth Assessment Report (IPPC, 2014). The data used were downloaded under one Global Climate Models (Access-1.0, CSIRO-BOM, Australia; <http://www.worldclim.org>). For each period, the data was simulated under two Representative Concentration Pathways (RCPs) scenario RCP 4.5 and RCP 8.5. The scenarios were selected to make a comparison between a scenario that is likely to occur (RCP 4.5) and a worst-case scenario that is highly unlikely to occur (RCP 8.5) (Hausfather & Peters, 2020). The RCP 4.5 scenario represents CO<sub>2</sub> emissions that stabilise without overshoot to ~ 650 ppm by 2100, whereas RCP 8.5 represents CO<sub>2</sub> emissions that continued to rise under the current trajectory to ~ 1370 ppm by 2100 (Moss et al., 2010). Under the RCP 4.5 scenario temperature is predicted to increase by between 0.9 to 2 °C in 2050 and 1.1 to 2.6 °C in 2070, while under the RCP 8.5 scenario it is projected to increase by 1.4 to 2.6 °C in 2050 and 2.6 to 4.8 °C in 2070 (IPPC, 2014). These scenarios have previously been used to predict the potential impact of climate change on fish distribution (e.g., Merriam et al., 2017; Shechonge et al., 2019). Bioclim variables for the two climate models and emission scenarios were obtained from Worldclim v.2.1 (<http://www.worldclim.org>). Variables were downloaded at a spatial resolution of 30 arc seconds and were prepared in ArcMap® 10.4 (ArcGIS™; ESRI®, Redlands, CA, U.S.A.). Models were then developed using the same methods as outlined for current climate models.

### *Area-based invasion debt under current climate*

Area-based invasion debt represents the difference between the area where a species is currently known to have established (i.e., occupancy) and areas that are predicted to be climatically suitable but are still invasion-free (Rouget et al., 2016). For species that are already invasive in a region, area-based invasion debt is composed of: 1) the climatic suitability of a

region for each species and occupancy; and 2) the rate of spread (both natural and human-mediated) of that species (Rouget et al., 2016). A deductive qualitative threshold was used to assess the current introduction status of rainbow trout in South Africa following Khosa et al. (2019). Rainbow trout were considered invasive in the country because there are known to have naturalised in more than 10% of the quaternary catchments. Niche models were then used to delineate areas that were climatically suitable for rainbow trout under the current climate.

Occupancy was inferred from areas designated as trout areas by the Mpumalanga Nature Conservation Act No. 10 of 1998 and the Department of Forestry, Fisheries and the Environment-South African National Biodiversity Institute (DFFE-SANBI) consultative mapping areas exercise that delineated areas where rainbow trout is known to occur in Mpumalanga Province. The Department of Forestry, Fisheries and the Environment (DFFE) initiated a mapping exercise in consultation with provincial conservation authorities, angling agencies and the aquaculture industry to delineate areas where trout are known to occur. The main tenant for this mapping process was that utilisation of rainbow trout will be allowed in areas where it has naturalised and in areas where it has been historically stocked for a put and take fishery. These maps should, however, be viewed with a low degree of confidence because they are based on expert opinion and have not been verified through a formal mapping process that is based on recent surveys with adequate ground-truthing.

The river length (km) that is suitable for rainbow trout under current climate conditions and with known rainbow trout occupancy (river length in quaternary catchments with known occurrence records from the mapping exercise) was then derived and extracted from the SDMs in each quaternary catchment and designated a value of 1, and a 0 was designated to river streams without known occurrence for rainbow trout. River segments that were predicted as unsuitable but had known rainbow trout occupancy were not considered in the area-based invasion debt calculations. The South African River shapefile (scale 1: 500,000) was

downloaded from the Department of Water Affairs, South Africa (<http://www.dwaf.gov.za/iwqs>). The area-based invasion debt analysis was undertaken using ArcMap® 10.4 (ArcGIS™; ESRI®, Redlands, CA, U.S.A.).

## Results

### *Current climate*

The areas that were predicted as climatically suitable for rainbow trout were mainly located in quaternary catchments in the Olifants and Komati Water Management Areas (Figure 2.1). Model performance was good (AUC = 0.94; CBI = 0.9) and the bioclimatic variables that contributed most to model performance were mean temperature of the coldest quarter (37%), isothermality (37%), and annual mean temperature (10%) (Table 2.1).

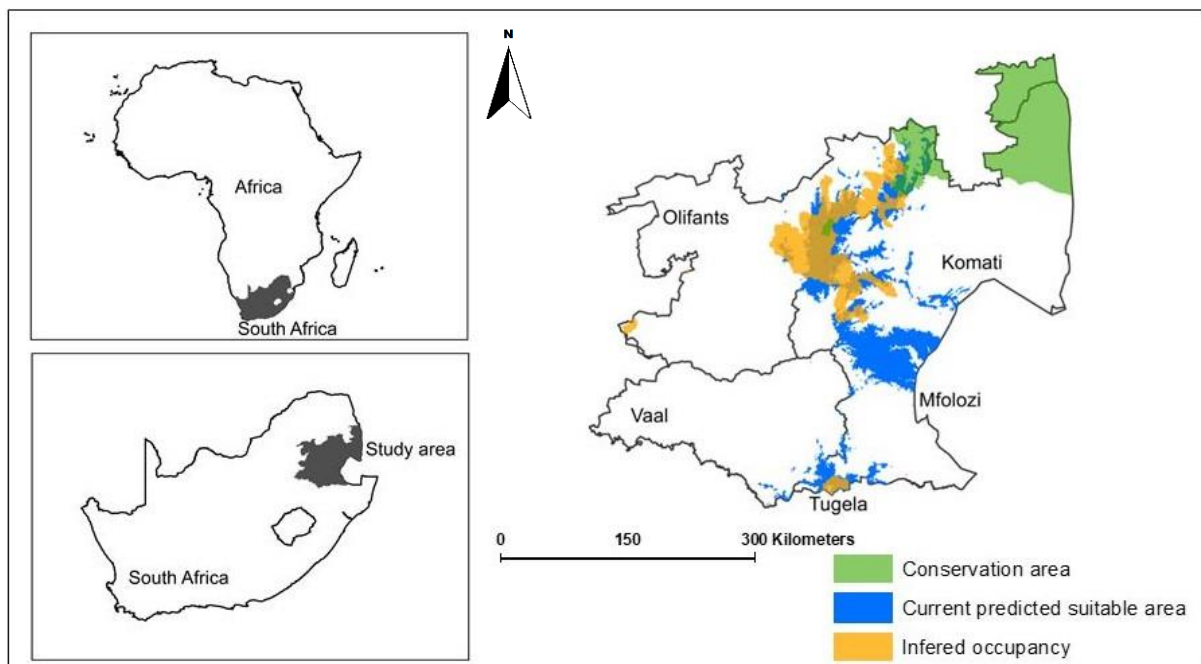


**Figure 2.1:** The predicted distributional range of rainbow trout (*Oncorhynchus mykiss*) across five Water Management Areas (Komati, Mfolozi, Olifants, Vaal and Tugela) in Mpumalanga Province, South Africa. Areas with predicted suitable conditions are indicated by blue, current distribution (occupancy) of rainbow trout in yellow, and protected conservation areas in green. Insert the maps of Africa (top left) and South Africa (bottom left).

The response curves indicated that the areas predicted as climatically suitable for rainbow trout had a mean temperature of the coldest quarter that ranged between -14 to 4°C, isothermality (28-46), and annual mean temperature (4-15 °C) (see Appendix 2.1). The variable with the most useful information by itself was the mean temperature of the coldest quarter, and the variable with the most information that was not present in the other bioclimatic variables was isothermality (see Appendix 2.2).

**Table 2.1:** Bioclimatic variables and their percentage contribution to model performance for predicted distributional range of rainbow trout (*Oncorhynchus mykiss*) under current and future (2050 and 2070) climatic conditions in Mpumalanga Province, South Africa. Two Representative Concentration Pathways (RCPs) scenarios (RCP 4.5 and RCP 8.5) were used to build the future climate change models.

| Climatic variables                                                | Current<br>climate | 2050       |         | 2070    |         |
|-------------------------------------------------------------------|--------------------|------------|---------|---------|---------|
|                                                                   |                    | RCP<br>4.5 | RCP 8.5 | RCP 4.5 | RCP 8.5 |
| BIO1 = Annual Mean Temperature                                    | 9.6                | 4.7        | 1.2     | 2.0     | 3.0     |
| BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)) | 0.8                | 1.1        | 1.4     | 1.1     | 1.7     |
| BIO3 = Isothermality (BIO2/BIO7) (* 100)                          | 36.6               | 37.3       | 69.0    | 53.6    | 53.3    |
| BIO4 = Temperature Seasonality (standard deviation *100)          | 0.9                | 0.3        | 0.9     | 1.5     | 1.4     |
| BIO5 = Max Temperature of Warmest Month                           | 0.9                | 0.6        | 1.4     | 0.6     | 1.1     |
| BIO6 = Min Temperature of Coldest Month                           | 0.8                | 17.0       | 0.5     | 3.7     | 0.5     |
| BIO7 = Temperature Annual Range (BIO5-BIO6)                       | 1.0                | 0.6        | 1.7     | 0.7     | 0.7     |
| BIO8 = Mean Temperature of Wettest Quarter                        | 0.8                | 2.0        | 0.2     | 2.0     | 0.3     |
| BIO9 = Mean Temperature of Driest Quarter                         | 0.4                | 0.1        | 0.9     | 0.2     | 0.3     |
| BIO10 = Mean Temperature of Warmest Quarter                       | 2.9                | 1.7        | 0.6     | 1.4     | 1.3     |
| BIO11 = Mean Temperature of Coldest Quarter                       | 36.7               | 27.8       | 6.7     | 27.1    | 30.3    |
| BIO12 = Annual Precipitation                                      | 0.0                | 0.0        | 0.3     | 0.0     | 0.1     |
| BIO13 = Precipitation of Wettest Month                            | 0.3                | 0.4        | 0.3     | 0.3     | 0.1     |
| BIO14 = Precipitation of Driest Month                             | 0.4                | 0.1        | 0.3     | 0.0     | 0.2     |
| BIO15 = Precipitation Seasonality (Coefficient of Variation)      | 0.3                | 0.3        | 0.3     | 0.7     | 0.5     |
| BIO16 = Precipitation of Wettest Quarter                          | 0.4                | 0.2        | 0.6     | 0.1     | 0.1     |
| BIO17 = Precipitation of Driest Quarter                           | 0.0                | 0.0        | 0.1     | 0.0     | 0.0     |
| BIO18 = Precipitation of Warmest Quarter                          | 0.8                | 0.8        | 0.2     | 0.3     | 0.3     |
| BIO19 = Precipitation of Coldest Quarter                          | 6.2                | 5.0        | 13.5    | 4.6     | 4.8     |

### *Current climate area-based invasion debt*

The total river length that was predicted as suitable for rainbow trout was *ca.* 3500 km in an extension of *ca.* 15,000 km (Table 2.2). Current occupancy (river lengths that were predicted as suitable and have known rainbow trout occurrence records) was *ca.* 1300 km (35%) and the invasion debt was therefore estimated as 65% (Figure 2.1). The river length predicted as unsuitable was *ca.* 11,400 km in an area of 15,000 km with an occupancy of *ca.* 720 km (6% of the unsuitable area).

### *Projected impact of climate change on the introduced range*

The river length that was predicted as suitable for rainbow trout in the current climate (*ca.* 3500 km) is projected to decrease by 67% in 2050 and by 14% in 2070 under the RCP 4.5 scenario (Figure 2.2a and b). In contrast, projections under the RCP 8.5 scenarios showed an overall increase in the extent of suitable area of 81% in 2050 and 20% in 2070 (Figure 2.2b and c). The extent of river length suitable for rainbow trout in conservation areas is expected to increase from 13% (*ca.* 450 km) in the current climate to over 14% in all the future RCP scenarios except RCP 4.5 2050 (Table 2.2). Additional information on variable contribution to model performance is provided in Appendix 2.3-2.10.

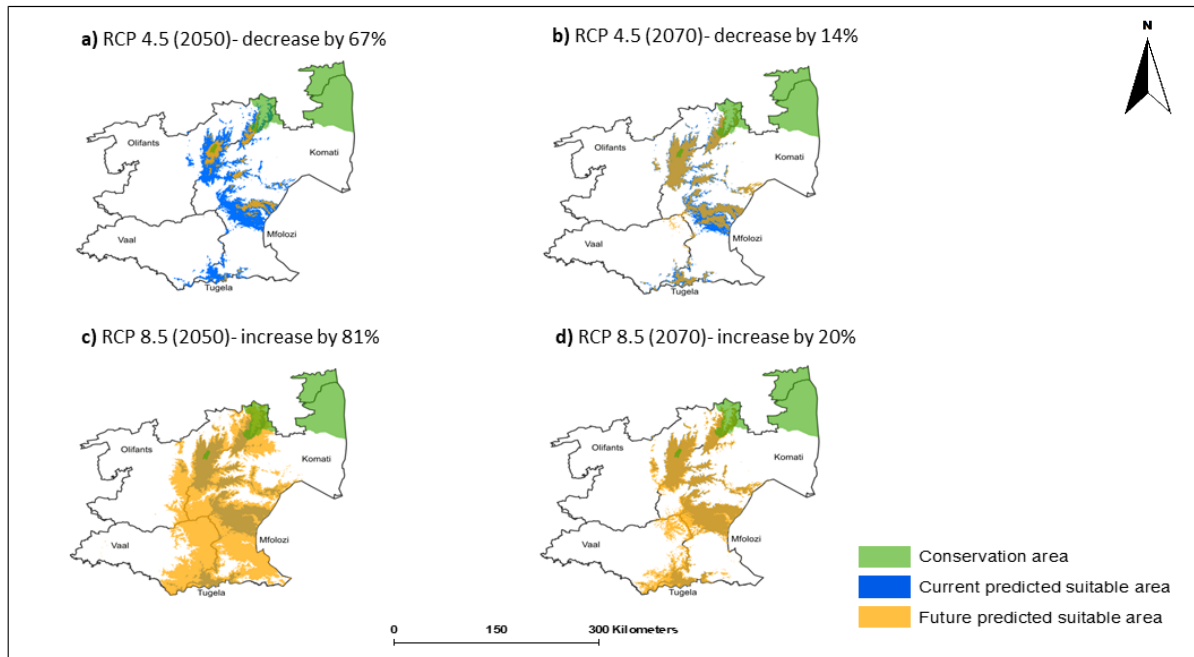


**Figure 2.2:** Projected changes in the extent of areas that were predicted as climatically suitable for rainbow trout (*Oncorhynchus mykiss*) in Mpumalanga Province, South Africa between 2050 and 2070 based on two Representative Concentration Pathways (RCP 4.5 and 8.5) scenarios: a) RCP 4.5 (2050), b) RCP 4.5 (2070), c) RCP 8.5 (2050), and d) RCP 8.5 (2070).

**Table 2.2:** The extent of river length that is predicted as suitable for rainbow trout (*Oncorhynchus mykiss*) under current and future (2050 and 2070) climatic conditions in Mpumalanga Province, South Africa. Two Representative Concentration Pathways (RCPs) scenarios (RCP 4.5 and RCP 8.5) were used to build the future climate change models.

| Climate scenario | Predicted suitable river length (km) | Predicted suitable river length (km) in conservation area |
|------------------|--------------------------------------|-----------------------------------------------------------|
| Current          | Ca. 3455.8                           | Ca. 431.6                                                 |
| RCP 4.5 2050     | Ca. 1142.6                           | Ca. 188.1                                                 |
| RCP 4.5 2070     | Ca. 2989.6                           | Ca. 489.6                                                 |
| RCP 8.5 2050     | Ca. 6285.7                           | Ca. 678.6                                                 |
| RCP 8.5 2070     | Ca. 4149.7                           | Ca. 532.3                                                 |



## Discussion

This study evaluated the extent of rainbow trout invasion in river systems in Mpumalanga Province, South Africa, and assessed how current and future climatic scenarios could affect its potential invasive range. The study evaluated the hypothesis that rainbow trout has a low spread debt in the Mpumalanga Province because sustained and widespread stocking in pre-selected suitable receiving environments might have allowed the species to establish in most of the areas where it has been introduced. There was no evidence to support this assertion, instead rainbow trout had a high invasion debt, and it has not established in most areas that were predicted as climatically suitable under current climate.

The predicted potential geographic range of rainbow trout in Mpumalanga Province shows an invasive potential over most of the Olifants and Komati catchments in the northern and central regions of the province. The bioclimatic variable that contributed most to the model performance was mean temperature of the coldest month. Temperature is a critical variable that determines suitable environments for the occurrence of rainbow trout (Matthews & Berg, 1997). The area that was predicted as climatic suitable for rainbow trout is known to be among the coldest regions in the province with a low average air temperature of 14 °C during winter and an annual average of 22 °C. This was reflected in the response curves which showed that the areas that were predicted as suitable for rainbow trout were mainly associated with areas that had cool annual mean temperatures (4-15 °C). This is consistent with other studies elsewhere in South Africa that have shown that low temperature is the primary variable that influences the invasions by rainbow trout (Ellender et al., 2011; Shelton et al., 2018; Rivers-Moore et al., 2019).

The results of this study are also consistent with previous assertions that have shown that despite sustained introduction effort, there is still a considerable area-based invasion debt for rainbow trout in some parts of the country (Ellender et al., 2016; Rivers-Moore et al., 2019).

Of the *ca.* 3500 km river length that was predicted to be suitable for rainbow trout in the province, only 35% is currently occupied, and the area-based invasion debt was estimated at 65%. There are several reasons that could account for such a high invasion debt, and these include natural and man-made barriers that impede fish migration, natural thermal barriers that obstruct fish migration, insufficient stocking efforts, protected areas where fish introductions are prohibited, anthropogenic activities e.g., mining and pollution from urban areas that make some river habitats unsuitable for aquatic fauna.

For example, Ellender et al. (2016) found a high invasion debt of trout in the upper Keiskamma catchments in the Eastern Cape and attributed this to limited fish migration due to stream fragmentation by impoundments. In addition, the impoundments also resulted in thermal barriers that influenced fish migrations between river sections. There is a natural thermal gradient between upper river sections and middle to lower sections where river reaches located at high altitude tend to have cooler water temperatures than river reaches located at lower altitude. Trout are cold-water species and are naturally restricted to the upper catchments during summer and migrate downstream during winter when temperature decreases (Ellender et al., 2016). A similar pattern was observed by Shelton et al. (2018) in Cape Fold Ecoregion where high temperatures in summer limited trout density and resulted in more localised occurrences at sites that remained relatively cool, and trout were generally absent from relatively warm sites - indicating seasonal migration between suitable sites.

Natural biogeographic barriers can also influence the potential spread of trout from points of introduction to potential suitable areas by preventing upstream migration of fish. For example, in Blyde River, trout were introduced to some sections of the river below the Christmas Pool falls but not in upper river sections above the falls (Engelbrecht & Roux, 1998). The waterfalls act as a natural barrier to upstream fish migration and as a result the river sections above the falls, although suitable for trout are still invasion free. In addition, the upper

river section above the falls were also declared a natural heritage conservation area, so human facilitated introductions are prohibited. Similarly, other areas that might be suitable for trout are located in conservation areas, where the introduction of trout is prohibited. The area currently designated as conservation areas in Mpumalanga Province is about *ca.* 2500 km<sup>2</sup> in extent and about 12.5% of the area is predicted as suitable for rainbow trout. The conservation area includes upper catchments of several river systems that are designated as fish sanctuaries for endemic river minnows that are threatened by human activities such as alien fish introductions. For example, the catchment of the Treur River is within the Blyde River Canyon Nature Reserve which is designated as a protected area partly because the Treur River is inhabited by the endemic *Enteromius treurensis* Groenewald, 1958 (Treur River barb) that is listed as critically endangered because of alien predatory fish such as rainbow trout, brown trout and *Micropterus dolomieu* (Lacepède, 1802) (smallmouth bass) (Roux & Hoffman, 2017).

Anthropogenic activities such as mining can also alter stream habitats, for example gold mining activities have been implicated in a decline and fragmentation of fish communities in the upper Blyde River catchment (Kleynhans, 1987). Water abstraction is another form of anthropogenic activity that was reported to causes destruction in fish habitats in South Africa, resulting in limited fish distribution. In the Cape Floristic Region and the Olifants River system, water abstraction leads to low river flows in dry and hot summer months limiting the availability of suitable habitats for species such as *Austroglanis barnard* (Skelton, 1981) (Barnard's rock catfish) and *Austroglanis gilli* (Barnard, 1943) (Clanwilliam rock catfish) (Weyl et al., 2014).

There are currently > 200 localities with the confirmed occurrence of rainbow trout in South Africa, and this may not represent a true reflection of current occurrence of the species due to the paucity of confirmed occurrence data. This maybe an artefact of low sampling effort rather than low spread rate. This notion is supported by the fact that the government led

consultative mapping stakeholder process indicates that trout might occur over a wider range than what is currently indicated from documented occurrence records. However, this exercise was based on expert opinion and needs to be verified through a formal ground truthing survey. A more accurate spread rate estimate could be given with verified survey records that can be used to predict an informed spread debt over a specific time frame.

### *Climate change*

The extent of the suitable area for rainbow trout in Mpumalanga Province varied under different climate change scenarios where it was projected to decrease under RCP 4.5 scenarios and increase under the RCP 8.5 scenarios. The significant shifts in the extent of area suitable for rainbow trout under the two scenarios was mainly attributed to changes in isothermality and the mean temperature of the coldest quarter. Isothermality is a measure of how diurnal temperature range fluctuates relative to annual temperature range, and there was a decline in the area predicted as suitable under the RCP 4.5 scenarios when seasonality is projected to be high. Other studies have also predicted that rainbow trout distribution may be influenced by larger temperature fluctuations within a month relative to the year (Ellender et al., 2016; Santiago et al., 2016; Shelton et al., 2018; Rivers-Moore et al., 2019). The increase in suitable area under the RCP 8.5 scenarios was unexpected and was largely due to a projected increase in the minimum temperatures from 11 to 15°C that resulted in a large proportion of the study area that occurs at lower altitudes and experiences warmer minimum water temperatures been predicted as suitable. We take cognisance that other variables (e.g. thermal thresholds) influence rainbow trout distributions and the larger proportion of area predicted as suitable for rainbow trout under a warming climate might be a modelling artifact that might be resolved by including mechanistic variables in the models (e.g., Kearney and Porter 2009, Evans et al., 2015; Rivers-Moore et al., 2019).

### *Management implications*

The management of rainbow trout in South Africa is contentious because of different value systems between stakeholders and conservation authorities (Woodfrod et al., 2016; Zengeya et al., 2017). Part of the management initiatives for rainbow trout includes managing it by area where utilisation is allowed in areas where it has established and in areas where it has been historically utilised for stocking (Ellender et al., 2014; Woodford et al., 2017). This management approach requires, accurate occurrence data to work effectively and reduce contestations around known trout distribution. The current records available on trout distribution in South Africa are limited and were mostly generated through stakeholder-government initiatives using expert opinion to map areas of occurrence. These records, however, have drawbacks that compromise their accuracy because they have not been verified, and highlight the need for regular monitoring programmes to generate long term distribution data for alien species in freshwater systems around the country. The findings of this study compliment this stakeholder-government initiative to map the distribution of trout by projecting potential suitable areas of occurrence and how the distribution is likely to be affected by climate change. The results indicated that rainbow trout only occupies a fraction of the current potential suitable river length in Mpumalanga Province which implies that there is a high area-based invasion debt and there is a risk that it may spread further. The large unoccupied projected suitable area may also imply that the range of current distribution of trout in Mpumalanga province may be wider than indicated, given the lack of ground truthing for verification of occurrence. This is especially worrying given that several studies have shown that trout can have a significant effect on fish communities and that there is a need to prevent human-facilitated introductions in biodiversity sensitive areas such as mountain headwater streams that are inhabited by endemic and range restricted minnows (e.g., Weyl et al., 2020; Maimela et al., 2021). It is also likely that if there is a range shift in suitable habitats for trout

due to climate change, new conflicts might arise due to the need to exploit suitable areas that are not currently designated as trout areas (Rivers-Moore et al., 2019).

The major findings of this study are that, there is a high invasion debt for trout in river systems in Mpumalanga Province and the areas predicted as suitable for trout in the province might not be static and are likely to shift with climate change. The estimates are however compounded by a lack of verified occurrence data and should be recognised as a high estimate, that can be improved upon through the establishment of regular monitoring to accurately document trout occurrence in the country.

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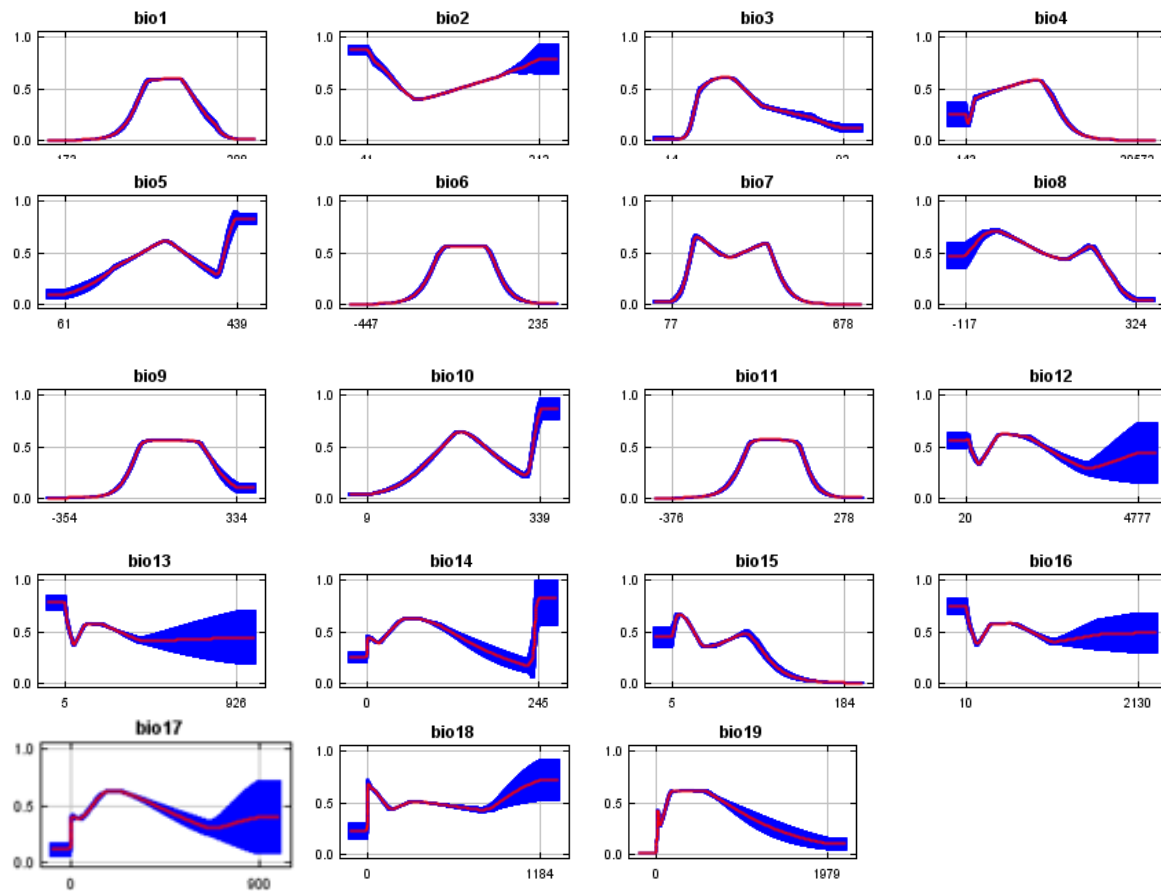
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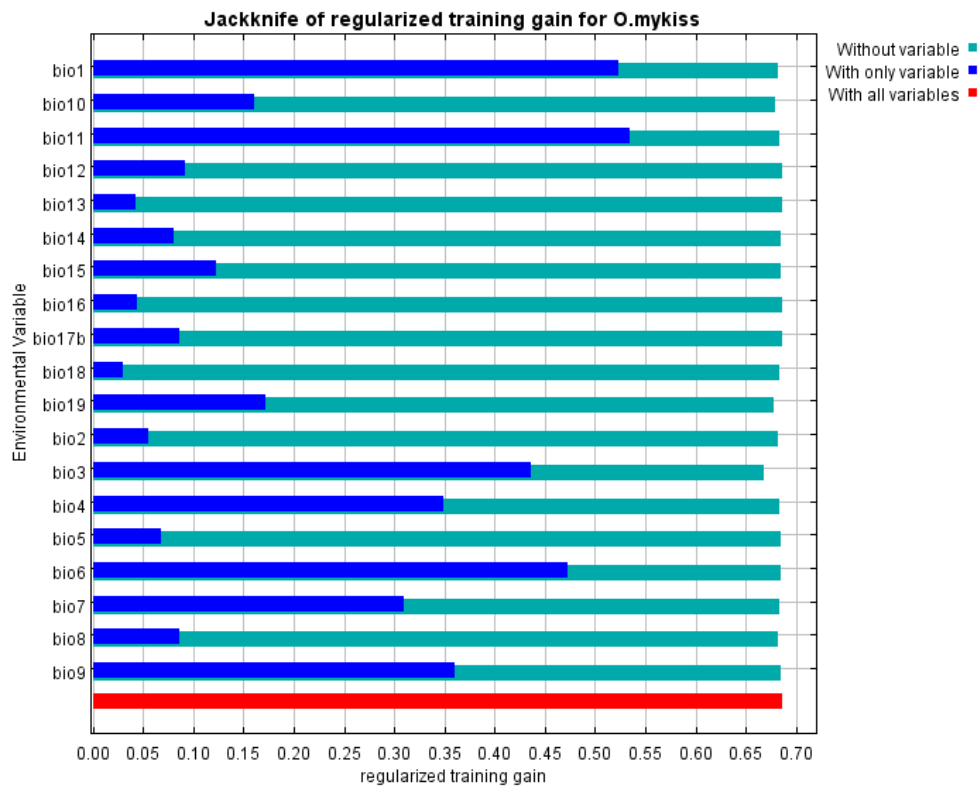
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## Appendices

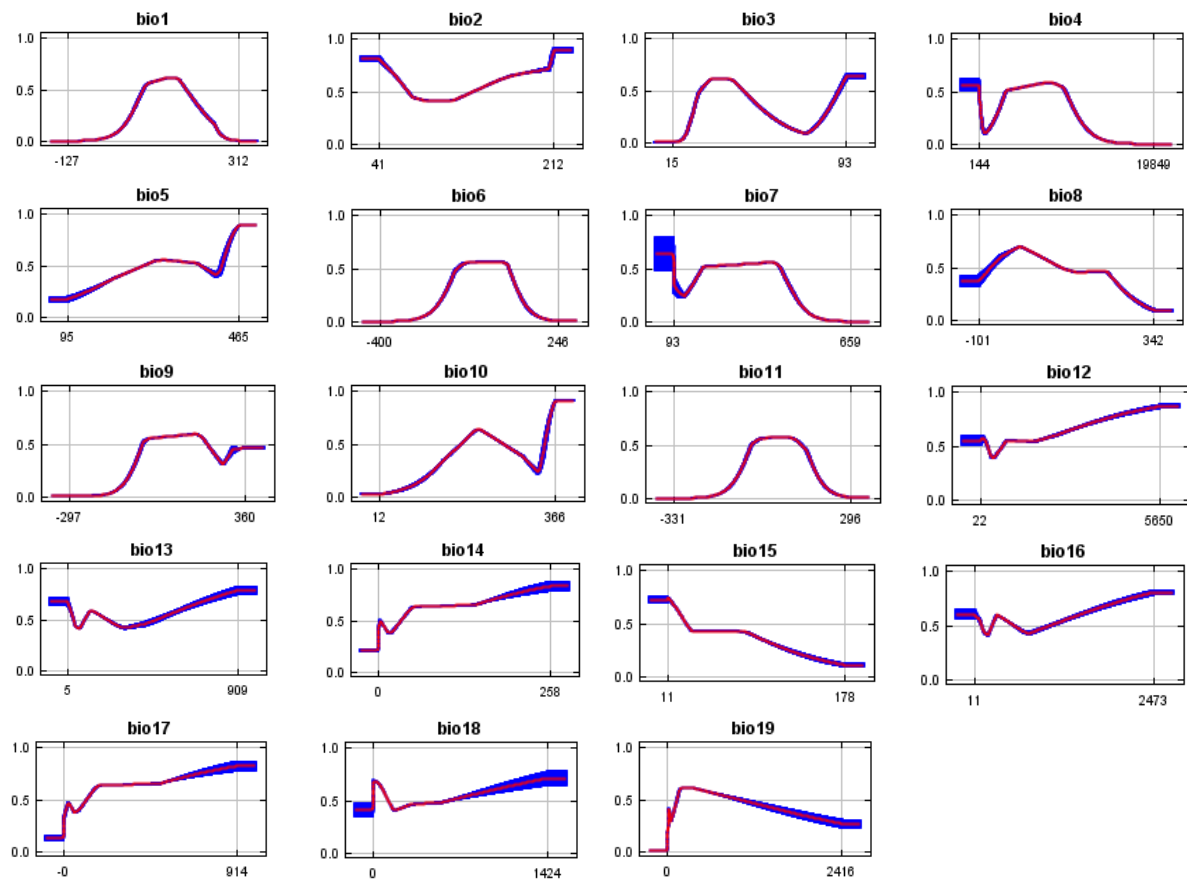


**Appendix 2.1:** Response curves obtained from models used to project for current distribution of rainbow trout (*Oncorhynchus mykiss*) in Mpumalanga Province, South Africa. BIO1 = Annual Mean Temperature, BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)), BIO3 = Isothermality (BIO2/BIO7) (\* 100), BIO4 = Temperature Seasonality (standard deviation \*100), BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO7 = Temperature Annual Range (BIO5-BIO6), BIO8 = Mean Temperature of Wettest Quarter, BIO9 = Mean Temperature of Driest Quarter, BIO10 = Mean Temperature of Warmest Quarter, BIO11 = Mean Temperature of Coldest Quarter, BIO12 = Annual Precipitation, BIO13 = Precipitation of Wettest Month, BIO14 = Precipitation of Driest Month, BIO15 = Precipitation Seasonality (Coefficient of Variation), BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter, BIO18 = Precipitation of Warmest Quarter, BIO19 = Precipitation of Coldest Quarter. Note that temperature values are in °C \* 10 (i.e. 354= 35.4 °C) and the precipitation data is in mm.

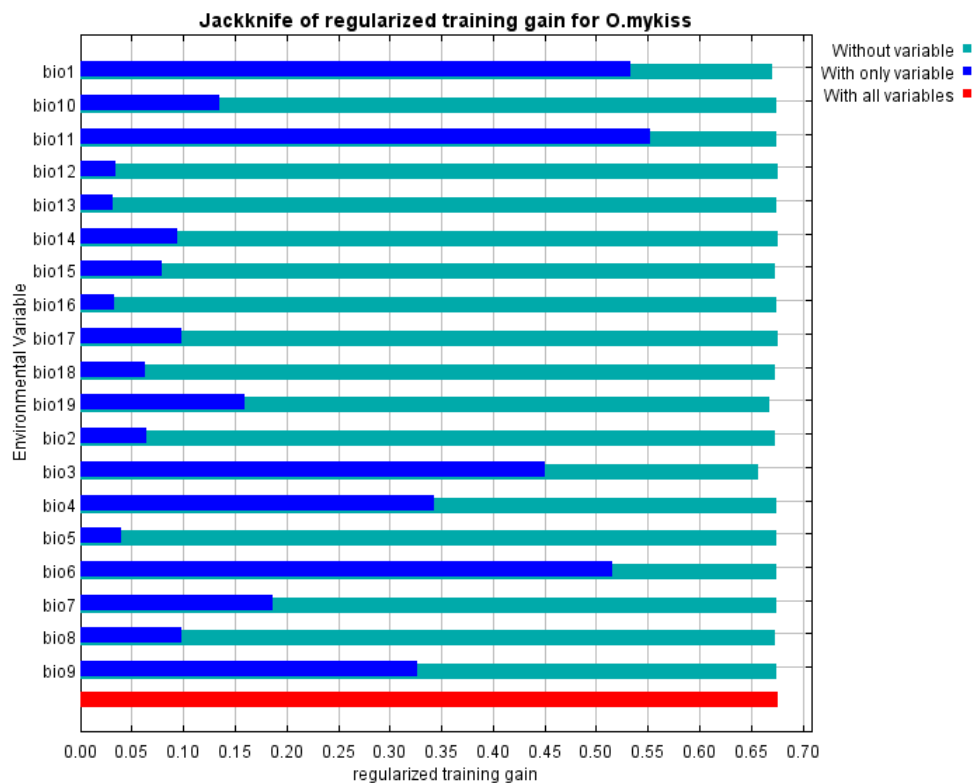


**Appendix 2.2:** Jack-knife test results for predicted current distribution of rainbow trout (*Oncorhynchus mykiss*) in Mpumalanga Province, South Africa. BIO1 = Annual Mean Temperature, BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)), BIO3 = Isothermality (BIO2/BIO7) (\* 100), BIO4 = Temperature Seasonality (standard deviation \*100), BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO7 = Temperature Annual Range (BIO5-BIO6), BIO8 = Mean Temperature of Wettest Quarter, BIO9 = Mean Temperature of Driest Quarter, BIO10 = Mean Temperature of Warmest Quarter, BIO11 = Mean Temperature of Coldest Quarter, BIO12 = Annual Precipitation, BIO13 = Precipitation of Wettest Month, BIO14 = Precipitation of Driest Month, BIO15 = Precipitation Seasonality (Coefficient of Variation), BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter, BIO18 = Precipitation of Warmest Quarter, BIO19 = Precipitation of Coldest Quarter.

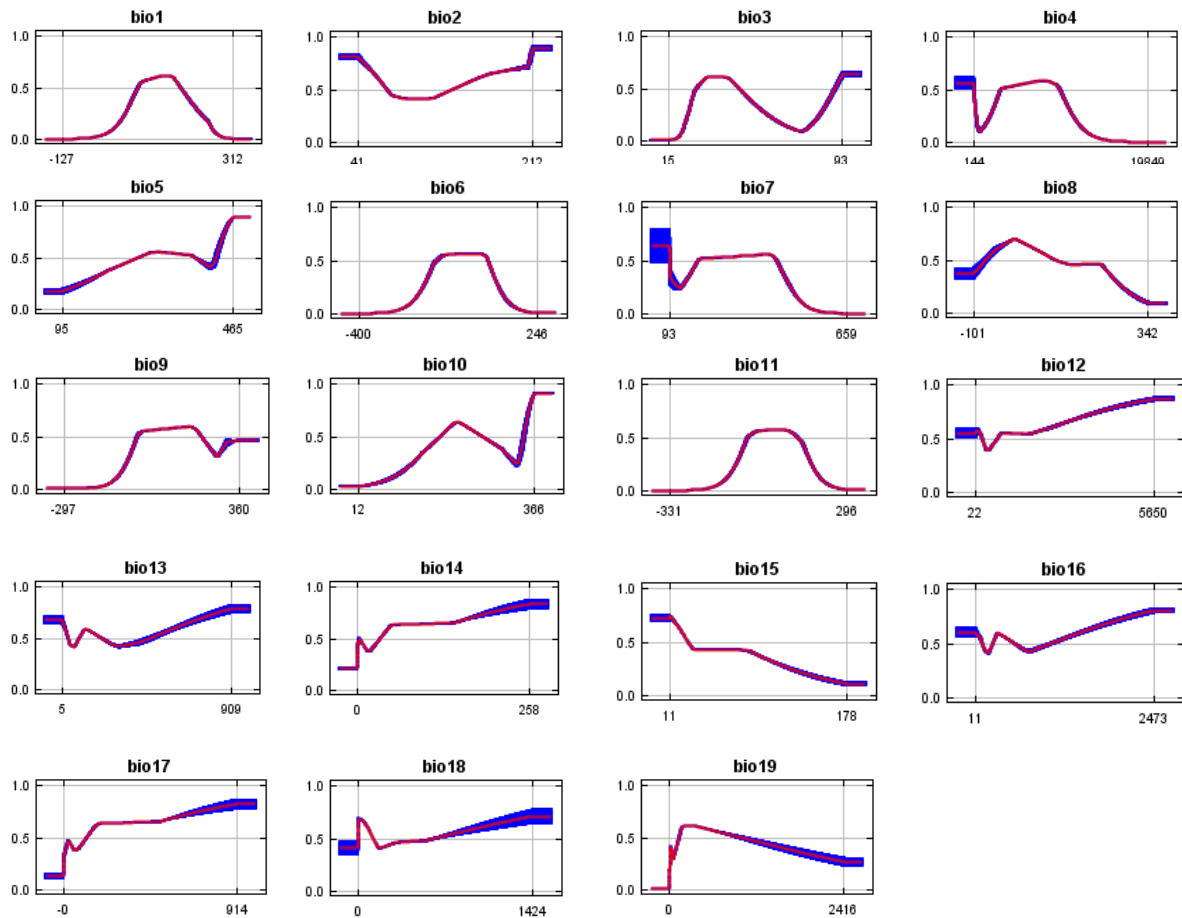




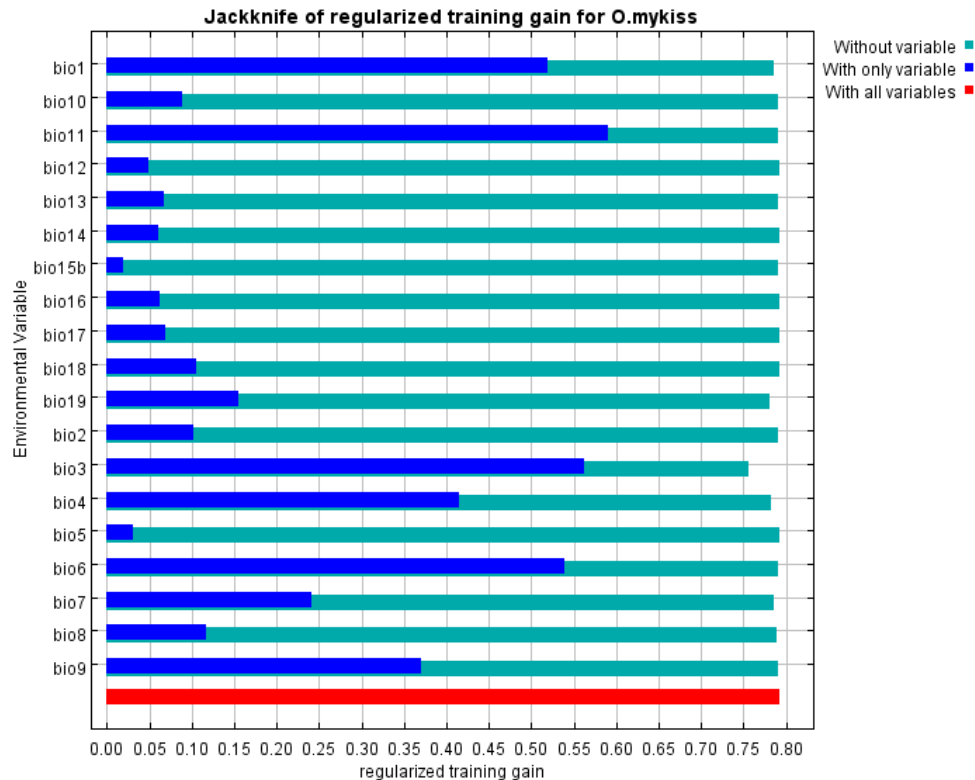
**Appendix 2.3:** Response curves obtained from models used to project for RCP 4.5 (2050) scenario distribution of rainbow trout (*Oncorhynchus mykiss*) in Mpumalanga Province South Africa. BIO1 = Annual Mean Temperature, BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)), BIO3 = Isothermality (BIO2/BIO7) (\* 100), BIO4 = Temperature Seasonality (standard deviation \*100), BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO7 = Temperature Annual Range (BIO5-BIO6), BIO8 = Mean Temperature of Wettest Quarter, BIO9 = Mean Temperature of Driest Quarter, BIO10 = Mean Temperature of Warmest Quarter, BIO11 = Mean Temperature of Coldest Quarter, BIO12 = Annual Precipitation, BIO13 = Precipitation of Wettest Month, BIO14 = Precipitation of Driest Month, BIO15 = Precipitation Seasonality (Coefficient of Variation), BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter, BIO18 = Precipitation of Warmest Quarter, BIO19 = Precipitation of Coldest Quarter. Note that temperature values are in  $^{\circ}\text{C} * 10$  (i.e. 354= 35.4  $^{\circ}\text{C}$ ) and the precipitation data is in mm.



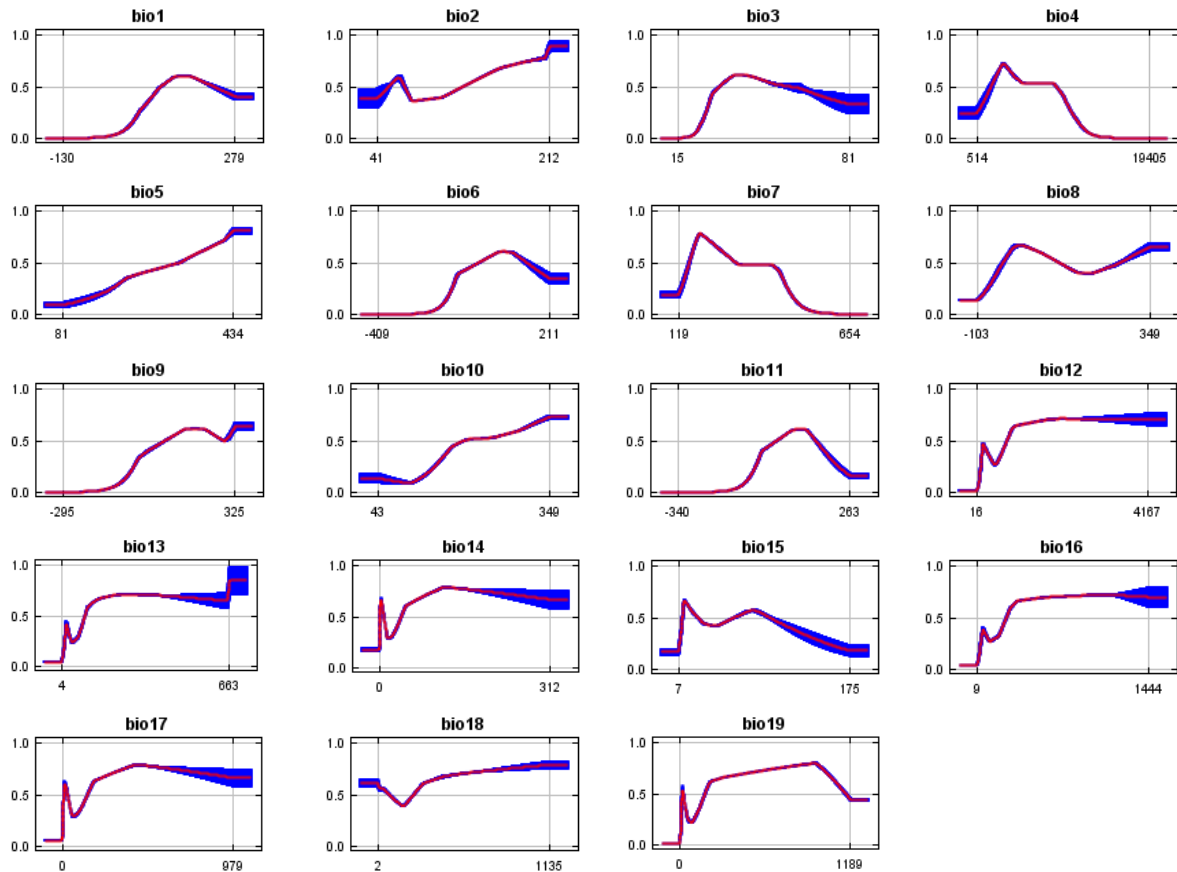
**Appendix 2.4:** Jack-knife test results obtained from models used to project for rainbow trout (*Oncorhynchus mykiss*) distribution under RCP 4.5 (2050) in Mpumalanga Province, South Africa. BIO1 = Annual Mean Temperature, BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)), BIO3 = Isothermality (BIO2/BIO7) (\* 100), BIO4 = Temperature Seasonality (standard deviation \*100), BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO7 = Temperature Annual Range (BIO5-BIO6), BIO8 = Mean Temperature of Wettest Quarter, BIO9 = Mean Temperature of Driest Quarter, BIO10 = Mean Temperature of Warmest Quarter, BIO11 = Mean Temperature of Coldest Quarter, BIO12 = Annual Precipitation, BIO13 = Precipitation of Wettest Month, BIO14 = Precipitation of Driest Month, BIO15 = Precipitation Seasonality (Coefficient of Variation), BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter, BIO18 = Precipitation of Warmest Quarter, BIO19 = Precipitation of Coldest Quarter.



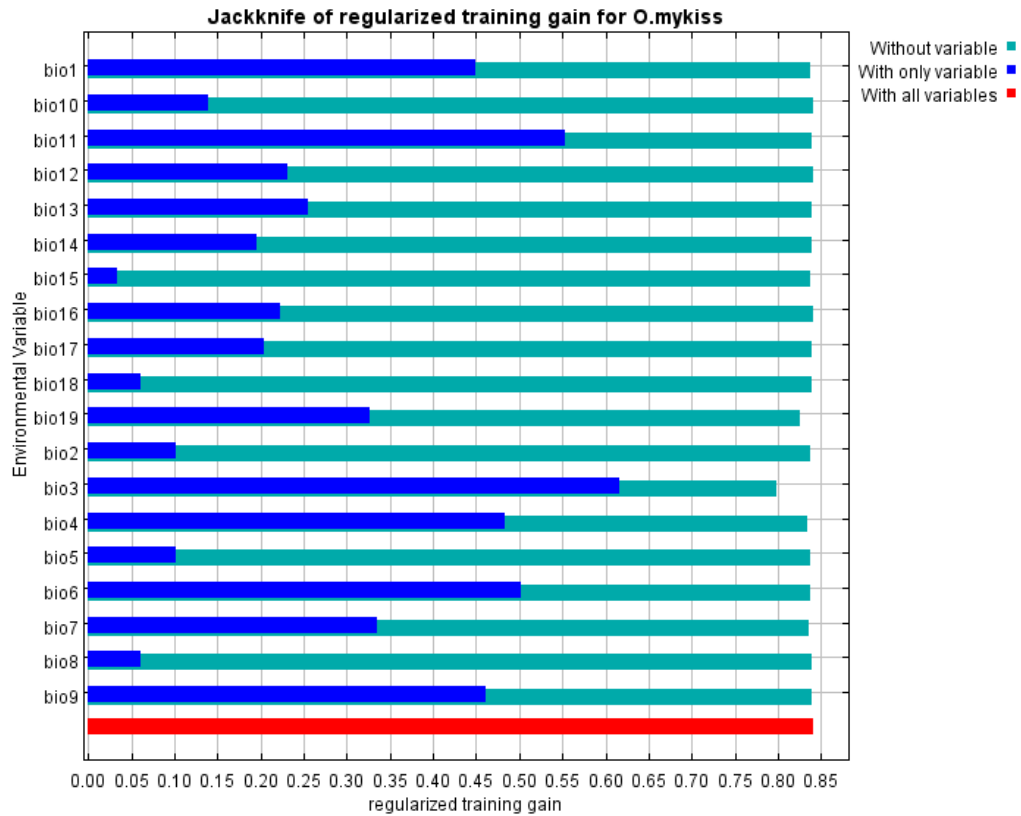
**Appendix 2.5:** Response curves obtained from models used to project for RCP 4.5 (2070) scenario distribution of rainbow trout (*Oncorhynchus mykiss*) in Mpumalanga Province South Africa. BIO1 = Annual Mean Temperature, BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)), BIO3 = Isothermality (BIO2/BIO7) (\* 100), BIO4 = Temperature Seasonality (standard deviation \*100), BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO7 = Temperature Annual Range (BIO5-BIO6), BIO8 = Mean Temperature of Wettest Quarter, BIO9 = Mean Temperature of Driest Quarter, BIO10 = Mean Temperature of Warmest Quarter, BIO11 = Mean Temperature of Coldest Quarter, BIO12 = Annual Precipitation, BIO13 = Precipitation of Wettest Month, BIO14 = Precipitation of Driest Month, BIO15 = Precipitation Seasonality (Coefficient of Variation), BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter, BIO18 = Precipitation of Warmest Quarter, BIO19 = Precipitation of Coldest Quarter. Note that temperature values are in °C \* 10 ( i.e. 354= 35.4 °C) and the precipitation data is in mm.



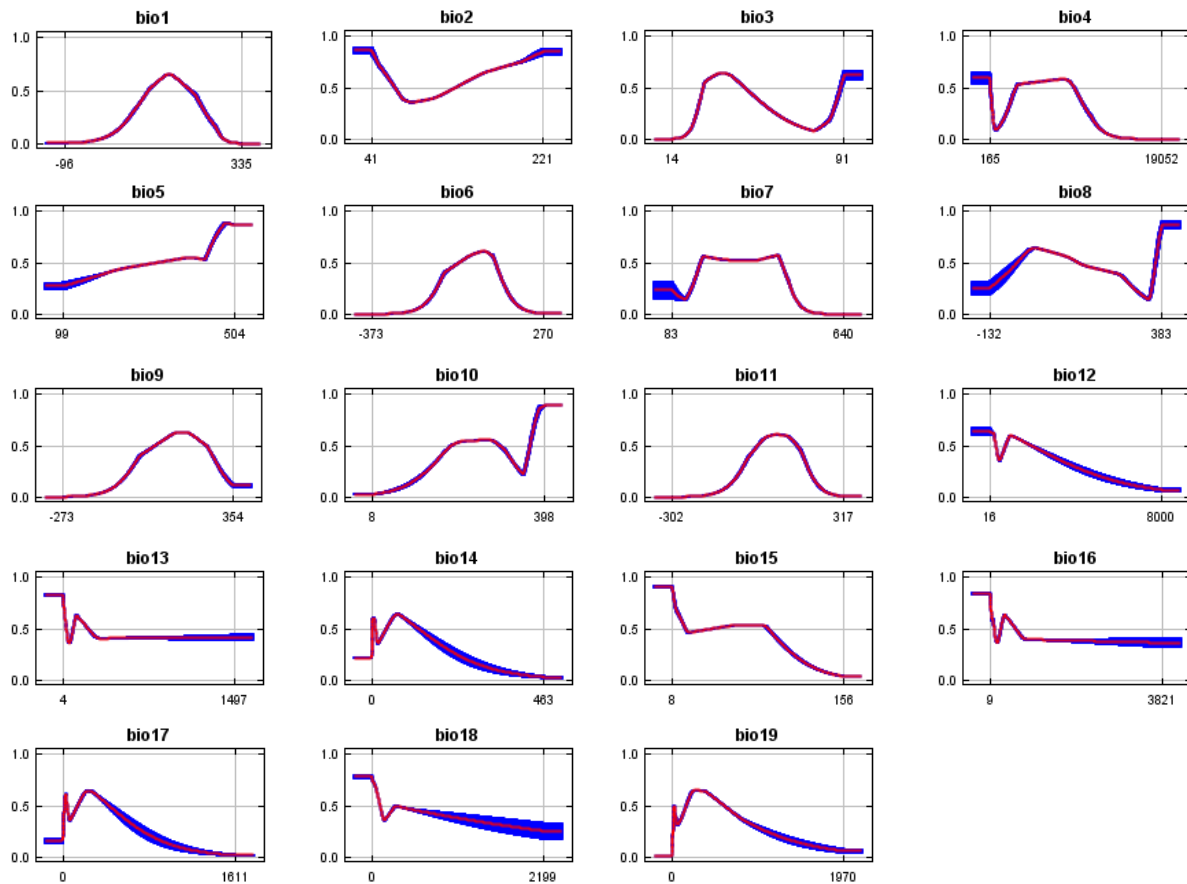
**Appendix 2.6:** Jack-knife test results obtained from models used to project for rainbow trout (*Oncorhynchus mykiss*) distribution under RCP 4.5 (2070) in Mpumalanga Province, South Africa. BIO1 = Annual Mean Temperature, BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)), BIO3 = Isothermality (BIO2/BIO7) (\* 100), BIO4 = Temperature Seasonality (standard deviation \*100), BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO7 = Temperature Annual Range (BIO5-BIO6), BIO8 = Mean Temperature of Wettest Quarter, BIO9 = Mean Temperature of Driest Quarter, BIO10 = Mean Temperature of Warmest Quarter, BIO11 = Mean Temperature of Coldest Quarter, BIO12 = Annual Precipitation, BIO13 = Precipitation of Wettest Month, BIO14 = Precipitation of Driest Month, BIO15 = Precipitation Seasonality (Coefficient of Variation), BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter, BIO18 = Precipitation of Warmest Quarter, BIO19 = Precipitation of Coldest Quarter.



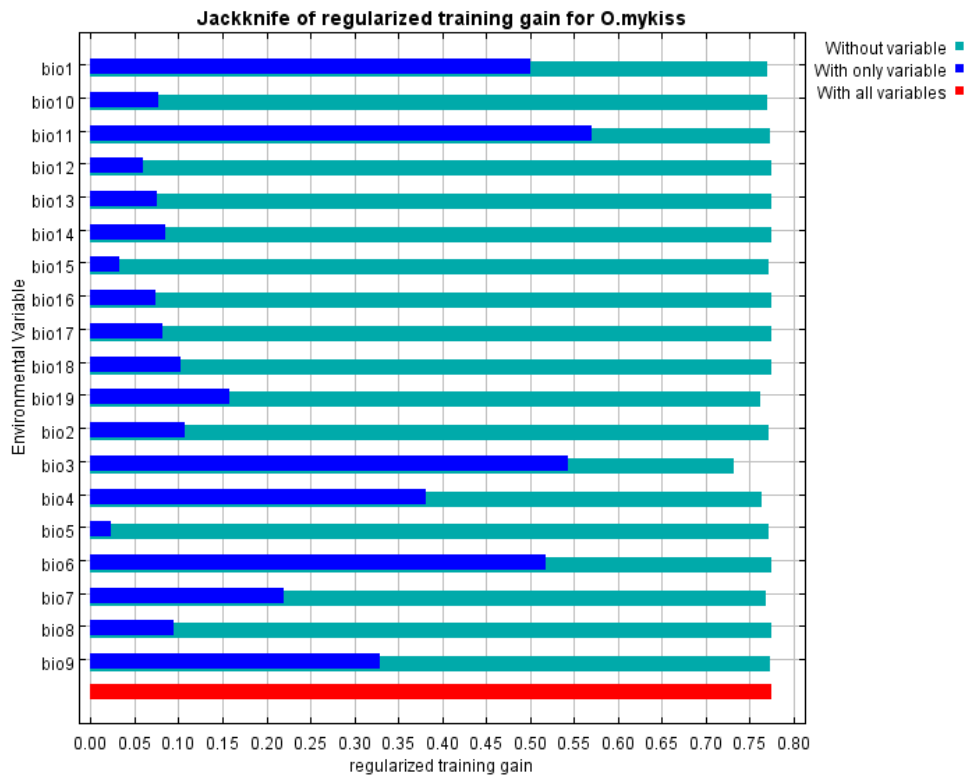
**Appendix 2.7:** Response curves obtained from models used to project for RCP 8.5 (2050) scenario distribution of rainbow trout (*Oncorhynchus mykiss*) in Mpumalanga Province South Africa. BIO1 = Annual Mean Temperature, BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)), BIO3 = Isothermality (BIO2/BIO7) (\* 100), BIO4 = Temperature Seasonality (standard deviation \*100), BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO7 = Temperature Annual Range (BIO5-BIO6), BIO8 = Mean Temperature of Wettest Quarter, BIO9 = Mean Temperature of Driest Quarter, BIO10 = Mean Temperature of Warmest Quarter, BIO11 = Mean Temperature of Coldest Quarter, BIO12 = Annual Precipitation, BIO13 = Precipitation of Wettest Month, BIO14 = Precipitation of Driest Month, BIO15 = Precipitation Seasonality (Coefficient of Variation), BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter, BIO18 = Precipitation of Warmest Quarter, BIO19 = Precipitation of Coldest Quarter. Note that temperature values are in °C \* 10 ( i.e. 354= 35.4 °C) and the precipitation data is in mm.



**Appendix 2.8:** Jack-knife test results obtained from models used to project for rainbow trout (*Oncorhynchus mykiss*) distribution under RCP 8.5 (2050) in Mpumalanga Province, South Africa. BIO1 = Annual Mean Temperature, BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)), BIO3 = Isothermality (BIO2/BIO7) (\* 100), BIO4 = Temperature Seasonality (standard deviation \*100), BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO7 = Temperature Annual Range (BIO5-BIO6), BIO8 = Mean Temperature of Wettest Quarter, BIO9 = Mean Temperature of Driest Quarter, BIO10 = Mean Temperature of Warmest Quarter, BIO11 = Mean Temperature of Coldest Quarter, BIO12 = Annual Precipitation, BIO13 = Precipitation of Wettest Month, BIO14 = Precipitation of Driest Month, BIO15 = Precipitation Seasonality (Coefficient of Variation), BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter, BIO18 = Precipitation of Warmest Quarter, BIO19 = Precipitation of Coldest Quarter.



**Appendix 2.9:** Response curves obtained from models used to project for RCP 8.5 (2070) scenario distribution of rainbow trout (*Oncorhynchus mykiss*) in Mpumalanga Province South Africa. BIO1 = Annual Mean Temperature, BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)), BIO3 = Isothermality (BIO2/BIO7) (\* 100), BIO4 = Temperature Seasonality (standard deviation \*100), BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO7 = Temperature Annual Range (BIO5-BIO6), BIO8 = Mean Temperature of Wettest Quarter, BIO9 = Mean Temperature of Driest Quarter, BIO10 = Mean Temperature of Warmest Quarter, BIO11 = Mean Temperature of Coldest Quarter, BIO12 = Annual Precipitation, BIO13 = Precipitation of Wettest Month, BIO14 = Precipitation of Driest Month, BIO15 = Precipitation Seasonality (Coefficient of Variation), BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter, BIO18 = Precipitation of Warmest Quarter, BIO19 = Precipitation of Coldest Quarter. Note that temperature values are in °C \* 10 ( i.e. 354= 35.4 °C) and the precipitation data is in mm



**Appendix 2.10:** Jack-knife test results obtained from models used to project for rainbow trout (*Oncorhynchus mykiss*) distribution under RCP 8.5 (2070) in Mpumalanga Province, South Africa. BIO1 = Annual Mean Temperature, BIO2 = Mean Diurnal Range (Mean of monthly (max temp - min temp)), BIO3 = Isothermality (BIO2/BIO7) (\* 100), BIO4 = Temperature Seasonality (standard deviation \*100), BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO7 = Temperature Annual Range (BIO5-BIO6), BIO8 = Mean Temperature of Wettest Quarter, BIO9 = Mean Temperature of Driest Quarter, BIO10 = Mean Temperature of Warmest Quarter, BIO11 = Mean Temperature of Coldest Quarter, BIO12 = Annual Precipitation, BIO13 = Precipitation of Wettest Month, BIO14 = Precipitation of Driest Month, BIO15 = Precipitation Seasonality (Coefficient of Variation), BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter, BIO18 = Precipitation of Warmest Quarter, BIO19 = Precipitation of Coldest Quarter.



**Appendix 2.11:** Global occurrence records of rainbow trout (*Oncorhynchus mykiss*) obtained from GBIF: Global Biodiversity Information Facility (GBIF) and the South African Institute for Aquatic Biodiversity (SAIAB) that were used to predict the potential distribution of rainbow trout (*Oncorhynchus mykiss*) under current and future (2050 and 2070) climatic conditions in Mpumalanga Province, South Africa.

| Species                    | Latitude | Longitude | Species                    | Latitude | Longitude | Species                    | Latitude | Longitude |
|----------------------------|----------|-----------|----------------------------|----------|-----------|----------------------------|----------|-----------|
| <i>Oncorhynchus mykiss</i> | -27.9069 | 29.8706   | <i>Oncorhynchus mykiss</i> | 51.0493  | -3.5072   | <i>Oncorhynchus mykiss</i> | 22.0449  | -159.5325 |
| <i>Oncorhynchus mykiss</i> | -29.0350 | 29.7628   | <i>Oncorhynchus mykiss</i> | 53.1107  | -1.5630   | <i>Oncorhynchus mykiss</i> | 19.5960  | -155.5774 |
| <i>Oncorhynchus mykiss</i> | -28.0250 | 30.5625   | <i>Oncorhynchus mykiss</i> | 54.2897  | -0.5136   | <i>Oncorhynchus mykiss</i> | 42.0432  | -90.3721  |
| <i>Oncorhynchus mykiss</i> | -29.1111 | 29.4700   | <i>Oncorhynchus mykiss</i> | 51.1268  | 0.4516    | <i>Oncorhynchus mykiss</i> | 42.4754  | -92.3100  |
| <i>Oncorhynchus mykiss</i> | -29.1031 | 29.4808   | <i>Oncorhynchus mykiss</i> | 52.0837  | -4.4525   | <i>Oncorhynchus mykiss</i> | 43.4749  | -92.0770  |
| <i>Oncorhynchus mykiss</i> | -29.1256 | 29.4406   | <i>Oncorhynchus mykiss</i> | 54.6161  | -2.0580   | <i>Oncorhynchus mykiss</i> | 42.8717  | -91.2026  |
| <i>Oncorhynchus mykiss</i> | -29.1339 | 29.4367   | <i>Oncorhynchus mykiss</i> | 50.1990  | -5.1450   | <i>Oncorhynchus mykiss</i> | 41.7713  | -88.9453  |
| <i>Oncorhynchus mykiss</i> | -29.1564 | 29.4183   | <i>Oncorhynchus mykiss</i> | 52.6990  | 0.6099    | <i>Oncorhynchus mykiss</i> | 40.5573  | -89.5407  |
| <i>Oncorhynchus mykiss</i> | -29.1561 | 29.4197   | <i>Oncorhynchus mykiss</i> | 54.9742  | -4.4959   | <i>Oncorhynchus mykiss</i> | 42.1634  | -87.4292  |
| <i>Oncorhynchus mykiss</i> | -29.1414 | 29.4261   | <i>Oncorhynchus mykiss</i> | 54.2568  | -6.6965   | <i>Oncorhynchus mykiss</i> | 38.5896  | -86.0968  |
| <i>Oncorhynchus mykiss</i> | -29.8323 | 29.5215   | <i>Oncorhynchus mykiss</i> | 57.5289  | -2.0409   | <i>Oncorhynchus mykiss</i> | 39.5328  | -85.7797  |
| <i>Oncorhynchus mykiss</i> | -29.7500 | 29.2167   | <i>Oncorhynchus mykiss</i> | 53.2322  | -3.2861   | <i>Oncorhynchus mykiss</i> | 41.3278  | -85.7597  |
| <i>Oncorhynchus mykiss</i> | -29.7444 | 29.2625   | <i>Oncorhynchus mykiss</i> | 52.9109  | -9.1155   | <i>Oncorhynchus mykiss</i> | 38.3387  | -87.3450  |
| <i>Oncorhynchus mykiss</i> | -29.7958 | 29.3528   | <i>Oncorhynchus mykiss</i> | 56.1338  | -3.8520   | <i>Oncorhynchus mykiss</i> | 37.4623  | -94.7854  |
| <i>Oncorhynchus mykiss</i> | -27.8856 | 29.7131   | <i>Oncorhynchus mykiss</i> | 56.1788  | -5.4261   | <i>Oncorhynchus mykiss</i> | 37.2217  | -98.7434  |
| <i>Oncorhynchus mykiss</i> | -27.8856 | 29.7131   | <i>Oncorhynchus mykiss</i> | 54.9819  | -8.3912   | <i>Oncorhynchus mykiss</i> | 38.9322  | -94.7538  |
| <i>Oncorhynchus mykiss</i> | -28.6958 | 28.9514   | <i>Oncorhynchus mykiss</i> | 51.6554  | -8.7955   | <i>Oncorhynchus mykiss</i> | 38.4831  | -100.9209 |
| <i>Oncorhynchus mykiss</i> | -27.8778 | 29.7367   | <i>Oncorhynchus mykiss</i> | 57.3642  | -5.4062   | <i>Oncorhynchus mykiss</i> | 38.6162  | -83.1559  |
| <i>Oncorhynchus mykiss</i> | -29.3333 | 30.2353   | <i>Oncorhynchus mykiss</i> | 60.2767  | -1.1883   | <i>Oncorhynchus mykiss</i> | 37.3670  | -84.0482  |
| <i>Oncorhynchus mykiss</i> | -29.8444 | 29.2083   | <i>Oncorhynchus mykiss</i> | 55.8779  | -2.2413   | <i>Oncorhynchus mykiss</i> | 36.7775  | -87.7210  |
| <i>Oncorhynchus mykiss</i> | -29.7792 | 29.2014   | <i>Oncorhynchus mykiss</i> | 57.5803  | -3.6363   | <i>Oncorhynchus mykiss</i> | 37.3190  | -85.7152  |
| <i>Oncorhynchus mykiss</i> | -30.0181 | 29.1667   | <i>Oncorhynchus mykiss</i> | 52.1022  | -2.5124   | <i>Oncorhynchus mykiss</i> | 37.4070  | -82.4397  |
| <i>Oncorhynchus mykiss</i> | -28.9361 | 29.2417   | <i>Oncorhynchus mykiss</i> | 57.2895  | -7.3967   | <i>Oncorhynchus mykiss</i> | 39.0917  | -84.5036  |
| <i>Oncorhynchus mykiss</i> | -27.5597 | 30.4208   | <i>Oncorhynchus mykiss</i> | 53.1852  | -7.6268   | <i>Oncorhynchus mykiss</i> | 30.4277  | -91.1673  |
| <i>Oncorhynchus mykiss</i> | -27.5189 | 30.2278   | <i>Oncorhynchus mykiss</i> | 49.7261  | -124.6926 | <i>Oncorhynchus mykiss</i> | 39.3211  | -76.6470  |
| <i>Oncorhynchus mykiss</i> | -28.5667 | 29.1500   | <i>Oncorhynchus mykiss</i> | 50.6838  | -127.3507 | <i>Oncorhynchus mykiss</i> | 46.5708  | -68.3297  |
| <i>Oncorhynchus mykiss</i> | -27.8611 | 29.7444   | <i>Oncorhynchus mykiss</i> | 46.5682  | -124.1977 | <i>Oncorhynchus mykiss</i> | 44.3393  | -70.4245  |
| <i>Oncorhynchus mykiss</i> | -30.2456 | 29.1264   | <i>Oncorhynchus mykiss</i> | 49.2926  | -123.0445 | <i>Oncorhynchus mykiss</i> | 44.5585  | -82.3652  |
| <i>Oncorhynchus mykiss</i> | -29.9597 | 29.8125   | <i>Oncorhynchus mykiss</i> | 48.3020  | -124.0130 | <i>Oncorhynchus mykiss</i> | 47.9458  | -88.9000  |
| <i>Oncorhynchus mykiss</i> | -29.7542 | 29.4181   | <i>Oncorhynchus mykiss</i> | 51.5608  | 3.9529    | <i>Oncorhynchus mykiss</i> | 47.5788  | -87.2626  |
| <i>Oncorhynchus mykiss</i> | -29.3192 | 29.7161   | <i>Oncorhynchus mykiss</i> | 60.8179  | 10.8367   | <i>Oncorhynchus mykiss</i> | 47.6346  | -90.6546  |
| <i>Oncorhynchus mykiss</i> | -29.3375 | 29.9067   | <i>Oncorhynchus mykiss</i> | 60.2481  | 5.7748    | <i>Oncorhynchus mykiss</i> | 47.3691  | -92.4045  |
| <i>Oncorhynchus mykiss</i> | -29.3703 | 29.8611   | <i>Oncorhynchus mykiss</i> | 63.9094  | 11.2685   | <i>Oncorhynchus mykiss</i> | 44.5205  | -93.0002  |
| <i>Oncorhynchus mykiss</i> | -29.4242 | 29.5042   | <i>Oncorhynchus mykiss</i> | 59.5928  | 10.3295   | <i>Oncorhynchus mykiss</i> | 47.8939  | -96.2828  |
| <i>Oncorhynchus mykiss</i> | -29.3711 | 29.6214   | <i>Oncorhynchus mykiss</i> | 16.8000  | -95.0167  | <i>Oncorhynchus mykiss</i> | 46.2851  | -96.0764  |
| <i>Oncorhynchus mykiss</i> | -29.2175 | 29.5556   | <i>Oncorhynchus mykiss</i> | 54.5800  | -165.5000 | <i>Oncorhynchus mykiss</i> | 45.8636  | -92.5065  |
| <i>Oncorhynchus mykiss</i> | -29.2214 | 29.5458   | <i>Oncorhynchus mykiss</i> | 58.2500  | -153.1600 | <i>Oncorhynchus mykiss</i> | 48.1665  | -93.2409  |
| <i>Oncorhynchus mykiss</i> | -29.2731 | 29.5194   | <i>Oncorhynchus mykiss</i> | 50.7000  | -120.3500 | <i>Oncorhynchus mykiss</i> | 44.6798  | -95.2034  |
| <i>Oncorhynchus mykiss</i> | -29.3014 | 30.2278   | <i>Oncorhynchus mykiss</i> | 45.1167  | -67.0833  | <i>Oncorhynchus mykiss</i> | 36.8574  | -91.6584  |
| <i>Oncorhynchus mykiss</i> | -29.3333 | 30.2353   | <i>Oncorhynchus mykiss</i> | 46.4667  | -63.4333  | <i>Oncorhynchus mykiss</i> | 38.6697  | -91.5530  |
| <i>Oncorhynchus mykiss</i> | -29.7972 | 30.9931   | <i>Oncorhynchus mykiss</i> | 58.5000  | -156.0000 | <i>Oncorhynchus mykiss</i> | 34.0117  | -90.9709  |
| <i>Oncorhynchus mykiss</i> | -29.4619 | 29.5367   | <i>Oncorhynchus mykiss</i> | 46.7872  | 13.6122   | <i>Oncorhynchus mykiss</i> | 46.2748  | -106.6530 |
| <i>Oncorhynchus mykiss</i> | -29.2756 | 30.1283   | <i>Oncorhynchus mykiss</i> | -44.4431 | 168.8163  | <i>Oncorhynchus mykiss</i> | 45.3497  | -106.4161 |
| <i>Oncorhynchus mykiss</i> | -29.4911 | 29.8875   | <i>Oncorhynchus mykiss</i> | 38.9340  | -120.0405 | <i>Oncorhynchus mykiss</i> | 46.7312  | -108.8620 |
| <i>Oncorhynchus mykiss</i> | -27.5189 | 30.2278   | <i>Oncorhynchus mykiss</i> | 43.6759  | -72.7993  | <i>Oncorhynchus mykiss</i> | 47.9605  | -106.4383 |
| <i>Oncorhynchus mykiss</i> | -29.3333 | 30.2333   | <i>Oncorhynchus mykiss</i> | -38.5995 | 176.6152  | <i>Oncorhynchus mykiss</i> | 48.5308  | -108.6544 |
| <i>Oncorhynchus mykiss</i> | -31.1595 | 28.1115   | <i>Oncorhynchus mykiss</i> | -37.8368 | 176.0294  | <i>Oncorhynchus mykiss</i> | 48.3170  | -111.9145 |
| <i>Oncorhynchus mykiss</i> | -31.1746 | 28.1218   | <i>Oncorhynchus mykiss</i> | -36.9531 | 175.6449  | <i>Oncorhynchus mykiss</i> | 47.0365  | -111.5801 |
| <i>Oncorhynchus mykiss</i> | -30.8950 | 28.2139   | <i>Oncorhynchus mykiss</i> | -41.7181 | 173.1684  | <i>Oncorhynchus mykiss</i> | 48.8420  | -113.6089 |
| <i>Oncorhynchus mykiss</i> | -31.1744 | 28.1217   | <i>Oncorhynchus mykiss</i> | -39.2528 | 173.9519  | <i>Oncorhynchus mykiss</i> | 36.0030  | -84.0884  |
| <i>Oncorhynchus mykiss</i> | -31.4928 | 28.4769   | <i>Oncorhynchus mykiss</i> | -38.6007 | 175.5433  | <i>Oncorhynchus mykiss</i> | 35.8212  | -81.2089  |
| <i>Oncorhynchus mykiss</i> | -32.6252 | 26.9325   | <i>Oncorhynchus mykiss</i> | -43.3695 | 172.6248  | <i>Oncorhynchus mykiss</i> | 36.7032  | -79.0784  |
| <i>Oncorhynchus mykiss</i> | -30.6404 | 25.5208   | <i>Oncorhynchus mykiss</i> | -44.9412 | 169.2856  | <i>Oncorhynchus mykiss</i> | 41.2233  | -101.6991 |
| <i>Oncorhynchus mykiss</i> | -31.2250 | 28.0583   | <i>Oncorhynchus mykiss</i> | -38.8814 | 175.9700  | <i>Oncorhynchus mykiss</i> | 41.8601  | -103.4759 |
| <i>Oncorhynchus mykiss</i> | -31.0833 | 28.3000   | <i>Oncorhynchus mykiss</i> | -35.7992 | 173.6290  | <i>Oncorhynchus mykiss</i> | 41.3086  | -96.3566  |

| Species                    | Latitude | Longitude | Species                    | Latitude | Longitude | Species                    | Latitude | Longitude |
|----------------------------|----------|-----------|----------------------------|----------|-----------|----------------------------|----------|-----------|
| <i>Oncorhynchus mykiss</i> | -30.9833 | 28.2611   | <i>Oncorhynchus mykiss</i> | -37.9541 | 176.3453  | <i>Oncorhynchus mykiss</i> | 42.6684  | -103.4746 |
| <i>Oncorhynchus mykiss</i> | -30.9778 | 28.2778   | <i>Oncorhynchus mykiss</i> | -45.0654 | 167.9895  | <i>Oncorhynchus mykiss</i> | 42.6518  | -101.1472 |
| <i>Oncorhynchus mykiss</i> | -30.8639 | 28.2000   | <i>Oncorhynchus mykiss</i> | -44.7402 | 170.4937  | <i>Oncorhynchus mykiss</i> | 42.4867  | -98.7263  |
| <i>Oncorhynchus mykiss</i> | -30.9500 | 28.2000   | <i>Oncorhynchus mykiss</i> | -44.9367 | 171.1380  | <i>Oncorhynchus mykiss</i> | 32.3742  | -107.7203 |
| <i>Oncorhynchus mykiss</i> | -30.8167 | 28.2000   | <i>Oncorhynchus mykiss</i> | -38.0933 | 175.1029  | <i>Oncorhynchus mykiss</i> | 34.9387  | -106.6833 |
| <i>Oncorhynchus mykiss</i> | -31.1306 | 28.0861   | <i>Oncorhynchus mykiss</i> | -41.1305 | 172.6250  | <i>Oncorhynchus mykiss</i> | 32.9068  | -106.1186 |
| <i>Oncorhynchus mykiss</i> | -31.0333 | 28.4153   | <i>Oncorhynchus mykiss</i> | -42.3796 | 172.3127  | <i>Oncorhynchus mykiss</i> | 33.7762  | -104.7229 |
| <i>Oncorhynchus mykiss</i> | -31.1250 | 28.2333   | <i>Oncorhynchus mykiss</i> | -35.4753 | 174.2987  | <i>Oncorhynchus mykiss</i> | 35.9066  | -104.3379 |
| <i>Oncorhynchus mykiss</i> | -31.2000 | 28.0806   | <i>Oncorhynchus mykiss</i> | -44.5075 | 170.0543  | <i>Oncorhynchus mykiss</i> | 36.6931  | -107.9286 |
| <i>Oncorhynchus mykiss</i> | -31.0833 | 28.2972   | <i>Oncorhynchus mykiss</i> | -46.1358 | 167.1210  | <i>Oncorhynchus mykiss</i> | 34.9231  | -108.8894 |
| <i>Oncorhynchus mykiss</i> | -30.9500 | 28.4500   | <i>Oncorhynchus mykiss</i> | -39.7423 | 176.2688  | <i>Oncorhynchus mykiss</i> | 33.5726  | -108.8999 |
| <i>Oncorhynchus mykiss</i> | -31.0667 | 28.4833   | <i>Oncorhynchus mykiss</i> | -39.3892 | 176.8690  | <i>Oncorhynchus mykiss</i> | 38.2402  | -115.0849 |
| <i>Oncorhynchus mykiss</i> | -30.9167 | 28.3667   | <i>Oncorhynchus mykiss</i> | -43.2287 | 171.5607  | <i>Oncorhynchus mykiss</i> | 41.3273  | -114.2798 |
| <i>Oncorhynchus mykiss</i> | -31.1708 | 28.1200   | <i>Oncorhynchus mykiss</i> | -39.5173 | 175.0515  | <i>Oncorhynchus mykiss</i> | 40.0624  | -119.5635 |
| <i>Oncorhynchus mykiss</i> | -31.1542 | 28.1167   | <i>Oncorhynchus mykiss</i> | -42.8038 | 171.1293  | <i>Oncorhynchus mykiss</i> | 40.6278  | -118.3451 |
| <i>Oncorhynchus mykiss</i> | -31.1500 | 28.3333   | <i>Oncorhynchus mykiss</i> | -39.5229 | 174.2349  | <i>Oncorhynchus mykiss</i> | 37.8499  | -114.3339 |
| <i>Oncorhynchus mykiss</i> | -31.1750 | 28.0717   | <i>Oncorhynchus mykiss</i> | -38.1217 | 177.2860  | <i>Oncorhynchus mykiss</i> | 42.7369  | -75.0861  |
| <i>Oncorhynchus mykiss</i> | -30.7083 | 27.9444   | <i>Oncorhynchus mykiss</i> | -38.7323 | 177.5903  | <i>Oncorhynchus mykiss</i> | 42.1954  | -76.3411  |
| <i>Oncorhynchus mykiss</i> | -30.9019 | 27.9111   | <i>Oncorhynchus mykiss</i> | -45.4733 | 169.5729  | <i>Oncorhynchus mykiss</i> | 42.9859  | -77.8596  |
| <i>Oncorhynchus mykiss</i> | -30.2919 | 28.3947   | <i>Oncorhynchus mykiss</i> | -41.2909 | 172.1502  | <i>Oncorhynchus mykiss</i> | 40.9025  | -72.9442  |
| <i>Oncorhynchus mykiss</i> | -30.2850 | 28.3722   | <i>Oncorhynchus mykiss</i> | -37.6548 | 178.3042  | <i>Oncorhynchus mykiss</i> | 42.1525  | -81.2267  |
| <i>Oncorhynchus mykiss</i> | -30.2958 | 28.3275   | <i>Oncorhynchus mykiss</i> | -40.1615 | 175.8180  | <i>Oncorhynchus mykiss</i> | 41.4462  | -82.7689  |
| <i>Oncorhynchus mykiss</i> | -30.9583 | 27.6083   | <i>Oncorhynchus mykiss</i> | -45.8504 | 170.0325  | <i>Oncorhynchus mykiss</i> | 34.0512  | -96.3387  |
| <i>Oncorhynchus mykiss</i> | -30.8167 | 28.2000   | <i>Oncorhynchus mykiss</i> | -44.0111 | 169.8126  | <i>Oncorhynchus mykiss</i> | 36.8482  | -102.8740 |
| <i>Oncorhynchus mykiss</i> | -30.8167 | 28.2000   | <i>Oncorhynchus mykiss</i> | -41.2444 | 173.8091  | <i>Oncorhynchus mykiss</i> | 45.9157  | -117.4610 |
| <i>Oncorhynchus mykiss</i> | -30.8167 | 28.2000   | <i>Oncorhynchus mykiss</i> | -35.1688 | 173.4333  | <i>Oncorhynchus mykiss</i> | 45.0890  | -122.0223 |
| <i>Oncorhynchus mykiss</i> | -30.8667 | 27.9500   | <i>Oncorhynchus mykiss</i> | -40.4688 | 175.2422  | <i>Oncorhynchus mykiss</i> | 43.7114  | -118.3596 |
| <i>Oncorhynchus mykiss</i> | -30.8833 | 27.8833   | <i>Oncorhynchus mykiss</i> | -37.0486 | 175.2491  | <i>Oncorhynchus mykiss</i> | 44.1099  | -120.7941 |
| <i>Oncorhynchus mykiss</i> | -30.8167 | 27.8667   | <i>Oncorhynchus mykiss</i> | -37.3147 | 174.6845  | <i>Oncorhynchus mykiss</i> | 41.0473  | -77.0499  |
| <i>Oncorhynchus mykiss</i> | -30.7500 | 27.7167   | <i>Oncorhynchus mykiss</i> | -43.6040 | 172.0291  | <i>Oncorhynchus mykiss</i> | 40.7691  | -80.4337  |
| <i>Oncorhynchus mykiss</i> | -30.8833 | 27.8833   | <i>Oncorhynchus mykiss</i> | -46.1764 | 167.9138  | <i>Oncorhynchus mykiss</i> | 43.4195  | -103.4614 |
| <i>Oncorhynchus mykiss</i> | -32.5353 | 26.9769   | <i>Oncorhynchus mykiss</i> | -39.3200 | 174.6708  | <i>Oncorhynchus mykiss</i> | 44.8091  | -96.7236  |
| <i>Oncorhynchus mykiss</i> | -32.5167 | 27.4500   | <i>Oncorhynchus mykiss</i> | -36.1799 | 174.6303  | <i>Oncorhynchus mykiss</i> | 42.8509  | -97.4680  |
| <i>Oncorhynchus mykiss</i> | -33.8000 | 25.0167   | <i>Oncorhynchus mykiss</i> | 23.7298  | -105.4950 | <i>Oncorhynchus mykiss</i> | 45.4191  | -98.5017  |
| <i>Oncorhynchus mykiss</i> | -32.7336 | 27.2964   | <i>Oncorhynchus mykiss</i> | 34.1039  | -116.8067 | <i>Oncorhynchus mykiss</i> | 45.1511  | -102.3926 |
| <i>Oncorhynchus mykiss</i> | -32.7336 | 27.2964   | <i>Oncorhynchus mykiss</i> | 61.9822  | -151.3959 | <i>Oncorhynchus mykiss</i> | 36.6052  | -85.2917  |
| <i>Oncorhynchus mykiss</i> | -25.1000 | 30.7833   | <i>Oncorhynchus mykiss</i> | 35.5998  | -121.1075 | <i>Oncorhynchus mykiss</i> | 29.8693  | -98.1977  |
| <i>Oncorhynchus mykiss</i> | -26.1903 | 31.0503   | <i>Oncorhynchus mykiss</i> | 47.6845  | -123.0250 | <i>Oncorhynchus mykiss</i> | 41.2349  | -111.9989 |
| <i>Oncorhynchus mykiss</i> | -33.8460 | 19.1295   | <i>Oncorhynchus mykiss</i> | 36.3910  | -121.6285 | <i>Oncorhynchus mykiss</i> | 40.9742  | -109.5694 |
| <i>Oncorhynchus mykiss</i> | -32.5189 | 19.3506   | <i>Oncorhynchus mykiss</i> | 37.8784  | -122.1834 | <i>Oncorhynchus mykiss</i> | 39.9703  | -109.8014 |
| <i>Oncorhynchus mykiss</i> | -32.5189 | 19.3506   | <i>Oncorhynchus mykiss</i> | 39.1761  | -123.0157 | <i>Oncorhynchus mykiss</i> | 38.5654  | -78.0098  |
| <i>Oncorhynchus mykiss</i> | -33.5292 | 19.5400   | <i>Oncorhynchus mykiss</i> | 40.3074  | -121.2493 | <i>Oncorhynchus mykiss</i> | 37.6135  | -79.7420  |
| <i>Oncorhynchus mykiss</i> | -33.5290 | 19.5402   | <i>Oncorhynchus mykiss</i> | 38.4822  | -122.8323 | <i>Oncorhynchus mykiss</i> | 37.3278  | -77.0303  |
| <i>Oncorhynchus mykiss</i> | -33.4053 | 19.4181   | <i>Oncorhynchus mykiss</i> | 40.7302  | -122.4954 | <i>Oncorhynchus mykiss</i> | 44.0402  | -87.3413  |
| <i>Oncorhynchus mykiss</i> | -33.8917 | 19.2788   | <i>Oncorhynchus mykiss</i> | 37.3888  | -113.3153 | <i>Oncorhynchus mykiss</i> | 38.9708  | -80.9548  |
| <i>Oncorhynchus mykiss</i> | -33.8125 | 23.1750   | <i>Oncorhynchus mykiss</i> | 36.5610  | -114.4455 | <i>Oncorhynchus mykiss</i> | 41.3832  | -106.8072 |
| <i>Oncorhynchus mykiss</i> | -32.6858 | 19.2775   | <i>Oncorhynchus mykiss</i> | 36.2841  | -118.4353 | <i>Oncorhynchus mykiss</i> | 41.8188  | -109.7038 |
| <i>Oncorhynchus mykiss</i> | -33.7369 | 22.8208   | <i>Oncorhynchus mykiss</i> | 42.2129  | -122.0924 | <i>Oncorhynchus mykiss</i> | 43.3985  | -109.0995 |
| <i>Oncorhynchus mykiss</i> | -32.5342 | 19.2289   | <i>Oncorhynchus mykiss</i> | 61.1933  | -144.2819 | <i>Oncorhynchus mykiss</i> | 45.4158  | -109.5711 |
| <i>Oncorhynchus mykiss</i> | -33.3672 | 22.1761   | <i>Oncorhynchus mykiss</i> | 36.9732  | -122.0231 | <i>Oncorhynchus mykiss</i> | 44.1999  | -106.4136 |
| <i>Oncorhynchus mykiss</i> | -33.3675 | 22.1789   | <i>Oncorhynchus mykiss</i> | 34.7947  | -83.8908  | <i>Oncorhynchus mykiss</i> | 43.1587  | -122.1509 |
| <i>Oncorhynchus mykiss</i> | -32.5383 | 19.2564   | <i>Oncorhynchus mykiss</i> | 40.1550  | -83.7883  | <i>Oncorhynchus mykiss</i> | 47.9267  | -114.3980 |
| <i>Oncorhynchus mykiss</i> | -33.3986 | 21.3992   | <i>Oncorhynchus mykiss</i> | 35.6750  | -85.9756  | <i>Oncorhynchus mykiss</i> | 41.9373  | -69.9911  |
| <i>Oncorhynchus mykiss</i> | -33.3000 | 22.0522   | <i>Oncorhynchus mykiss</i> | 46.4875  | -88.9244  | <i>Oncorhynchus mykiss</i> | 38.1500  | -111.1670 |
| <i>Oncorhynchus mykiss</i> | -33.5667 | 19.7000   | <i>Oncorhynchus mykiss</i> | 33.7264  | -85.9550  | <i>Oncorhynchus mykiss</i> | 38.9349  | -114.2444 |
| <i>Oncorhynchus mykiss</i> | -33.9586 | 19.2978   | <i>Oncorhynchus mykiss</i> | 36.5564  | -81.7492  | <i>Oncorhynchus mykiss</i> | 46.6036  | -86.2059  |
| <i>Oncorhynchus mykiss</i> | -33.9586 | 19.2978   | <i>Oncorhynchus mykiss</i> | 35.5433  | -82.3539  | <i>Oncorhynchus mykiss</i> | 36.9499  | -118.6009 |
| <i>Oncorhynchus mykiss</i> | -33.9164 | 19.2908   | <i>Oncorhynchus mykiss</i> | 36.9483  | -93.7933  | <i>Oncorhynchus mykiss</i> | 32.2393  | -99.8809  |
| <i>Oncorhynchus mykiss</i> | -33.2683 | 22.0489   | <i>Oncorhynchus mykiss</i> | 37.7908  | -91.8283  | <i>Oncorhynchus mykiss</i> | 29.6386  | -95.1839  |
| <i>Oncorhynchus mykiss</i> | -33.1833 | 19.1569   | <i>Oncorhynchus mykiss</i> | 28.2575  | -108.2097 | <i>Oncorhynchus mykiss</i> | 30.6032  | -96.3027  |

| Species                    | Latitude | Longitude | Species                    | Latitude | Longitude | Species                    | Latitude | Longitude |
|----------------------------|----------|-----------|----------------------------|----------|-----------|----------------------------|----------|-----------|
| <i>Oncorhynchus mykiss</i> | -33.2069 | 19.1569   | <i>Oncorhynchus mykiss</i> | 39.6681  | -78.6069  | <i>Oncorhynchus mykiss</i> | 42.2637  | -79.7840  |
| <i>Oncorhynchus mykiss</i> | -33.8367 | 19.1114   | <i>Oncorhynchus mykiss</i> | 39.3184  | -120.6619 | <i>Oncorhynchus mykiss</i> | 34.8232  | -102.3992 |
| <i>Oncorhynchus mykiss</i> | -33.9303 | 19.1144   | <i>Oncorhynchus mykiss</i> | 42.8805  | -72.3268  | <i>Oncorhynchus mykiss</i> | 35.6509  | -101.6477 |
| <i>Oncorhynchus mykiss</i> | -33.8167 | 19.1000   | <i>Oncorhynchus mykiss</i> | 43.1789  | -71.1653  | <i>Oncorhynchus mykiss</i> | 31.8886  | -97.7022  |
| <i>Oncorhynchus mykiss</i> | -33.9500 | 19.3000   | <i>Oncorhynchus mykiss</i> | 45.0801  | -71.3558  | <i>Oncorhynchus mykiss</i> | 32.3657  | -95.9930  |
| <i>Oncorhynchus mykiss</i> | -33.9500 | 19.3000   | <i>Oncorhynchus mykiss</i> | 44.3001  | -71.9370  | <i>Oncorhynchus mykiss</i> | 33.0195  | -97.0624  |
| <i>Oncorhynchus mykiss</i> | -33.8500 | 18.9500   | <i>Oncorhynchus mykiss</i> | -22.2867 | -42.9817  | <i>Oncorhynchus mykiss</i> | 47.4900  | -113.5390 |
| <i>Oncorhynchus mykiss</i> | -33.7000 | 19.4000   | <i>Oncorhynchus mykiss</i> | -28.0239 | -49.3697  | <i>Oncorhynchus mykiss</i> | 42.5328  | -82.7847  |
| <i>Oncorhynchus mykiss</i> | -34.1000 | 18.4667   | <i>Oncorhynchus mykiss</i> | -24.1792 | -48.5703  | <i>Oncorhynchus mykiss</i> | 33.0570  | -95.0640  |
| <i>Oncorhynchus mykiss</i> | -33.7000 | 18.9333   | <i>Oncorhynchus mykiss</i> | 38.4422  | -109.0426 | <i>Oncorhynchus mykiss</i> | 31.0514  | -94.2711  |
| <i>Oncorhynchus mykiss</i> | -33.8606 | 23.1714   | <i>Oncorhynchus mykiss</i> | 43.7520  | -119.6595 | <i>Oncorhynchus mykiss</i> | 30.1352  | -93.9213  |
| <i>Oncorhynchus mykiss</i> | -33.0764 | 19.2169   | <i>Oncorhynchus mykiss</i> | 40.1184  | -105.5414 | <i>Oncorhynchus mykiss</i> | 34.1115  | -99.7526  |
| <i>Oncorhynchus mykiss</i> | -33.0519 | 19.2058   | <i>Oncorhynchus mykiss</i> | 35.9745  | -105.9174 | <i>Oncorhynchus mykiss</i> | 28.0644  | -97.8776  |
| <i>Oncorhynchus mykiss</i> | -33.8639 | 23.1517   | <i>Oncorhynchus mykiss</i> | -41.8800 | 146.2300  | <i>Oncorhynchus mykiss</i> | 28.8818  | -97.1332  |
| <i>Oncorhynchus mykiss</i> | -34.1500 | 18.9333   | <i>Oncorhynchus mykiss</i> | 46.7400  | -71.2900  | <i>Oncorhynchus mykiss</i> | 26.2095  | -97.7303  |
| <i>Oncorhynchus mykiss</i> | -33.2500 | 22.0333   | <i>Oncorhynchus mykiss</i> | 48.8200  | -125.1500 | <i>Oncorhynchus mykiss</i> | 33.5802  | -101.9163 |
| <i>Oncorhynchus mykiss</i> | -33.0519 | 19.2058   | <i>Oncorhynchus mykiss</i> | 49.2097  | 8.0449    | <i>Oncorhynchus mykiss</i> | 31.0510  | -98.1847  |
| <i>Oncorhynchus mykiss</i> | -33.0519 | 19.2058   | <i>Oncorhynchus mykiss</i> | 40.6840  | -75.3556  | <i>Oncorhynchus mykiss</i> | 35.8831  | -100.1868 |
| <i>Oncorhynchus mykiss</i> | -33.0764 | 19.2169   | <i>Oncorhynchus mykiss</i> | 17.2092  | -96.4129  | <i>Oncorhynchus mykiss</i> | 31.5878  | -96.5272  |
| <i>Oncorhynchus mykiss</i> | -33.7000 | 18.9333   | <i>Oncorhynchus mykiss</i> | 40.4442  | -111.7041 | <i>Oncorhynchus mykiss</i> | 31.4517  | -100.4490 |
| <i>Oncorhynchus mykiss</i> | -33.9333 | 18.8667   | <i>Oncorhynchus mykiss</i> | 44.2198  | -85.7667  | <i>Oncorhynchus mykiss</i> | 34.4436  | -101.0520 |
| <i>Oncorhynchus mykiss</i> | -34.1000 | 18.4667   | <i>Oncorhynchus mykiss</i> | 64.8326  | -147.6508 | <i>Oncorhynchus mykiss</i> | 32.9745  | -116.7389 |
| <i>Oncorhynchus mykiss</i> | -34.1000 | 18.8167   | <i>Oncorhynchus mykiss</i> | 64.1568  | -145.8425 | <i>Oncorhynchus mykiss</i> | 34.4902  | -120.2290 |
| <i>Oncorhynchus mykiss</i> | -32.7336 | 27.2964   | <i>Oncorhynchus mykiss</i> | 63.1297  | -145.5475 | <i>Oncorhynchus mykiss</i> | 34.3769  | -119.3079 |
| <i>Oncorhynchus mykiss</i> | -33.0519 | 19.2058   | <i>Oncorhynchus mykiss</i> | 34.8206  | -86.8852  | <i>Oncorhynchus mykiss</i> | 34.0821  | -118.6489 |
| <i>Oncorhynchus mykiss</i> | -33.0519 | 19.2058   | <i>Oncorhynchus mykiss</i> | 31.6615  | -88.0843  | <i>Oncorhynchus mykiss</i> | 32.0235  | -102.5215 |
| <i>Oncorhynchus mykiss</i> | -33.0764 | 19.2169   | <i>Oncorhynchus mykiss</i> | 30.4375  | -87.9878  | <i>Oncorhynchus mykiss</i> | 26.5784  | -99.1430  |
| <i>Oncorhynchus mykiss</i> | -33.7000 | 18.9333   | <i>Oncorhynchus mykiss</i> | 36.4925  | -92.8894  | <i>Oncorhynchus mykiss</i> | 32.8626  | -98.5351  |
| <i>Oncorhynchus mykiss</i> | -33.9333 | 18.8667   | <i>Oncorhynchus mykiss</i> | 34.1544  | -93.7213  | <i>Oncorhynchus mykiss</i> | 31.8020  | -95.1929  |
| <i>Oncorhynchus mykiss</i> | -34.1000 | 18.4667   | <i>Oncorhynchus mykiss</i> | 35.9303  | -93.9489  | <i>Oncorhynchus mykiss</i> | 30.4461  | -99.8003  |
| <i>Oncorhynchus mykiss</i> | -34.1000 | 18.8167   | <i>Oncorhynchus mykiss</i> | 35.4967  | -93.0160  | <i>Oncorhynchus mykiss</i> | 31.7533  | -106.4030 |
| <i>Oncorhynchus mykiss</i> | -29.3206 | 29.2028   | <i>Oncorhynchus mykiss</i> | 34.6828  | -91.3160  | <i>Oncorhynchus mykiss</i> | 47.6673  | -111.3312 |
| <i>Oncorhynchus mykiss</i> | -29.4089 | 29.3592   | <i>Oncorhynchus mykiss</i> | 35.7554  | -91.6205  | <i>Oncorhynchus mykiss</i> | 46.1972  | -118.9540 |
| <i>Oncorhynchus mykiss</i> | -29.3672 | 29.4206   | <i>Oncorhynchus mykiss</i> | 34.4817  | -114.3718 | <i>Oncorhynchus mykiss</i> | 40.1406  | -115.4945 |
| <i>Oncorhynchus mykiss</i> | -29.3568 | 29.0641   | <i>Oncorhynchus mykiss</i> | 35.0922  | -114.6309 | <i>Oncorhynchus mykiss</i> | 44.9036  | -124.0190 |
| <i>Oncorhynchus mykiss</i> | -29.5569 | 29.2341   | <i>Oncorhynchus mykiss</i> | 34.1017  | -111.2799 | <i>Oncorhynchus mykiss</i> | 37.3251  | -80.8864  |
| <i>Oncorhynchus mykiss</i> | -29.5430 | 29.2500   | <i>Oncorhynchus mykiss</i> | 36.1922  | -111.7957 | <i>Oncorhynchus mykiss</i> | 32.6702  | -90.6690  |
| <i>Oncorhynchus mykiss</i> | -29.5569 | 29.2341   | <i>Oncorhynchus mykiss</i> | 36.9680  | -111.4762 | <i>Oncorhynchus mykiss</i> | 39.7072  | -82.6067  |
| <i>Oncorhynchus mykiss</i> | -29.5608 | 29.2652   | <i>Oncorhynchus mykiss</i> | 31.7773  | -109.3178 | <i>Oncorhynchus mykiss</i> | 44.4564  | -108.0395 |
| <i>Oncorhynchus mykiss</i> | -29.7250 | 29.1069   | <i>Oncorhynchus mykiss</i> | 41.4854  | -120.0909 | <i>Oncorhynchus mykiss</i> | 34.8125  | -111.5625 |
| <i>Oncorhynchus mykiss</i> | -29.8980 | 29.1222   | <i>Oncorhynchus mykiss</i> | 35.5878  | -116.3794 | <i>Oncorhynchus mykiss</i> | 34.1333  | -109.2860 |
| <i>Oncorhynchus mykiss</i> | -29.1711 | 28.4836   | <i>Oncorhynchus mykiss</i> | 33.7853  | -114.5155 | <i>Oncorhynchus mykiss</i> | 44.8922  | -73.6589  |
| <i>Oncorhynchus mykiss</i> | -29.1833 | 28.4805   | <i>Oncorhynchus mykiss</i> | 38.1549  | -119.3488 | <i>Oncorhynchus mykiss</i> | 35.2506  | -112.2170 |
| <i>Oncorhynchus mykiss</i> | -29.3277 | 28.4833   | <i>Oncorhynchus mykiss</i> | 38.1800  | -104.1337 | <i>Oncorhynchus mykiss</i> | 32.8139  | -109.8500 |
| <i>Oncorhynchus mykiss</i> | -29.3250 | 28.4822   | <i>Oncorhynchus mykiss</i> | 39.4587  | -102.5856 | <i>Oncorhynchus mykiss</i> | 35.8703  | -114.6590 |
| <i>Oncorhynchus mykiss</i> | -29.3261 | 28.4591   | <i>Oncorhynchus mykiss</i> | 40.6397  | -106.4055 | <i>Oncorhynchus mykiss</i> | 32.3844  | -110.7920 |
| <i>Oncorhynchus mykiss</i> | -29.0136 | 28.5575   | <i>Oncorhynchus mykiss</i> | 38.9988  | -108.0424 | <i>Oncorhynchus mykiss</i> | 31.4269  | -110.4550 |
| <i>Oncorhynchus mykiss</i> | -29.0144 | 28.5666   | <i>Oncorhynchus mykiss</i> | 37.7061  | -105.8927 | <i>Oncorhynchus mykiss</i> | 41.3083  | -122.9410 |
| <i>Oncorhynchus mykiss</i> | -29.0161 | 28.5536   | <i>Oncorhynchus mykiss</i> | 39.5917  | -107.1843 | <i>Oncorhynchus mykiss</i> | 46.8333  | -91.2660  |
| <i>Oncorhynchus mykiss</i> | -29.0177 | 28.5544   | <i>Oncorhynchus mykiss</i> | 40.3225  | -102.4283 | <i>Oncorhynchus mykiss</i> | 39.0010  | -115.4073 |
| <i>Oncorhynchus mykiss</i> | -29.0194 | 28.5480   | <i>Oncorhynchus mykiss</i> | 39.3947  | -105.3391 | <i>Oncorhynchus mykiss</i> | 47.7135  | -102.2826 |
| <i>Oncorhynchus mykiss</i> | -29.1958 | 28.4694   | <i>Oncorhynchus mykiss</i> | 41.9548  | -73.4446  | <i>Oncorhynchus mykiss</i> | 47.5333  | -100.8712 |
| <i>Oncorhynchus mykiss</i> | -29.1797 | 28.4838   | <i>Oncorhynchus mykiss</i> | 41.5315  | -71.8084  | <i>Oncorhynchus mykiss</i> | 38.2747  | -112.5551 |
| <i>Oncorhynchus mykiss</i> | -29.1655 | 28.4855   | <i>Oncorhynchus mykiss</i> | 39.7055  | -75.6148  | <i>Oncorhynchus mykiss</i> | 39.5805  | -111.2369 |
| <i>Oncorhynchus mykiss</i> | -29.1616 | 28.4794   | <i>Oncorhynchus mykiss</i> | 38.7766  | -75.3317  | <i>Oncorhynchus mykiss</i> | 40.4931  | -108.8137 |
| <i>Oncorhynchus mykiss</i> | -29.0833 | 28.4922   | <i>Oncorhynchus mykiss</i> | 30.5711  | -86.5448  | <i>Oncorhynchus mykiss</i> | 37.6700  | -109.4440 |
| <i>Oncorhynchus mykiss</i> | -29.0711 | 28.4700   | <i>Oncorhynchus mykiss</i> | 34.1340  | -84.6284  | <i>Oncorhynchus mykiss</i> | 38.8794  | -111.5501 |
| <i>Oncorhynchus mykiss</i> | -29.1022 | 28.4961   | <i>Oncorhynchus mykiss</i> | 34.0666  | -82.4651  | <i>Oncorhynchus mykiss</i> | 41.6796  | -118.7185 |
| <i>Oncorhynchus mykiss</i> | -29.1000 | 28.4986   | <i>Oncorhynchus mykiss</i> | 33.2961  | -81.8624  | <i>Oncorhynchus mykiss</i> | 41.6324  | -116.1469 |
| <i>Oncorhynchus mykiss</i> | -29.1527 | 28.4888   | <i>Oncorhynchus mykiss</i> | 32.1311  | -84.6724  | <i>Oncorhynchus mykiss</i> | 39.5833  | -118.6676 |

| Species                    | Latitude | Longitude | Species                    | Latitude | Longitude | Species                    | Latitude | Longitude |
|----------------------------|----------|-----------|----------------------------|----------|-----------|----------------------------|----------|-----------|
| <i>Oncorhynchus mykiss</i> | -29.1527 | 28.4888   | <i>Oncorhynchus mykiss</i> | 21.4531  | -158.0054 | <i>Oncorhynchus mykiss</i> | 40.8249  | -119.5373 |
| <i>Oncorhynchus mykiss</i> | -29.1852 | 28.4797   | <i>Oncorhynchus mykiss</i> | 66.2305  | 19.7718   | <i>Oncorhynchus mykiss</i> | 52.0715  | 5.5524    |
| <i>Oncorhynchus mykiss</i> | -29.0194 | 28.5480   | <i>Oncorhynchus mykiss</i> | 59.2761  | 18.1912   | <i>Oncorhynchus mykiss</i> | 5.2752   | -74.0236  |
| <i>Oncorhynchus mykiss</i> | -29.1797 | 28.4838   | <i>Oncorhynchus mykiss</i> | 48.3400  | 11.6400   | <i>Oncorhynchus mykiss</i> | 18.1508  | -96.8556  |
| <i>Oncorhynchus mykiss</i> | -29.1833 | 28.4805   | <i>Oncorhynchus mykiss</i> | 30.7923  | -115.7461 | <i>Oncorhynchus mykiss</i> | 19.2953  | -99.3533  |
| <i>Oncorhynchus mykiss</i> | -29.0833 | 28.5088   | <i>Oncorhynchus mykiss</i> | -32.9106 | -70.3000  | <i>Oncorhynchus mykiss</i> | 29.8796  | -108.7343 |
| <i>Oncorhynchus mykiss</i> | -29.3519 | 28.5202   | <i>Oncorhynchus mykiss</i> | 40.1413  | -123.8083 | <i>Oncorhynchus mykiss</i> | 55.5720  | -132.5519 |
| <i>Oncorhynchus mykiss</i> | -28.7332 | 28.6166   | <i>Oncorhynchus mykiss</i> | 24.4290  | -105.9518 | <i>Oncorhynchus mykiss</i> | -31.5766 | 147.7204  |
| <i>Oncorhynchus mykiss</i> | -28.7332 | 28.6166   | <i>Oncorhynchus mykiss</i> | 35.2911  | -118.6269 | <i>Oncorhynchus mykiss</i> | 46.6257  | -120.5502 |
| <i>Oncorhynchus mykiss</i> | -28.7667 | 28.6166   | <i>Oncorhynchus mykiss</i> | 60.5680  | -137.3256 | <i>Oncorhynchus mykiss</i> | 61.8640  | 9.3088    |
| <i>Oncorhynchus mykiss</i> | -28.7667 | 28.6333   | <i>Oncorhynchus mykiss</i> | 36.7517  | 139.4475  | <i>Oncorhynchus mykiss</i> | 58.6241  | 8.9241    |
| <i>Oncorhynchus mykiss</i> | -29.0167 | 28.5499   | <i>Oncorhynchus mykiss</i> | 54.2375  | -124.1771 | <i>Oncorhynchus mykiss</i> | 68.5126  | 15.3731   |
| <i>Oncorhynchus mykiss</i> | -29.1667 | 28.4832   | <i>Oncorhynchus mykiss</i> | 51.9757  | -122.5596 | <i>Oncorhynchus mykiss</i> | 65.9948  | 12.3104   |
| <i>Oncorhynchus mykiss</i> | -29.0832 | 28.5000   | <i>Oncorhynchus mykiss</i> | 60.2302  | -158.5170 | <i>Oncorhynchus mykiss</i> | 58.0853  | 6.7525    |
| <i>Oncorhynchus mykiss</i> | -29.3327 | 29.4207   | <i>Oncorhynchus mykiss</i> | 60.6889  | -146.3234 | <i>Oncorhynchus mykiss</i> | 64.2278  | 13.4095   |
| <i>Oncorhynchus mykiss</i> | -29.0349 | 29.7628   | <i>Oncorhynchus mykiss</i> | 40.2146  | 20.6468   | <i>Oncorhynchus mykiss</i> | 62.3206  | 6.2309    |
| <i>Oncorhynchus mykiss</i> | -29.9113 | 29.1182   | <i>Oncorhynchus mykiss</i> | 50.9409  | 10.7403   | <i>Oncorhynchus mykiss</i> | 63.2497  | 8.3332    |
| <i>Oncorhynchus mykiss</i> | -28.0249 | 30.5625   | <i>Oncorhynchus mykiss</i> | 46.9959  | -121.9199 | <i>Oncorhynchus mykiss</i> | 64.9238  | 11.0542   |
| <i>Oncorhynchus mykiss</i> | -28.6867 | 28.6716   | <i>Oncorhynchus mykiss</i> | 49.7040  | -116.8896 | <i>Oncorhynchus mykiss</i> | 59.2176  | 5.4058    |
| <i>Oncorhynchus mykiss</i> | -27.9069 | 29.8705   | <i>Oncorhynchus mykiss</i> | 52.2556  | -120.2230 | <i>Oncorhynchus mykiss</i> | 70.0208  | 20.9726   |
| <i>Oncorhynchus mykiss</i> | -28.8785 | 28.8330   | <i>Oncorhynchus mykiss</i> | 54.2870  | -130.2801 | <i>Oncorhynchus mykiss</i> | 62.5450  | 11.4971   |
| <i>Oncorhynchus mykiss</i> | -28.9219 | 29.0483   | <i>Oncorhynchus mykiss</i> | 50.0034  | -123.1227 | <i>Oncorhynchus mykiss</i> | 69.3340  | 23.9874   |
| <i>Oncorhynchus mykiss</i> | -29.4088 | 29.3591   | <i>Oncorhynchus mykiss</i> | 50.4667  | -126.2826 | <i>Oncorhynchus mykiss</i> | 45.6992  | -87.4072  |
| <i>Oncorhynchus mykiss</i> | -29.3672 | 29.4206   | <i>Oncorhynchus mykiss</i> | 51.6786  | -127.1887 | <i>Oncorhynchus mykiss</i> | 45.0142  | -85.0300  |
| <i>Oncorhynchus mykiss</i> | -29.5314 | 29.2591   | <i>Oncorhynchus mykiss</i> | 53.1508  | -121.5979 | <i>Oncorhynchus mykiss</i> | 37.2502  | -119.7513 |
| <i>Oncorhynchus mykiss</i> | -29.3206 | 29.2028   | <i>Oncorhynchus mykiss</i> | 50.9911  | -118.1756 | <i>Oncorhynchus mykiss</i> | 40.5198  | -82.0999  |
| <i>Oncorhynchus mykiss</i> | -29.4088 | 29.3591   | <i>Oncorhynchus mykiss</i> | 50.5086  | -116.0967 | <i>Oncorhynchus mykiss</i> | 64.0003  | -150.0003 |
| <i>Oncorhynchus mykiss</i> | -29.3672 | 29.4206   | <i>Oncorhynchus mykiss</i> | -17.2247 | -65.8917  | <i>Oncorhynchus mykiss</i> | 62.3933  | -96.8182  |
| <i>Oncorhynchus mykiss</i> | 59.4664  | 12.5934   | <i>Oncorhynchus mykiss</i> | 57.1167  | -127.5667 | <i>Oncorhynchus mykiss</i> | 56.5256  | 15.5359   |
| <i>Oncorhynchus mykiss</i> | 45.1265  | -116.0222 | <i>Oncorhynchus mykiss</i> | 54.8167  | -127.2167 | <i>Oncorhynchus mykiss</i> | 65.4756  | 21.5316   |
| <i>Oncorhynchus mykiss</i> | 43.9555  | -115.8586 | <i>Oncorhynchus mykiss</i> | 53.3667  | -117.7500 | <i>Oncorhynchus mykiss</i> | -0.1383  | -77.6217  |
| <i>Oncorhynchus mykiss</i> | 43.1393  | -115.5378 | <i>Oncorhynchus mykiss</i> | 57.6167  | -128.8000 | <i>Oncorhynchus mykiss</i> | -33.2683 | 22.0489   |
| <i>Oncorhynchus mykiss</i> | 48.1351  | -116.1557 | <i>Oncorhynchus mykiss</i> | 49.4333  | -126.9667 | <i>Oncorhynchus mykiss</i> | -27.8611 | 29.7444   |
| <i>Oncorhynchus mykiss</i> | 46.7860  | -116.8026 | <i>Oncorhynchus mykiss</i> | 48.8500  | -126.8667 | <i>Oncorhynchus mykiss</i> | -33.2069 | 19.1569   |
| <i>Oncorhynchus mykiss</i> | 45.8933  | -115.8886 | <i>Oncorhynchus mykiss</i> | 56.2833  | -120.2167 | <i>Oncorhynchus mykiss</i> | -30.2456 | 29.1264   |
| <i>Oncorhynchus mykiss</i> | 43.8183  | -111.7415 | <i>Oncorhynchus mykiss</i> | 54.1167  | -126.4333 | <i>Oncorhynchus mykiss</i> | -29.0144 | 28.5667   |
| <i>Oncorhynchus mykiss</i> | 48.9687  | -116.2096 | <i>Oncorhynchus mykiss</i> | 52.2167  | -125.3833 | <i>Oncorhynchus mykiss</i> | -29.3333 | 30.2353   |
| <i>Oncorhynchus mykiss</i> | 44.9488  | -113.7782 | <i>Oncorhynchus mykiss</i> | 57.5722  | -154.4625 | <i>Oncorhynchus mykiss</i> | -30.9500 | 27.5833   |
| <i>Oncorhynchus mykiss</i> | 44.2116  | -114.1390 | <i>Oncorhynchus mykiss</i> | 53.0000  | -119.6667 | <i>Oncorhynchus mykiss</i> | -30.6404 | 25.5208   |
| <i>Oncorhynchus mykiss</i> | 43.0791  | -112.6886 | <i>Oncorhynchus mykiss</i> | 54.0333  | -117.0500 | <i>Oncorhynchus mykiss</i> | 59.7700  | -155.6600 |
| <i>Oncorhynchus mykiss</i> | 42.3573  | -112.4478 | <i>Oncorhynchus mykiss</i> | 53.5833  | -122.9167 | <i>Oncorhynchus mykiss</i> | 63.0000  | -150.0000 |
| <i>Oncorhynchus mykiss</i> | 47.4569  | -116.8021 | <i>Oncorhynchus mykiss</i> | 53.1667  | -126.1833 | <i>Oncorhynchus mykiss</i> | 58.3800  | -134.6300 |
| <i>Oncorhynchus mykiss</i> | 42.1431  | -114.7349 | <i>Oncorhynchus mykiss</i> | 49.2500  | -121.2667 | <i>Oncorhynchus mykiss</i> | 55.9100  | -130.7700 |
| <i>Oncorhynchus mykiss</i> | 42.3510  | -115.9015 | <i>Oncorhynchus mykiss</i> | 33.1000  | -5.1667   | <i>Oncorhynchus mykiss</i> | 56.2300  | -134.6500 |
| <i>Oncorhynchus mykiss</i> | 42.8623  | -117.6415 | <i>Oncorhynchus mykiss</i> | 40.3275  | -76.5075  | <i>Oncorhynchus mykiss</i> | 54.3653  | -119.8736 |
| <i>Oncorhynchus mykiss</i> | 44.3923  | -116.8513 | <i>Oncorhynchus mykiss</i> | 42.7711  | -106.5320 | <i>Oncorhynchus mykiss</i> | 4.4893   | -74.0322  |
| <i>Oncorhynchus mykiss</i> | 42.0681  | -111.3174 | <i>Oncorhynchus mykiss</i> | 44.5428  | -109.3830 | <i>Oncorhynchus mykiss</i> | 6.6793   | -75.4463  |
| <i>Oncorhynchus mykiss</i> | 43.4281  | -113.8234 | <i>Oncorhynchus mykiss</i> | 57.9167  | -145.4167 | <i>Oncorhynchus mykiss</i> | -11.9167 | -75.9167  |
| <i>Oncorhynchus mykiss</i> | 46.6038  | -114.3586 | <i>Oncorhynchus mykiss</i> | -37.4686 | 145.8160  | <i>Oncorhynchus mykiss</i> | -13.5911 | -70.9570  |
| <i>Oncorhynchus mykiss</i> | 49.0050  | -117.6218 | <i>Oncorhynchus mykiss</i> | -38.7700 | 143.4000  | <i>Oncorhynchus mykiss</i> | 1.2889   | 34.7401   |
| <i>Oncorhynchus mykiss</i> | 46.9381  | -115.2717 | <i>Oncorhynchus mykiss</i> | -36.2861 | 146.7280  | <i>Oncorhynchus mykiss</i> | 4.9082   | -75.4430  |
| <i>Oncorhynchus mykiss</i> | 47.8944  | -118.3415 | <i>Oncorhynchus mykiss</i> | -31.1675 | 151.5800  | <i>Oncorhynchus mykiss</i> | 38.8372  | -117.3870 |
| <i>Oncorhynchus mykiss</i> | 44.4925  | -111.2828 | <i>Oncorhynchus mykiss</i> | -36.1300 | 144.7500  | <i>Oncorhynchus mykiss</i> | 36.0000  | -109.0000 |
| <i>Oncorhynchus mykiss</i> | 45.9158  | -114.4604 | <i>Oncorhynchus mykiss</i> | -36.8800 | 146.8700  | <i>Oncorhynchus mykiss</i> | 45.3700  | -111.6210 |
| <i>Oncorhynchus mykiss</i> | 51.4320  | -1.0570   | <i>Oncorhynchus mykiss</i> | 7.2500   | 39.7500   | <i>Oncorhynchus mykiss</i> | 47.8538  | -120.6800 |
| <i>Oncorhynchus mykiss</i> | 50.6510  | -96.5680  | <i>Oncorhynchus mykiss</i> | 41.2209  | -87.9768  | <i>Oncorhynchus mykiss</i> | 9.5594   | -83.8032  |
| <i>Oncorhynchus mykiss</i> | -54.7816 | -68.2124  | <i>Oncorhynchus mykiss</i> | 65.4745  | 29.3788   | <i>Oncorhynchus mykiss</i> | 58.9431  | -157.2052 |
| <i>Oncorhynchus mykiss</i> | 60.1083  | -149.4417 | <i>Oncorhynchus mykiss</i> | 48.5999  | 13.4547   | <i>Oncorhynchus mykiss</i> | -42.7586 | 146.9710  |
| <i>Oncorhynchus mykiss</i> | 34.1200  | 36.0200   | <i>Oncorhynchus mykiss</i> | 35.0724  | 135.9790  | <i>Oncorhynchus mykiss</i> | -35.2830 | 138.7660  |
| <i>Oncorhynchus mykiss</i> | 45.3208  | -107.9070 | <i>Oncorhynchus mykiss</i> | 34.4106  | 135.6300  | <i>Oncorhynchus mykiss</i> | -34.1660 | 140.7500  |

| Species                    | Latitude | Longitude | Species                    | Latitude | Longitude | Species                    | Latitude | Longitude |
|----------------------------|----------|-----------|----------------------------|----------|-----------|----------------------------|----------|-----------|
| <i>Oncorhynchus mykiss</i> | 0.0000   | -99.0000  | <i>Oncorhynchus mykiss</i> | 32.8800  | 35.6300   | <i>Oncorhynchus mykiss</i> | -35.7000 | 137.1000  |
| <i>Oncorhynchus mykiss</i> | 62.8286  | 17.1241   | <i>Oncorhynchus mykiss</i> | 49.5900  | 18.5300   | <i>Oncorhynchus mykiss</i> | -34.0391 | 139.6786  |
| <i>Oncorhynchus mykiss</i> | 39.7161  | -121.6350 | <i>Oncorhynchus mykiss</i> | 50.1600  | 15.8100   | <i>Oncorhynchus mykiss</i> | 47.6735  | -64.9966  |
| <i>Oncorhynchus mykiss</i> | 43.5859  | -106.9530 | <i>Oncorhynchus mykiss</i> | -32.5333 | 115.7167  | <i>Oncorhynchus mykiss</i> | 52.5198  | 13.4385   |
| <i>Oncorhynchus mykiss</i> | 29.6832  | -99.7469  | <i>Oncorhynchus mykiss</i> | -34.4167 | 116.0167  | <i>Oncorhynchus mykiss</i> | 61.6847  | 17.9954   |
| <i>Oncorhynchus mykiss</i> | 27.1803  | -107.1819 | <i>Oncorhynchus mykiss</i> | -45.8771 | -67.4833  | <i>Oncorhynchus mykiss</i> | -37.2264 | 143.8350  |
| <i>Oncorhynchus mykiss</i> | -43.3740 | -65.8048  | <i>Oncorhynchus mykiss</i> | -50.2167 | -71.4333  | <i>Oncorhynchus mykiss</i> | 31.9953  | 130.7720  |
| <i>Oncorhynchus mykiss</i> | 35.4000  | -87.5128  | <i>Oncorhynchus mykiss</i> | -52.2200 | -71.4400  | <i>Oncorhynchus mykiss</i> | 39.7400  | 140.1300  |
| <i>Oncorhynchus mykiss</i> | 28.1168  | -99.8379  | <i>Oncorhynchus mykiss</i> | 44.4322  | -118.7895 | <i>Oncorhynchus mykiss</i> | 47.3781  | -84.5667  |
| <i>Oncorhynchus mykiss</i> | 37.8038  | -118.2715 | <i>Oncorhynchus mykiss</i> | 44.2212  | -124.0594 | <i>Oncorhynchus mykiss</i> | 43.1135  | -123.5078 |
| <i>Oncorhynchus mykiss</i> | 33.3012  | -79.7121  | <i>Oncorhynchus mykiss</i> | 48.5106  | -122.3375 | <i>Oncorhynchus mykiss</i> | 14.6500  | 98.5667   |
| <i>Oncorhynchus mykiss</i> | 38.4735  | -107.1922 | <i>Oncorhynchus mykiss</i> | 34.7116  | -77.0710  | <i>Oncorhynchus mykiss</i> | -41.2261 | -72.6856  |
| <i>Oncorhynchus mykiss</i> | 37.4107  | -107.5164 | <i>Oncorhynchus mykiss</i> | 51.0500  | -114.0833 | <i>Oncorhynchus mykiss</i> | 33.1799  | -108.2065 |
| <i>Oncorhynchus mykiss</i> | 37.2186  | -105.0469 | <i>Oncorhynchus mykiss</i> | 53.6167  | -114.0667 | <i>Oncorhynchus mykiss</i> | 47.2239  | -94.8578  |
| <i>Oncorhynchus mykiss</i> | 38.6915  | -105.0502 | <i>Oncorhynchus mykiss</i> | 53.3292  | -116.0372 | <i>Oncorhynchus mykiss</i> | 42.5583  | -85.7222  |
| <i>Oncorhynchus mykiss</i> | 37.6281  | -89.0960  | <i>Oncorhynchus mykiss</i> | 59.5500  | -112.2333 | <i>Oncorhynchus mykiss</i> | 59.5458  | -154.2858 |
| <i>Oncorhynchus mykiss</i> | 41.9088  | -105.2907 | <i>Oncorhynchus mykiss</i> | 50.2333  | -114.2000 | <i>Oncorhynchus mykiss</i> | 48.2066  | -2.7259   |
| <i>Oncorhynchus mykiss</i> | 41.9497  | -108.0112 | <i>Oncorhynchus mykiss</i> | 49.5500  | -113.7667 | <i>Oncorhynchus mykiss</i> | 49.1504  | 1.9720    |
| <i>Oncorhynchus mykiss</i> | 45.4272  | -75.7028  | <i>Oncorhynchus mykiss</i> | 52.0833  | -114.4833 | <i>Oncorhynchus mykiss</i> | 44.5137  | 6.3350    |
| <i>Oncorhynchus mykiss</i> | 34.7419  | -81.3915  | <i>Oncorhynchus mykiss</i> | -33.8160 | 150.9000  | <i>Oncorhynchus mykiss</i> | 44.1769  | 0.5608    |
| <i>Oncorhynchus mykiss</i> | 34.4174  | -79.7064  | <i>Oncorhynchus mykiss</i> | -33.0000 | 150.0000  | <i>Oncorhynchus mykiss</i> | 43.6640  | 2.9380    |
| <i>Oncorhynchus mykiss</i> | 41.3877  | -79.1908  | <i>Oncorhynchus mykiss</i> | -35.6160 | 148.4000  | <i>Oncorhynchus mykiss</i> | 47.4036  | 6.1168    |
| <i>Oncorhynchus mykiss</i> | 41.2831  | -91.3475  | <i>Oncorhynchus mykiss</i> | -36.0830 | 148.6660  | <i>Oncorhynchus mykiss</i> | 42.8019  | 0.3591    |
| <i>Oncorhynchus mykiss</i> | 43.9863  | -89.9626  | <i>Oncorhynchus mykiss</i> | -35.0000 | 148.5660  | <i>Oncorhynchus mykiss</i> | 48.0749  | 3.3357    |
| <i>Oncorhynchus mykiss</i> | 45.4522  | -91.2603  | <i>Oncorhynchus mykiss</i> | -33.5502 | 150.1217  | <i>Oncorhynchus mykiss</i> | 45.1012  | 2.1736    |
| <i>Oncorhynchus mykiss</i> | 44.4245  | -100.3807 | <i>Oncorhynchus mykiss</i> | -28.3330 | 152.2660  | <i>Oncorhynchus mykiss</i> | 49.1153  | -0.0826   |
| <i>Oncorhynchus mykiss</i> | 40.0359  | -81.0105  | <i>Oncorhynchus mykiss</i> | -30.8728 | 151.1586  | <i>Oncorhynchus mykiss</i> | 47.7894  | 1.0633    |
| <i>Oncorhynchus mykiss</i> | 44.3639  | -102.9443 | <i>Oncorhynchus mykiss</i> | -36.7295 | 148.4347  | <i>Oncorhynchus mykiss</i> | 46.3533  | 1.3743    |
| <i>Oncorhynchus mykiss</i> | 36.5714  | -104.5794 | <i>Oncorhynchus mykiss</i> | -35.1160 | 147.3660  | <i>Oncorhynchus mykiss</i> | 48.8709  | 4.8406    |
| <i>Oncorhynchus mykiss</i> | 51.0680  | -121.3338 | <i>Oncorhynchus mykiss</i> | 46.2747  | 2.8052    | <i>Oncorhynchus mykiss</i> | 46.1733  | 4.6204    |
| <i>Oncorhynchus mykiss</i> | 56.7970  | 9.0805    | <i>Oncorhynchus mykiss</i> | 24.9400  | 121.9000  | <i>Oncorhynchus mykiss</i> | 47.0805  | -1.6816   |
| <i>Oncorhynchus mykiss</i> | 54.9029  | 10.3243   | <i>Oncorhynchus mykiss</i> | 53.6997  | 9.1329    | <i>Oncorhynchus mykiss</i> | 42.4927  | 2.3319    |
| <i>Oncorhynchus mykiss</i> | 55.8872  | 10.6774   | <i>Oncorhynchus mykiss</i> | -32.6252 | 26.9325   | <i>Oncorhynchus mykiss</i> | 44.9212  | 3.8237    |
| <i>Oncorhynchus mykiss</i> | 57.2292  | 11.0692   | <i>Oncorhynchus mykiss</i> | 49.0167  | -65.0500  | <i>Oncorhynchus mykiss</i> | 41.3236  | 13.8831   |
| <i>Oncorhynchus mykiss</i> | 54.6965  | 11.8695   | <i>Oncorhynchus mykiss</i> | 60.7667  | -135.0833 | <i>Oncorhynchus mykiss</i> | 45.6956  | 9.7183    |
| <i>Oncorhynchus mykiss</i> | 55.8669  | 12.2020   | <i>Oncorhynchus mykiss</i> | 51.8074  | -116.6325 | <i>Oncorhynchus mykiss</i> | 44.3136  | 10.9181   |
| <i>Oncorhynchus mykiss</i> | 55.2694  | 14.7628   | <i>Oncorhynchus mykiss</i> | 51.1647  | -115.5588 | <i>Oncorhynchus mykiss</i> | 44.5947  | 9.2228    |
| <i>Oncorhynchus mykiss</i> | 44.0415  | -77.0600  | <i>Oncorhynchus mykiss</i> | 52.4089  | -117.0650 | <i>Oncorhynchus mykiss</i> | 42.7819  | 13.2964   |
| <i>Oncorhynchus mykiss</i> | 52.6975  | -118.2757 | <i>Oncorhynchus mykiss</i> | 46.2820  | -81.9286  | <i>Oncorhynchus mykiss</i> | 36.8814  | 14.9147   |
| <i>Oncorhynchus mykiss</i> | 50.6792  | -100.0052 | <i>Oncorhynchus mykiss</i> | 46.6006  | -84.1249  | <i>Oncorhynchus mykiss</i> | 37.9000  | 14.8494   |
| <i>Oncorhynchus mykiss</i> | 44.0000  | -79.0667  | <i>Oncorhynchus mykiss</i> | -39.8333 | -72.3000  | <i>Oncorhynchus mykiss</i> | 38.4772  | 16.4839   |
| <i>Oncorhynchus mykiss</i> | 53.8304  | -101.2555 | <i>Oncorhynchus mykiss</i> | 45.3015  | -80.0373  | <i>Oncorhynchus mykiss</i> | 42.6642  | 11.6897   |
| <i>Oncorhynchus mykiss</i> | 49.4009  | -119.5786 | <i>Oncorhynchus mykiss</i> | 48.3068  | -86.1589  | <i>Oncorhynchus mykiss</i> | 45.3806  | 11.1122   |
| <i>Oncorhynchus mykiss</i> | 52.0500  | -100.7500 | <i>Oncorhynchus mykiss</i> | 46.1433  | -79.1467  | <i>Oncorhynchus mykiss</i> | 45.7625  | 12.4758   |
| <i>Oncorhynchus mykiss</i> | 50.0000  | -120.0000 | <i>Oncorhynchus mykiss</i> | 60.4642  | -150.6013 | <i>Oncorhynchus mykiss</i> | 43.8269  | 12.3900   |
| <i>Oncorhynchus mykiss</i> | 48.8000  | -87.2500  | <i>Oncorhynchus mykiss</i> | -33.5792 | -69.3264  | <i>Oncorhynchus mykiss</i> | 39.6735  | 9.4030    |
| <i>Oncorhynchus mykiss</i> | 52.3747  | -126.7520 | <i>Oncorhynchus mykiss</i> | 44.3278  | -68.3374  | <i>Oncorhynchus mykiss</i> | 46.6488  | 10.9896   |
| <i>Oncorhynchus mykiss</i> | 45.8833  | -83.3500  | <i>Oncorhynchus mykiss</i> | 45.2366  | -69.4083  | <i>Oncorhynchus mykiss</i> | 45.6595  | 14.8357   |
| <i>Oncorhynchus mykiss</i> | 44.5667  | -80.6500  | <i>Oncorhynchus mykiss</i> | 61.7108  | -150.0602 | <i>Oncorhynchus mykiss</i> | 43.5675  | 16.7110   |
| <i>Oncorhynchus mykiss</i> | 47.5837  | -52.8532  | <i>Oncorhynchus mykiss</i> | 39.5269  | -123.7408 | <i>Oncorhynchus mykiss</i> | 42.7445  | 20.2135   |
| <i>Oncorhynchus mykiss</i> | 45.0833  | -78.1500  | <i>Oncorhynchus mykiss</i> | 35.0947  | -120.5622 | <i>Oncorhynchus mykiss</i> | 46.6496  | 16.0490   |
| <i>Oncorhynchus mykiss</i> | 60.0000  | -161.0000 | <i>Oncorhynchus mykiss</i> | 45.9963  | -121.5222 | <i>Oncorhynchus mykiss</i> | 43.2588  | 18.8416   |
| <i>Oncorhynchus mykiss</i> | 55.3333  | -123.3333 | <i>Oncorhynchus mykiss</i> | 42.3075  | -124.4104 | <i>Oncorhynchus mykiss</i> | 41.6064  | 21.9221   |
| <i>Oncorhynchus mykiss</i> | -15.9167 | -68.8333  | <i>Oncorhynchus mykiss</i> | 41.2297  | -124.0928 | <i>Oncorhynchus mykiss</i> | 44.7251  | 17.1577   |
| <i>Oncorhynchus mykiss</i> | 43.1167  | -80.4000  | <i>Oncorhynchus mykiss</i> | 33.5372  | -117.5536 | <i>Oncorhynchus mykiss</i> | 44.5505  | 18.7128   |
| <i>Oncorhynchus mykiss</i> | 38.8600  | -0.2900   | <i>Oncorhynchus mykiss</i> | 40.5917  | -124.4250 | <i>Oncorhynchus mykiss</i> | 33.4436  | -111.8154 |
| <i>Oncorhynchus mykiss</i> | 40.0500  | -1.3000   | <i>Oncorhynchus mykiss</i> | 66.4580  | -147.1964 | <i>Oncorhynchus mykiss</i> | 48.6857  | 10.1469   |
| <i>Oncorhynchus mykiss</i> | 41.4100  | 1.5000    | <i>Oncorhynchus mykiss</i> | 45.9839  | 8.1283    | <i>Oncorhynchus mykiss</i> | 40.7500  | -0.1000   |
| <i>Oncorhynchus mykiss</i> | 42.1300  | -1.7300   | <i>Oncorhynchus mykiss</i> | -25.1000 | 30.7833   | <i>Oncorhynchus mykiss</i> | 56.7170  | -124.7330 |
| <i>Oncorhynchus mykiss</i> | 38.4400  | -2.4800   | <i>Oncorhynchus mykiss</i> | -26.1903 | 31.0503   | <i>Oncorhynchus mykiss</i> | 55.3170  | -120.2670 |



| Species                    | Latitude | Longitude | Species                    | Latitude | Longitude | Species                    | Latitude | Longitude |
|----------------------------|----------|-----------|----------------------------|----------|-----------|----------------------------|----------|-----------|
| <i>Oncorhynchus mykiss</i> | 37.1800  | -2.8300   | <i>Oncorhynchus mykiss</i> | -18.2500 | 32.8000   | <i>Oncorhynchus mykiss</i> | 53.9170  | -118.6630 |
| <i>Oncorhynchus mykiss</i> | 42.5000  | -3.0600   | <i>Oncorhynchus mykiss</i> | -33.8000 | 25.0167   | <i>Oncorhynchus mykiss</i> | 51.5830  | -56.0000  |
| <i>Oncorhynchus mykiss</i> | 37.6300  | -4.1900   | <i>Oncorhynchus mykiss</i> | 56.9967  | 12.7247   | <i>Oncorhynchus mykiss</i> | 50.2500  | -57.5830  |
| <i>Oncorhynchus mykiss</i> | 41.3200  | -4.6100   | <i>Oncorhynchus mykiss</i> | 57.6448  | 15.9280   | <i>Oncorhynchus mykiss</i> | 50.2830  | -65.9670  |
| <i>Oncorhynchus mykiss</i> | 43.0100  | -5.6400   | <i>Oncorhynchus mykiss</i> | 58.3674  | 12.3736   | <i>Oncorhynchus mykiss</i> | 44.8930  | -65.2810  |
| <i>Oncorhynchus mykiss</i> | 43.4700  | -7.0800   | <i>Oncorhynchus mykiss</i> | 60.1453  | 14.5832   | <i>Oncorhynchus mykiss</i> | 65.3330  | -113.6670 |
| <i>Oncorhynchus mykiss</i> | 43.1300  | -8.9400   | <i>Oncorhynchus mykiss</i> | 57.7400  | 18.4072   | <i>Oncorhynchus mykiss</i> | 39.1787  | -96.5541  |
| <i>Oncorhynchus mykiss</i> | 39.5900  | -5.5000   | <i>Oncorhynchus mykiss</i> | 58.3030  | 14.2866   | <i>Oncorhynchus mykiss</i> | 57.0311  | -132.7159 |
| <i>Oncorhynchus mykiss</i> | 36.8900  | -5.4100   | <i>Oncorhynchus mykiss</i> | 60.5650  | 17.4408   | <i>Oncorhynchus mykiss</i> | 62.0950  | -146.2765 |
| <i>Oncorhynchus mykiss</i> | 40.9700  | -2.7000   | <i>Oncorhynchus mykiss</i> | 61.2620  | 15.8651   | <i>Oncorhynchus mykiss</i> | 25.3570  | -100.3080 |
| <i>Oncorhynchus mykiss</i> | 39.7900  | 2.7100    | <i>Oncorhynchus mykiss</i> | 65.1440  | 16.3177   | <i>Oncorhynchus mykiss</i> | 64.0348  | 15.9961   |
| <i>Oncorhynchus mykiss</i> | 51.6277  | -124.1422 | <i>Oncorhynchus mykiss</i> | 29.9227  | -90.3193  | <i>Oncorhynchus mykiss</i> | 58.9690  | 16.2797   |
| <i>Oncorhynchus mykiss</i> | 45.1483  | -118.4456 | <i>Oncorhynchus mykiss</i> | 31.6167  | -115.6233 | <i>Oncorhynchus mykiss</i> | -42.2500 | 145.2500  |
| <i>Oncorhynchus mykiss</i> | 44.8080  | -121.1034 | <i>Oncorhynchus mykiss</i> | 29.0000  | -105.0000 | <i>Oncorhynchus mykiss</i> | -25.8870 | 29.6970   |
| <i>Oncorhynchus mykiss</i> | 44.1387  | -122.3694 | <i>Oncorhynchus mykiss</i> | 32.8333  | -115.0000 | <i>Oncorhynchus mykiss</i> | 39.1600  | 139.9000  |
| <i>Oncorhynchus mykiss</i> | 42.8369  | -118.8892 | <i>Oncorhynchus mykiss</i> | 37.9167  | -120.9667 | <i>Oncorhynchus mykiss</i> | 35.0125  | 134.9560  |
| <i>Oncorhynchus mykiss</i> | 42.4198  | -123.2042 | <i>Oncorhynchus mykiss</i> | 19.8161  | -101.7906 | <i>Oncorhynchus mykiss</i> | 35.5625  | 134.6940  |
| <i>Oncorhynchus mykiss</i> | 43.0468  | -121.1729 | <i>Oncorhynchus mykiss</i> | 19.8169  | -97.3603  | <i>Oncorhynchus mykiss</i> | 38.1231  | 140.5800  |
| <i>Oncorhynchus mykiss</i> | 42.2784  | -120.4967 | <i>Oncorhynchus mykiss</i> | 21.0167  | -101.2569 | <i>Oncorhynchus mykiss</i> | 31.9847  | -104.7984 |
| <i>Oncorhynchus mykiss</i> | 46.0299  | -123.7444 | <i>Oncorhynchus mykiss</i> | 20.2033  | -98.5756  | <i>Oncorhynchus mykiss</i> | 55.7000  | -124.8330 |
| <i>Oncorhynchus mykiss</i> | 58.3000  | -129.5000 | <i>Oncorhynchus mykiss</i> | 46.1669  | -112.2070 |                            |          |           |

### Chapter 3: The effect of rainbow trout (*Oncorhynchus mykiss*) invasions on native fish communities in the subtropical Blyde River, Mpumalanga province, South Africa<sup>2</sup>

#### Abstract

This study investigated the effects of rainbow trout (*Oncorhynchus mykiss*) invasion on native fish communities in the upper Blyde River catchment. A fish survey was undertaken between September 2017 and October 2018 from 11 sites in the Blyde and Treur Rivers using electrofishing and fyke nets. Differences in species composition, relative abundance, and community structure among sites were tested using multivariate analysis. A total of ten fish species were captured. There were significant differences in composition and abundance between fish communities that could be attributed to *O. mykiss* invasion and variation in habitats. Populations of native species that historically occurred throughout the upper catchment, such as *Enteromius treurensis*, were greatly reduced and fragmented in the presence of *O. mykiss*. However, instream migration barriers such as waterfalls have prevented upstream migration of *O. mykiss*, and these invasion-free areas have remnant populations of native fishes that appear to be largely intact. This finding is consistent with other studies that have shown that introduced alien predatory fish can have a significant effect on fish communities and highlighted the need to prevent human-facilitated introductions in biodiversity sensitive areas, such as mountain headwater streams, that are inhabited by endemic and range-restricted minnows.

**Keywords:** Abundance, biogeographic barriers, composition, distribution, *Enteromius treurensis*, Treur River.

<sup>2</sup>This chapter is essentially the text of a paper that was published under the following full citation and is presented in the format of the journal:

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<https://doi.org/10.2989/16085914.2021.1949260>

## Introduction

The rainbow trout (*Oncorhynchus mykiss*) is a popular angling fish native to North America that has been introduced across the world, mainly for aquaculture and angling purposes (Crawford and Muir 2007). In some cases, introduced *O. mykiss* have become invasive and have caused adverse impacts to native fish and ecosystems (McDowall 2006; Young et al. 2010; Kadye et al. 2013; Stanković et al. 2015). For more than a century, *O. mykiss* has been widely introduced into lakes and rivers in South Africa to create and enhance sport-fishing opportunities (Ellender and Weyl 2014). It is a cold-water species, often introduced into cool, well-oxygenated mountain headwaters. However, these habitats are also inhabited by some threatened and endemic species (Weyl et al. 2020). These introductions of *O. mykiss* have, in some cases, caused declines in native invertebrates, frogs, and fish, extirpating some populations (Karssing et al. 2012; Rivers-Moore et al. 2013; Shelton et al. 2015a). In addition, *O. mykiss* introductions have altered food web structures (Shelton et al. 2015b), changed habitat coupling, as well as causing other overall ecosystem-level impacts (Jackson et al. 2016). These studies represent a small, but growing number of studies within South Africa, that provide evidence that trout invasions in areas of conservation concern can lead to adverse impacts on biodiversity, as demonstrated in other parts of the world (McDowall 2006; McIntosh et al. 2010).

This study investigated the impact of the *O. mykiss* on community structure of native fish species in the upper catchments of the Blyde River in Mpumalanga province, South Africa. The upper catchment of the Blyde River is located on the northern part of the Great Drakensburg Escarpment where *O. mykiss* has been introduced into several headwater streams and has established naturalised populations (Engelbrecht and Roux 1998). These upland areas form part of trout angling areas where the stocking and utilisation of trout is allowed (such as the Crocodile River from its source up to its confluence with the Santa River, the Sabie River



from its source up to the waterfall in the town of Sabie, and the Elands River from its source up to its confluence with the Swartkops River) by the Mpumalanga Nature Conservation Act No. 10 of 1998.

These headwater streams are also inhabited by range-restricted and endemic river minnows, such as the Treur River barb (*Enteromius treurensis*), that are listed as critically endangered, because of alien predatory fish, such as *O. mykiss*, brown trout (*Salmo trutta*) and smallmouth bass (*Micropterus dolomieu*) (Roux and Hoffman 2017). *Enteromius treurensis* has a small geographic range (4.5 km<sup>2</sup>) and extant populations are fragmented and restricted to two localities within the upper Blyde River catchments (Kleynhans 1987). The species was originally described from the Treur River, a small tributary of the Blyde River (Groenewald 1958), but it became extirpated from the river in the 1960s, likely as a result of the introduction of *O. mykiss* and *M. dolomieu* (Jubb 1967; Klenyhans 1987). A small and isolated population of *E. treurensis* was then discovered in the upper Blyde River in the late 1960s (Pott 1981). The upper sections of the Blyde River are isolated by the Christmas Pool waterfalls, a natural geographic barrier that has prevented upstream migration of *O. mykiss* from the lower sections where it occurs. *Enteromius treurensis* was then re-introduced into the Treur River in 1995, where it has successfully managed to re-establish in several sections of the river that are free of alien predatory fish (Engelbrecht and Roux 1998).

The historic distribution of *E. treurensis* is thought to have encompassed the whole of the upper catchment. Its current fragmented distribution has been attributed to introduction and continued stocking of *O. mykiss*, and to gold mining activities that may have led to its decline and extirpation in river sections between the two localities with remnant populations (Kleynhans 1987). These remnant populations are largely intact, because of a series of waterfalls that prevent upstream fish migration from downstream river sections where alien fish introductions occurred.

The present study evaluated the ecological impact of *O. mykiss* invasions on native fish communities in the upper Blyde River by comparing fish communities in river reaches invaded by *O. mykiss* and river sections free of *O. mykiss* invasion. More specifically, the study evaluated the effects of *O. mykiss* invasion on native fish species composition, relative abundance, and community structure. The study tested the hypothesis that the presence of *O. mykiss* would create specific differences in species composition and community structure, such as a decline and fragmentation of native fish species populations, in invaded river sections.

## **Materials and methods**

### *Study area*

The study area encompassed the headwaters of the Blyde River and the Treur River that are located on the northern part of the Great Drakensberg escarpment in Mpumalanga province, South Africa (Figure 3.1). The study sites were located on the upper slopes of the escarpment (1 200–1 500 m above sea level) (Table 3.1) that are characterised by grassland vegetation that is interspersed with Afromontane forest, cool to moderate temperatures (10–18 °C), moderate to high rainfall (800–1 200 mm), and mean annual precipitation of more than 1 000 mm (WRC 2001). To assess the impact of *O. mykiss* on fish community structure, eight sampling sites were selected from the non-invaded (sites 1 and 2) and invaded (sites 3–8) river sections of upper Blyde River (Table 3.1). Three additional sites (9–11) were located in the upper sections of the Treur River that are free of alien fish.

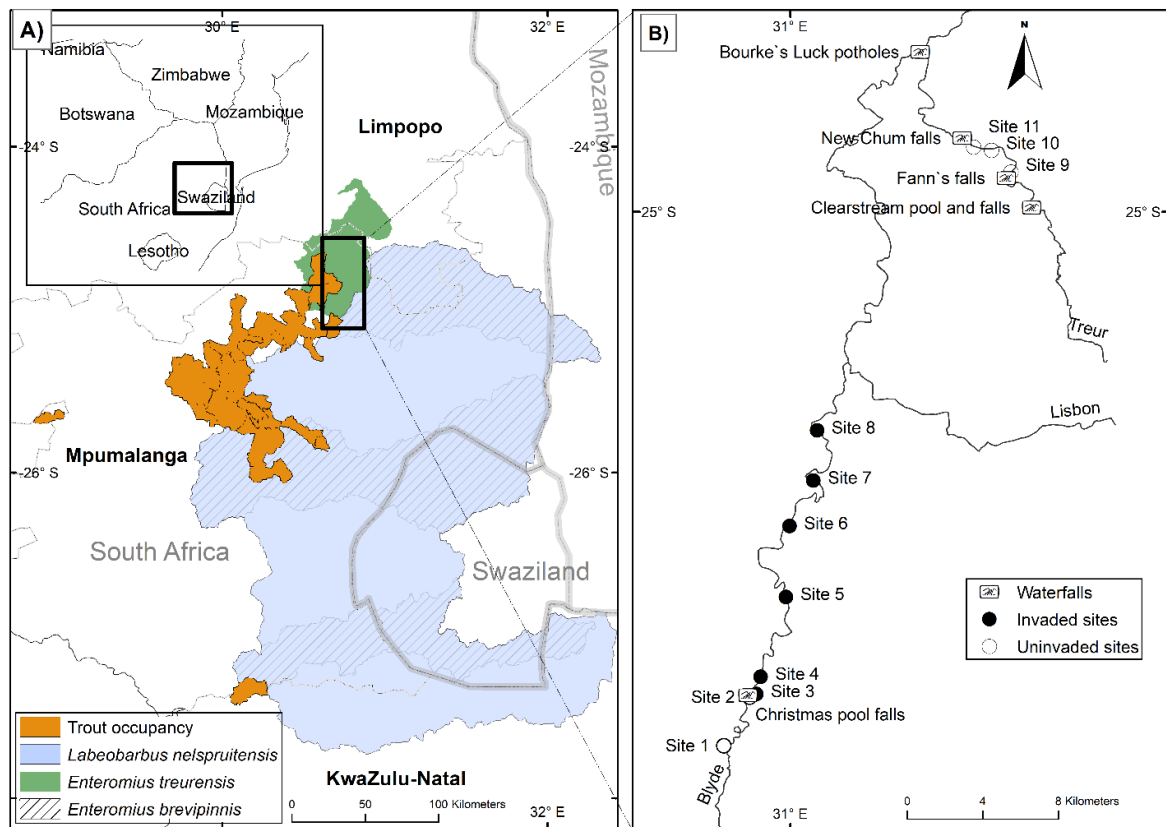


**Figure 3.1:** A map showing (A) the distribution of native and threatened fish species (*Enteromius treurensis*, *Enteromius brevipinnis* and *Labeobarbus nelspruitensis*) in relation to the presence of *Oncorhynchus mykiss*; and (B) surveyed sites with the invasive rainbow trout (*Oncorhynchus mykiss*) (●) and sites free of invasion (○) in the upper catchment of Blyde and Treur Rivers in Mpumalanga province, South Africa. Trout occupancy refers to areas where trout is known to occur, based on a consultative stakeholder mapping process done by the Department of Forestry, Fisheries and the Environment, and the South African National Biodiversity Institute. Data sources for the distribution of native fish species were obtained from IUCN (International Union for Conservation of Nature) 2007a, 2007b, 2007c.

### Sampling

Fish were sampled between September 2017 and October 2018 from 11 sampling sites (Figure 3.1; Table 3.1) and each site was sampled once every three months on five different occasions. Each sampling event took place over a period of 4–5 days and each site was sampled randomly depending on when landowner permission to access the site was confirmed. All the sites were

sampled using a SAMUS725MP electrofisher (Samus Special Electronics, Warsaw, Poland). Whereas, fyke nets were used at all sites on the Blyde River, but not in the Treur River, because of the low water levels. A river stretch of approximately 50 m was blocked off to prevent fish escape and electrofishing was conducted for ~30 minutes, with the electrofisher being operated in an upstream direction with a 1 m deep  $\times$  2 m wide, 5 mm mesh mobile block net being used behind to catch stunned fish missed by the operator (Kimberg et al. 2014). Fyke nets were set in the evening and retrieved the following morning. Fish were sorted according to species, weighed (g), and the total length (TL, mm) measured. A subsample of the fish was then collected and preserved in absolute ethanol, and the rest of the catch was released back into the river. At each sampling site, the following physical and chemical variables were recorded once for each sampling event using a Multi-Parameter Test 35 series water quality probe (Oakton Instruments, Vernon Hills, USA.): temperature ( $^{\circ}\text{C}$ ), conductivity ( $\mu\text{S cm}^{-1}$ ), and pH. The accuracy of the multiparameter meter was 1% full scale and it was calibrated before use at each site.

**Table 3.1:** Sampling sites and their geographic coordinates (sites 1–11) where surveys were undertaken on the Blyde and Treur Rivers in Mpumalanga province, South Africa. Invasion status was defined as either invaded when rainbow trout (*Oncorhynchus mykiss*) was present or uninvaded when it was absent.

| River       | Site | Location                                                                 | Invasion status | Geographic coordinates       | Elevation (m) | Land use            |
|-------------|------|--------------------------------------------------------------------------|-----------------|------------------------------|---------------|---------------------|
| Blyde River | 1    | 5 km above the first Christmas Pools waterfall                           | Uninvaded       | 25°00'14.2"S<br>30°43'06.3"E | 1432          | Forestry plantation |
|             | 2    | Christmas Pools below the first waterfall                                | Uninvaded       | 24°58'51.0"S<br>30°43'50.4"E | 1372          | Forestry plantation |
|             | 3    | Christmas Pools below the second waterfall                               | Invaded         | 24°58'45.6"S<br>30°44'01.9"E | 1362          | Forestry plantation |
|             | 4    | 3km downstream of the second waterfall                                   | Invaded         | 24°58'15.9"S<br>30°44'09.5"E | 1341          | Forestry plantation |
|             | 5    | Third bridge from Christmas Pools                                        | Invaded         | 24°55'59.4"S<br>30°44'52.8"E | 1285          | Forestry plantation |
|             | 6    | First bridge from Pilgrim's Rest                                         | Invaded         | 24°53'57.9"S<br>30°44'58.9"E | 1242          | Mining, Peri urban  |
|             | 7    | Second bridge from Pilgrim's Rest                                        | Invaded         | 24°52'40.0"S<br>30°45'39.8"E | 1215          | Peri urban          |
|             | 8    | Third bridge from Pilgrim's Rest                                         | Invaded         | 24°51'14.1"S<br>30°45'46.1"E | 1194          | Agriculture         |
| Treur River | 9    | Pools below Treur River waterfall, 2.5 km upstream of Potluck Boskombuis | Uninvaded       | 24°43'52.2"S<br>30°51'18.5"E | 1293          | Protected area      |
|             | 10   | Pools next to Potluck Boskombuis restaurant                              | Uninvaded       | 24°43'15.0"S<br>30°50'45.0"E | 1272          | Protected area      |
|             | 11   | Pools downstream of bridge to Potluck Boskombuis restaurant              | Uninvaded       | 24°43'09.4"S<br>30°50'14.5"E | 1246          | Protected area      |

### *Statistical analyses*

To minimise biases caused by gear selectivity, catch data were transformed to presence and absence data for comparisons on differences in species composition among sites and comparisons for differences in species abundance were restricted to data obtained from electrofishing. The differences in community structure among the sites were tested using multivariate PERMANOVA based on a Bray–Curtis similarity matrix of fourth root transformed abundance data with 9 999 permutations. The PERMANOVA was based on algorithms in PAST v3. A non-metric multidimensional scaling (nMDS) was then used to assess the relationship between species abundance and two categorical factors: site and invasion status. A site was considered invaded when *O. mykiss* was present and uninvaded when it was absent, taking cognisance that it is difficult to provide absolute evidence of absence. The nMDS was based on three axis ordinations in order to achieve a good model fit (i.e., stress < 0.11). The similarity between and among sites was evaluated using an agglomerative hierarchical cluster analysis (using group-average linking), based on a Bray Curtis similarity matrix. A Spearman rank correlation analysis was used to assess the correlation between each species and the two categorical factors, site and invasion status. The nMDS, cluster and Spearman rank analyses were all performed using Primer v6 (PRIMER-E LTD, 2007, Lutton, United Kingdom).

Canonical correspondence analysis (CCA) was then used to assess the possible effects of environmental variables on fish community structure among the sampling sites. First, species occurrence data were  $\log(x + 1)$  transformed to reduce the effect of rare or very common species and environmental data were then Box-Cox  $(x + 1)$  transformed to dampen the influence of outliers. Second, a partial CCA was used to remove the effects of spatial autocorrelation among the eight environmental variables [temperature, pH, salinity, conductivity, total dissolved solids, altitude, and invasion status (presence or absence of *O.*

*mykiss*)). The partial CCA indicated collinearity among some physico-chemical variables, such as salinity, conductivity, and total dissolved solids and between temperature and altitude. As a result, only four out of the initial eight variables (altitude, pH, conductivity, and invasion status) that were non-correlated were included in the full CCA model. The significance of the CCA model, CCA axis and environmental variables were then tested using Monte Carlo permutation test with 999 unrestricted permutations. All the CCA analysis was done using individual values for each site in the VEGAN package in the R Computing Programme.

## Results

### *Species composition and abundance*

A total of 610 specimens representing ten species from five families were collected from the Blyde and Treur Rivers (Table 3.2). The most widespread and abundant species were *E. treurensis* (nine out of 11 sampling sites) and the line spotted barb (*E. lineomaculatus*) (seven out of 11) that collectively accounted for 62% of the catch. There were significant differences in species composition (PERMANOVA:  $p = 0.01$ ) and species abundance (PERMANOVA:  $p < 0.001$ ) among fish assemblages from the different sites in the two rivers (Table 3.2). In the Blyde River, species richness and abundance generally increased with decreasing altitude and increasing stream size (Table 3.2). Sampling sites (1 and 2) located in upper river sections above the Christmas Pool waterfalls had low species richness, and only two species, *E. treurensis* and the stargazer mountain catfish (*Amphilius uranoscopus*) were collected, of which *E. treurensis* was highly abundant. Sampling sites (3 and 4) located below the waterfalls were invaded by *O. mykiss* and were characterised by a lower abundance of *E. treurensis*, compared with sites 1 and 2. Sampling sites (6 to 8) located farther downstream and in lower river sections had higher species richness and were characterised by higher abundances of

species, such as *E. lineomaculatus*, the largescale yellowfish (*Labeobarbus marequensis*) and the shortspine suckermouth (*Chiloglanis pretoriae*) than at other sites.

**Table 3.2.** Composition and abundance of fish communities in Blyde and Treur rivers in Mpumalanga Province, South Africa. Numbers outside parentheses indicate total number of individuals with standard deviation collected using electrofishing (n= 436) and those in parentheses using fyke nets (n = 174).

| Family      | Species               | IUCN<br>List<br>threat<br>category | Red | Blyde River |        |        |        |        |        |        |        | Treur River |         |         |
|-------------|-----------------------|------------------------------------|-----|-------------|--------|--------|--------|--------|--------|--------|--------|-------------|---------|---------|
|             |                       |                                    |     | Site1       | Site 2 | Site 3 | Site 4 | Site 5 | Site 6 | Site 7 | Site 8 | Site 9      | Site 10 | Site 11 |
| Cyprinidae  | <i>Enteromius</i>     | Least                              |     |             |        |        |        | 25 ±   | 28 ±   | 19 ±   | 31 ±   | 13 ±        | 4 ±     | 3 ±     |
|             | <i>lineomaculatus</i> | Concern                            |     |             |        |        |        | 11.2   | 11.4   | 6.1    | 7.6    | 4.3         | 1.1     | 1.3     |
|             |                       |                                    |     |             |        |        |        | (33 ±  |        |        | (13 ±  |             |         |         |
|             |                       |                                    |     |             |        |        |        | 10.5)  |        |        | 3.7)   |             |         |         |
|             | <i>Labeobarbus</i>    | Least                              |     |             |        |        |        |        | 9 ±    | 17 ±   | 28 ±   |             |         |         |
|             | <i>marequensis</i>    | Concern                            |     |             |        |        |        |        | 4.0    | 4.9    | 7.8    |             |         |         |
|             |                       |                                    |     |             |        |        |        |        |        | (5 ±   | (16 ±  |             |         |         |
|             |                       |                                    |     |             |        |        |        |        |        | 2.2)   | 4.8)   |             |         |         |
|             | <i>Enteromius</i>     | Critically                         |     | 50 ±        | 40 ±   | 1 ±    | 4 ±    |        | 13 ±   |        | 3 ±    | 3 ±         | 6 ±     | 14 ±    |
|             | <i>treurensis</i>     | endangered                         |     | 11.9        | 10.7   | 0.4    | 1.8    |        | 5.8    |        | 1.3    | 1.3         | 1.3     | 2.9     |
| Mochokidae  |                       |                                    |     | (22 ±       | (47 ±  | (1 ±   |        |        |        |        |        |             |         |         |
|             |                       |                                    |     | 9.8)        | 21.0)  | 0.4)   |        |        |        |        |        |             |         |         |
|             | <i>Labeobarbus</i>    | Near                               |     |             |        |        |        |        |        | 1 ±    | 2 ±    |             |         |         |
|             | <i>nelspruitensis</i> | Threatened                         |     |             |        |        |        |        |        | 0.4    | 0.9    |             |         |         |
|             | <i>Enteromius</i>     | Least                              |     |             |        |        |        |        |        | (1 ±   |        |             |         |         |
|             | <i>paludinosus</i>    | Concern                            |     |             |        |        |        |        |        | 0.4)   |        |             |         |         |
|             | <i>Enteromius</i>     | Least                              |     |             |        |        |        |        |        |        |        | 15 ±        | 4 ±     |         |
|             | <i>anoplus</i>        | Concern                            |     |             |        |        |        |        |        |        |        | 6.7         | 1.8     |         |
|             | <i>Chiloglanis</i>    | Least                              |     |             |        |        |        |        | 10 ±   | 3 ±    | 12 ±   |             |         |         |
|             | <i>pretoriae</i>      | Concern                            |     |             |        |        |        |        | 2.1    | 0.9    | 1.9    |             |         |         |
| Amphiliidae |                       |                                    |     |             |        |        |        |        |        | (2 ±   | (6 ±   |             |         |         |
|             |                       |                                    |     |             |        |        |        |        |        | 0.9)   | 2.7)   |             |         |         |
|             | <i>Amphilius</i>      | Least                              |     |             | 1 ±    |        | 3 ±    |        |        |        | 1 ±    | 15 ±        | 9 ±     |         |
| Cichlidae   | <i>urancopis</i>      | Concern                            |     |             | 0.4 (1 |        | 1.3    |        |        |        | 0.4    | 3.7         | 2.5     |         |
|             |                       |                                    |     |             | ± 0.4) |        | (1 ±   |        |        |        | (7 ±   |             |         |         |
|             |                       |                                    |     |             |        |        | 0.4)   |        |        |        | 2.2)   |             |         |         |
| Salmonidae  | <i>Tilapia</i>        | Least                              |     |             |        |        |        |        |        |        |        | 4 ±         | 17 ±    | 14 ±    |
|             | <i>sparrmanii</i>     | Concern                            |     |             |        |        |        |        |        |        |        | 1.1         | 3.5     | 3.8     |
| Salmonidae  | <i>Oncorhynchus</i>   | Not assessed                       |     |             |        | 10 ±   | 2 ±    | (1 ±   |        | 1 ±    | 1 ±    |             |         |         |
|             | <i>mykiss*</i>        |                                    |     |             |        | 2.7    | 0.9    | 0.4)   |        | 0.4    | 0.4    |             |         |         |
|             |                       |                                    |     |             |        | (5 ±   | (13 ±  |        |        |        |        |             |         |         |
|             |                       |                                    |     |             |        | 1.8)   | 5.7)   |        |        |        |        |             |         |         |

\* indicates alien species and the IUCN Red List threat category indicates the conservation status of fish species caught in the upper catchment of the Blyde River (see IUCN 2021, for detailed assessments of each species).



In contrast, species composition and abundance were generally similar among sites in the Treur River, except for site 11 that had markedly lower species richness than the other two sites (Table 3.2). Species composition was largely similar between the two rivers, the only differences were for *O. mykiss* and straightfin barb (*E. paludinosus*) that were only collected from the Blyde River and chubbyhead barb (*E. anoplus*) and banded tilapia (*Tilapia sparrmanii*) were only collected from the Treur River.

#### *Community structure*

There were significant differences in fish communities among the sampling sites, based on the location (PERMANOVA:  $p < 0.001$ ) and invasion status (PERMANOVA:  $p = 0.01$ ). The nMDS analysis (2D Stress = 0.11) indicated a complete and clear separation of sampling sites into four clusters (60% Bray–Curtis similarity) (Figure 3.2). The first two clusters comprised sites 1–4 from the upper section of the Blyde River. Sites 1 and 2 were characterised by the co-occurrence of *E. treurensis* and *A. uranoscopus* and sites 3–4 were defined by occurrence of *O. mykiss*. The second cluster comprised sites 9–11 from the Treur River that were characterised by species, such as the *A. uranoscopus*, *E. anoplus*, *E. treurensis* and *T. sparrmanii* (Figure 3.2). The third cluster comprised of sites 6–8 was characterised by species such as *E. lineomaculatus* and *L. marequensis* (Figure 3.2). Site 5 formed the last cluster and was defined by the occurrence of *O. mykiss*.

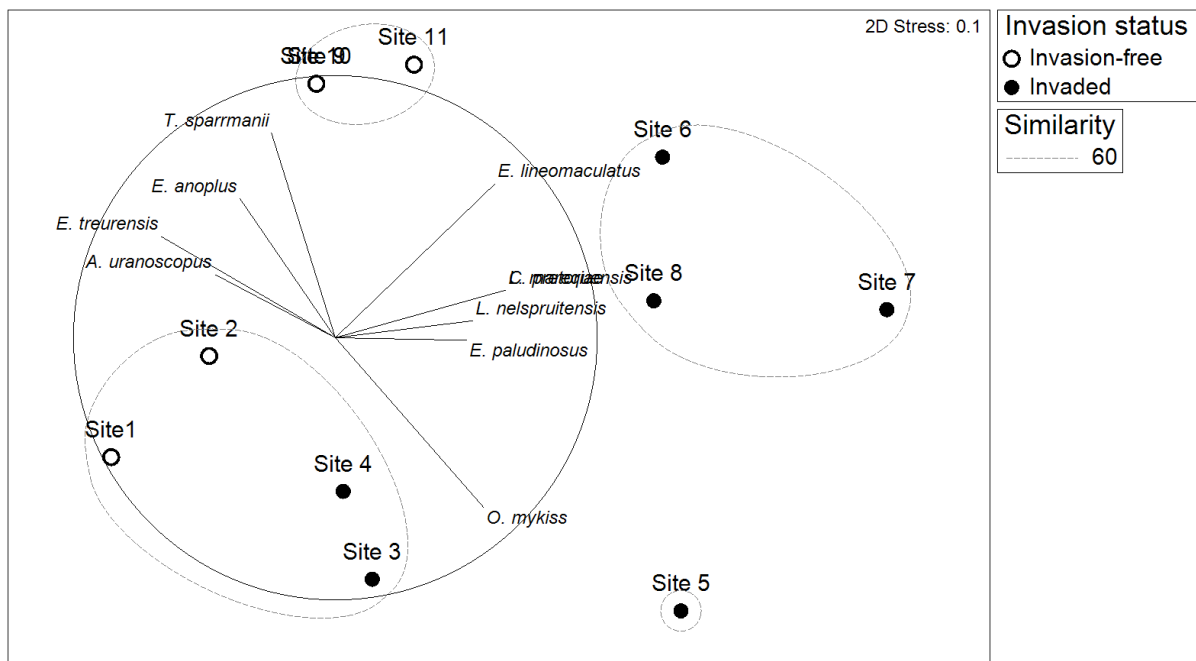


**Figure 3.2:** A non-metric multidimensional scaling (nMDS) showing sampling sites similarity, based on species composition in the invaded and uninvaded sections of Blyde River and the uninvaded Treur River in Mpumalanga province, South Africa. The dashed circles indicate similarity (60%) between and among sites evaluated using an agglomerative hierarchical cluster analysis (using group-average linking), based on a Bray–Curtis similarity matrix.

### *Effect of environmental variables*

The ordination results from the CCA indicated that the first two axes explained 38.2% variation in the fish community structure. The first CCA axis accounted for 26.6% of the total species variance and was positively correlated with pH, conductivity, and invasion status, but negatively correlated with elevation (Figure 3.3). The second CCA axis accounted for 11.6% of the total variance and was positively correlated with pH and conductivity, but negatively correlated with altitude and invasion status. The permutation tests indicated that the CCA model, first CCA axis, and two environmental variables (altitude and invasion status) were significant predictors of variation in the fish community structure ( $p < 0.01$ ). Sampling sites formed four clusters, based on invasion status and water quality variables (Figure 3.3). Sites

1–2 and sites 9–11 represented sites that were free of *O. mykiss*, whereas sites 3–4 and 5–8 represented trout-invaded areas.

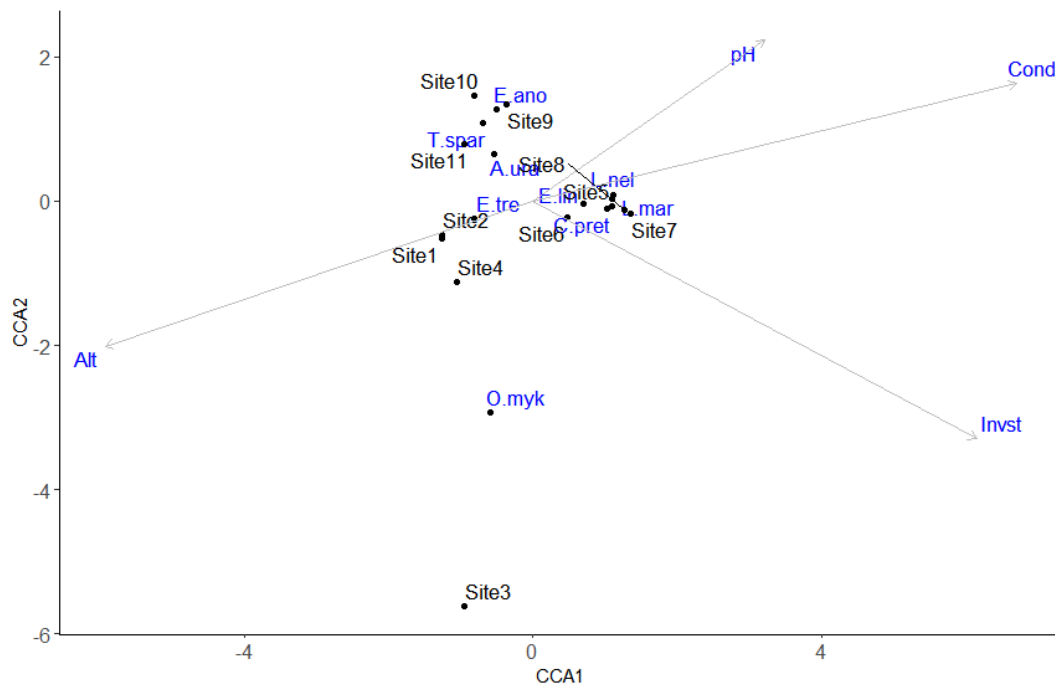


**Figure 3.3:** Canonical correspondence analysis showing the relationship between species composition and environmental variables among the invaded and uninvaded sections of Blyde River and the uninvaded Treur River in Mpumalanga Province, South Africa. *A. ura* = *Amphilius uranoscopus*, *C. pre* = *Chiloglanis pretoriae*, *E. ano* = *Enteromius anoplus*, *E. lin* = *Enteromius lineomaculatus*, *E. tre* = *Enteromius treurensis*, *L. mar* = *Labeobarbus marequensis*, *L. nel* = *Labeobarbus nelspruitensis*, *O. myk* = *Oncorhynchus mykiss*, *T. spa* = *Tilapia sparrmanii*. Alt = Altitude and Invst = Invasion status which refers to the presence or absence of *O. mykiss*.

In addition, sites from areas free of *O. mykiss* invasion could be further separated into two groups: sites 1–2 on the Blyde River that were at a higher elevation and had lower water temperatures versus sites 9–11 on the Treur River that were at a lower elevation with relatively higher temperature and pH (Table 3.3). Similarly, sites from invaded areas could be split into two groups based on physicochemical variables: sites 5–8 with higher conductivity versus sites 3–4 with relatively lower conductivity values.

**Table 3.3.** Water quality parameters recorded at sites where fish surveys were undertaken in the Blyde and Treur rivers in Mpumalanga Province, South Africa.

| River       | Site | Temperature (°C) | pH        | Conductivity (µS cm <sup>-1</sup> ) |
|-------------|------|------------------|-----------|-------------------------------------|
| Blyde River | 1    | 15.5 ± 2.3       | 7.8 – 9.0 | 21.9 ± 4.5                          |
|             | 2    | 15.5 ± 3.6       | 8.0 – 9.0 | 22.9 ± 8.3                          |
|             | 3    | 15.1 ± 5.0       | 8.0 – 8.4 | 23.2 ± 1.9                          |
|             | 4    | 16.3 ± 6.2       | 7.9 – 8.3 | 24.5 ± 1.4                          |
|             | 5    | 17.4 ± 2.8       | 8.1 – 8.5 | 71.9 ± 21.9                         |
|             | 6    | 17.4 ± 2.8       | 8.6 – 9.0 | 105.5 ± 28.3                        |
|             | 7    | 17.6 ± 2.9       | 8.5 – 9.0 | 140.3 ± 35.9                        |
|             | 8    | 17.2 ± 3.5       | 8.6 – 9.0 | 142.5 ± 35.0                        |
| Treur River | 9    | 19.9 ± 7.1       | 8.2 – 8.8 | 52.4 ± 11.0                         |
|             | 10   | 19.6 ± 3.2       | 8.1 – 9.0 | 53.8 ± 6.7                          |
|             | 11   | 19.6 ± 3.3       | 8.5       | 49.5 ± 7.9                          |

## Discussion

### *Effect of O. mykiss invasion*

The establishment of invasive predatory species within recipient systems is known to reduce native populations through various mechanisms, such as predation and competitive exclusion for resources such as food and habitat (Eby et al. 2006). Salmonid fishes, in particular *O. mykiss* and *S. trutta* have caused major declines in native fish populations in areas of introduction around the world (e.g., McDowall 2006). In the current study, there was low abundance of native fish species, specifically *E. treurensis* (96% lower), in areas where *O. mykiss* occurred. This is likely because of predation. This assertion is supported by observations from elsewhere that have shown that *O. mykiss* selectively consume small river minnows (McIntosh et al. 2010; Shelton et al. 2015a). In addition, other recent assessments have demonstrated that predation by *O. mykiss* can lead to the decline, and in some cases, the local extirpation of fish in invaded areas (Weyl et al. 2020). For example, *O. mykiss* has been implicated in the extirpation of the endangered boarder barb (*Amatolacypris trevelyani*) in the headwaters of the Keiskamma River system (Ellender 2013) and causing a decline in the abundance of native fish, such as the

Breede River redbfin (*Pseudobarbus burchelli*), the Cape kurper (*Sandelia capensis*), and the Cape galaxias (*Galaxias zebratus*) in the Breede River system (Shelton et al. 2015a).

Although *O. mykiss* had a demonstrable impact on native species at sampling sites below the Christmas Pool waterfalls where it was abundant, its effect was less pronounced at sites located farther downstream where it was less abundant. This is a well-known and characterised phenomenon in trout invasions globally, where impacts are more severe in river segments with high trout density than in segments with low densities (Woodford and Impson 2004; McIntosh et al. 2010; Shelton et al. 2015a). *Oncorhynchus mykiss* is a cold-water species that inhabits cool, well-oxygenated headwater streams and its abundance declines naturally with decreasing altitude (Rivers-Moore et al. 2019). This habitat preference may limit downstream migration to lower river sections that are characterised by higher water temperatures. In addition, the higher species richness observed in lower river sections, including native omnivores, such as *L. marequensis*, that are capable of piscivory (Lombard et al. 2018), may also explain the diminished vulnerability to *O. mykiss* predation observed in small-bodied fish, such as *E. lineomaculatus*. Furthermore, *E. lineomaculatus* is a widespread species occurring across the Limpopo basin, and it has coevolved with facultative piscivores like the African sharptooth catfish (*Clarias gariepinus*) and the canary kurper (*Chetia flaviventris*). This is in sharp contrast to *E. treurensis*, which being a headwater stream endemic is likely to be far more vulnerable to novel invasive predators. This contrast has been observed before with different responses to the largemouth bass (*Micropterus salmoides*) invasions by the Marico barb (*E. motebensis*), a headwater specialist, and the straight fin barb (*E. paludinosus*), a lowland specialist, in the Groot Marico River (Kimberg et al. 2014). Species rich river systems with multiple native top predators are therefore likely to be more robust to the addition of introduced predators (Finke and Denno 2004).

There are other river minnows that are known to occur in the upper Blyde River catchment that were not recorded in this study. These include the shortfin barb (*E. brevipinnis*) and the side spot barb (*E. neefi*), whose known distribution partly overlaps with trout angling areas in the catchment (Figure 3.1). This is of concern, especially for *E. brevipinnis* that is listed as near threatened, because of habitat loss and deterioration, and predation by alien fish, such as trout and bass (*Micropterus* spp.) (Engelbrecht et al. 2017). In addition, evidence from previous and ongoing taxonomic revisions of freshwater fishes in southern Africa is showing that some of the species that were considered to have wide distribution ranges comprise several narrow range endemic species (e.g. Chakona and Skelton 2017; Mazungula and Chakona 2021). Many of these are highly threatened. This could be the case for some of the species in the study area, such as *E. neefi* and the goldie barb (*E. pallidus*) (Engelbrecht et al. 2002; Chakona et al. 2015). This raises additional concerns on the potential impacts of trout invasions on the revised native species that are endemic, and range restricted to the river system.

#### *Effect of environmental variables*

Some of the differences in the fish assemblages among sampling sites were attributed to habitat differences related to altitudinal changes in river profiles, natural biogeographic barriers, such as waterfalls, that prevent upstream fish migration, and water quality variables. In the Blyde River, sampling sites located in the headwater river sections had low species richness relative to sampling sites located farther downstream and in the lower river sections. It has been suggested that the direct relationship between fish species richness and stream size can be attributed to the fact that larger streams tend to provide a wide variety of habitats that are able to support a greater diversity of species than smaller streams (Kadye and Marshall 2007; Weyl et al. 2013). For example, headwater sections of mountain streams, such as the Blyde River, have limited habitat diversity and are inhabited by a few habitat-specific species, such as *E. treurensis* and *A. uranoscopus*, that are known to prefer rocky pools, riffles of clear, and cool

waters (Kleynhans 1987), whereas lower sections had relatively higher number of species and were characterised by species, such as *E. lineomaculatus* and *L. marequensis*, that tend to favour vegetated habitats and slow-moving water. In addition, the low number of fish species in the headwater sections of the Blyde River can also be attributed to the presence of the Christmas Pool waterfalls that forms a geographic barrier for upstream fish migration. Habitat connectivity is a key factor that determines the distribution of species in aquatic ecosystems (Rahel 2007). Physical barriers, such as waterfalls, rapids and steep gradients, impede the upstream movement of species and this often leads to different fish assemblages among isolated river reaches in freshwater systems (Dias et al. 2013). Well-known examples of waterfall barriers within the region that have promoted distinct ichthyofauna among isolated river reaches include the Augrabies Falls on the Orange River and the Victoria Falls on the Zambezi River (Skelton and Cambray 1981; Zengeya and Marshall 2008; Tweddle 2010). In addition, the instream barriers also protect biodiversity by preventing natural upstream dispersal of introduced alien fish. For example, waterfalls have prevented the upstream invasion of headwater streams by largemouth bass (*M. salmoides*) in the Groot Marico River system (Kimberg et al. 2014) and trout (*O. mykiss* and *S. trutta*) in the uKhahlamba Drakensberg Park (Karssing et al. 2012; Rivers-Moore et al. 2013).

Differences in the fish community structure may also reflect the effects of anthropogenic pollution in some sections of the upper catchment, as suggested by Kleynhans (1987). Fish abundance was markedly lower at sites (6–7) that were adjacent to point sources of pollution such as gold mining and sewerage discharge, that were characterised by higher conductivity values likely as a result of elevated nutrients and inorganic chemicals than at sites farther downstream of the pollution sources and sites located on the Treur River, which is considered to be in a near pristine state (Nel et al. 2011). Although species composition was broadly similar between the Blyde and Treur Rivers, the latter was characterised by species

such as *A. uranoscopus* and *T. sparrmanii*, which have a wider altitudinal range and are known to tolerate a wide range of temperatures (Skelton 2001). Sampling sites located on the Treur River had a higher mean water temperature relative to sampling sites in the Blyde River. These differences in water temperatures can be related to differences in stream hydrology. Sites on the Treur River are relatively shallow and have a rocky riverbed and the elevated temperatures likely result from greater solar heating of the rocky riverbed surface.

## Conclusions

This study demonstrated that the populations of native fish species, such as *E. treurensis*, that historically occurred throughout the upper catchment were greatly reduced and fragmented in the presence of *O. mykiss*. However, instream migration barriers, such as waterfalls, have prevented upstream migration of *O. mykiss*, and these invasion free areas have remnant populations of native fishes that appear to be largely intact. Alien fish species have often-circumscribed natural migration barriers through intentional stocking of upstream reaches by humans. This is of concern as stocking of trout in the upper Blyde River is still on going, as parts of the catchment are designated as trout angling areas. However, areas with remnant populations of *E. treurensis* have remained free of human facilitated alien fish introductions, because they were designated as natural heritage sites. This designation of areas where trout utilisation is allowed and prohibited appears to have diffused potential conflicts between utilisation of trout and conservation concerns, unlike other areas in the country (see Woodford et al. 2017 and Zengeya et al. 2017). It is therefore crucial that the conservation status of these alien-free areas is maintained and that they are regularly monitored and kept free of alien fish species for the conservation of endemic and range-restricted minnows that occur in the system.



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## Appendices

**Appendix 3.1:** Spearman's rank correlation scores showing the contribution of species on the variation of site structure. nMDS = non-metric multidimensional scaling.

| Species                           | nMDS Axis 1 | nMDS Axis |
|-----------------------------------|-------------|-----------|
| <i>Enteromius anoplus</i>         | 0.07        | -0.67     |
| <i>Enteromius lineomaculatus</i>  | 0.84        | -0.48     |
| <i>Enteromius paludinosus</i>     | 0.60        | 0.07      |
| <i>Enteromius treurensis</i>      | -0.52       | -0.45     |
| <i>Labeobarbus marequensis</i>    | 0.78        | -0.13     |
| <i>Labeobarbus nelspruitensis</i> | -0.78       | 0.32      |
| <i>Chiloglanis pretoriae</i>      | 0.78        | -0.13     |
| <i>Amphilius uranoscopus</i>      | 0.12        | -0.36     |
| <i>Amphilius natalensis</i>       | -0.19       | -0.65     |
| <i>Tilapia sparrmanii</i>         | 0.00        | -0.71     |
| <i>Oncorhynchus mykiss</i>        | 0.29        | 0.75      |

**Appendix 3.2:** Bray Curtis similarity matrix between the sampling sites in Blyde and Treur River, in Mpumalanga Province, South Africa.

| Site | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|------|------|------|------|------|------|------|------|------|------|------|
| 1    |      |      |      |      |      |      |      |      |      |      |
| 2    | 85.5 |      |      |      |      |      |      |      |      |      |
| 3    | 54.3 | 46.6 |      |      |      |      |      |      |      |      |
| 4    | 49.7 | 43.7 | 83.5 |      |      |      |      |      |      |      |
| 5    | 23.1 | 19.9 | 44.8 | 37.9 |      |      |      |      |      |      |
| 6    | 45.9 | 41.5 | 34.0 | 33.3 | 49.0 |      |      |      |      |      |
| 7    | 14.6 | 13.3 | 28.8 | 25.7 | 56.3 | 68.4 |      |      |      |      |
| 8    | 26.7 | 24.8 | 36.3 | 49.3 | 50.4 | 73.5 | 75.6 |      |      |      |
| 9    | 32.1 | 42.0 | 29.8 | 45.7 | 37.9 | 43.8 | 28.6 | 49.3 |      |      |
| 10   | 36.1 | 48.3 | 30.3 | 46.3 | 32.1 | 41.8 | 24.1 | 42.6 | 85.2 |      |
| 11   | 58.1 | 51.3 | 42.3 | 40.3 | 42.3 | 56.6 | 29.1 | 37.1 | 60.4 | 70.5 |

**Appendix 3.3:** Canonical correspondence analysis model explaining variation observed in fish communities in the invaded and uninvaded sections of Blyde River and the uninvaded Treur River in Mpumalanga Province, South Africa.

Model: cca (formula = spe ~ Altitude + pH + Conductivity + InvasionStatus + Condition(x + y), data = envspatial)

|               | Inertia | Proportion | Rank |
|---------------|---------|------------|------|
| Total         | 2.4397  | 1.0000     |      |
| Conditional   | 0.9655  | 0.3957     | 2    |
| Constrained   | 0.9480  | 0.3886     | 4    |
| Unconstrained | 0.5262  | 0.2157     | 4    |

\*Inertia is scaled Chi-square

#### Appendix 3.4: Eigenvalues for constrained and unconstrained axes

|                    | CCA1    | CCA2    | CCA3    | CCA4    |
|--------------------|---------|---------|---------|---------|
| constrained axes   | 0.5020  | 0.3870  | 0.0511  | 0.0080  |
| unconstrained axes | 0.26665 | 0.16392 | 0.05151 | 0.04412 |

#### Appendix 3.5: The significance of the full CCA model tested using Monte Carlo permutation

test with 999 unrestricted permutations.

Model: cca (formula = spe ~ Altitude + pH + Conductivity + InvasionStatus, data = env)

|          | Df | ChiSquare | F      | Pr(>F)   |
|----------|----|-----------|--------|----------|
| Model    | 4  | 1.3818    | 1.9592 | 0.006 ** |
| Residual | 6  | 1.0579    |        |          |

---

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1



**Appendix 3.6:** The significance of environmental variables tested using Monte Carlo permutation test with 999 unrestricted permutations

Model: cca(formula = spe ~ Altitude + pH + Conductivity + InvasionStatus, data = env)

|                | Df | ChiSquare | F      | Pr(>F)   |
|----------------|----|-----------|--------|----------|
| Altitude       | 1  | 0.53549   | 3.0371 | 0.004 ** |
| pH             | 1  | 0.09511   | 0.5394 | 0.799    |
| Conductivity   | 1  | 0.29955   | 1.6989 | 0.107    |
| InvasionStatus | 1  | 0.45160   | 2.5613 | 0.007 ** |
| Residual       | 6  | 1.05791   |        |          |

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

**Appendix 3.7:** The significance of the CCA tested using Monte Carlo permutation test with 999 unrestricted permutations

Model: cca (formula = spe ~ Altitude + pH + Conductivity + InvasionStatus, data = env)

|          | Df | ChiSquare | F      | Pr(>F)   |
|----------|----|-----------|--------|----------|
| CCA1     | 1  | 0.763781  | 3.6174 | 0.004 ** |
| CCA2     | 1  | 0.47989   | 2.7217 | 0.138    |
| CCA3     | 1  | 0.19345   | 1.0972 | 0.655 ** |
| CCA4     | 1  | 0.07060   | 0.4004 | 0.857    |
| Residual | 6  | 1.05791   |        |          |

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1 ' ' 1

## Chapter 4: Niche expansion by indigenous fish species following the introduction of rainbow trout (*Oncorhynchus mykiss*) in a subtropical river system, upper Blyde River, South Africa<sup>3</sup>

### Abstract

The introduction of alien predatory fish such as rainbow trout (*Oncorhynchus mykiss*) can have a significant effect on indigenous fish communities such as altering the structure and dynamics of food webs. Quantifying the trophic niche utilised by the alien fish species is therefore important to aid our understanding of how their feeding strategies might aid establishment, define their functional role and inform on potential impacts. This study assessed food web interactions between fish communities in river reaches that are invaded by *O. mykiss* and sections that are free of invasions in the upper Blyde River catchment, South Africa. It specifically evaluated the hypothesis that *O. mykiss* invasion is likely to lead to a decrease in the trophic functional diversity through predation and that indigenous fish will shift their trophic niche to either minimise competition with, or avoid predation, by *O. mykiss*. Gut content and stable isotope analyses were used to determine trophic interactions. Fish communities in uninvaded areas utilised fewer and similar food sources and occupied lower trophic levels, than fish communities in invaded areas. *Oncorhynchus mykiss* fed mainly on invertebrates and at trophic levels similar to and or lower than indigenous fishes. This suggests that their current impact on indigenous fish communities is mainly through competition for resources. We posit that *O. mykiss* invasions reduced the abundance of indigenous fishes and thereby reduced predation pressure on aquatic invertebrates, with a knock-on effect on the trophic interrelationships among fish assemblages. Our findings are consistent with other studies in South Africa that have shown that the impacts of *O. mykiss* invasion can lead to a decline and fragmentation of indigenous species populations and niche shifts.

**Keywords:** Competition, *Enteromius treurensis*, niche position, predation, Treur River, trophic dispersion.

<sup>3</sup>This chapter is essentially the text of a paper that was published under the following full citation and is presented in the format of the journal:

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## Introduction

Predatory freshwater fish species have been introduced worldwide to enhance angling and inland fisheries (Cambray, 2003; Arlinghaus and Cooke, 2009). Rainbow trout (*Oncorhynchus mykiss*) is one of the most widely distributed fish species for angling (Crawford and Muir, 2008). It is native to the western seaboard of the USA, Canada, and northern Mexico (Page and Burr, 2011). In its introduced range, *O. mykiss* has been implicated in causing major impacts on indigenous fauna and ecosystems mainly through competition and predation (Drenner and Hambright, 2002; Simon and Townsend, 2003; McDowall, 2006; Fausch, 2007), modifying aquatic-terrestrial linkages (e.g., Epanchin et al., 2010; Jackson et al., 2016), altering food-web structure (Flecker and Townsend, 1994), and disrupting nutrient cycles (Schindler et al., 2001; Eby et al., 2006).

*Oncorhynchus mykiss* was introduced into South Africa in 1897, mainly for angling and aquaculture (Cambray, 2003; Ellender et al. 2014). Currently, *O. mykiss* has established populations in the mountain streams and upland reservoirs in over 80% of the major drainage basins in the country (Weyl et al., 2020). There is, however, limited information on the impacts of *O. mykiss* invasions in South Africa (Zengeya et al. 2020; van Wilgen et al. 2022). The few available studies have, however, shown that *O. mykiss* can cause a decline, and in some cases local extirpation of indigenous invertebrates, frogs, and fishes (Karssing et al., 2012; Rivers-Moore et al., 2013; Shelton et al., 2015a; Jackson et al., 2016; Weyl et al., 2020). For example, *O. mykiss* invasions in the uKhahlamba Drakensberg Park in Kwa-Zulu Natal have been implicated in the reduction of macroinvertebrate communities and the abundance of amphibians probably likely through predation (Karssing et al., 2012; Rivers-Moore et al., 2013). Similarly, *O. mykiss* invasions have also been implicated in the decline in the abundance of populations of amphibians in the upper Krom River in the Western Cape (Avidon et al., 2018). *Oncorhynchus mykiss* invasions have also led to a decline in the abundance of river minnows such as the Breede River redbin (*Pseudobarbus burchelli*), the Cape kurper (*Sandelia*

*capensis*), and the Cape galaxias (*Galaxias zebratus*) in the Breede River system, Western Cape (Shelton et al., 2015a). Also, in the Breede River, *O. mykiss* invasions were shown to induce a trophic cascade by releasing some herbivorous invertebrates from predation, leading to an increase in grazing pressure and lower algal biomass at invaded sites (Shelton et al., 2015b). *Oncorhynchus mykiss* invasions in several river systems such as the Keiskamma River (Eastern Cape), the Thukela and the Umgeni River systems (KwaZulu Natal) have been shown to modify aquatic-terrestrial food-web linkages by competing for and reducing the trophic subsidies available for riparian consumers such as spiders (Jackson et al., 2016).

In this study, we examined the trophic structure of fish communities in the upper Blyde River catchment in Mpumalanga where *O. mykiss* was introduced into several headwater streams of the catchment in the early 1900s for sport fishing (Engelbrecht and Roux, 1998). The subsequent establishment of naturalised populations of *O. mykiss* poses a risk to endangered indigenous fish species through predation and competition for habitat and food resources as a result of resource overlaps with *O. mykiss*. For example, the Treur River barb (*Enteromius treurensis*) is endemic to the upper reaches of the Blyde River (Kleynhans, 1987). It was extirpated from several sections of the Blyde River system invaded by *O. mykiss*, brown trout (*Salmo trutta*), and smallmouth bass (*Micropterus dolomieu*) (Gaigher, 1969; Kleynhans, 1987; Engelbrecht and Roux, 1998). The remnant populations of the Treur River barb are fragmented but largely intact, restricted to the upper river sections of the catchment because a series of waterfalls have prevented upstream migrations of invasive predatory fishes from lower river sections where introductions occurred. A recent study in the upper Blyde River catchment demonstrated that *O. mykiss* invasions have caused a decline in the abundance of populations of indigenous fish species such as *E. treurensis* (Maimela et al., 2021). However, the mechanism(s) through which these impacts have manifested remains unknown. Trophic niche analysis has been used to assess the ecological opportunities available to alien species in

terms of food resources and how factors that affect access to, and utilisation of, food resources facilitate the successful establishment and adverse impacts in a recipient ecosystem (e.g., Tonella et al. 2018). This study, therefore, investigated the trophic interrelationship between *O. mykiss* and the indigenous fish species in the upper Blyde River catchment, by assessing whether *O. mykiss* invasion altered community structure and function, such as trophic functional diversity and trophic niche size of indigenous fish species. It is likely, as demonstrated elsewhere, that *O. mykiss* invasions could lead to niche shifts and a decline in indigenous fish populations through either predation or competitive exclusion from food resources (e.g., McDowall 2006; Kadye et al. 2013; Shelton et al. 2015a; Weyl et al. 2020). This study, therefore, tested the hypotheses that the *O. mykiss* invasion in the upper Blyde River catchment has decreased the trophic functional diversity of indigenous fish species through predation and that indigenous species have shifted their niche width (i.e., the variety of food items utilised by a species) and position (i.e., type of food resources utilised) to minimise competition with, or avoid predation, by *O. mykiss*.

## **Materials and methods**

### *Study area and sampling*

The study area included the headwaters of the Blyde and Treur rivers in the northern part of the Great Drakensburg escarpment, Mpumalanga Province, South Africa (Figure 4.1). The study sites were located on the upper slopes of the escarpment (1200-1500 m above sea level (a.s.l.)) that are characterised by grassland vegetation that is interspaced by Afromontane forests. The climate is cool to moderate (10-18 °C), moderate to high annual rainfall (800-1200 mm), and mean annual precipitation of more than 1000 mm (WRC, 2001).

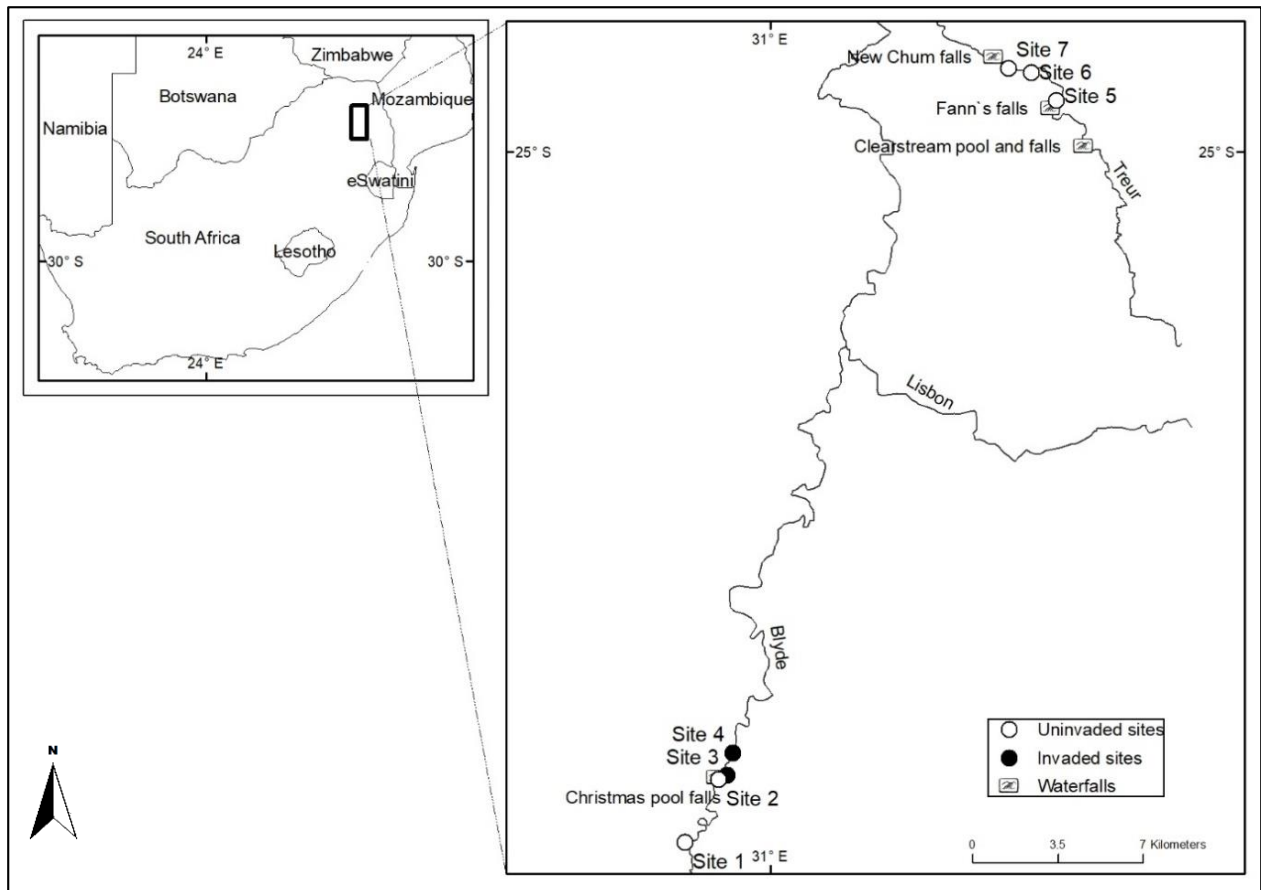


**Figure 4.1:** A map showing the location of sites sampled. Sites invaded by rainbow trout (*Oncorhynchus mykiss*) (●) and sites free of invasion (○) in the Blyde and Treur rivers in Mpumalanga Province, South Africa. Insert map of South Africa (top left).

Fish were sampled between September 2017 and October 2018 from 7 sampling sites (Figure 4.1; Table 4.1) and each site was sampled once every three months on five different occasions. To assess the impact of *O. mykiss* invasion on trophic niche utilised by indigenous fishes, sites were grouped based on their invasion status. A site was categorised as invaded if *O. mykiss* was present at the site or at upstream sites where downstream dispersal is possible. Four sampling sites were selected from the upper Blyde River, two in uninvaded sites (sites 1 and 2) and two in invaded river sections (sites 2-4) (Table 4.1). Three additional sites (sites 5-7) were located in the upper sections of the Treur River that are free of alien fish. All the sites were sampled using a SAMUS725MP electrofisher (Samus Special Electronics, Warsaw,

Poland), while fyke nets were used at all sites on the Blyde River but not in the Treur River because of low water levels. A river stretch of ~50 m was blocked off to prevent fish escapes, and electrofishing was conducted for ~30 minutes, with the electrofisher being operated in an upstream direction with a 1 m deep x 2 m wide, 5 mm mesh mobile block net behind to catch stunned fish missed by the operator (Kimberg et al., 2014). Fyke nets were set in the evening and retrieved the following morning. Fish were sorted according to species, weighed (g), and total length (TL, mm) recorded, and then preserved in ethanol for further analysis.

**Table 4.1:** Sampling sites on the Blyde and Treur rivers in Mpumalanga Province, South Africa and their associated rainbow trout (*Oncorhynchus mykiss*) invasion status, geographic coordinates, and elevation.

| River       | Site | Location                                                                 | Invasion status | Geographic coordinates       | Elevation (m) |
|-------------|------|--------------------------------------------------------------------------|-----------------|------------------------------|---------------|
| Blyde River | 1    | 5 km above the first Christmas Pools waterfall                           | Uninvaded       | 25°00'14.2"S<br>30°43'06.3"E | 1432          |
|             | 2    | Christmas Pools below the first waterfall                                | Uninvaded       | 24°58'51.0"S<br>30°43'50.4"E | 1372          |
|             | 3    | Christmas Pools below the second waterfall                               | Invaded         | 24°58'45.6"S<br>30°44'01.9"E | 1362          |
|             | 4    | 3 km downstream of the second waterfall                                  | Invaded         | 24°58'15.9"S<br>30°44'09.5"E | 1341          |
| Treur River | 5    | Pools below Treur River waterfall, 2.5 km upstream of Potluck Boskombuis | Uninvaded       | 24°43'52.2"S<br>30°51'18.5"E | 1293          |
|             | 6    | Pools next to Potluck Boskombuis restaurant                              | Uninvaded       | 24°43'15.0"S<br>30°50'45.0"E | 1272          |
|             | 7    | Pools downstream of the bridge to Potluck Boskombuis restaurant          | Uninvaded       | 24°43'09.4"S<br>30°50'14.5"E | 1246          |

#### *Determination of diet and trophic interactions*

Gut content and stable isotope analyses were used to determine diet and trophic interactions between *O. mykiss* and indigenous fish species. The simultaneous use of gut content analysis and stable isotope analysis (SIA) allows for a better estimate of the overall fish diet and better insights into the trophic levels of fish communities that reflect different spatial and temporal scales (see Hyslop, 1980; Fry, 2006; Finlay and Kendall, 2007; Marshall et al., 2007; Zengeya et al., 2011; Kadye and Booth, 2012). Gut content analysis was used to identify possible food

sources, and this was achieved by sampling fish from both invaded and uninvaded sites to obtain an overall diet spectrum for each sampled species, SIA was then used to differentiate food niches among fish species concerning trophic space, width, and the degree of overlap.

Fish gut contents were examined using a microscope and identified to the lowest possible taxonomic level. The diet of each fish species was determined using the frequency of occurrence (% F) (Hyslop, 1980). The approach provides estimates of the number of stomachs containing a specific prey item as a percentage of all analysed stomachs. It has been shown to provide a more robust and interpretable measure of diet composition than other quantitative approaches (Baker et al., 2014; Buckland et al., 2017; Amundsen and Sánchez-Hernández, 2019). The observed food items included algae, plant material and insects (Appendix 4.1). The food items identified in the gut content analysis were then collected from the environment to delineate the food web structure in the river system. Algae and plant material were collected by hand, while aquatic invertebrates were collected using kick-net sampling (mesh size = 1 mm) on all available substrates at each site following the SASS protocol (Dickens and Graham 2002). The aquatic invertebrates were identified up to family level using a photographic identification manual developed for South African river systems (Gerber and Gabriel, 2002). The differences in community structure of fish and invertebrates among the sites were tested using multivariate PERMANOVA based on a Bray–Curtis similarity matrix of fourth root transformed abundance data with 9 999 permutations. The PERMANOVA was based on algorithms in PAST v3 (Hammer and Ryan 2001)

#### *Stable isotope analysis (SIA)*

Muscle tissue was excised from all fish samples while insects were analysed whole following similar studies done in the region (e.g., Lübcker et al. 2016; Talyor et al. 2017; Lombard et al. 2018; Bokhutlo et al. 2021). Insects were combined so that they included representatives from the following seven orders: Coleoptera, Diptera, Ephemeroptera, Hemiptera, Lepidoptera,



Odonata and Trichoptera. Algae, plant material, insect samples and muscle tissue were oven-dried at 70° C for 24 hours. SIA was undertaken on a Flash EA 1112 Series coupled to a Delta V Plus stable light isotope ratio mass spectrometer via a ConFlo IV system (all equipment supplied by Thermo Fischer, Bremen, Germany), housed at the Stable Isotope Laboratory, Mammal Research Institute (MRI), University of Pretoria, Pretoria, South Africa. A laboratory running standard (Merck Gel:  $\delta^{13}\text{C} = -20.57\text{‰}$ ;  $\delta^{15}\text{N} = 6.8\text{‰}$ ;  $\text{C}\% = 43.83$ ;  $\text{N}\% = 14.64$ ) and blank sample were run after every 12 samples. The standards were Vienna Pee Dee Belemnite limestone for  $\delta^{13}\text{C}$  (Craig, 1957) and atmospheric nitrogen for  $\delta^{15}\text{N}$  (Ehleringer and Rundel, 1989). Results were expressed in delta notation using a parts per thousand scale following the standard equation by Craig (1961) (Equation 1):

$$\delta X (\text{‰}) = [(R_{\text{sample}} - R_{\text{standard}}) / R_{\text{standard}}] \times 1000 \text{ (Equation 1)}$$

Where  $X = ^{15}\text{N}$  or  $^{13}\text{C}$  and  $R = ^{15}\text{N}/^{14}\text{N}$  or  $^{13}\text{C}/^{12}\text{C}$ , respectively. Analytical precision was  $< 0.05\text{‰}$  for  $\delta^{13}\text{C}$  and  $< 0.09\text{‰}$  for  $\delta^{15}\text{N}$ .

#### *Isotope baseline corrections*

Stable isotope values for basal resources can vary considerably along spatial and temporal gradients, and to correct for these differences, nitrogen values ( $\delta^{15}\text{N}$ ) were converted to the trophic position of each consumer (TP), and carbon values ( $\delta^{13}\text{C}$ ) were corrected to the carbon of each consumer ( $\text{C}_{\text{corr}}$ ) following Olsson et al. (2009); (Equations 2 and 3)

$$\text{TP} = \left( \frac{\delta^{15}\text{N}_{\text{consumer}} - \delta^{15}\text{N}_{\text{baseline}}}{3.4} \right) + 2 \text{ (Equation 2)}$$

where  $\delta^{15}\text{N}_{\text{consumer}}$  = the isotopic ratio of each consumer, and  $\delta^{15}\text{N}_{\text{baseline}}$  = the isotopic ratio and trophic position of a primary consumer. The trophic enrichment factor was set 3.4 following the meta-analysis of Post (2002).

$$\delta^{13}C_{corr} = \left( \frac{\delta^{13}C_{consumer} - \delta^{13}C_{meaninv}}{CR_{inv}} \right) \text{ (Equation 3)}$$

where  $\delta^{13}C_{consumer}$  = the isotopic ratio of each consumer,  $\delta^{13}C_{meaninv}$  = the mean invertebrate isotope ratio, and  $CR_{inv}$  = the invertebrate carbon range ( $\delta^{13}C_{max} - \delta^{13}C_{min}$ ).

Ideally, the  $\delta^{15}N_{baseline}$  is estimated using the isotopic signature of a long-lived filter-feeding primary consumer (e.g., bivalves; Vander Zanden et al., 1999; Post, 2002), but the absence of long-lived filter-feeding primary consumers at the study sites necessitated the use of mean nitrogen values of aquatic insects as recommended by Jackson and Briton (2014). These include several families of dragonflies (Odonata), damselflies (Odonata), mayflies (Ephemeroptera), crane flies (Diptera), giant water bug (Hemiptera), and whirligig beetles (Coleoptera). The insect families that occurred at all sampling sites were dragonflies, mayflies, crane flies, and whirligig beetles. The isotopic signatures of mayfly insects showed no significant differences for  $\delta^{15}N$  (Welch:  $F = 1.12$ ,  $df = 12.92$ ,  $P > 0.05$ ) and  $\delta^{13}C$  values (Welch:  $F = 0.02$ ,  $df = 13.62$ ,  $P > 0.05$ ) between sampling sites, and were used to determine nitrogen baseline ( $\delta^{15}N_{baseline}$ ), mean carbon invertebrate ratio ( $\delta^{13}C_{meaninv}$ ), and the invertebrate carbon range ( $CR_{inv}$ ). The isotopic baseline correction for nitrogen ( $\delta^{15}N$ ) and carbon values ( $\delta^{13}C$ ) to trophic position (TP) and carbon corrected values ( $C_{corr}$ ) allowed for comparisons of trophic interactions among fish communities across a stream where sampling sites were grouped into qualitative categories based on their invasion status (i.e., free of, or invaded by *O. mykiss*) and location (Figure 4.1).

#### *Stable isotope mixing models to quantify consumer diets*

A Bayesian mixing model (simmr, Parnell 2010; R Core Team 2022) was used to estimate the relative proportion of basal food resources that were assimilated by *O. mykiss* and indigenous fish species. The mixing model was calibrated using food sources that were identified from the gut content analysis. Food items were grouped into broad taxonomic categories: algae, plant

material, and insects were grouped into orders (Coleoptera, Diptera, Ephemeroptera, Hemiptera, and Odonata). Models were constructed using uncorrected stable isotope data. The trophic enrichment factors were set at  $3.37 \pm 1.30\%$  for nitrogen and  $0.54 \pm 0.53\%$  for carbon following Talyor et al. (2017) and Bokhutlo et al. (2021). Model performance and fit were checked using the convergence diagnostic tool and by visually checking the posterior probability distributions.

#### *Trophic niche position and dispersion*

Shifts in trophic niche position for each fish species were determined using measures of central tendency (i.e., the difference in centroid position between species) following the approach by Turner et al. (2010). Several metrics, trophic position range (TP range), corrected carbon (Ccorr range), mean distance to the centroid (CD) and mean nearest neighbour distance (NND) were used to calculate niche dispersion (see Layman et al., 2007). TP range provides an estimate of the trophic length of the community, the Ccorr range provides an estimate of the diversity of food resources, the CD represents the mean of Euclidean distance of each species to the sample bi-plot centroid, where the mean of TP values and Ccorr of all species in the food web represent the sample centroid. NND represents the mean of Euclidean distances to each species' nearest neighbour in a TP and Ccorr - bi-plot. A lower dispersion in the two dispersion metrics of trophic diversity of a system indicates trophic redundancy. The significance of the test statistics for the niche position and dispersion metrics were then evaluated using null distributions generated from nested linear models and a residual permutation procedure (Turner et al. 2010). Post-hoc analysis of significant differences was done using one-way analysis of variance (ANOVA) posthoc test.

A residual permutation procedure was used to assess if changes in the trophic niche position of a species were due to the invasion status of the sampling site (see Turner et al., 2010). This was done by comparing the magnitude (path length) and direction of change (path

direction) in centroid positions for each species sampled in the invaded and uninvaded sites. Path length was taken as the Euclidean distance between a pair of centroid positions sampled from different sites, and path direction was defined as the angle ( $\theta$ ) between the first principal component (PC1) vectors (see Collyer and Adams, 2007; Adam and Collyer, 2009).

### *Niche size and overlap*

The niche space utilised by the fish species was delineated using sample size-corrected standard ellipse area (SEAc) that were derived using the R package *Stable Isotope Ellipses* (SIBER) (Jackson et al., 2011). The SEAc were constructed using variance and covariance of the isotope biplot that contained only 40% of the data, which represents the core isotopic and typical resources utilised by a species. A Markov Chain Monte Carlo (MCMC) simulation with  $10^4$  iterations that provides 95% confidence limits of the isotopic niche size for each species sampled was used for a Bayesian estimate of SEAc and its area (Jackson et al., 2011). A maximum likelihood-fitted SEAc was used to quantify the magnitude of niche size overlap between species and was expressed as the proportional area that overlapped between a pair of SEAc divided by the total area of both ellipses (Jackson et al., 2011). Extent of overlap was classified as low ( $< 40\%$ ), intermediate (40 to 60%) and high ( $> 60\%$ ) (Langton, 1982).

## **Results**

### *Species composition and abundance*

There were no significant differences in composition (PERMANOVA:  $P > 0.05$ ) and abundance (PERMANOVA:  $P > 0.05$ ) among the invertebrate assemblages based on the invasion status of the site (Table 4.2). The most abundant taxa across all sampling sites were Odonata (64% of the total) and Diptera (11%) which collectively made up 76% of the total number of invertebrates collected (Table 4.2). There were however significant differences in species composition (PERMANOVA:  $P < 0.05$ ) and abundance (PERMANOVA:  $P < 0.05$ )

among fish assemblages based on invasion status and site location (Blyde or Treur River) (Table 4.2). In the Blyde River, sites (1 and 2) were uninvaded by *O. mykiss* and only two species were collected from these sites, *E. treurensis* and the stargazer mountain catfish (*Amphilius uranoscopus*), of which *E. treurensis* was highly abundant. In contrast, *O. mykiss* was abundant at sites 3 and 4 but *A. uranoscopus* and *E. treurensis* were sparse. Sites 5-7 were located on the Treur River and were uninvaded by *O. mykiss*. The sites had a higher species diversity because of three additional species chubbyhead barb (*E. anoplus*), *E. lineomaculatus* (line spotted barb) and banded tilapia (*Tilapia sparrmanii*) that were caught from these sites but not on the Blyde River (Table 4.2).

**Table 4.2:** The composition and abundance (by numbers) of invertebrate and fish taxa sampled from sites invaded by rainbow trout (*Oncorhynchus mykiss*) on the Blyde River and sites free of invasion both the Blyde River and Treur rivers. The numbers of fish outside parentheses indicate the total number of individuals collected using electrofishing and those in parentheses using fyke nets.

| Taxa                  | Blyde River<br>(Uninvaded)       |        | Blyde<br>(invaded) |        | Treur<br>(uninvaded) |        |        |
|-----------------------|----------------------------------|--------|--------------------|--------|----------------------|--------|--------|
|                       | Site 1                           | Site 2 | Site 3             | Site 4 | Site 5               | Site 6 | Site 7 |
| Aquatic invertebrates | Coleoptera                       |        |                    |        | 1                    |        |        |
|                       | Diptera                          |        | 3                  |        | 13                   |        |        |
|                       | Ephemeroptera                    |        | 3                  |        | 6                    |        |        |
|                       | Hemiptera                        |        | 3                  |        | 5                    |        |        |
|                       | Odonata                          |        | 1                  |        | 1                    |        |        |
|                       | Opisthopora                      |        | 23                 |        | 2                    |        |        |
|                       | Trichoptera                      |        | 15                 |        | 27                   |        |        |
| Fishes                | <i>Amphilius uranoscopus</i>     |        | 1 (1)              |        | 3 (1)                |        |        |
|                       | <i>Enteromius anoplus</i>        |        |                    |        | 15                   |        |        |
|                       | <i>Enteromius lineomaculatus</i> |        |                    |        | 4                    |        |        |
|                       | <i>Enteromius treurensis</i>     |        | 50 (22) 40 (47)    |        | 13                   |        |        |
|                       | <i>Oncorhynchus mykiss</i>       |        | 1 (1) 4            |        | 4                    |        |        |
|                       | <i>Tilapia sparrmanii</i>        |        | 10 (5) 2 (13)      |        | 3                    |        |        |

#### Niche position and size

Fish communities in the uninvaded river sections of the Blyde River comprised only two species, *E. treurensis* and *A. uranoscopus*, that both primarily fed on Diptera and Ephemeroptera (Table 4.3). The two species however occupied significantly different centroid positions ( $P < 0.05$ ) because of differences in Ccorr values (ANOVA:  $F_{2, 56} = 29.8$ ;  $P < 0.05$ ) but the TP values were similar (ANOVA:  $F_{2, 56} = 3.3$ ;  $P > 0.05$ ) (Figure 4.2a).

**Table 4.3:** Proportion (% of isotopic value) of food sources utilised by rainbow trout (*Oncorhynchus mykiss*) and indigenous fish species in the catchments of the Blyde and Treur rivers, Mpumalanga Province, South Africa.  $\pm$  denotes standard deviation.

| Site and invasion status           | Species                  | Algae           | Macrophytes     | Coleoptera      | Diptera         | Ephemeroptera   | Hemiptera      | Odonata         |
|------------------------------------|--------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|-----------------|
| Blyde River, sites 1-2 (uninvaded) | <i>A. uranoscopus</i>    | 0.05 $\pm$ 0.05 | 0.04 $\pm$ 0.03 |                 | 0.23 $\pm$ 0.24 | 0.61 $\pm$ 0.27 |                | 0.07 $\pm$ 0.06 |
|                                    |                          | 0.07 $\pm$ 0.03 |                 |                 | 0.11 $\pm$ 0.08 |                 |                | 0.05 $\pm$ 0.03 |
|                                    | <i>E. treurensis</i>     | 0.03 $\pm$ 0.02 |                 |                 | 0.75 $\pm$ 0.06 |                 |                | 0.03            |
| Blyde River, sites 3-4 (invaded)   | <i>A. uranoscopus</i>    | 0.21 $\pm$ 0.13 | 0.09 $\pm$ 0.06 |                 | 0.16 $\pm$ 0.13 | 0.15 $\pm$ 0.11 | 0.21 $\pm$ 0.1 | 0.17 $\pm$ 0.14 |
|                                    |                          | 0.25 $\pm$ 0.11 |                 |                 | 0.15 $\pm$ 0.11 |                 | 0.23 $\pm$ 0.1 | 0.16 $\pm$ 0.12 |
|                                    | <i>E. treurensis</i>     | 0.25 $\pm$ 0.08 | 0.06 $\pm$ 0.04 |                 | 0.11 $\pm$ 0.07 | 0.15 $\pm$ 0.09 | 0.28 $\pm$ 0.1 | 0.11 $\pm$ 0.07 |
|                                    | <i>O. mykiss</i>         | 0.03 $\pm$ 0.02 | 0.03 $\pm$ 0.02 |                 | 0.23 $\pm$ 0.09 | 0.23 $\pm$ 0.09 | 0.44 $\pm$ 0.1 | 0.40 $\pm$ 0.23 |
| Treur River, sites 5-7 (uninvaded) | <i>A. uranoscopus</i>    | 0.04 $\pm$ 0.03 | 0.04 $\pm$ 0.03 | 0.18 $\pm$ 0.13 |                 | 0.10 $\pm$ 0.10 | 0.24 $\pm$ 0.1 | 0.40 $\pm$ 0.23 |
|                                    | <i>E. anoplus</i>        | 0.04 $\pm$ 0.03 | 0.05 $\pm$ 0.03 | 0.13 $\pm$ 0.08 |                 | 0.10 $\pm$ 0.09 | 0.49 $\pm$ 0.1 | 0.18 $\pm$ 0.14 |
|                                    | <i>E. lineomaculatus</i> | 0.06 $\pm$ 0.03 | 0.06 $\pm$ 0.04 | 0.15 $\pm$ 0.08 |                 | 0.17 $\pm$ 0.11 | 0.43 $\pm$ 0.0 | 0.14 $\pm$ 0.08 |
|                                    | <i>E. treurensis</i>     | 0.04 $\pm$ 0.02 | 0.04 $\pm$ 0.03 | 0.12 $\pm$ 0.07 |                 | 0.10 $\pm$ 0.08 | 0.57 $\pm$ 0.0 | 0.14 $\pm$ 0.10 |
|                                    |                          | 0.14 $\pm$ 0.06 |                 |                 |                 |                 | 0.53 $\pm$ 0.0 | 0.08 $\pm$ 0.06 |
|                                    | <i>T. sparrmanii</i>     | 0.08 $\pm$ 0.05 | 0.05 $\pm$ 0.03 | 0.05 $\pm$ 0.03 |                 | 0.12 $\pm$ 0.10 | 0.8            | 0.06            |

Fish communities in the invaded river reach of the Blyde River comprised three species that fed mainly on insects but also consumed algae, and macrophytes (Table 4.3). The three species occupied significantly different centroid positions ( $P < 0.05$ ) because of differences in TP values (ANOVA:  $F_{2, 37} = 9.29$ ;  $P < 0.05$ ) but Ccorr values were similar (ANOVA:  $F_{5, 120} = 3.9$ ;  $P > 0.05$ ) (Figure 4.2b). *Enteromirus treurensis* ( $SEA_c = 0.05$ ) and *O. mykiss* ( $SEA_c = 0.03$ ) utilised similar-sized isotopic niche spaces ( $P > 0.05$ ) that were significantly larger than the isotopic niche space utilised by *A. uranoscopus* ( $SEA_c = 0.01$ ) (Figure 4.2e). The extent of overlap between *A. uranoscopus* - *E. treurensis* (0.11), and *A. uranoscopus* - *O. mykiss* (0.11)

was low but there was an intermediate overlap between *E. treurensis* and *O. mykiss* (0.55) (Figure 4.2e).

The fish species from the uninvaded Treur River could be separated into two groups. Four insectivores, *A. uranoscopus*, *E. anoplus*, *E. treurensis*, and *E. lineomaculatus*, fed mainly on insects while *T. sparrmanii* was an omnivore and fed on algae and insects (Table 4.3). *Amphilius uranoscopus* had the highest TP values (TP =  $2.72 \pm 0.14$ , Ccorr =  $0.53 \pm 0.09$ ) that was significantly different from *E. lineomaculatus* (TP =  $2.35 \pm 0.12$ , Ccorr =  $0.57 \pm 0.11$ ) and *E. treurensis* (TP =  $2.51 \pm 0.11$ , Ccorr =  $0.63 \pm 0.10$ ), while *T. sparrmanii* (TP =  $2.15 \pm 0.27$ , Ccorr =  $0.58 \pm 0.12$ ) had the lowest TP values that were significantly different from all the other species (ANOVA:  $F_{5,120} = 18.24$ ;  $P < 0.05$ ) (Figure 4.2c, Appendix 4.2). There were no significant differences in Ccorr values (range = 0.41-0.63) among the five species (ANOVA:  $F_{5, 120} = 3.9$ ;  $P > 0.05$ ). *Tilapia sparrmanii* utilised the largest isotopic niche (SEAc =  $0.11 \pm 0.1$ ) while the rest of the species utilised smaller but similar-sized isotopic niches (*A. uranoscopus* =  $0.03 \pm 0.03$ , *E. anoplus* =  $0.03 \pm 0.02$ , *E. lineomaculatus* =  $0.04 \pm 0.04$ , and *E. treurensis* =  $0.04 \pm 0.03$ ) (SIBER  $P < 0.05$ ) (Figure 4.2f, Appendix 4.2). The extent of overlap was low for most species except for intermediate overlap between *E. lineomaculatus* and *E. treurensis* (45%) and high overlap between *E. anoplus* and *E. treurensis* (62%) (Appendix 4.4).

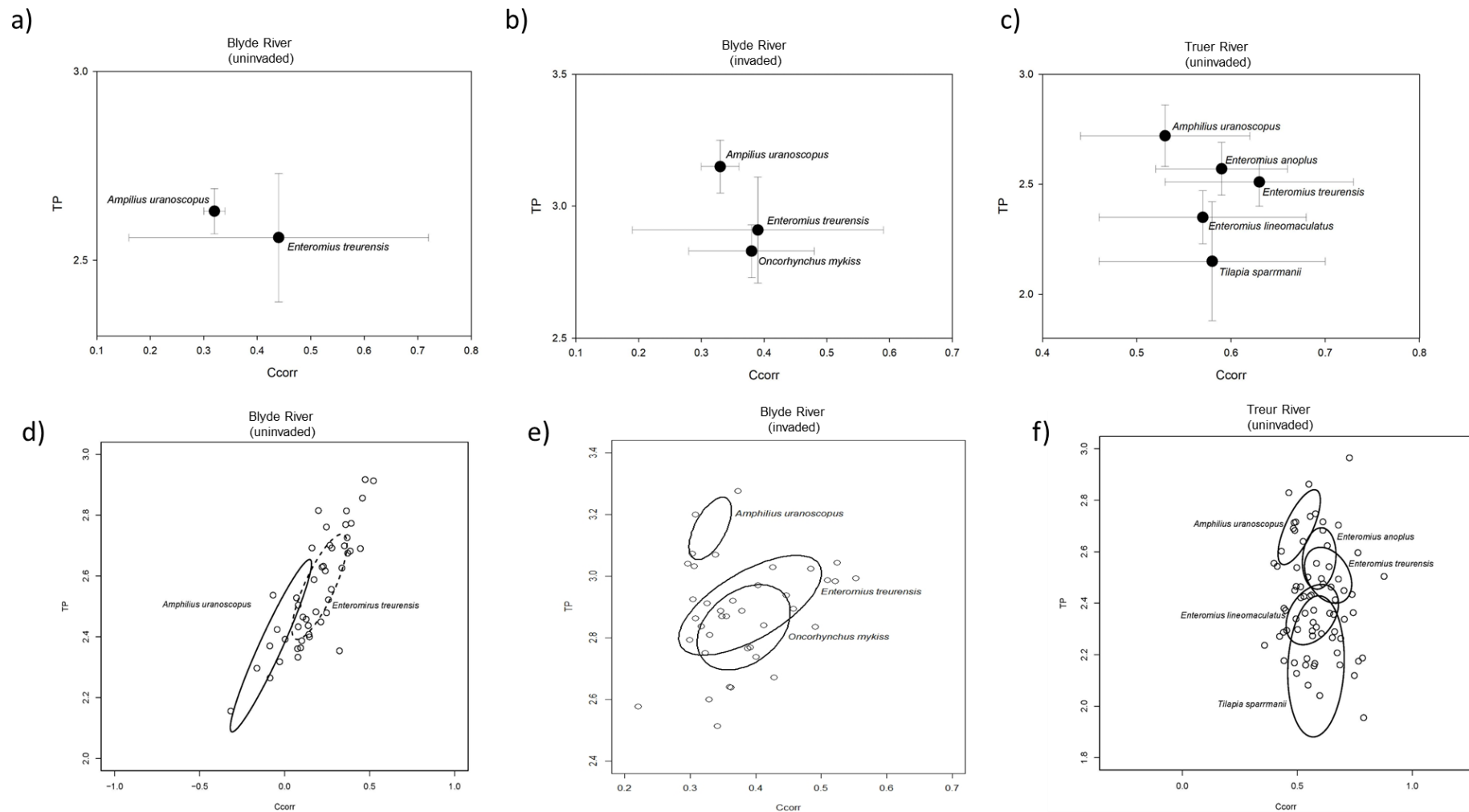


**Figure 4.2:** Centroid positions, and estimates of niche size and overlap using sample size-corrected standard ellipse areas (SEAc) of fish species sampled from sites invaded by rainbow trout (*Oncorhynchus mykiss*) on the Blyde River (b, e) and sites free of invasion both the Blyde River (a, d) and Treur rivers (c, f).



### *Spatial differences in food web structure*

The isotopic food web varied in structure across the invaded and uninvaded sites from the Blyde and Treur rivers. The fish communities from the invaded section of the Blyde River had smaller niche metrics [total area of the convex hull (TA), trophic range (TP range), and Ccorr range] than fish communities in the uninvaded sections in the Blyde and Treur rivers (Appendix 4.5). In addition, there were significant differences ( $P < 0.05$ ) in the mean community centroid positions across sites in the uninvaded (Ccorr = 0.19, TP = 2.55) and invaded (Ccorr = 0.38, TP = 2.88) sections of the Blyde River and invasion free Treur River (Ccorr = 0.58, TP = 2.37). The mean distance to the centroid of fish communities in uninvaded sections of the Blyde (CD = 0.22) and Treur River (CD = 0.24) was higher and significantly different ( $P < 0.05$ ) from fish communities in the invaded section of the Blyde River (0.15). In contrast, the nearest-neighbour distance (NND) was not significantly different ( $P > 0.05$ ) (Appendix 4.5).

Only two species (*A. uranoscopus* and *E. treurensis*) were sampled across invaded and uninvaded sites in the Blyde and Treur rivers. The two species occupied significantly different centroid positions from each other across the uninvaded and invaded sites (Figure 4.3). The centroid position of *A. uranoscopus* from uninvaded sections of the Blyde River was characterised by depleted TP ( $2.37 \pm 0.06$ ) and Ccorr values ( $0.16 \pm 0.01$ ) relative to invaded sections (TP =  $3.15 \pm 0.09$  and Ccorr values =  $0.33 \pm 0.03$ ) and invasion free Treur River (TP =  $2.72 \pm 0.14$  and Ccorr =  $0.53 \pm 0.09$ ). A similar trend was also observed for *E. treurensis* where the centroid position in invaded section of the Blyde river had enriched TP and Ccorr values (TP =  $2.91 \pm 0.11$  and Ccorr =  $0.39 \pm 0.15$ ) relative to invasion free sections of both the Blyde (TP =  $2.56 \pm 0.17$ , Ccorr =  $0.22 \pm 0.11$ ) and Treur rivers (TP =  $2.51 \pm 0.11$  and Ccorr values =  $0.63 \pm 0.1$ ). There were no significant differences ( $P > 0.05$ ) in path length, direction and shape between the centroid positions of the two species among invaded and uninvaded sites across the two rivers (Figure 4.3).

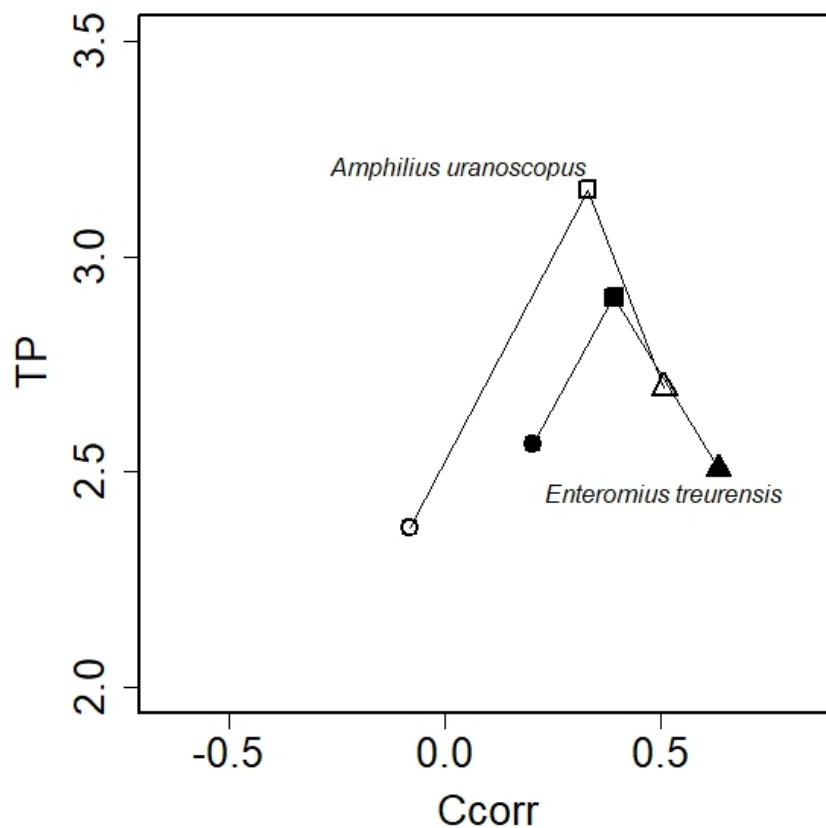


**Figure 4.3:** The magnitude and direction of change in centroid positions of *Enteromius treurensis* and *Amphilius uranoscopus* across invaded and uninvaded sites on the Blyde and Treur rivers in Mpumalanga Province, South Africa.

## Discussion

This study assessed food web interactions between fish communities in river sections invaded by *O. mykiss* and sections that are still free of invasion in the upper reaches of the Blyde River catchment. *Oncorhynchus mykiss* was an insectivore and fed at a similar trophic level to that of indigenous fish species. Similar results have been reported elsewhere in the uKhahlamba Drakensberg Park and Cape Floristic Region of South Africa where introduced trout (*S. trutta* and *O. mykiss*) have been observed to feed at similar and or lower trophic levels to indigenous fishes (e.g., Rivers-Moore, et al., 2013; Jackson et al., 2016; Weyl et al., 2020). *Oncorhynchus*

*mykiss* is known to impact indigenous fish fauna through various mechanisms such as competition for resources (food and space), predation, alteration of food web structures and changes in habitat coupling, as well as overall ecosystem-level effects (e.g., McDowall, 2006; Eby et al., 2006; Karssing et al., 2012; Ellender, 2013; Shelton et al., 2015a). Isolating the relative individual contribution of each of these mechanisms to the overall impact on the food web is difficult (e.g., see Crowl et al., 1992, Townsend, 2003). The fact that *O. mykiss* and indigenous fish communities were feeding at the same trophic level suggests that their present impact on indigenous fish communities in the upper Blyde River Catchment is more likely through competition for resources.

Competition for food and space between *Oncorhynchus mykiss* and indigenous species can lead to adverse impacts on community structure and function (e.g., Eby et al., 2006). Such impacts include a decline and fragmentation of indigenous species populations and niche shifts (e.g., Kadye et al., 2013, Shelton et al., 2015a). *Oncorhynchus mykiss* and *E. treurenensis* utilised a similar-sized isotopic niche that had intermediate overlap (55%). *Oncorhynchus mykiss* is a general predator but it has been shown to feed primarily on terrestrial invertebrates, while *E. treurenensis* utilises a wider variety of invertebrate prey (Kleynhans 1987). This is consistent with observations from gut contents in this study where *O. mykiss* fed mainly on aquatic invertebrates but the *E. treurenensis* had a broader diet spectrum that included algae and aquatic invertebrates. The high proportion of aquatic invertebrates in the diets of *O. mykiss* and *E. treurenensis* likely lead to the observed high niche overlap between the two species. This indicates that *O. mykiss* is not using a vacant trophic niche in this system but is instead using similar food resources to *E. treurenensis*, potentially competitively displacing it. This notion is supported by the fact that river sections with high *O. mykiss* densities were characterised by a low abundance of *E. treurenensis* (96% lower) relative to uninvaded areas.

In addition, competition often leads to niche shifts by the weaker competitor to minimise competition (Kramer and Drake 2014). However, the effects of interspecific competition on the niche widths of consumers are often context-specific (Araújo et al. 2011). For example, competing species can utilise smaller niche spaces to reduce competition by minimising overlap in resource use (e.g., Bolnick et al. 2010, Jackson et al. 2016) or increase their niche width in order to maintain access to limited resources (e.g., Svanbäck and Bolnick 2007). In this study, *A. uranoscopus* and *E. treurensis* shifted their niche and fed at a higher trophic level in invaded areas than in uninvaded areas. The increase in trophic level was likely associated with an increase in the variety of food items utilised by a species in invaded sections relative to uninvaded areas. Both species fed predominately on Ephemeroptera larvae in uninvaded sections of the Blyde River and on Hemiptera and Odonata in the uninvaded Treur River but increased their niche width in invaded sections of the Blyde River to include greater proportions of algae and other aquatic invertebrates such as Diptera, Hemiptera and Odonata. The niche shift by *A. uranoscopus* and *E. treurensis* between invaded and uninvaded river sections may be linked to differences in access to food resources rather than food availability as there were no clear differences in food resources (aquatic invertebrates) available to fishes based on the invasion status. There were however significant differences in fish composition and abundance among sites. Indigenous fish species such as *E. treurensis* occurred at high densities at uninvaded sites relative to invaded sites. It is therefore likely that intraspecific competition for food resources might have constricted the niche width of indigenous fishes at uninvaded sites and conversely, niche expansion occurred at invaded sites because of increased access to food resources that may have been otherwise depleted or monopolised by competitors (Bolnick et al., 2010). This notion is supported by other comparative studies that have observed increases in invertebrate diversity in areas invaded by *O. mykiss* that might be due to *O. mykiss* invasions reducing the abundance of indigenous fish and thereby reducing predation pressure

on aquatic invertebrates, with knock-on effect on the structure of these assemblages. For example, in the upper Breede catchment, *O. mykiss* were characterised as weaker regulators of invertebrate abundance than the indigenous river minnows which they replace (Shelton et al., 2015b; 2017). Similar observations were found in mountain headwater streams in eastern Zimbabwe where there was a higher abundance of some invertebrate taxa in areas invaded by trout which could be linked to decreased predation pressure from indigenous invertebrates and fish that occurred in lower abundance in invaded areas (Kadye et al., 2013).

Although not observed in this study, *O. mykiss* has also been observed to selectively consume small river minnows (McIntosh et al., 2010; Shelton et al., 2015a). The processes of competition and predation by alien fish are often linked and interact to determine net effects in invaded systems (e.g., Eby et al., 2006, David et al., 2017). It is, therefore, possible that the decline in populations of indigenous fishes in the upper Blyde River catchment might have been through a combination of predation and competition from *O. mykiss* invasions. The trophic niche concept has been used to assess the impacts of alien species on community structure and function but its use can be hindered by several limitations some of which were evident in this study. These include a lack of long-term monitoring studies to track trends. The sites sampled in this study have been invaded for over a century and there are no monitoring studies that have been done to measure long-term trends in community absolute abundance, predator demands and community compensation mechanisms. Therefore the observed trophic interrelationships may represent a point-in-time snapshot of foodweb dynamics that may shift over time. Second, there are difficulties in determining the food utilised by fish species from sites that are in a continuum along a river profile as upstream river segments often affect nutrient dynamics in downstream segments. In this study, to minimise spatial dependencies of food webs along a river continuum, an isotopic baseline correction was done to allow for comparisons of trophic interactions among fish communities along spatial gradients (see

Olsson et al. 2009, Jackson & Britton 2014). Third, the number of individuals varied significantly among sites, where a species could be abundant at one site but rare at other sites. To avoid data dependency problems among sites, sampling effort was standardised and sites were pooled together based on the invasion status (presence or absence of *O. mykiss*) and location. However, some sites had low sample sizes and the confidence level in some of the estimates of food web matrices could be improved by increasing the sample sizes. Despite these caveats, this study demonstrated that there are spatial differences in trophic functional diversity among the fish communities in the upper Blyde River catchment that are correlated to *O. mykiss* invasions. Fish communities in uninvaded areas had greater trophic redundancy than fish communities in invaded areas. These spatial differences in trophic functional diversity are likely a result of *O. mykiss* invasion through competition for resources with indigenous fishes. We posit *O. mykiss* invasions have reduced the abundance of indigenous fishes and thereby reducing predation pressure on aquatic invertebrates, with a knock-on effect on the trophic interrelationships among fish assemblages. This is consistent with observations elsewhere that have noted that *O. mykiss* invasions can influence the diet and trophic niches of indigenous fish by altering the structure and dynamics of food webs through various mechanisms such as predation and competition.

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## Appendices

**Appendix 4.1:** Frequency of occurrence (%) of prey items in the diets of indigenous and alien invasive fish species in the catchments of the Blyde and Treur rivers, Mpumalanga Province, South Africa.

| Sites and invasion status         | Species                          | Cyanophyta | Green algae | Periphyton | Fine detritus | Macrophytes | Zooplankton | Insects |
|-----------------------------------|----------------------------------|------------|-------------|------------|---------------|-------------|-------------|---------|
| Blyde River sites 1-2 (Uninvaded) | <i>Enteromius treurensis</i>     | 10         | 13          | 23         | 80            | 3           | 13          | 57      |
|                                   | <i>Amphilius uranoscopus</i>     | -          | -           | -          | -             | -           | -           | -       |
| Blyde River sites 3-4 (Invaded)   | <i>Amphilius uranoscopus</i>     | 10         | 40          | 0          | 50            | 10          | 60          | 100     |
|                                   | <i>Enteromius treurensis</i>     | 21         | 63          | 74         | 100           | 37          | 84          | 63      |
|                                   | <i>Oncorhynchus mykiss</i>       | 12         | 0           | 0          | 77            | 15          | 39          | 100     |
|                                   | <i>Enteromius anoplus</i>        | 0          | 80          | 0          | 100           | 0           | 40          | 80      |
| Treur River sites 5-7 (Uninvaded) | <i>Amphilius uranoscopus</i>     | 60         | 10          | 20         | 90            | 0           | 40          | 90      |
|                                   | <i>Enteromius lineomaculatus</i> | 0          | 75          | 0          | 50            | 0           | 62.5        | 50      |
|                                   | <i>Enteromius treurensis</i>     | 38         | 56          | 13         | 94            | 0           | 81          | 44      |
|                                   | <i>Tilapia sparrmanii</i>        | 38         | 88          | 31         | 88            | 19          | 50          | 69      |

**Appendix 4.2:** Trophic position (TP), corrected Carbon (Ccorr) and values of isotopic niche (SEAc) for indigenous and alien invasive (bold) fish species sampled in uninvaded and invaded catchments of the Blyde and Treur rivers, Mpumalanga Province, South Africa.

| Site                              | Species                          | TP          | Ccorr       | Isotopic niche (SEAc) |
|-----------------------------------|----------------------------------|-------------|-------------|-----------------------|
| Blyde River sites 1-2 (Uninvaded) | <i>Amphilius uranoscopus</i>     | 2.37 ± 0.06 | 0.16 ± 0.01 | 0.13                  |
|                                   | <i>Enteromius treurensis</i>     | 2.56 ± 0.17 | 0.22 ± 0.14 | 0.05                  |
| Blyde River sites 3-4 (Invaded)   | <i>Amphilius uranoscopus</i>     | 3.15 ± 0.09 | 0.33 ± 0.03 | 0.01                  |
|                                   | <i>Enteromius treurensis</i>     | 2.91 ± 0.11 | 0.39 ± 0.15 | 0.05                  |
|                                   | <i>Oncorhynchus mykiss</i>       | 2.83 ± 0.07 | 0.38 ± 0.14 | 0.03                  |
| Treur River sites 5-7 (Uninvaded) | <i>Amphilius uranoscopus</i>     | 2.72 ± 0.14 | 0.53 ± 0.09 | 0.03                  |
|                                   | <i>Enteromius anoplus</i>        | 2.57 ± 0.12 | 0.59 ± 0.07 | 0.03                  |
|                                   | <i>Enteromius lineomaculatus</i> | 2.35 ± 0.12 | 0.57 ± 0.11 |                       |
|                                   | <i>Enteromius treurensis</i>     | 2.51 ± 0.11 | 0.63 ± 0.1  | 0.04                  |
|                                   | <i>Tilapia sparrmanii</i>        | 2.15 ± 0.27 | 0.58 ± 0.12 | 0.11                  |

**Appendix 4.3:** Isotopic niche overlap among fish species in river sections invaded by rainbow trout (*Oncorhynchus mykiss*) on the Blyde River, South Africa. Extent of overlap was classified as low (< 40%), intermediate (40 to 60%) and high (> 60%) (Langton 1982).

|                       | <i>E. treurensis</i> | <i>O. mykiss</i> |
|-----------------------|----------------------|------------------|
| <i>A. uranoscopus</i> | 0.11                 | 0.11             |
| <i>E. treurensis</i>  |                      | 0.55             |

**Appendix 4.4:** Isotopic niche overlap among fish species in the Treur River, South Africa that is free of rainbow trout (*Oncorhynchus mykiss*) invasion. Extent of overlap was classified as low (< 40%), intermediate (40 to 60%) and high (> 60%) (Langton 1982).

|                          | <i>A. uranoscopus</i> | <i>E. anoplus</i> | <i>E. lineomaculatus</i> | <i>E. treurensis</i> | <i>T. sparrmanii</i> |
|--------------------------|-----------------------|-------------------|--------------------------|----------------------|----------------------|
| <i>T. sparrmanii</i>     | 0.15                  | 0.26              | 0.39                     | 0.32                 |                      |
| <i>E. treurensis</i>     | 0.24                  | <b>0.62</b>       | <b>0.45</b>              |                      |                      |
| <i>E. lineomaculatus</i> | 0.12                  | 0.34              |                          |                      |                      |
| <i>E. anoplus</i>        | 0.33                  |                   |                          |                      |                      |

**Appendix 4.5:** Isotopic matrices of food webs of fish communities sampled in sites invaded by rainbow trout and sites free of invasion on the Blyde and Treur rivers, Mpumalanga Province, South Africa.

| Community matrix                              | Blyde River          |                            | Treur river              |
|-----------------------------------------------|----------------------|----------------------------|--------------------------|
|                                               | Sites<br>(Uninvaded) | 1-2 Sites 3-8<br>(Invaded) | Sites 5-7<br>(Uninvaded) |
| <b>Total convex hull area (TA)</b>            | 0.26                 | 0.14                       | 0.73                     |
| <b>Trophic length (TP range)</b>              | 2.16 -2.92           | 2.51-3.28                  | 1.24-2.96                |
| <b>Ccorr range</b>                            | -0.32-0.52           | 0.22-0.55                  | 0.27-0.88                |
| <b>Mean distance to the centroid (CD)</b>     | 0.22                 | 0.15                       | 0.24                     |
| <b>Mean nearest neighbour distance (MNND)</b> | 0.05                 | 0.04                       | 0.06                     |

## Chapter 5: The potential risk associated with invasive salmonid species in South Africa

### Abstract

Salmonids are a group of freshwater fish species that have been widely introduced worldwide for angling and aquaculture. The species have both negative and positive impacts which complicate their management. This study assessed the risks associated with the introduction of salmonid species to South Africa using the recently developed Risk Analysis for Alien Taxa framework (RAAT). The main objective was to propose appropriate recommendations to guide the regulations responsible for managing the alien species in South Africa. Six trout species (*Oncorhynchus mykiss*, *Oncorhynchus kisutch*, *Oncorhynchus tshawytscha*, *Salmo salar*, *Salmo trutta*, and *Salvelinus fontinalis*) that are known to have been introduced to South Africa were assessed. Of these, four species (*O. mykiss*, *O. kisutch*, *O. tshawytscha*, and *S. trutta*) were considered to have a high risk of invasion because they are already present in South Africa and have a high potential to cause moderate to major impacts. *Salmo salar* and *Salvelinus fontinalis* were classified as low risk because they are not present in the country and are known to cause minor to moderate impacts in their global invasive range. The recommendations from the risk analyses largely support the current management interventions as prescribed by the NEM:BA A&IS Regulations. The two key recommendations from the risk analyses are that *O. mykiss* and *S. trutta* should be included on the list of species regulated by the NEM:BA A&IS regulations, and that National Management Plans should be developed for each trout species that is known to be present in South Africa. The tenet of these management plans should be to preserve the benefits while limiting the negative. This can be achieved by managing trout by area, where utilisation is allowed in areas where trout have naturalised and/or where historically stocked while preventing introductions into new areas. There is also a need for broader consultative process when these management plans are been developed to minimise contestations around the proposed management plans.

**Keywords:** Environmental impacts, risk communication, risk management, risk analysis, risk assessment, socio-economic impacts, trout.

## Introduction

Biological invasions are a major threat to biodiversity and are known to affect community structure and functioning through many ways (Pyšek et al. 2020). Examples include hybridisation with indigenous species (e.g., Firmat et al. 2013), extirpation of indigenous species through competition, predation (e.g., Wely et al. 2020) and or disease transmission (e.g., Hulme 2014), modifying aquatic-terrestrial linkages (e.g., Epanchin et al. 2010; Jackson et al. 2016), altering food-web structure (Flecker and Townsend 1994), and disrupting nutrient cycles (Schindler et al. 2001; Eby et al. 2006). The negative impacts of alien invasive species on biodiversity have presented a global need to develop protocols that can be used to assess their impacts and provide insight towards the implementation of appropriate management interventions (e.g. Kumschick et al. 2020a). For example, quantifying the magnitude of impacts caused by alien species is one of the priority goals of several international conventions such as the Convention on Biological Diversity's (CBD) 2020 Aichi Target 9 and the on-going discussion around the revised 2030 and 2050 targets (Essl et al. 2020). The proposed CBD target 5 for 2030 is:

*“to greatly reduce the rate of new invasive alien species introductions by monitoring the pathways through which these introductions are made and eradicate them to minimise their impacts”* (Essl et al. 2020).

A major challenge to meet this goal is that although studies of the impact of alien species on the environment are increasingly being carried out, there has been an ongoing debate about how to standardise the description of these impacts. For example, there are many studies that have been done to assess the impacts of alien fish species, and these strengthen the evidence base for identifying the impacts of introduced fish species (e.g., Gozlan et al. 2010; Cucherousset and Olden 2011; Haubrock et al 2022; Bernery et al. 2022). However, most of

these studies were done using different methods and at different scales and therefore unsuitable for drawing robust conclusions (e.g., see Zengeya et al. 2020).

There has been, however, a global effort to develop standardised protocols for assessing the impact of alien species and alleviate the problem of comparing impacts using different approaches (Roy et al. 2018). Some of the key frameworks that have been developed include the Environmental Impact Classification of Alien Taxa (EICAT, Blackburn et al. 2014; Hawkins et al. 2015) for assessing negative environmental impacts and the Socio-Economic Impact Classification for Alien Taxa (SEICAT, Bacher et al. 2018) for assessing negative non-environmental impacts. EICAT was recently adopted by the IUCN as a global standard (IUCN 2020). Alien species can have both negative and positive impacts but there is biasness toward protocols that only assess negative impacts (Vimercati et al. 2020). A recent development is the EICAT+ framework that enables the classification of positive impacts of alien taxa on native biodiversity (Vimercati et al. 2022).

Many countries have a long history of alien species introductions and the primary reasons for such introductions have been to meet societal needs such as the provision of food and raw materials, ornamentation and biological control (Bernery et al. 2022). Despite the benefits that have been derived from many alien species, some have become invasive and have caused adverse impacts in recipient areas (e.g., van Wilgen et al. 2022). This has presented a major challenge in the utilisation of alien species and several countries have developed risk analysis protocols to restrict the importation of high-risk alien species while allowing for the introduction and utilisation of species with low-risk (Roy et al. 2018). In South Africa, a risk analysis framework termed Risk Analysis for Alien Taxa (RAAT) was recently developed which outlines a normative process to assess an alien taxon's likelihood of invasion, realised and potential impacts, and options for management in a given area (Kumschick et al. 2018, 2020b). It specifically attempts to align with major international developments in dealing with

the classification of pathways of introduction (Hulme et al. 2008), the introduction-naturalisation-invasion continuum (Blackburn et al. 2011), and formal assessments for environmental (EICAT; Blackburn et al. 2014; Hawkins et al. 2015) and non-environmental impacts of alien taxa (SEICAT; Bacher et al. 2018). In addition, the RAAT framework can also be applied consistently across taxa, regions and realms, explicitly sets out uncertainties, and provides decision-makers with information both on the risks posed and on what can be done to mitigate or prevent impacts (Kumschick et al. 2020b).

This study applied the RAAT framework to evaluate the risk posed by the introduction of trout species to South Africa. So far, six trout species have introduction records in South Africa, these include *Oncorhynchus mykiss* (Walbaum, 1792) (rainbow trout), *Oncorhynchus kisutch* (Walbaum, 1792) (coho salmon), *Oncorhynchus tshawytscha* (Walbaum, 1792) (Chinook salmon), *Salmo salar* Linnaeus, 1758 (Atlantic salmon), *Salmo trutta* Linnaeus, 1758 (brown trout), and *Salvelinus fontinalis* (Mitchill, 1815) (brook trout) (Ellender et al. 2014; Marr et al. 2017, Weyl et al. 2020). *Oncorhynchus mykiss* and *S. trutta* have naturalised in several mountain headwater streams in the country, *O. kisutch* and *O. tshawytscha* are restricted to aquaculture facilities and the introduction of *Salmo salar* and *Salvelinus fontinalis* was not successful (Ellender et al. 2014; Zengeya and Wilson 2020). Trout species have both positive and negative impacts and this has complicated their management in South Africa (van Wilgen and Wilson 2018). The contestations are mainly on how the risk of the introduction of several trout species has been quantified and the proposed control measures (Zengeya et al. 2017, Woodford et al. 2017). These conflicts have highlighted the need for an objective, transparent and consultative process for developing appropriate management interventions for invasive species in South Africa (e.g., Novoa et al. 2018). The RAAT framework provides a formal science-based risk analysis to support policy decision-makers on the risks posed by alien trout introductions and recommended potential mitigation measures to prevent the

introduction of harmful species and to minimise impacts. This study therefore intends to apply the RAAT framework to provide policy decision-makers with information both on the risks posed by the trout introductions and provide recommendations on what can be done to mitigate or prevent impacts.

## **Material and Methods**

### *Risk Analysis for Alien Taxa (RAAT) Framework*

The study evaluated the risk posed by the introduction of several trout species to South Africa using the Risk Analysis for Alien Taxa (RAAT) framework as outlined by Kumschick et al. (2018, 2020b). The RAAT framework consists of the following four components: 1) risk identification; 2) risk assessment; 3) risk management and 4) risk communication.

***Risk identification:*** Biological invasions present various risks that can be broadly grouped in terms of species, pathways, and areas (Kumschick et al. 2020a). In this study, the risks associated with biological invasions from trout species in South Africa was identified based on species impacts (Kumschick et al. 2020a). The risk analyses was restricted to six species that are known to have been introduced in South Africa, and these include *Oncorhynchus mykiss*, *Oncorhynchus kisutch*, *Oncorhynchus tshawytscha*, *Salmo salar*, *Salmo trutta*, and *Salvelinus fontinalis* (Ellender et al. 2014; Marr et al. 2017). The invasion status of the six trout species in South Africa was quantified using the unified framework (see Blackburn et al. 2011), and varied from: 1) introduced = introduced but are not naturalized in the wild; 2) established = established in the wild but are not yet invasive; and 3) invasive = species with self-sustaining populations that have spread from initial sites of introduction (Table 5.1). The risk communication protocols used are outlined below.

### *Risk assessment*



The risk assessment component evaluated the likelihood of a particular trout species being introduced, establishing and spreading in South Africa, and the consequences of the introduction (Kumschick et al. 2020b). The probability scores for the likelihood of entry, establishment, and spread were assigned for each respective parameter where the lowest probability was when the chances of an event occurring was extremely unlikely ( $P = 0.000001$ ) and the highest probability was when the chances were probable ( $P = 1$ ). The highest score of each sub-section was then multiplied to get an overall probability for likelihood a particular trout species being introduced, establishedd spreading in the country.

The potential negative consequences of trout introductions was estimated using the impact classification schemes for environmental (EICAT; Balckburn et al. 2014) and non-environmental (SEICAT; Bacher et al. 2018) impacts. EICAT classifies impacts based on 12 mechanisms that vary from direct impacts on individual native species (e.g., competition and predation) to changes in ecosystem structure and functioning. In addition, EICAT classifies impacts into five levels based on the orginisationl level of the species affected (i.e., Minimal Concern, Minor, Moderate, Major and Massive). For example, impacts classified as of minimal concern do not affect the performance of a native species, moderate impacts lead to a reduction in population size of at least one native species but do not lead to extirpation and or extinction, while massive impacts lead to irreversible community changes such as species extinction. Similarly, SEICAT framework assesses non-environmental impacts by evaluating how alien species adversely affect several facets of human well-being such as safety, material and immaterial assets, health, and social, spiritual, and cultural relations (Bacher et al. 2018). The impacts are then classified based on their magnnitude into five levels of the impact (i.e., Minimal Concern, Minor, Moderate, Major and Massive).

These frameworks offer a simple, objective, and transparent method to classify alien taxa according to the magnitude of their impacts in the introduced range based on published evidence. The highest scores for the consequence and likelihood sections were then used to determine the risk (Kumschick et al. 2018, 2020b). The risk score was categorized as either low, medium, or high (Kumschick et al. 2018; 2020b).

### *Risk management*

Invasive species with documented adverse impacts in their introduced systems are often managed through control measures to limit or eliminate the risks. In this section the various management strategies that could be used to manage the impacts of trout in South Africa were evaluated (Kumschick et al. 2020a). This can include eradication methods or restricted utilisation of the species. In South Africa, alien species are controlled by use of the Alien and Invasive Species (AIS) Regulations which comprise of lists of alien species and stipulated control measures for each listed species (van Wilgen and Wilson 2018). This species are classified into four categories based on the nature of their impacts: Category 1a) species that should be eradicated; Category 1b) species that should be controlled as part of national programmes, and cannot be traded or allowed to spread; Category 2) species that have the same restrictions as Category 1b but a permit should be issued to allow utilisation under specific conditions that aim to prevent spread and minimise impacts; and Category 3) species that can be utilised without a permit but they cannot be traded or further propagated and their occurrence in the biodiversity-sensitive areas such as protected areas or riparian zones must be controlled (Kumschick et al. 2020a). The regulations only apply on the alien species that are already introduced in South Africa and introduction of new alien species is only allowed through restrictive permits which can only be issued after evaluation of the impacts of the species and has indicated the lowest possible risk (Kumschick et al. 2020a). Ease of management score

(low, medium and high) is estimated based on how accessible the species are, propagule persistence, and how often the species reproduce (Kumschick et al. 2020b).

#### *Risk communication and recommendation*

This included the collation and summary of the complete background information of the RAAT framework process to make recommendations for management, regulations, and stakeholder engagement with relevant stakeholders.

## **Results**

### *Species analysed*

The six trout species have been introduced globally to areas outside their natural ranges to enhance angling opportunities and aquaculture (Cambray 2003a; Crawford and Muir 2008; Stanković et al. 2015). The three *Oncorhynchus* species are native to North America and parts of Asia, and have been widely introduced to several countries around the world (Figure 5.1). *Salmo trutta* is native to Europe and Asia and *S. salar* is native to North America, and both species have been introduced to many countries in Africa, Europe, North America, Russia, South America, and Oceania. *Salvelinus fontinalis* is native to North America and it has been introduced widely in North America and several countries in Europe, South America, Asia, Africa, and Oceania.

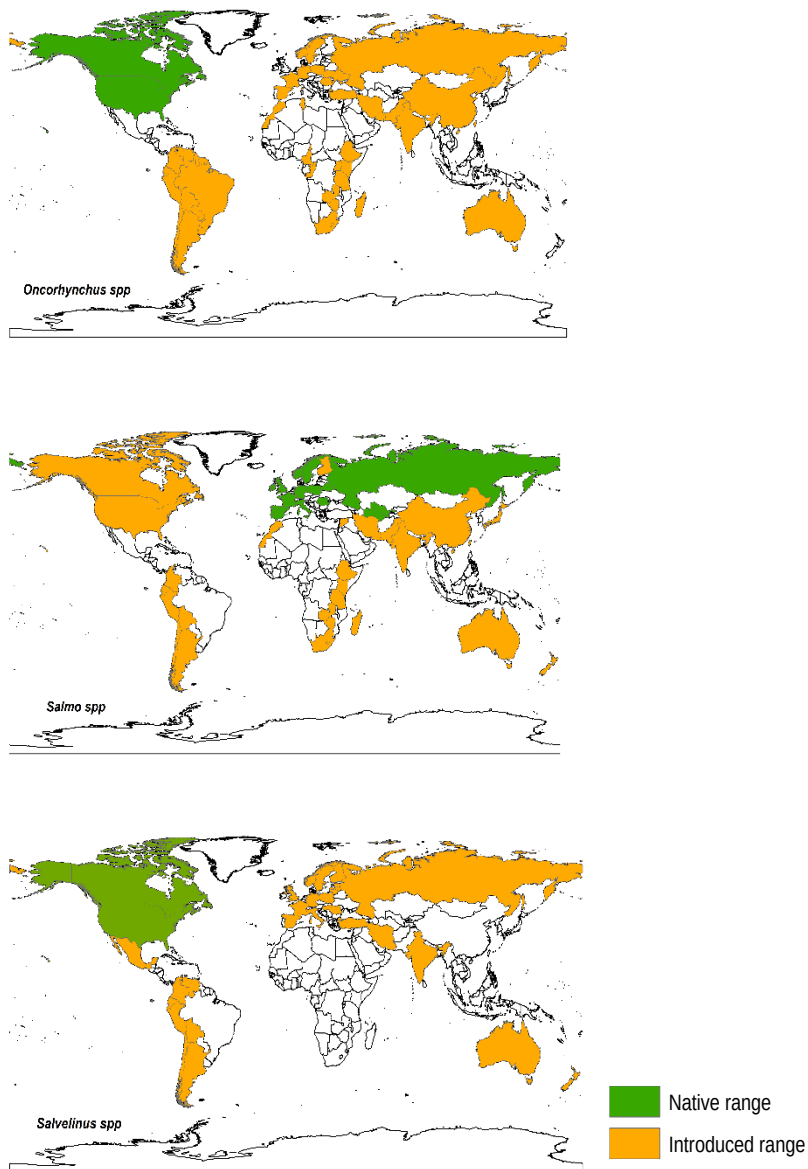


**Figure 5.1:** The native and global introduction ranges of salmonids species (*Oncorhynchus*, *Salmo*, and *Salvelinus* spp). Source: Muhlfeld et al. (2019), <https://doi.org/10.47886/9781934874547>.

## Risk assessment

### *Likelihood of entry*

The likelihood of the the six species to enter, establish and spread in the South Africa was assigned a score of probable for *O. kisutch*, *O. tshawytscha*, *O. mykiss* and *S. trutta* (Table 5.1). *Oncorhynchus mykiss* and *S. trutta* are known to be invasive in South Africa, while *O. kisutch* and *O. tshawytscha* have been introduced but have not naturalised. *Salmo salar* and *Salvelinus fontinalis* where introduced but the introduction were not successful and are no longer present (see Appendices 5.1-5.6 for detailed risk analyses).

### *Consequences*

Four of the six species (*O. kisutch*, *O. tshawytscha*, *O. mykiss* and *S. trutta*) that are known to be present in South Africa were assessed as a high risk for invasion (Table 5.1). These species have the potential to cause moderate to major environmental impacts through various mechanisms, such as competition, predation and the transmission of diseases. They also have the potential to cause moderate non-environmental impacts through declines in economic returns from stock farming. *Salmo salar* and *Salvelinus fontinalis* obtained low risk scores because they are not present in South Africa, are not likely to be introduced in the near future and are known to cause moderate environmental impacts through hybridisation with native fish and predation of native fish, amphibians and macroinvertebrates.

### *Risk management*

The ease of management for all six trout species was classified as medium because some aspects of proposed interventions are difficult to manage. This is largely because trout are a conflict-generating group of invasive species that have major negative environmental impacts, but also have socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Part of the proposed management initiatives for trout species that are not present in South Africa (*Salmo salar* and *Salvelinus fontinalis*) is to restrict importation through

permitting and for species such as *O. kisutch* and *O. tshawytscha* that are present in the country but likely still confined to aquaculture facilities is to manage utilisation through permitting and implement post border intervention measures that minimise the potential release of the species into the wild. For species that are present and already invasive such as *O. mykiss* and *S. trutta* part of the proposed management initiatives includes managing it by area where utilisation is to be allowed in areas where trout have naturalised and in areas where it has been historically utilised for stocking.

#### *Risk communication and recommendation*

The recommendations from the risk analyses for *O. kisutch*, *O. tshawytscha*, *Salmo salar* and *Salvelinus fontinalis* support the current listing under the A&IS Regulations while the risk analyses for *O. mykiss* and *S. trutta* that are currently not listed, recommend a listing in under Category 2 with exemptions (Table 5.1).

**Table 5.1:** A summary of the risk analyses for six trout species that known to be invasive or have been introduced in South Africa.

| Species                         | Native range                                                                                                     | Introduction status in South Africa | Likelihood    | Consequences <sup>1</sup> | Risk | Management | Current AIS listing | Recommended listing <sup>2</sup>               |
|---------------------------------|------------------------------------------------------------------------------------------------------------------|-------------------------------------|---------------|---------------------------|------|------------|---------------------|------------------------------------------------|
| <i>Oncorhynchus kisutch</i>     | Arctic and Pacific drainages from Point Hope, Alaska, to Monterey Bay, California, and also in northeastern Asia | Introduced but not naturalised      | Probable      | MO                        | High | Medium     | Category 2          | No change                                      |
| <i>Oncorhynchus mykiss</i>      | North America and east Russia                                                                                    | Invasive                            | Probable      | MR                        | High | Medium     | Not listed          | Category 2 with exemptions (see Appendix MAN6) |
| <i>Oncorhynchus tshawytscha</i> | North America from southern California to Alaska, and north-eastern Asia from northern Japan to Kamchatka        | Introduced but not naturalised      | Probable      | MO                        | High | Medium     | Category 2          | No change                                      |
| <i>Salmo salar</i>              | North Atlantic on both the European (Portugal to Russia) and North American (Cape Cod to Labrador) sides         | Introduced but no longer present    | Very unlikely | MO                        | Low  | Medium     | Not listed          | No change                                      |
| <i>Salmo trutta</i>             | Europe, northern Africa and western Asia                                                                         | Invasive                            | Probable      | MR                        | High | Medium     | Not listed          | Category 2 with exemptions (see Appendix MAN6) |
| <i>Salvelinus fontinalis</i>    | Eastern North America                                                                                            | Introduced but no longer present    | Very unlikely | MO                        | Low  | Medium     | Not listed          | No change                                      |

<sup>1</sup> Trout species that have been introduced to South Africa and assessed using the Environmental Impact Classification for Alien Taxa (EICAT) and The Socio-economic Impact Classification for Alien taxa (SEICAT) to have moderate (MO), and major (MR) impacts on biodiversity and or society in South Africa

<sup>2</sup> The management options under the NEM:BA A&IS regulations are grouped into four categories: 1) Category 1a) species that should be eradicated; 2) Category 1b) species that should be controlled as part of national programmes, and cannot be traded or allowed to spread; 3) Category 2) species that have the same restrictions as Category 1b species but a permit can be issued to allow utilisation under specific conditions that aim to prevent spread and minimise impacts; and 4) Category 3) species that can be utilised without a permit but they cannot be traded or further propagated and should be controlled in the way they occur in biodiversity-sensitive areas such as protected areas or riparian zones

## Discussion

The study conducted formal risk analyses for trout species that have been introduced in South Africa. It specifically intended to provide policy decision-makers with information both on the risks posed and recommendations on what can be done to mitigate or prevent impacts. The study identified six trout species that have been introduced into South Africa of which four were classified as high risk because they are already present in the country and have a high potential to cause moderate to major impacts. The remaining two species were classified as low risk because they are not present in the country and are unlikely to be introduced in the near future. In addition they are known to cause minor to moderate impacts in their global invasive range.

## Risk assessment

### *Likelihood*

Trout species have a long history of introduction into South Africa as they have been widely introduced into lakes and rivers in the country to create and enhance sport-fishing opportunities for more than a century (Ellender and Weyl 2014). Six trout species have introduction records in South Africa, these include *O. mykiss*, *O. kisutch*, *O. tshawytscha*, *Salmo salar*, *S. trutta* and *Salvelinus fontinalis* (Ellender et al. 2014; Marr et al. 2017; Weyl et al. 2020; SANBI and CIB 2020). There is evidence that they are present in the country and in some case in neighbouring countries such as Zimbabwe, Lesotho, Swaziland, and Morocco (Welcomme 1988; de Moor and Bruton 1988; Crawford and Muir 2008; Weyl et al. 2017). Therefore, the probability that they will enter, establish and spread in South Africa was assessed as probable. *Oncorhynchus mykiss* and *S. trutta* have naturalised in several mountain headwater streams in the country (Weyl et al. 2020). This can be attributed to sustained and widespread stocking for sport fishing, initially by government agencies and later by angling societies and private individuals, and a pre-selection of suitable receiving environments that are similar to the species' native ranges



(de Moor and Bruton 1998; Ellender et al. 2014). *Oncorhynchus mykiss* and *S. trutta* are among some of the most widely introduced fish species for sport fishing globally (Cambray 2003b). They have been introduced in more than 80 countries globally and have established feral populations throughout their introduced range (Crawford and Muir 2008; Cambray 2003b). There are several import permit records for *O. tshawytscha* and *O. kisutch* into South Africa (SANBI and CIB 2020), and it is likely that the two species are present in aquaculture facilities but there are no known records of naturalised populations in the country.

The likelihood of score for *Salmo salar* and *Salvelinus fontinalis* was assessed as very unlikely because they are no known populations of the two species in South Africa and previous introduction pathways such as angling and aquaculture have been infrequently used. *Salmo salar* and *Salvelinus fontinalis* were introduced in South Africa in the late 19 century but these introductions were not successful, probably due to lack of suitable habitats (Ellender et al. 2014; Weyl et al. 2017). Similar failed introductions of *S. salar* have been observed elsewhere in the world (i.e., Washington, California, and British Columbia) and likely due to unsuitable environmental conditions (MacCrimmon and Gots 1979, Lever 1996), and primitive hatchery methods (Volpe 2001).

### *Consequences*

In South Africa, a national level Environmental Impact Classification of Alien Taxa (EICAT) assessment indicated the potential adverse impacts of introduced salmonids species on native fauna (Marr et al. 2017). *Oncorhynchus mykiss* and *S. trutta* are known to cause major (MR) impacts through competition and predation that has led to fragmentation and in some cases local extirpation of native species such as invertebrates, frogs and fishes (Karssing et al. 2012; Jackson et al. 2016; Weyl et al. 2017; Weyl et al. 2020). For example, *O. mykiss* invasions in the Blyde River (Mpumalanga Province) have been implicated in the reduction of populations of the endangered Treur River barb (*Enteromius treurensis*) by 96% in invaded areas (Maimela

et al. 2021). This was also observed elsewhere in the Breede River (Western Cape Province) where *O. mykiss* invasions reduced the abundance of native species such as Breede River redbfin (*Pseudobarbus burchelli*), Cape kurper (*Sandelia capensis*), and Cape galaxias (*Galaxias zebratus*) (Shelton et al. 2015). *Oncorhynchus mykiss* has also been implicated in the extirpation of the endangered boarder barb (*Amatolacypris trevelyani*) probably through predation in the Keiskamma River (Eastern Cape Province) (Ellender 2013). In its global invasive range, *O. mykiss* has aslo been shown to cause fragmentation and population declines of native species through competition and predation (Morita et al. 2004; McIntosh et al. 2010; Kadye et al. 2013). *Oncorhynchus mykiss* invasion have been especially severe on galaxioid species in New Zealand as a result most of them are regarded as threatened (Deans et al. 2004; McDowall 2006; McIntosh et al. 2010). In the Colorado River (USA) trout consumed a much greater proportion of native fish than non-native fish despite the greater abundance of non-native fishes in the river (Yard et al. 2011).

Similary, *S. trutta* have been implicated in causing major declines, and in some cases local extirpation, of native invertebrates, frogs and fish through competition and predation in South Africa (Marr et al. 2017, Weyl et al. 2020). For example, broad food niche overlap between *S. trutta* and native fish species such as the mountain catfish *Amphilius natalensis* suggest that their present impact on native fish in uKhahlamba Drakensberg Park (KwaZulu-Natal Porvince) is likely to come about through competition for resources (Potgieter 2014; Weyl et al. 2017). In addition, trout invasions (*S. trutta* and co-occurring *Oncorhynchus mykiss*) in the park have been implicated in the reduction of macroinvertebrate communities and the abundance of amphibians probably due to predation (Karssing et al. 2012; Rivers-Moore et al. 2013). *Salmo trutta* invasions have also been implicated in the decline of native species such as the Maloti minnow, *Pseudobarbus quathlambae* (de Moor and Bruton 1988) and the Border barb, *Barbus trevelyani* (Ellender 2013). Similar impacts have aslo been observed in *S. trutta*

global invasive range. For example, *S. trutta* have been implicated in causing a decline in the abundance of amphibians in the USA and Australia (Kats and Ferrer 2003) and native fish such as *Galaxias* in New Zealand and Australia (Crowl et al. 1992; McIntosh et al. 1992; Townsend 2003). *Salmo trutta* have also been implicated in causing the local extinction and fragmented distribution of native fish species in Europe (Legalle et al. 2005; van Liefferinge et al. 2005; Lorenzoni et al. 2018), and Chile (Soto et al. 2006; Arismendi et al. 2009).

There are no documented impacts caused by the other four trout species (*O. kisutch*, *O. tshawytscha*, *Salmo salar* and *Salvelinus fontinalis*) in South Africa (Marr et al. 2017). However, there are records from each of the respective species' introduction ranges that indicate that they might cause minor to moderate environmental impacts through competition, predation and hybridisation (Muhlfeld et al. 2019). For example in Chile, introduced salmon (including *O. kisutch* and *S. salar*) have been shown to negatively affect native fishes due to predatory and interference competition (Soto et al. 2001; Arismendi et al. 2009; 2012, Penaluna et al. 2009; Young et al. 2009; 2010; García de Leaniz et al. 2010). In Lake Michigan and Lake Ontario, a decline in populations of native species such as alewife (*Alosa pseudoharengus*) has been linked to predation by introduced *O. tshawytscha* (Elliott 1993; Rybicki and Clapp 1996; Holey et al. 1998). Similarly, predation by both *O. tshawytscha* and *O. mykiss* has also been implicated in the decline of native fishes in Australia and New Zealand (Cadwallader and Eden 1982; Glova and Sagar 1993). In addition, alien salmonid species such as *O. kisutch* have also been implicated in causing non-environmental impacts that affect material and immaterial assest such as animal production (usually aquaculture) through the transmission of pathogens, which may cause relatively high expenses (van der Veer and Nentwig 2015).

## Risk management

Management of trout species in South Africa is relatively difficult. This is because trout are conflict-generating invasive species that have major negative environmental impacts, but also have socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Trout species have socio-economic values and are utilised in recreational fisheries in their global invasive range (e.g., Muhlfeld et al. 2019). In South Africa, there are several studies that have assessed the economic benefits of trout (mainly for *Oncorhynchus mykiss*) and these strengthen the evidence base for quantifying the benefits derived from introduced fish species (Britz et al. 2009; Britz and Venter 2016; Du-Preez and Lee 2010; Anchor Environmental Consulting 2010). However, the studies were done using different methods and at small scales (e.g. towns, and discrete catchments), and the results still have to be extrapolated to larger scales (e.g. national). *Salmo trutta* is of lower importance than *O. mykiss* as it is currently used exclusively for recreational fishing, and not for commercial production (Stander and Brink 2009). No studies have been done for the other four species (*O. kisutch*, *O. tshawytscha*, *Salmo salar* and *Salvelinus fontinalis*) in South Africa.

Management of trout in South Africa is further complicated given the logistical challenges of finding and treating populations. Populations of *O. mykiss* and *S. trutta* in South Africa can be found in several mountain rivers that may be difficult to access. Populations in containment (including those of *O. kisutch* and *O. tshawytscha*) are often on private land and permission would be needed to access these areas for control. Many control options harm native species (though subsequent recovery may be good), and control operations have been met with resistance from some stakeholders (Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017). There have been no studies that have addressed the country-wide eradication of trout species in South Africa. An attempt to extirpate *O. mykiss* from a

discrete catchment of the Kroom River in the Cederberg was unsuccessful because of gear selectivity and budgetary constraints (Shelton et al. 2017).

### **Risk communication and recommendations**

In South Africa, alien taxa are managed under the NEM:BA Alien and Invasive Species (A&IS) Regulations which comprise of lists (i.e., notices) for regulated species and the management and control option for each listed species (van Wilgen and Wilson 2018). The recommendations from the trout risk analyses proposed in this study largely support the current management interventions as prescribed by the A&IS Regulations, except for two species *O. mykiss* and *S. trutta* that are currently not listed. *Oncorhynchus mykiss* and *S. trutta* were published for listing as invasive species in the South African Government Gazette on 18 September 2020, but the promulgation of the lists was delayed because of ongoing consultation with stakeholders. A note indicating the NEM:BA A&IS lists would be promulgated without *Oncorhynchus mykiss* or *Salmo trutta* was published on 24 Feb 2021, and the lists were promulgated on 1 March 2021. The proposed listing of *O. mykiss* and *S. trutta* was category 2 with “All persons are exempted from requiring a permit for restricted activities “b” and “j” under Notice 1. Activity b is “having in possession or exercising physical control over any specimen of a listed invasive species”, and activity “j” is “Catch and release of a specimen of a listed invasive fresh-water fish or listed invasive fresh-water invertebrate species”. Although *O. mykiss* and *S. trutta* are not listed at a national-level, under the NEM:BA A&IS lists, they are managed in some regions (e.g. the Western Cape Province) under provincial legislation (Woodford et al. 2017). It is recommended that *O. mykiss* and *S. trutta* should be relisted as Category 2 species on the the NEM:BA A&IS lists.

The NEM:BA A&IS lists however included *O. kisutch* and *O. tshawytscha* as category 2 invasive species but *Salvelinus fontinalis* and *Salmo salar* were not listed. The recommended management options for species that are not present in the country such as *S. salar* and *S.*

*fontinalis* are to restrict importation through permitting and for species that are already present in the country, managing them by area where utilisation is to be allowed in areas where they have naturalised and in areas where they have been historically utilised for stocking. The two key aims for the management of trout should be to prevent the spread of trout species to new areas; and limit the negative environmental impacts by controlling naturalised populations in key fish conservation areas. To this end, those catchments where trout does not yet occur but where suitable habitat exists, and key fish conservation areas (with and without trout populations) would need to be identified in National Management Plans that contains appropriate maps for each trout species. The inclusion of maps outlining areas where permits may be granted would greatly facilitate the application and processing of permits. The beneficial uses of trout could then be managed as follows:

- Permits for existing or new aquaculture facilities could be granted, but only if such activities do not result in new sites becoming invaded or spread of trout into key fish conservation areas. As such permits would not be issued for aquaculture facilities in discrete catchment systems in which trout does not yet occur or that include key fish conservation areas. Permits could, however, be granted for aquaculture facilities in part of a discrete catchment system where trout occurs, provided there are natural or artificial habitat barriers (for example waterfalls, dams or weirs) that would prevent the spread of trout to other parts of the catchment system where it is currently absent, but where suitable habitat exists.
- In terms of restocking, the same considerations as for aquaculture facilities would apply.
- In terms of angling, catch-and-release (i.e. the practice of anglers to return a fish to the water where it was caught) is exempt in any discrete-catchments that are specified on maps produced as per the National Management Plan. At all other sites catch-and-kill

should be practised. This provision could be incorporated into provincial freshwater angling licences.

- The transport of live fish or eggs would always require a permit, but any dead specimens (e.g. for personal consumption or commercial trade) would, of course, be exempt.

To facilitate the implementation of these criteria and to ensure the process is transparent, it would be important to draw up a National Management Plan for each of the four trout species (*O. tshawytscha*, *O. kisutch*, *O. mykiss* and *S. trutta*) that are known to occur in South Africa. The plans will need to include maps of the catchments where permits may be issued for commercial production purposes, where permits may be issued for restocking, and where catch-and-release angling is exempt. Maps of key fish conservation areas would also be useful to indicate areas where catch-and-kill would need to be practised. The National Management Plans would also need to specify the standards that should be met to limit the risk of escape or unintentional or illegal re-distribution to new areas. Concerned stakeholders have highlighted the need for broader consultations and transparency on the evidence used to assess the risks posed by trout to biodiversity and the benefits derived from their utilisation (Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017). There is, therefore, a need for broader consultative process when management plans are been developed (Novoa et al. 2018).

### *Conclusion*

Management of trout species in South Africa is difficult because they are a conflict-generating invasive species that have major negative environmental impacts, but also have socio-economic benefits. This study demonstrated that the RAAT framework provides a formal science-based risk analysis to support policy decision-makers on the risks posed by alien trout introductions and recommended potential mitigation measures to allow utilisation and minimise impacts. The recommendations from the risk analyses largely support the current

management inversions as prescribed by the A&IS Regulations, except for two species *O. mykiss* and *S. trutta* that are currently not listed. The recommendation is that *O. mykiss* and *S. trutta* should be included on the list of species regulated by the NEM:BA A&IS regulations. Another key recommendation is the development of National Management Plans for each of the four trout species (*O. tshawytscha*, *O. kisutch*, *O. mykiss* and *S. trutta*) that are known to occur in South Africa. The prescript of the management plans is to preserve the benefits while limiting the negative. This could be achieved by managing trout by area where utilisation is to be allowed in areas where trout have naturalised and/or where historically stocked while preventing introductions to new areas. There is also need for a broader consultative process when the management plans are being developed to minimise constestations around the proposed management plans.

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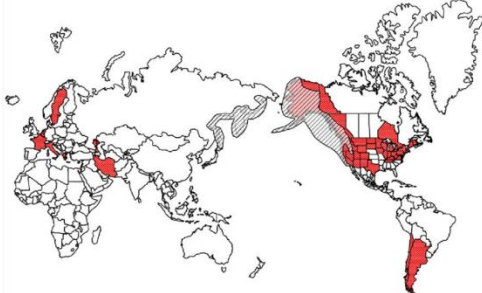
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## Appendices- Risk analysis reports

### Appendix 5.1<sup>3</sup>: Coho salmon (*Oncorhynchus kisutch*)

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                                                                   |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Taxon:</b> <i>Oncorhynchus kisutch</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | <b>Area:</b> South Africa                                                                                                                                                                                                                                                                                                                         |
| <b>Compiled by:</b> Lerato Maimela                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | <b>Approved by:</b>                                                                                                                                                                                                                                                                                                                               |
| <b>Picture of Taxon</b><br>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | <b>Alien distribution map (BAC8)</b><br><br> Crawford and Muir 2007, <a href="https://doi.org/DOI/10.1007/s11160-007-9079-1">https://doi.org/DOI/10.1007/s11160-007-9079-1</a> |
| <b>Risk Assessment summary:</b><br><i>Oncorhynchus kisutch</i> (Coho salmon) is native to the Arctic and Pacific drainages from Point Hope, Alaska, to Monterey Bay, California, infrequently as far south as Chamalu Bay, Baja California, and Also in northeastern Asia. It has been introduced to several countries in Asia, Europe and South America. It has been introduced in South Africa (date fo first introduction uncertain) for angling and aquaculture. Evidence from elsewhere, suggests that <i>O. kisutch</i> can cause minimal environmental impacts through competition with native fish, predation of native fish, amphibians and macroinvertebrates, and moderate non-enviromental impacts through declines in economic returns from stock farming                                                                                                                                                                                                                                    |                                                                                                                                                                                                                                                                                                                                                   |
| <b>Risk score:</b><br><br>High                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                                                                                                                                                                                                                                                                                                                                   |
| <b>Management options summary:</b><br>Management of trout species in South Africa is difficult. This is because trout are a conflict-generating invasive species that have major negative environmental impacts, but also have socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Part of the proposed management initiatives for <i>O. kisutch</i> is to restrict importation through permitting and implement post border intervention measures similar to those proposed for other trout species in South Africa. This includes managing the species by area where utilisation is to be allowed in areas where trout species have naturalised and in areas where they have been historically utilised for stocking. However, concerned stakeholders have highlighted the need for broader consultations and transparency on the evidence used to assess the risks posed by trout to biodiversity and the benefits derived from their utilisation. |                                                                                                                                                                                                                                                                                                                                                   |
| <b>Ease of management:</b><br><br>Medium                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                                                                                                                                                                                                                                                                                   |
| <b>Recommendations:</b><br>Given that <i>O. kisutch</i> has both major negative environmental impacts and high socio-economic benefits, the recommendation is retain the listing of <i>O. kisutch</i> as category 2 (with limitations and exemptions as outlined in Appendix MAN6). In particular, to facilitate the regulation of <i>O. kisutch</i> it is                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                                                                                                                                                                                                                                                                                   |
| <b>Listing under NEM:BA A&amp;IS lists of 2014 as amended 2021:</b><br>2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                                                                                                                                                                                                                                                                                   |

<sup>3</sup> This risk analyses report for *Oncorhynchus kisutch* (Coho salmon) is presented as submitted to the South African Alien Species Risk Analysis Review Panel (ASRARP), a committee that is tasked with reviewing risk analyses attached to import applications and listing of species under national legislation to ensure they are scientifically robust and take into account the best available evidence (see Kumschick et al. 2020 for details). ASRARP is an independent body and its members consist of scientists and taxon experts working on various issues on biological invasions. The committee provides recommendations to an interdepartmental panel set up by the Department of Forestry, Fisheries and the Environment tasked with granting import permits and/or approving changes to regulations on biological invasions.

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| recommended that a National Management Plan be developed with appropriate maps. It will be important to ensure there is broad consultation and transparency both on the evidence of the impact <i>O. kisutch</i> invasions cause to biodiversity, and on the benefits derived from the use of <i>O. kisutch</i> . | <b>Recommended listing category:</b><br>No change |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------|

## 1. Background

|                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                   |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| <b>BAC1 Name of assessor(s)</b>                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                   |
| Name of lead assessor                                                                                                                                                                                                                                                                                                                                                                                     | Lerato Maimela                                                                                                                    |
| Additional assessor (1)                                                                                                                                                                                                                                                                                                                                                                                   | TA Zengeya                                                                                                                        |
| Additional assessor (2)                                                                                                                                                                                                                                                                                                                                                                                   | CT Chimimba                                                                                                                       |
| <b>BAC2 Contact details of assessor (s)</b>                                                                                                                                                                                                                                                                                                                                                               |                                                                                                                                   |
| Lead assessor                                                                                                                                                                                                                                                                                                                                                                                             | Organisational affiliation: University of Pretoria<br>email: lerato.maimela@zoology.up.ac.za<br>Phone: 012 420 4315               |
| Additional assessor (1)                                                                                                                                                                                                                                                                                                                                                                                   | Organisational affiliation: South African National Biodiversity Institute<br>email: t.zengeya@sanbi.org.za<br>Phone: 021 799 8408 |
| Additional assessor (2)                                                                                                                                                                                                                                                                                                                                                                                   | Organisational affiliation: University of Pretoria<br>email: chris.chimimba@up.ac.za<br>Phone: 012 420 3808                       |
| <b>BAC3 Name(s) and contact details of expert(s) consulted</b>                                                                                                                                                                                                                                                                                                                                            |                                                                                                                                   |
| Expert (1)                                                                                                                                                                                                                                                                                                                                                                                                | Name:<br>email:<br>Phone:                                                                                                         |
| Expert (2)                                                                                                                                                                                                                                                                                                                                                                                                | Name:<br>email:<br>Phone:                                                                                                         |
| Comments:                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                   |
| <b>BAC4 Scientific name of <i>Taxon</i> under assessment</b>                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                   |
| <i>Taxon</i> name: <i>Oncorhynchus kisutch</i>                                                                                                                                                                                                                                                                                                                                                            | Authority: Walbaum, 1792                                                                                                          |
| Comments: <i>Oncorhynchus kisutch</i> is the accepted taxonomic name for this fish in the family Salmonidae (GBIF 2021). FishBase (2022) lists nine subspecies of <i>O. kisutch</i> and all were considered in this assessment                                                                                                                                                                            |                                                                                                                                   |
| References:<br>GBIF. 2021. ' <i>Oncorhynchus kisutch</i> (Walbaum, 1792)', in <i>GBIF Backbone Taxonomy, Checklist dataset</i> , viewed 15 November 2022, from <a href="https://www.gbif.org/species/5204034">https://www.gbif.org/species/5204034</a> .                                                                                                                                                  |                                                                                                                                   |
| <b>BAC5 Synonym(s) considered</b>                                                                                                                                                                                                                                                                                                                                                                         |                                                                                                                                   |
| Synonyms:<br><i>Salmo kisatch</i> Walbaum, 1792<br><i>Salmo kisutch</i> Walbaum, 1792<br><i>Oncorhynchus kisatch</i> (Walbaum, 1792)<br><i>Oncorhynchus kisutsh</i> (Walbaum, 1792)<br><i>Salmo hisatch</i> Walbaum, 1792<br><i>Salmo hisutch</i> Walbaum, 1792<br><i>Salmo milkschutsch</i> Walbaum, 1792<br><i>Oncorhynchus milkschutsch</i> (Walbaum, 1792)<br><i>Salmo tsuppitch</i> Richardson, 1836 |                                                                                                                                   |
| Comments: Froese and Pauly (2022) lists nine synonyms of <i>O. kisutch</i> and all were considered in this assessment                                                                                                                                                                                                                                                                                     |                                                                                                                                   |

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| References:<br>Froese R, Pauly D (Editors). 2022. FishBase. World Wide Web electronic publication.<br>www.fishbase.org, version (06/2022).                                                                                                                                                                                                                                                 |                    |
| <b>BAC6 Common name(s) considered</b>                                                                                                                                                                                                                                                                                                                                                      |                    |
| Common names: The most used common name for <i>Oncorhynchus kisutch</i> is coho salmon                                                                                                                                                                                                                                                                                                     |                    |
| Comments: Globally, there are several common names include: Blueback, Coho, Coho salmon, Grilse, Hooknose, Sea trout, Silver salmon, Slivers (Froese and Pauly 2022)                                                                                                                                                                                                                       |                    |
| References:<br>Froese R, Pauly D (Editors). 2022. FishBase. World Wide Web electronic publication.<br>www.fishbase.org, version (06/2022).                                                                                                                                                                                                                                                 |                    |
| <b>BAC7 What is the native range of the Taxon?</b> (add map in Appendix BAC7)                                                                                                                                                                                                                                                                                                              |                    |
| Response:<br><i>Oncorhynchus kisutch</i> is native to the Arctic and Pacific drainages from Point Hope, Alaska, to Monterey Bay, California, infrequently as far south as Chamalu Bay, Baja California, and Also in northeastern Asia (Page and Burr 1991).                                                                                                                                | Confidence: High   |
| Comments:<br>They are primarily found in coastal waters. Coho salmon do not range widely in the open ocean like that of many other salmon species. <i>Oncorhynchus kisutch</i> are also found in fresh water, during their first year and later while spawning. They are found in fresh streams of the North Pacific, ranging from Baja, California to Alaska (Wheeler 1985).              |                    |
| References:<br>Page LM, Burr BM. 1991. A field guide to freshwater fishes of North America north of Mexico. <i>The Peterson Field Guide Series</i> , 42. Houghton Mifflin Company, Boston, MA.<br>Wheeler A. 1985. The World Encyclopedia of Fishes. Ferndale Editions.                                                                                                                    |                    |
| <b>BAC8 What is the global alien range of the Taxon?</b> (add map in Appendix BAC8)                                                                                                                                                                                                                                                                                                        |                    |
| Response:<br>Introduced to several countries in Asia (Israel and Iran), Europe (Belgium, France, Greece, Latvia, Netherlands, and Sweden) and South America (Argentina and Chile). Also introduced in some sea areas such as the Atlantic Northeast (CABI 2022; Froese and Pauly 2022)                                                                                                     | Confidence: High   |
| Comments:                                                                                                                                                                                                                                                                                                                                                                                  |                    |
| References:<br>CABI. 2022. <i>Oncorhynchus kisutch</i> . In: Invasive Species Compendium. Wallingford, UK: CABI International, VIWED 15 November 2022, from <a href="https://www.cabi.org/isc/datasheet/71807">https://www.cabi.org/isc/datasheet/71807</a><br>Froese R, Pauly D (Editors). 2022. FishBase. World Wide Web electronic publication.<br>www.fishbase.org, version (06/2022). |                    |
| <b>BAC9 Geographic scope = the Area under consideration</b>                                                                                                                                                                                                                                                                                                                                |                    |
| Area of assessment: South Africa                                                                                                                                                                                                                                                                                                                                                           |                    |
| Comments:                                                                                                                                                                                                                                                                                                                                                                                  |                    |
| <b>BAC10 Is the Taxon present in the Area?</b>                                                                                                                                                                                                                                                                                                                                             |                    |
| Response: Yes                                                                                                                                                                                                                                                                                                                                                                              | Confidence: Medium |
| Comments:<br>There are several import permit records <i>O. kisutch</i> into South Africa and it is likely present in aquaculture facilities (SANBI and CIB 2020).                                                                                                                                                                                                                          |                    |
| References:<br>SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch.<br><a href="http://dx.doi.org/10.5281/zenodo.3947810">http://dx.doi.org/10.5281/zenodo.3947810</a>   |                    |
| <b>BAC11 Availability of physical specimen</b>                                                                                                                                                                                                                                                                                                                                             |                    |

|                                                                                                                                                                                                                                                                                                                                                                                       |                     |                        |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|------------------------|
| Response: No                                                                                                                                                                                                                                                                                                                                                                          |                     | Confidence in ID: High |
| Herbarium or museum accession number: N/A                                                                                                                                                                                                                                                                                                                                             |                     |                        |
| References:                                                                                                                                                                                                                                                                                                                                                                           |                     |                        |
| <b>BAC12 Is the <i>Taxon</i> native to the Area or part of the Area?</b>                                                                                                                                                                                                                                                                                                              |                     |                        |
| The <i>Taxon</i> is native to (part of) the Area.                                                                                                                                                                                                                                                                                                                                     | No                  | Confidence: High       |
| The <i>Taxon</i> is alien in (part of) the Area.                                                                                                                                                                                                                                                                                                                                      | Yes                 | Confidence: High       |
| Comments:<br><i>Oncorhynchus kisutch</i> is native to Arctic and Pacific drainages from Point Hope, Alaska, to Monterey Bay, California, infrequently as far south as Chamalu Bay, Baja California (Page and Burr 1991).                                                                                                                                                              |                     |                        |
| References:<br>Page LM, Burr BM. 1991. A field guide to freshwater fishes of North America north of Mexico. <i>The Peterson Field Guide Series 42</i> . Houghton Mifflin Company, Boston, MA.                                                                                                                                                                                         |                     |                        |
| <b>BAC13 What is the <i>Taxon's</i> introduction status in the Area?</b>                                                                                                                                                                                                                                                                                                              |                     |                        |
| The <i>Taxon</i> is in cultivation/containment.                                                                                                                                                                                                                                                                                                                                       | Yes                 | Confidence: Medium     |
| The <i>Taxon</i> is present outside of cultivation/containment.                                                                                                                                                                                                                                                                                                                       | No                  | Confidence: High       |
| The <i>Taxon</i> has established/naturalised.                                                                                                                                                                                                                                                                                                                                         | No                  | Confidence: High       |
| The <i>Taxon</i> is invasive.                                                                                                                                                                                                                                                                                                                                                         | No                  | Confidence: High       |
| Comments:<br>There are several import permit records <i>O. kisutch</i> into South Africa and it is likely present in aquaculture facilities (SANBI and CIB 2020).                                                                                                                                                                                                                     |                     |                        |
| References:<br>SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <a href="http://dx.doi.org/10.5281/zenodo.3947810">http://dx.doi.org/10.5281/zenodo.3947810</a> |                     |                        |
| <b>BAC14 Primary (introduction) pathways</b>                                                                                                                                                                                                                                                                                                                                          |                     |                        |
| Release                                                                                                                                                                                                                                                                                                                                                                               | fishery in the wild | Confidence: High       |
| Escape                                                                                                                                                                                                                                                                                                                                                                                | N/A                 | Confidence: High       |
| Contaminant                                                                                                                                                                                                                                                                                                                                                                           | N/A                 | Confidence: High       |
| Stowaway                                                                                                                                                                                                                                                                                                                                                                              | N/A                 | Confidence: Low        |
| Corridor                                                                                                                                                                                                                                                                                                                                                                              | N/A                 | Confidence: High       |
| Unaided                                                                                                                                                                                                                                                                                                                                                                               | N/A                 | Confidence: High       |
| Comments:<br>There are several import permit records of <i>O. kisutch</i> into South Africa and it is likely present in aquaculture facilities (SANBI and CIB 2020). There are no populations that are known to have established in the wild.                                                                                                                                         |                     |                        |
| References:<br>SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <a href="http://dx.doi.org/10.5281/zenodo.3947810">http://dx.doi.org/10.5281/zenodo.3947810</a> |                     |                        |



## 2. Likelihood

| <b>LIK1 Likelihood of entry via unaided primary pathways</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                    |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| Response: present in country (p=1)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Confidence: Medium |
| <p>Rationale:<br/><i>Oncorhynchus kisutch</i> is present in the country and is likely confined to aquaculture facilities (SANBI and CIB 2020). There are no population that are known to have established in the wild and there are no introduction records in neighboring countries.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                    |
| <p>References:<br/>SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <a href="http://dx.doi.org/10.5281/zenodo.3947810">http://dx.doi.org/10.5281/zenodo.3947810</a></p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |
| <b>LIK2 Likelihood of entry via human aided primary pathways</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                    |
| Response: present in country (p=1)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Confidence: Medium |
| <p>Rationale:<br/><i>Oncorhynchus kisutch</i> is present in the country and has is likely confined to aquaculture facilities (SANBI and CIB 2020). Main pathways for introduction for angling and aquaculture.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                    |
| <p>References:<br/>SANBI and CIB 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <a href="http://dx.doi.org/10.5281/zenodo.3947810">http://dx.doi.org/10.5281/zenodo.3947810</a></p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                    |
| <b>LIK3 Habitat suitability</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                    |
| Response: Fairly probable (p=0.5)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Confidence: Medium |
| <p>Rationale:<br/>Similar to rainbow trout and brown trout, coho salmon prefer clear, cool, well-oxygenated creeks, small to medium rivers, and lakes (prefer streams with cool, flowing waters and rocky substrate (Page and Burr 2011). These habitat are found in several headwater mountain streams in South Africa. However confidence is marked as medium because previous introduction attempts in the wild were not successful (see Ellender et al. 2014).</p>                                                                                                                                                                                                                                                                                                                                                                                                                         |                    |
| <p>References:<br/>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b>: 117–132.<br/>Page LM, Burr BM. 2011. A field guide to freshwater fishes of North America north of Mexico. Boston: Houghton Mifflin Harcourt, 663p.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                    |
| <b>LIK4 Climate suitability</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                    |
| Response: Probable (p=1)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Confidence: High   |
| <p>Rationale:<br/>Coho salmon only thrive in streams that are cool (0–25 °C) with constantly flowing water, clean and well oxygenated (Brett 1952; Bell 1986). These climatic conditions can be found in the headwaters of many rivers in South Africa, especially the eastern escarpment stretching from the south-western Cape to Northern Kwa-Zulu Natal as indicated by systematic climate modelling studies (Picker and Griffiths 2011; Weyl and Keevey 2012; Ellender et al. 2016; Rivers-Moore et al. 2019).</p>                                                                                                                                                                                                                                                                                                                                                                        |                    |
| <p>References:<br/>Bell MC. 1986. Fisheries handbook of engineering requirements and biological criteria. Fish Passage Development and Evaluation Program. U.S. Army Corps of Engineers, 209 pp.<br/>Brett JR. 1952. Temperature Tolerance in Young Pacific Salmon, Genus <i>Oncorhynchus</i>. Pacific Biological Station, and Department of Zoology, University of Toronto. <i>Journal of the Fisheries Research Board of Canada</i> <b>9</b>: 265–308.<br/>Ellender BR, Rivers-Moore NA, Coppinger CR, Bellingan TA, Weyl OLF. 2016. Towards using thermal stress thresholds to predict salmonid invasion potential. <i>Biological Invasions</i> <b>18</b>: 3513–3525.<br/>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b>: 117–132.</p> |                    |

Picker MD, Griffiths CL. 2011. Alien and invasive animals – A South African Perspective, Randomhouse/Struik, Cape Town, South Africa, 240 pp.

Rivers-Moore NA, Ellender BR, Weyl OLF. 2019. Modelling expected trout ranges under current and future water temperature regimes in the Eastern Cape, South Africa. *African Journal of Aquatic Science* **44**: 35–42.

Weyl OLF, Keevey G. 2012. Deliverable 17. Report on GIS mapping and bibliography of dams with inland fisheries potential. Water Research Commission, Baseline and scoping study on the development and sustainable utilisation of storage dams for inland fisheries and their contribution to rural livelihoods Project Title: K5/1957/4.

#### LIK5 Unaided secondary (dispersal) pathways

Response: Unlikely ( $P = 0.027$ )

Confidence: Medium

##### Rationale:

In South Africa, populations of *O. kisutch* are mainly aquaculture facilities and there are no known naturalised populations (SANBI and CIB 2020). Therefore, the dispersal capabilities of *O. kisutch* through unaided pathways are limited.

##### References:

SANBI and CIB 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <http://dx.doi.org/10.5281/zenodo.3947810>

#### LIK6 Human aided secondary (dispersal) pathways

Response: probable ( $p=1$ )

Confidence: Medium

Rationale: *Oncorhynchus kisutch* is stocked in aquaculture facilities (SANBI and CIB 2020). Therefore, it is probable that it will disperse through human aided secondary pathways for angling and aquaculture purposes.

##### References:

SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <http://dx.doi.org/10.5281/zenodo.3947810>

### 3. Consequences

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                    |
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| <b>CON1 Environmental impact</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                    |
| <b>CON1a: Competition</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                    |
| Response: MC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Confidence: Medium |
| <p><b>Rationale:</b><br/>Evidence from across the invaded range including eastern North America and Chile show that <i>O. kisutch</i> competes with native fauna for habitat and food resources (Sepúlveda et al. 2013, Fausch and White 1986; Page and Laird 1993). For example in Chile, introduced (including <i>O. kisutch</i>) have been shown to negatively affect native fishes due to predatory and interference competition (Soto et al. 2001; Arismendi et al. 2009, 2012; Penaluna et al. 2009; Young et al. 2009, 2010, García de Leaniz et al. 2010). In South Africa, there are no reported impacts from <i>O. kisutch</i>.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |
| <p><b>References:</b><br/>Arismendi I, González J, Soto D, Penaluna B. 2012. Piscivory and diet overlap between two non-native fishes in southern Chile. <i>Austral Ecology</i> <b>37</b>: 346–354.<br/>Arismendi I, Soto D, Penaluna B, Jara C, Leal C, LeónMuñoz J. 2009. Aquaculture, non-native salmonid invasions and associated declines of native fishes in Northern Patagonian lakes. <i>Freshwater Biology</i> <b>54</b>: 1135–1147.<br/>Correa C, Hendry AP. 2012. Invasive salmonids and lake order interact in the decline of puye grande <i>Galaxias platei</i> in western Patagonia lakes. <i>Ecological Applications</i> <b>22</b>: 828-842.<br/>Fausch KD, White RJ. 1986. Competition among juveniles of coho salmon, brook trout, and brown trout in a laboratory stream, and implications for Great Lakes tributaries. <i>Transactions of the American Fisheries Society</i> <b>115</b>: 363-381.<br/>García de Leaniz C, Cajardo C, Consuegra S. 2010. From best to pest: changing perspectives on the impact of exotic salmonids in the southern hemisphere. <i>Systematics and Biodiversity</i> <b>8</b>: 447–459.<br/>Page LM, Laird CA. 1993. The identification of the non-native fishes inhabiting Illinois waters. Report prepared by Center for Biodiversity, Illinois Natural History Survey, Champaign, for Illinois Department of Conservation, Springfield. <i>Center for Biodiversity Technical Report 4</i>: 39 pp.<br/>Penaluna B, Arismendi I, Soto D. 2009. Evidence of interactive segregation between introduced trout and native fishes in Northern Patagonian Rivers, Chile. <i>Transactions of the American Fisheries Society</i> <b>138</b>: 839–845.<br/>Soto D, Jara F, Moreno C. 2001. Escaped salmon in the inner seas, southern Chile: facing ecological and social conflicts. <i>Ecological Applications</i> <b>11</b>: 1750-1762.<br/>Vanhaecke D, García de Leaniz C, Gajardo G, Thomas CJ, Consuegra S. 2012. Metapopulation dynamics of a diadromous galaxiid fish and potential effects of salmonid aquaculture. <i>Freshwater Conservation</i> <b>57</b>: 1241–1252</p> |                    |
| <b>CON1b: Predation</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                    |
| Response: MC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Confidence: Medium |
| <p><b>Rationale:</b><br/>Coho salmon are general predators that feed on planktonic crustaceans as juveniles and adults expand their niche to include jellyfish, squids and fishes (Morrow 1980; Welch and Parsons 1993; Coad and Reist 2004). In their globally introduced range, Coho salmon are a major predator of fry of juveniles in riverine and lacustrine habitats, largely because they are often occur in abundance than other piscivores (McCart 1967; Ruggerone and Rogers 1992, Tabor et al. 2014, van der Veer and Nentwig 2015). In South Africa, there are no reported impacts from <i>O. kisutch</i>.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                    |
| <p><b>References:</b><br/>Coad BW, Reist JD. 2004. Annotated list of the arctic marine fishes of Canada. <i>Canadian Manuscript Report of Fisheries and Aquatic Sciences</i> <b>2674</b>:112 p.<br/>McCart P. 1967. Behavior and ecology of sockeye salmon fry in the Babine River. <i>Journal of the Fisheries Research Board of Canada</i> <b>24</b>: 375-428.<br/>Morrow JE. 1980. The freshwater fishes of Alaska. University of. B.C. Animal Resources Ecology Library. 248 p.<br/>Ruggerone GT, Rogers DE. 1992. Predation on sockeye salmon fry by juvenile coho salmon in the Chignik Lakes, Alaska: implications for salmon management. <i>North American Journal of Fisheries Management</i> <b>12</b>: 87-102.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |

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|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| <p>Tabor RA, Berge HB, Klungle MM, Thompson BE, Lantz DW, Price BE. 2014. Predation of juvenile salmonids by resident trout and other fishes in the lower Cedar River, Washington. Final report to Seattle public utilities, US fish and wildlife service.</p> <p>van der Veer, G, Nentwig W. 2015. Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system. <i>Ecology of Freshwater Fishes</i> <b>24</b>: 646-656.</p> <p>Welch D, Parsons T. 1993. <math>\delta^{13}C</math>-<math>\delta^{15}N</math> values as indicators of trophic position and competitive overlap for Pacific salmon (<i>Oncorhynchus</i> spp.). <i>Fisheries Oceanography</i> <b>2</b>: 11-23.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                    |
| <b>CON1c: Hybridisation</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                    |
| Response: DD                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Confidence: Low    |
| <p>Rationale: Hybridisation is common among salmonid species (Moyle 2002). There are no native Salmonidae species in South Africa, therefore there is no risk of hybridisation (Skelton 2001).</p> <p>References:<br/>Moyle P. 2002. Inland Fishes of California, 2nd Edition, Berkeley, University of California Press.<br/>Skelton P. 2001. A complete guide to the freshwater fishes of Southern Africa. Struik Publishers, Cape Town.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                    |
| <b>CON1d: Transmission of disease</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                    |
| Response: MC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Confidence: Medium |
| <p>Rationale:<br/>Studies in several countries (e.g., Ireland, Scotland, Norway, Canada, the USA, and Chile) suggest the occurrence of several diseases is often correlated introduction of alien salmonids (Krkosek et al. 2005; Naylor et al. 2005; Sepulveda et al. 2013; van der Veer and Nentwig 2015). These include diseases such as rickettsial septicemia, sea lice (<i>Caligus</i> spp.), pancreatic necrosis virus, and salmon anemia virus (Rodríguez Saint Jean et al. 2003, Asche et al. 2010; Niklitschek et al. 2013).</p> <p>References:<br/>Asche F, Hansen H, Tveteras R, Tveteras S. 2010. The salmon disease crisis in Chile. <i>Marine Resource Economics</i> <b>24</b>: 405-411.<br/>Krkosek M, Lewis MA, Volpe JP. 2005. Transmission dynamics of parasitic sea lice from farms to wild salmon. <i>Proceedings of the Royal Society</i> <b>272</b>: 689-696.<br/>Naylor R, Hindar K, Fleming IA, Goldburg R, Williams S, Volpe J, Whoriskey F, Eagle J, Kelso D, Mangel M. 2005. Fugitive salmon: assessing the risks of escaped fish from net-pen aquaculture. <i>Bioscience</i> <b>55</b>: 427-437.<br/>Niklitschek EJ, Soto D, Lafon A, Molinet C, Toledo P. 2013. Southward expansion of the Chilean salmon industry in the Patagonian Fjords: main environmental challenges. <i>Reviews in Aquaculture</i> <b>4</b>: 1-24.<br/>Rodríguez Saint-Jean S, Borrego J, Pérez-Prieto S. 2003. Infectious pancreatic necrosis virus: biology, pathogenesis and diagnostic methods. <i>Advances in Virus Research</i> <b>62</b>: 113-165.<br/>Sepulveda M, Arismendi I, Soto D, Jara F, Farias F. 2013. Escaped farmed salmon and trout in Chile: incidence, impacts, and the need for an ecosystem view. <i>Aquaculture Environment Interactions</i> <b>4</b>: 273-283.</p> |                    |
| <b>CON1e: Parasitism</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                    |
| Response: MC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Confidence: Medium |
| <p>Rationale:<br/>Coho salmon are infected by numerous parasite species (Hoffman1999; Love and Moser 1983; McDonald and Margolis 1995; Bravo et al. 2011, van der Veer and Nentwig 2015), and some studies have indicated that certain parasites can be linked to host mortality. For example, Jacobson et al. (2008) demonstrated that a common digenean, <i>Nanophyetus salmincola</i>, is associated with early ocean mortality of coho salmon. Other common diseases include ceratomyxosis, which is caused by a parasite (<i>Ceratomyxa shasta</i>), columnaris - a bacterial infection caused by <i>Flavobacterium columnare</i>, Ichthyophthiriasis (Ich) - caused by the protozoan parasite <i>Ichthyophthirius multifiliis</i></p> <p>References:<br/>Bravo S, Boxshall G, Conroy G. 2011. New cultured host and a significant expansion in the known geographical range of the sea louse <i>Caligus rogercresseyi</i>. <i>Bulletin of the European Association of Fish Pathologists</i> <b>31</b>:156-160.<br/>Hoffman G. 1999. Parasites of North American Freshwater Fishes, 2nd ed. Comstock Publishing Associates, Ithaca, NY.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |

Jacobson KC, Teel D, Van Doornik DM, Castillas E. 2008. Parasite-associated mortality of juvenile Pacific salmon caused by the trematode *Nanophyetus salmincola* during early marine residence. *Marine Ecology Progress Series* **354**: 235–244.

Love MS, Moser M. 1983. A checklist of parasites of California, Oregon, and Washington marine and estuarine fishes. NOAA Technical Reports NMFS SSRF-777, 576 p.

McDonald T, Margolis L. 1995. Synopsis of the parasites of fishes of Canada: supplement (1978–1993). *Canadian Special Publication of Fisheries and Aquatic Sciences* **122**: 265 p.

Washington State Department of Ecology (WDOE). 2002. Evaluating Standards for Protecting Aquatic Life in Washington's Surface Water Quality Standards: Temperature Criteria. Draft Discussion Paper and Literature Summary. Publication Number 00-10-070. 189 pp.

van der Veer G, Nentwig W. 2015. Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system. *Ecology of Freshwater Fishes* **24**: 646-656.

**CON1f: Poisoning/toxicity**

Response:DD Confidence: Low

Rationale: No documented information available to assess the level of impact

References:

**CON1g: Bio-fouling or other direct physical disturbance**

Response:DD Confidence: Low

Rationale: No documented information available to assess the level of impact

References:

**CON1h: Grazing/herbivory/browsing**

Response:DD Confidence: Low

Rationale: No documented information available to assess the level of impact

References:

**CON1i: Chemical, physical or structural impact on ecosystem**

Response:DD Confidence: Low

Rationale: No documented information available to assess the level of impact

References:

**CON1k: Indirect impacts through interactions with other species**

Response: DD Confidence: Medium

Rationale: No documented information available to assess the level of impact

References:

**CON1 Maximum environmental impact (Figure S3)**

Response: MC Confidence: High

Rationale:  
In its introduced range, Coho salmon has been reported to impact native species mainly through predation and transmission of diseases (van der Veer and Nentwig 2015).

References:  
van der Veer G, Nentwig W. 2015. Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system. *Ecology of Freshwater Fishes* **24**: 646-656.

**CON2 Socio-economic impact**

**CON2a: Safety**

Response: DD Confidence:Low

Rationale: No documented information available to assess the level of impact

References:

**CON2b: Material and immaterial assets**

Response: MO Confidence: Low

Rationale: Alien salmonid species can affect animal production (usually aquacultures) through the transmission of pathogens, which may cause relatively high expenses (van der Veer and Nentwig 2015).

References:  
van der Veer G, Nentwig W. 2015. Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system. *Ecology of Freshwater Fishes* **24**: 646-656.

|                                                                                                                                                                                                                                             |                    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| <b>CON2c: Health</b>                                                                                                                                                                                                                        |                    |
| Response: DD                                                                                                                                                                                                                                | Confidence:        |
| Rationale:                                                                                                                                                                                                                                  |                    |
| References:                                                                                                                                                                                                                                 |                    |
| <b>CON2d: Social, spiritual and cultural relations</b>                                                                                                                                                                                      |                    |
| Response: DD                                                                                                                                                                                                                                | Confidence:        |
| Rationale:                                                                                                                                                                                                                                  |                    |
| References:                                                                                                                                                                                                                                 |                    |
| <b>CON2 Maximum socio-economic impact (Figure S3)</b>                                                                                                                                                                                       |                    |
| Response: MO                                                                                                                                                                                                                                | Confidence: Medium |
| Rationale: Alien salmonid species can affect animal production (usually aquacultures) through the transmission of pathogens, which may cause relatively high expenses (van der Veer and Nentwig 2015).                                      |                    |
| References:<br>van der Veer G, Nentwig W. 2015. Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system. <i>Ecology of Freshwater Fishes</i> <b>24</b> : 646-656. |                    |

|                                                                                                         |             |
|---------------------------------------------------------------------------------------------------------|-------------|
| <b>CON3 Closely related species' environmental impact</b>                                               |             |
| Response: Not Scored as CON1 scored                                                                     | Confidence: |
| Rationale: There is information to score CON1, so CON3 does not need to be scored as per the framework. |             |
| References:                                                                                             |             |

|                                                                                                         |             |
|---------------------------------------------------------------------------------------------------------|-------------|
| <b>CON4 Closely related species' socio-economic impact</b>                                              |             |
| Response: Not Scored as CON2 scored                                                                     | Confidence: |
| Rationale: There is information to score CON2, so CON3 does not need to be scored as per the framework. |             |
| References:                                                                                             |             |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| <b>CON5 Potential impact</b>                                                                                                                                                                                                                                                                                                                                                                                                                                            |                    |
| Response: MO                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Confidence: Medium |
| Rationale:<br>In South Africa, a national-level EICAT assessment classified impacts caused by closely related species ( <i>Salmo trutta</i> and <i>Oncorhynchus mykiss</i> ) as Major (MR) as they are known to cause declines, and in some cases local extinction of native invertebrates, frogs and fish through predation and competition (Marr et al. 2017). If <i>Oncorhynchus kisutch</i> is introduced and becomes invasive, it likely to cause similar impacts. |                    |
| References:<br>Marr S, Ellender B, Woodford D, Alexander M, Wasserman R, Ivey P, Zengeya T, Weyl O. 2017. Evaluating invasion risk for freshwater fishes in South Africa. <i>Bothalia</i> <b>47</b> : 1–10.                                                                                                                                                                                                                                                             |                    |

#### 4. Management

|                                                                                                                                                                                                                                                                                                                                                                   |                  |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| <b>MAN1 What is the feasibility to stop future immigration?</b>                                                                                                                                                                                                                                                                                                   |                  |
| Response: High                                                                                                                                                                                                                                                                                                                                                    | Confidence: High |
| Rationale: <i>Oncorhynchus kisutch</i> is already present in South Africa in aquaculture facilities SANBI and CIB 2020). Therefore, it is probable that <i>O. kisutch</i> will be dispersed through human-aided secondary pathways for angling purposes, as observed for other salmonid species (Ellender and Weyl 2014; Ellender et al. 2014, Weyl et al. 2020). |                  |
| References:<br>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b> : 117–132.                                                                                                                                     |                  |



- Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non-native fishes in southern Africa. *Journal of Fish Biology* **85**: 1890–1906.
- SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <http://dx.doi.org/10.5281/zenodo.3947810>
- Weyl OLF, Ellender BR, Ivey P, Jackson MC, Tweddle D, Wasserman RJ, Woodford DJ, Zengeya TA. 2017. Africa: Brown trout introductions, establishment, current status, impacts and conflicts. In Lobón-Cerviá J, Sanz N (eds), *Brown Trout: Biology, Ecology and Management*, Wiley, Oxford, pp 623–639.

## MAN2 Benefits of the Taxon

### MAN2a Socio-economic benefits of the Taxon

Response: High

Confidence: Medium

#### Rationale:

Trout species have socio-economic value and are utilised in recreational fisheries in their global invasive range (e.g., Muhlfeld et al. 2019). In South Africa, there are several studies that have assessed the economic benefits of trout (mainly for *Oncorhynchus mykiss*) and these strengthen the evidence base for quantifying the benefits derived from introduced fish species (Britz et al. 2009; Britz and Venter 2016; Du Preez and Lee 2010; Anchor Environmental Consulting 2010). However, the studies were done using different methods and at small scales (e.g. towns, and discrete catchments), and the results still have to be extrapolated to larger scales (e.g. national). *Salmo trutta* is of lower importance than *O. mykiss* (rainbow trout) as it is currently used exclusively for recreational fishing, and not for commercial production (Stander and Brink 2009). No studies have been done for *O. kisutch*. In addition, native fish species are also available as alternatives for recreational angling (e.g. various yellowfish species, Hoogendoorn 2014).

#### References:

- Anchor Environmental Consulting. 2010. The nature, distribution and value of aquatic ecosystem services of the Olifants, Inkomati and Usutu to Mhlatuze Water Management Areas. Contract report for Department: Water Affairs and Forestry, 378 pp.
- Britz P, Venter S. 2016. Aquaculture review: South Africa. *World Aquaculture* **47**: 20–28.
- Britz PJ, Lee B, Botes L. 2009. AISA 2009 Aquaculture Benchmarking Survey: Primary Production and Markets, AISA report produced by Enviro-Fish Africa (Pty) Ltd, 117 pp.
- Du-Preez M, Lee DE. 2010. The contribution of trout fly fishing to the economy of Rhodes, North Eastern Cape, South Africa. *Development Southern Africa* **27**: 241–253.
- Hoogendoorn G. 2014. Mapping fly-Fishing Tourism in Southern Africa. *African Journal of Hospitality, Tourism and Leisure* **3**: 13 pp.
- Muhlfeld CC, Dauwalter DC, D'Angelo VS, Ferguson A, Giersch JJ, Impson D, Koizumi I, Kovach R, McGinnity P, Schöffmann J, Vøllestad LA. 2019. Global status of trout and char: Conservation challenges in the twenty-first century. *Trout and char of the world*, pp 717-60.
- Stander H, Brink D. 2009. Trout farming In South Africa: Expanding local markets work with ecotourism. *Global Aquaculture Advocate*, November/December 2009

### MAN2b Environmental benefits of the Taxon

Response: DD

Confidence: Medium

#### Rationale:

There are currently no known environmental benefits on record.

#### References:

## MAN3 Ease of management

### MAN3a How accessible are populations?

Response: 1 (moderately accessible)

Confidence: High

#### Rationale:

*Oncorhynchus kisutch* is present in South Africa in aquaculture facilities (SANBI and CIB 2020). These facilities are often on private land and permission would be needed to access these areas.

#### References:

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                    |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <a href="http://dx.doi.org/10.5281/zenodo.3947810">http://dx.doi.org/10.5281/zenodo.3947810</a>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                    |
| <b>MAN3b Is detectability critically time-dependent?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                    |
| Response: 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Confidence: High   |
| <p>Rationale:<br/>Trout can be detected at any time, but it does require special equipment (e.g. electrofishing gear) and trained specialists to operate such equipment. Detection is thus logistically challenging, but not time-dependent</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                    |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                    |
| <b>MAN3c Time to reproduction</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                    |
| Response: 1 (1-3 years)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Confidence: Medium |
| <p>Rationale:<br/>Spawning migrations begin after increased stream flows in fall and early winter allow the fish to move into coastal rivers. Upstream migration usually occurs when stream flows are either rising or falling. The timing of their return varies considerably, but in general coho salmon return earlier in the season in more northern areas and in larger river systems (Moyle et al. 2008). Sexual maturity is reached in about 3 years.</p>                                                                                                                                                                                                                                                                                                                                                                                                                       |                    |
| <p>References:<br/>Moyle PB, Israel JA, Purdy SE. 2008. Salmon, Steelhead, and trout in California. Status of an emblematic fauna, a report commissioned by California trout. Center for watershed sciences, University of California, Davis.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                    |
| <b>MAN3d Propagule persistence</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                    |
| Response: 0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Confidence: low    |
| <p>Rationale:<br/>The persistence of the introduced fry or juveniles is dependent on the suitability of the habitat for survival, which is mainly dependent on the climate of the environment.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                    |
| <p>References:<br/>Karas N. 2002 Brook trout: A Thorough Look at North America's Great Native Trout- Its history, biology, and angling possibilities. Revised edition, Skyhorse publishing, New York, NY 10018.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                    |
| <b>MAN3 Ease of management (SUM from Table S4)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                    |
| Response: Medium                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Confidence: High   |
| <p>Rationale: Management of <i>O. kisutch</i> is scored here as medium. However, several issues make management challenging. These include the fact that many control options could also harm native species, and that control operations would likely be met with resistance from certain interest groups (see Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                    |
| <p>References:<br/>Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. <i>Journal of Fish Biology</i> <b>85</b>: 1890–1906.<br/>Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. <i>Bothalia</i> <b>47</b>: 1–9.<br/>Woodford DJ, Richardson DM, MacIsaac HJ, Mandrak NE, van Wilgen BW, Wilson JR, Weyl OLF. 2016. Confronting the wicked problem of managing invasive species. <i>Neobiota</i> <b>31</b>: 63–86.<br/>Zengeya T, Ivey P, Woodford DJ, Weyl O, Novoa A, Shackleton R, Richardson D, Van Wilgen B. 2017. Managing conflict-generating invasive species in South Africa: challenges and trade-offs. <i>Bothalia</i> <b>47</b>: 1–11.</p> |                    |
| <b>MAN4 Has the feasibility of eradication been evaluated?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                    |
| Response: No                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Confidence: High   |
| <p>Rationale:<br/>There have been no studies that have addressed the country-wide eradication of <i>O. kisutch</i> in South Africa. There was an attempt to extirpate another trout species, <i>O. mykiss</i>, from a discrete</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                    |



catchment of the Kroom River in the Cederberg was unsuccessful because of gear selectivity and budgetary constraints (Shelton et al. 2017).

**References:**

Shelton J, Weyl O, Van Der Walt J, Marr S, Impson D, Maciejewski K, Tye D, Dallas H, Esler K. 2017. Effect of an intensive mechanical removal effort on a population of non-native rainbow trout *Oncorhynchus mykiss* in a South African headwater stream. *Aquatic Conservation: Marine and Freshwater Ecosystems* **27**: 1051–1055.

**MAN5 Control options and monitoring approaches available for the Taxon**

**Response:**

Management of trout species in South Africa is relatively difficult. This because trout are conflict-generating invasive species that have major negative environmental impacts, but also some socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Known populations of *O. kisutch* in South Africa are restricted to aquaculture facilities and the recommended management option is to restrict utilisation through permitting with key conditions to prevent potential spread and impacts. For example, the proposed management initiatives could include managing it by area where utilisation is restricted to a few areas where trout species have been historically been stocked. Concerned stakeholders have highlighted the need for broader consultations and transparency on the evidence used to assess the risks posed by trout to biodiversity and the benefits derived from their utilisation see (Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017).

**References:**

Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. *Journal of Fish Biology* **85**: 1890–1906.

Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. *Bothalia* **47**: 1–9.

Woodford DJ, Richardson DM, MacIsaac HJ, Mandrak N, van Wilgen BW, Wilson JR, Weyl OLF. 2016. Confronting the wicked problem of managing invasive species. *Neobiota* **31**: 63–86.

Zengeya T, Ivey P, Woodford DJ, Weyl O, Novoa A, Shackleton R, Richardson D, Van Wilgen B. 2017. Managing conflict-generating invasive species in South Africa: challenges and trade-offs. *Bothalia* **47**: 1–11.

**MAN6 Any other management considerations to highlight? (if yes, fill in Appendix MAN6)**

|          |                        |
|----------|------------------------|
| Response | Yes, see Appendix MAN6 |
|----------|------------------------|

## 5. Calculations

**Likelihood** = Probable

| Parameter | Likelihood      | Stages                      | Final assessment        |
|-----------|-----------------|-----------------------------|-------------------------|
| LIK1      | Probable        | P(entry) = Probable         | P (invasion) = Probable |
| LIK2      | Probable        |                             |                         |
| LIK3      | Fairly probable | P(establishment) = Probable |                         |
| LIK4      | Probable        |                             |                         |
| LIK5      | Unlikely        | P (spread) = Probale        |                         |
| LIK6      | Probable        |                             |                         |

**Consequence** = Moderate (MO)

| Parameter | Mechanism/sector     | Response |
|-----------|----------------------|----------|
| CON1a     | Competition          | MC       |
| CON1b     | Predation            | MC       |
| CON1c     | Hybridisation        | DD       |
| CON1d     | Disease transmission | MC       |
| CON1e     | Parasitism           | DD       |
| CON1f     | Poisoning/toxicity   | DD       |

|       |                                                                                                   |                              |
|-------|---------------------------------------------------------------------------------------------------|------------------------------|
| CON1g | Bio-fouling or other direct physical disturbance                                                  | DD                           |
| CON1h | Grazing/herbivory/browsing                                                                        | DD                           |
| CON1i | Chemical, physical, structural impact                                                             | DD                           |
| CON1k | Indirect impacts through interactions with other species                                          | DD                           |
| CON1  | Maximum environmental impact                                                                      | MC                           |
| CON2a | Safety                                                                                            | DD                           |
| CON2b | Material and immaterial assets                                                                    | MO                           |
| CON2c | Health                                                                                            | DD                           |
| CON2d | Social, spiritual and cultural relations                                                          | DD                           |
| CON2  | Maximum socio-economic impact                                                                     | MO                           |
| CON3  | Environmental impact of closely related taxa<br>(only score if CON1a-k are all DD, otherwise NA)  | Not scored as<br>CON1 scored |
| CON4  | Socio-economic impact of closely related taxa<br>(only score if CON2a-g are all DD, otherwise NA) | Not scored as<br>CON1 scored |
| CON5  | Potential impact based on traits, experiments, or models                                          | MO                           |

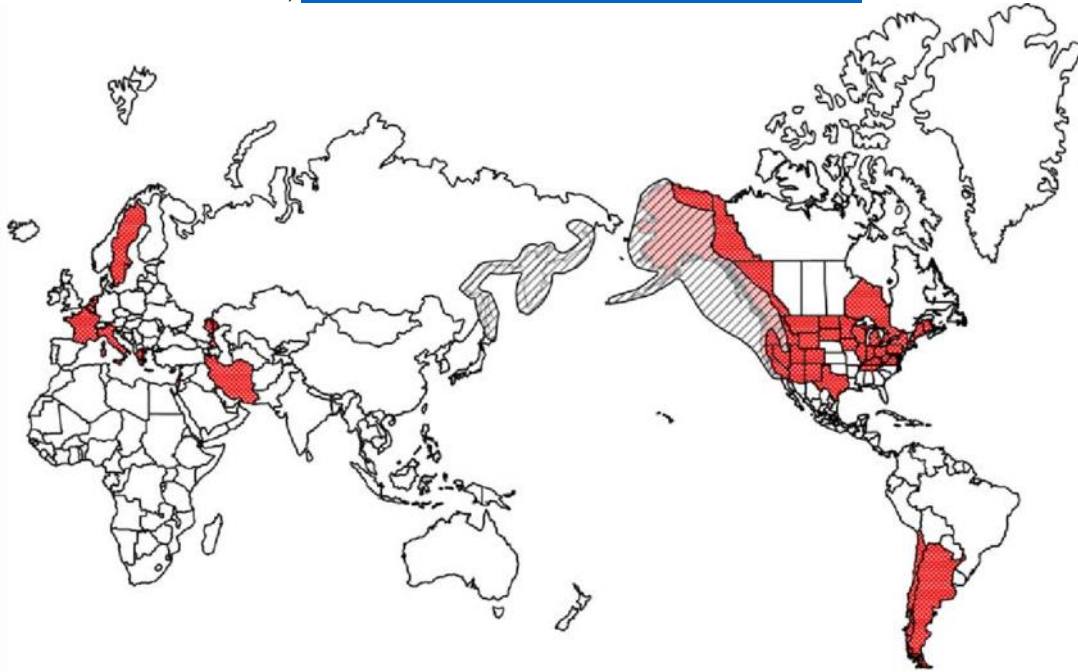
**Risk score = High**

|            |                    | Consequences |        |        |        |        |
|------------|--------------------|--------------|--------|--------|--------|--------|
|            |                    | MC           | MN     | MO     | MR     | MV     |
| Likelihood | Extremely unlikely | low          | low    | low    | medium | medium |
|            | Very unlikely      | low          | low    | low    | medium | high   |
|            | Unlikely           | low          | low    | medium | high   | high   |
|            | Fairly probable    | medium       | medium | high   | high   | high   |
|            | Probable           | medium       | high   | high   | high   | high   |

**Ease of management = Medium**

| Parameter   | Question                                    | Response |
|-------------|---------------------------------------------|----------|
| MAN3a       | How accessible are populations?             | 1        |
| MAN3b       | Is detectability critically time-dependent? | 2        |
| MAN3c       | Time to reproduction                        | 1        |
| MAN3d       | Propagule persistence                       | 0        |
| <b>MAN3</b> | <b>SUM</b>                                  | <b>4</b> |

**Appendix BAC7:** Native distribution of coho salmon (*Oncorhynchus kisutch*; black diagonal) and countries, states or provinces into which this species has been introduced (red stipple). Sources: Crawford and Muir 2007, <https://doi.org/DOI 10.1007/s11160-007-9079-1>



## **Appendix MAN6:** Proposed listing options for *Oncorhynchus kisutch* under the NEM:BA A&IS Regulations

### **Current listing as per NEM:BA A&IS lists of 2020**

**Taxon:** *Oncorhynchus kisutch* (Walbaum, 1792)

**Common name:** Coho Salmon

**Category:** 2

*Oncorhynchus kisutch* (Walbaum, 1792) was listed as Category 2 invasive species in the South African Government Gazette on 18 September 2020, and in the NEM:BA A&IS Lists promulgated on 1 March 2021. There are no exemptions specified as per the provisions of section 71(3) / prohibition in terms of section 71a(1).

### **Rationale**

*Oncorhynchus kisutch* is present in South Africa and is likely confined to aquaculture facilities. There are no known naturalised populations. Management of trout species in South Africa is relatively difficult. This because trout are conflict-generating invasive species that have major negative environmental impacts, but also some socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Therefore, the recommended management option is to restrict importation through permitting and implement intervention measures similar to those proposed for other trout species in South Africa to prevent spread and minimise impacts (Woodford et al. 2017).

### **Potential criteria for permits and exemptions**

Two key aims for the management of trout species in South Africa should be to: a) prevent the spread to new areas; and b) limit the negative environmental impacts by controlling trout populations in key fish conservation areas. To this end, those catchments where trout does not yet occur but where suitable habitat exists, and key fish conservation areas (with and without trout populations) would need to be identified in a National Management Plan that contains appropriate maps. The inclusion of maps outlining areas where permits may be granted would greatly facilitate the application and processing of permits.

The beneficial uses of trout species could then be managed as follows:

- Permits for existing or new aquaculture facilities could be granted, but only if such activities do not result in new sites becoming invaded or spread of trout into key fish conservation areas. As such permits would not be issued for aquaculture facilities in discrete catchment systems in which trout does not yet occur or that include key fish conservation areas. Permits could, however, be granted for aquaculture facilities in part of a discrete catchment system where trout occurs, providing there are natural or artificial habitat barriers (for example waterfalls, dams or weirs) that would prevent the spread of trout to other parts of the catchment system where it is currently absent, but where suitable habitat exists.
- In terms of restocking the same considerations as for aquaculture facilities would apply.
- In terms of angling, catch-and-release (i.e. the practice of anglers to return a fish to the water where it was caught) is exempt in any discrete-catchments that are specified on maps produced as per the National Management Plan. At all other sites catch-and-kill should be practised. This provision could be incorporated into provincial freshwater angling licences.
- The transport of live fish or eggs would always require a permit, but any dead specimens (e.g. for personal consumption or commercial trade) would, of course, be exempt.

### **National Management Plan**

To facilitate the implementation of these criteria and to ensure the process is transparent, it would be important to draw up a National Management Plan for each trout species. The plan would need to

include maps of the catchments where permits may be issued for commercial production purposes, where permits may be issued for restocking, and where catch-and-release angling is exempt. Maps of key fish conservation areas would also be useful to indicate areas where catch-and-kill would need to be practised.

The National Management Plan would also need to specify the standards that should be met to limit the risk of escape or unintentional or illegal re-distribution to new areas.

### **Overall recommendation**

#### **Proposed listing**

**Taxon:** *Oncorhynchus kisutch* (Walbaum, 1792)

**Common name:** coho salmon

**Category:** no change

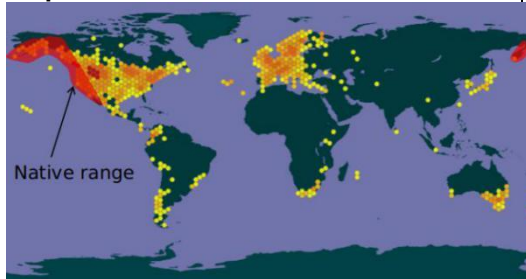
**Exemption:** catch-and-release is exempt in areas specified in maps produced as part of a National Management Plan for *O. kisutch*.

Permits may only be issued in line with the considerations discussed in the “Potential criteria for permits and exemptions” section above.

#### **Reference**

Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. *Bothalia* **47**: a2138.

## Appendix 5.2<sup>4</sup>: Rainbow trout (*Oncorhynchus mykiss*)

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                                                                                                                                                                                                                                                                           |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Taxon:</b> <i>Oncorhynchus mykiss</i> (Walbaum, 1792)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | <b>Area:</b> South Africa                                                                                                                                                                                                                                                                 |
| <b>Compiled by:</b> Lerato Maimela                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | <b>Approved by:</b>                                                                                                                                                                                                                                                                       |
| <b>Picture of Taxon</b><br> <p>Photo: iNaturalist contributors, iNaturalist (2022).<br/>         accessed via GBIF.org on 2022-03-15.<br/> <a href="https://www.gbif.org/occurrence/3031889457">https://www.gbif.org/occurrence/3031889457</a></p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | <b>Global Native and Alien distribution map</b><br> <p>Reference: GBIF, viewed 26 July 2021,<br/>         from <a href="https://doi.org/10.15468/dl.q8dh3t">https://doi.org/10.15468/dl.q8dh3t</a>.</p> |
| <b>Risk Assessment summary:</b><br><i>Oncorhynchus mykiss</i> (rainbow trout) is native to western North America and was intentionally introduced to South Africa in the 18 <sup>th</sup> century mainly for angling. <i>Oncorhynchus mykiss</i> has since become invasive in mountain streams and catchments across South Africa. Documented evidence from South Africa and other parts of the global invasive range of <i>O. mykiss</i> indicate <i>O. mykiss</i> has major environmental impacts through competition with native fish and predation on native fish, amphibians, and macroinvertebrates.                                                                                                                                                                                                                                                                                                                                                                                                                    | <b>Risk score:</b><br><br>High                                                                                                                                                                                                                                                            |
| <b>Management options summary:</b><br>Management of <i>O. mykiss</i> is, as for all freshwater fish, complicated by the logistical challenges of finding and treating populations. However, it takes at least a year for fish to reach reproductive maturity and the eggs are relatively short lived. Control operations require substantial investment of time, expertise, and money. There has been only one control project for <i>O. mykiss</i> in South Africa that unsuccessfully tried to extirpate <i>O. mykiss</i> from the Kroom River in the Cederberg. However, several projects have successfully extirpated other alien fish species from discrete stretches of river in South Africa with excellent recovery of native biodiversity in the years following such treatments. <i>Oncorhynchus mykiss</i> has high socio-economic benefits in South Africa both from angling (culturally and via tourism) and as an important aquaculture species. There are no acceptable native alternatives for such benefits. | <b>Ease of management:</b><br><br>Medium                                                                                                                                                                                                                                                  |
| <b>Recommendations:</b><br>Given that <i>O. mykiss</i> has both major negative environmental impacts and high socio-economic benefits, the recommendation is to list <i>O. mykiss</i> as category 2 (with limitations and exemptions as outlined in Appendix MAN6). In particular, to facilitate the regulation of <i>O. mykiss</i> it is recommended that a National Management Plan be developed with appropriate maps. It will be important to ensure there is broad consultation and transparency both on the evidence of the impact <i>O. mykiss</i> invasions cause to biodiversity, and on the benefits derived from the use of <i>O. mykiss</i> .                                                                                                                                                                                                                                                                                                                                                                     | <b>Listing under NEM:BA A&amp;IS lists of 2021:</b><br><br>Not listed <sup>5</sup>                                                                                                                                                                                                        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | <b>Recommended listing category: 2</b><br>(with exemptions)                                                                                                                                                                                                                               |

<sup>4</sup> This risk analyses report for rainbow trout (*Oncorhynchus mykiss*) is presented as submitted to the South African Alien Species Risk Analysis Review Panel (ASRARP), a committee that is tasked with reviewing risk analyses attached to import applications and listing of species under national legislation to ensure they are scientifically robust and take into account the best available evidence (see Kumschick et al. 2020 for details). ASRARP is an independent body and its members consist of scientists and taxon experts working on various issues on biological invasions. The committee provides recommendations to an interdepartmental panel set up by the Department of Forestry, Fisheries and the Environment that is tasked with granting import permits and or approving changes to regulations on biological invasions.

<sup>5</sup> A proposal for listing was published in the Government Gazette but not promulgated, see Appendix MAN6 for details.



|  |                     |
|--|---------------------|
|  | (see Appendix MAN6) |
|--|---------------------|

## 1. Background

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                   |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| <b>BAC1 Name of assessor(s)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                   |
| Name of lead assessor                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Lerato Maimela                                                                    |
| Additional assessor (1)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Tsungai Zengeya                                                                   |
| Additional assessor (2)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Anicia Malebajoa Maoela                                                           |
| Additional assessor (3)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Humbelani Thenga                                                                  |
| <b>BAC2 Contact details of assessor (s)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                                                                   |
| Lead assessor                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Organisational affiliation: University of Pretoria                                |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | email: lerato.maimela@zoology.up.ac.za                                            |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Phone:                                                                            |
| Additional assessor (1)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Organisational affiliation: Dr Tsungai Zengeya                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | email: T.Zengeya@sanbi.org.za                                                     |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Phone: 021 799 8408                                                               |
| Additional assessor (2)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Organisational affiliation: Council for Scientific and Industrial Research (CSIR) |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | email: HThenga@csir.co.za                                                         |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Phone: +27 12 841 4112                                                            |
| Additional assessor (3)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Organisational affiliation: NA                                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | email: malebajoam@gmail.com                                                       |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Phone: +27 79 725 3786                                                            |
| <b>BAC3 Name(s) and contact details of expert(s) consulted</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                                   |
| Expert (1)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Name: Dr. Tatenda Dalu                                                            |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | email: dalutatenda@yahoo.co.uk                                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Phone: +27 13 002 0001                                                            |
| Comments: Dr Tatenda Dalu is a lecturer at the University of Mpumalanga and an honorary research associate at the South African Institute for Aquatic Biodiversity (SAIAB). He provided information on the negative impacts of <i>Oncorhynchus mykiss</i> .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                                                                   |
| <b>BAC4 Scientific name of Taxon under assessment</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                   |
| Taxon name: <i>Oncorhynchus mykiss</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Authority: (Walbaum, 1792)                                                        |
| Comments: <i>Oncorhynchus mykiss</i> is the accepted taxonomic name for this fish in the family Salmonidae (GBIF 2021). <i>Oncorhynchus mykiss</i> was originally named <i>Salmo mykiss</i> by Walbaum in 1792 (Behnke 1966), and was later named <i>Salmo gairdnerii</i> by Richardson from fish taken from the Columbia River at Fort Vancouver in 1836 (Baynes et al. 1981). The species was reclassified as <i>Oncorhynchus mykiss</i> in 1989 as it is more closely related to Pacific salmon than to other trout species (Billard 1989). ITIS (2021) lists eight subspecies of <i>O. mykiss</i> and all were considered in this assessment.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                                                                   |
| References:<br>Baynes SM, Scott AP, Dawson AP. 1981. Rainbow trout, <i>Salmo gairdnerii</i> Richardson, spermatozoa: effects of cations and pH on motility. <i>Journal of Fish Biology</i> <b>19</b> : 259–267.<br>Behnke RJ. 1966. Relationships of the Far Eastern Trout, <i>Salmo mykiss</i> walbaum. <i>Copeia</i> <b>2</b> : 346.<br>Billard P. 1989. Taxonomic change in rainbow trout scientific name. <i>Salmo gairdnerii</i> (Richardson, 1836) becomes <i>Oncorhynchus mykiss</i> (Walbaum, 1792). <i>Aquatic Living Resources</i> <b>2</b> : 189–189.<br>GBIF 2021. <i>Oncorhynchus mykiss</i> (Walbaum, 1792)', in GBIF Backbone Taxonomy, Checklist dataset, viewed 19 August 2021, from <a href="https://www.gbif.org/species/5204019">https://www.gbif.org/species/5204019</a> .<br>Integrated Taxonomic Information System (ITIS). 2021. ' <i>Oncorhynchus mykiss</i> (Walbaum, 1792)', viewed 16 September 2021, from <a href="https://www.itis.gov/servlet/SingleRpt/SingleRpt?search_topic=TSN&amp;search_value=161989#null">https://www.itis.gov/servlet/SingleRpt/SingleRpt?search_topic=TSN&amp;search_value=161989#null</a> . |                                                                                   |

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| <b>BAC5 Synonym(s) considered</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                  |
| Synonyms: <i>Salmo mykiss</i> Walbaum, 1792; <i>Salmo gairdnerii</i> Richardson, 1836                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                  |
| Comments: More than 15 synonyms of <i>O. mykiss</i> are listed by CABI (2021) and GBIF (2021). However, in this assessment, only <i>Salmo mykiss</i> and <i>S. gairdnerii</i> were used in the literature search, given that they were previously used as the scientific names of <i>O. mykiss</i> (Behnke 1966; Baynes et al. 1981).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                  |
| References:<br>Baynes, S.M., Scott, A.P. & Dawson, A.P., 1981, 'Rainbow trout, <i>Salmo gairdnerii</i> Richardson, spermatozoa: effects of cations and pH on motility', <i>Journal of Fish Biology</i> 19(3), 259–267. <a href="https://doi.org/10.1111/j.1095-8649.1981.tb05830.x">https://doi.org/10.1111/j.1095-8649.1981.tb05830.x</a> .<br>Behnke, R.J., 1966, 'Relationships of the Far Eastern Trout, <i>Salmo mykiss walbaum</i> ', <i>Copeia</i> 2, 346. <a href="https://doi.org/10.2307/1441145">https://doi.org/10.2307/1441145</a> .<br>CABI, 2021, ' <i>Oncorhynchus mykiss</i> (rainbow trout)', in <i>Invasive Species Compendium</i> , viewed 19 August 2021, from <a href="https://www.cabi.org/isc/datasheet/71813">https://www.cabi.org/isc/datasheet/71813</a> .<br>GBIF, 2021, ' <i>Oncorhynchus mykiss</i> (Walbaum, 1792)', in <i>GBIF Backbone Taxonomy, Checklist dataset</i> , viewed 19 August 2021, from <a href="https://www.gbif.org/species/5204019">https://www.gbif.org/species/5204019</a> . |                  |
| <b>BAC6 Common name(s) considered</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                  |
| Common names: Rainbow trout                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                  |
| Comments: Rainbow trout was considered during the literature search for this assessment as it is the widely used English common name of <i>O. mykiss</i> (Baltz et al. 1991; Fausch et al. 2001; Woodford and Impson 2004; Quiroga et al. 2017).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                  |
| References:<br>Baltz DM, Vondracek B, Brown LR, Moyle PB. 1991. Seasonal changes in microhabitat selection by rainbow trout in a small stream. <i>Transactions of the American Fisheries Society</i> <b>120</b> : 166–176.<br>Fausch KD, Taniguchi Y, Nakano S, Grossman GD, Townsend CR. 2001. Flood disturbance regimes influence rainbow trout invasion success among five Holarctic regions. <i>Ecological Applications</i> <b>11</b> : 1438–1455.<br>Quiroga S, Acacioris F, García I, Povedano H, Velasco M, Zalba S. 2017. Invasive rainbow trout <i>Oncorhynchus mykiss</i> preying on the endangered naked characin <i>Gymnocharacinus bergii</i> at its thermal limits. <i>Journal of Fish Biology</i> <b>91</b> : 1745–1749.<br>Woodford D, Impson N. 2004. A preliminary assessment of the impact of alien rainbow trout ( <i>Oncorhynchus mykiss</i> ) on indigenous fishes of the upper Berg River, Western Cape Province, South Africa. <i>African Journal of Aquatic Science</i> <b>29</b> : 107–111.           |                  |
| <b>BAC7 What is the native range of the Taxon?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                  |
| Response: Northern Pacific rim (Western North America and Eastern Russia, see Appendix BAC7)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Confidence: High |
| Comments: <i>Oncorhynchus mykiss</i> is a cold-water fish native to western North America and the extreme east of Russia and (for anadromous populations) the northern Pacific Ocean (Brungs and Jones 1977; Behnke 2002; Crawford and Muir 2008).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                  |
| References:<br>Behnke R.J. 2002. Trout and Salmon of North America, New York, USA: The Free Press, 359 pp.<br>Brungs WA, Jones BR. 1977. <i>Temperature Criteria for Freshwater Fish: Protocol and Procedures</i> , US Environmental Protection Agency Environmental Research Laboratory, Duluth, Minn. EPA-600/3-77-061.<br>Crawford SS, Muir AM. 2008. Global introductions of salmon and trout in the genus <i>Oncorhynchus</i> : 1870–2007. <i>Reviews in Fish Biology and Fisheries</i> <b>18</b> : 313–344.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                  |
| <b>BAC8 What is the global alien range of the Taxon?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |
| Response: Africa, Asia, Europe, parts of North America, South America and Oceania (see Appendix BAC8)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Confidence: High |
| Comments: <i>Oncorhynchus mykiss</i> has been introduced to more than 80 countries around the world and occurs on all continents except for Antarctica (Welcomme 1988; Cambrary 2003; Fausch 2007; Crawford and Muir 2008; McIntosh et al. 2010; Stanković et al. 2015).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |



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|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|------------------------|
| References:                                                                                                                                                                                                                                                                                                                                                                |     |                        |
| Cambray JA. 2003. The global impact of alien trout species-a review; with reference to their impact in South Africa. <i>African Journal of Aquatic Science</i> <b>28</b> : 61-67.                                                                                                                                                                                          |     |                        |
| Crawford SS, Muir AM. 2008. Global introductions of salmon and trout in the genus <i>Oncorhynchus</i> : 1870-2007. <i>Reviews in Fish Biology and Fisheries</i> <b>18</b> : 313–344.                                                                                                                                                                                       |     |                        |
| Fausch KD. 2007. Introduction, establishment and effects of non-native salmonids: considering the risk of rainbow trout invasion in the United Kingdom. <i>Journal of Fish Biology</i> <b>71</b> : 1–32.                                                                                                                                                                   |     |                        |
| McIntosh AR, McHugh PA, Dunn NR, Goodman JM, Howard SW, Jellyman PG, Brien LKO, Nyström P, Woodford DJ. 2010. The impact of trout on galaxiid fishes in New Zealand. <i>New Zealand Journal of Ecology</i> <b>34</b> : 195–206.                                                                                                                                            |     |                        |
| Stanković D, Crivelli A, Snoj A. 2015. Rainbow trout in Europe: introduction, naturalization and impacts. <i>Reviews in Fisheries Science and Aquaculture</i> <b>23</b> : 39–71.                                                                                                                                                                                           |     |                        |
| Welcomme RL. 1988. International introductions of inland aquatic species. FAO. United Nations, <i>Fisheries and Technical Papers</i> 294, 1–318.                                                                                                                                                                                                                           |     |                        |
| <b>BAC9 Geographic scope = the Area under consideration</b>                                                                                                                                                                                                                                                                                                                |     |                        |
| Area of assessment: South Africa                                                                                                                                                                                                                                                                                                                                           |     |                        |
| Comments: The geographic scope of this assessment is limited to South Africa.                                                                                                                                                                                                                                                                                              |     |                        |
| <b>BAC10 Is the <i>Taxon</i> present in the Area?</b>                                                                                                                                                                                                                                                                                                                      |     |                        |
| Response: Yes                                                                                                                                                                                                                                                                                                                                                              |     | Confidence: High       |
| Comments: <i>Oncorhynchus mykiss</i> have naturalised in several mountain headwater streams in the country (Ellender et al. 2014). This can be attributed to sustained and widespread stocking for sport fishing, initially by government agencies and later by angling societies and private individuals (de Moor & Bruton 1998; Ellender et al. 2014; Weyl et al. 2020). |     |                        |
| References:                                                                                                                                                                                                                                                                                                                                                                |     |                        |
| de Moor IJ, Bruton MN. 1988. Atlas of alien and translocated indigenous aquatic animals in southern Africa, Pretoria: South African National Scientific Programmes Report no.144.                                                                                                                                                                                          |     |                        |
| Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non–native fishes in southern Africa. <i>Journal of Fish Biology</i> <b>85</b> : 1890–1906.                                                                                                                                                             |     |                        |
| Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), <i>Biological invasions in South Africa</i> . Springer, Berlin, pp 153-183.                                                                                             |     |                        |
| <b>BAC11 Availability of physical specimen</b>                                                                                                                                                                                                                                                                                                                             |     |                        |
| Response: Yes                                                                                                                                                                                                                                                                                                                                                              |     | Confidence in ID: High |
| Herbarium or museum accession number:                                                                                                                                                                                                                                                                                                                                      |     |                        |
| SAIAB Collection - Catalogue #: 83136 (Collected by Karssing, R., Rivers-Moore, N. & Nkosi, N. on 2007/05/08)                                                                                                                                                                                                                                                              |     |                        |
| SAIAB Collection - Catalogue #: 83165 (Collected by Karssing, R., N., Nkosi, N. & Rivers-Moore, N. on 2007/05/07)                                                                                                                                                                                                                                                          |     |                        |
| SAIAB Collection - Catalogue #: 80753 (Collected by Kinya, J. on 2006/03/02)                                                                                                                                                                                                                                                                                               |     |                        |
| References:                                                                                                                                                                                                                                                                                                                                                                |     |                        |
| <b>BAC12 Is the <i>Taxon</i> native to the Area or part of the Area?</b>                                                                                                                                                                                                                                                                                                   |     |                        |
| The <i>Taxon</i> is native to (part of) the Area.                                                                                                                                                                                                                                                                                                                          | No  | Confidence: High       |
| The <i>Taxon</i> is alien in (part of) the Area.                                                                                                                                                                                                                                                                                                                           | Yes | Confidence: High       |
| Comments: <i>Oncorhynchus mykiss</i> is native to North America, the extreme east of Russia and (for anadromous populations) the northern Pacific Ocean (Behnke 2002; Crawford and Muir 2008; Page and Burr 2011).                                                                                                                                                         |     |                        |
| References:                                                                                                                                                                                                                                                                                                                                                                |     |                        |
| Behnke RJ. 2002. <i>Trout and Salmon of North America</i> , New York, USA: The Free Press, 359 pp.                                                                                                                                                                                                                                                                         |     |                        |
| Crawford SS, Muir AM. 2008. Global introductions of salmon and trout in the genus <i>Oncorhynchus</i> : 1870-2007. <i>Reviews in Fish Biology and Fisheries</i> <b>18</b> : 313–344.                                                                                                                                                                                       |     |                        |
| Page LM, Burr BM. 2011. A field guide to freshwater fishes of North America north of Mexico. Boston: Houghton Mifflin Harcourt, 663 p.                                                                                                                                                                                                                                     |     |                        |
| <b>BAC13 What is the <i>Taxon's</i> introduction status in the Area?</b>                                                                                                                                                                                                                                                                                                   |     |                        |
| The <i>Taxon</i> is in cultivation/containment.                                                                                                                                                                                                                                                                                                                            | Yes | Confidence: High       |
| The <i>Taxon</i> is present outside of cultivation/containment                                                                                                                                                                                                                                                                                                             | Yes | Confidence: High       |

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| The <i>Taxon</i> has established/naturalised.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Yes                       | Confidence: High |
| The <i>Taxon</i> is invasive.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Yes                       | Confidence: High |
| <p>Comments: <i>Oncorhynchus mykiss</i> was introduced to South Africa in 1897 (Cambray 2003) for angling purposes. <i>Oncorhynchus mykiss</i> occurs in the headwaters of approximately 75 % of South Africa's major river systems (van Rensburg et al. 2011). Populations of <i>O. mykiss</i> have naturalised and become invasive at some sites (de Moor and Bruton 1988; Clark and Ratcliffe 2007; van Rensburg et al. 2011), but at other sites, <i>O. mykiss</i> is stocked to maintain populations (McCafferty et al. 2012). <i>Oncorhynchus mykiss</i> is present in aquaculture farms and several hatcheries (McCafferty et al. 2012).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                           |                  |
| <p>References:</p> <p>Cambray JA. 2003. The global impact of alien trout species - a review; with reference to their impact in South Africa. <i>African Journal of Aquatic Science</i> <b>28</b>: 61–67.</p> <p>Clark B, Ratcliffe G (eds). 2007. Berg River Baseline Monitoring Programme: Final Report–Volume 5: Synthesis, Publication No P WMA 19/G10/00/2107. Pretoria: Department of Water Affairs.</p> <p>de Moor IJ, Bruton MN. 1988. Atlas of alien and translocated indigenous aquatic animals in southern Africa, Pretoria: South African National Scientific Programmes Report no.144.</p> <p>McCafferty JR, Ellender BR, Weyl OLF, Britz PJ. 2012. The use of water resources for inland fisheries in South Africa. <i>Water SA</i> <b>38</b>: 327–344.</p> <p>van Rensburg BJ, Weyl OLF, Davies SJ, van Wilgen NJ, Spear D, Chimimba CT, Peacock F. 2011. Invasive vertebrates of South Africa', in Pimentel, D. (Ed), <i>Biological invasions: Economic and environmental costs of alien plant, animal, and microbe species</i>, 325–380. Taylor &amp; Francis Group.</p> <p>McCafferty JR, Ellender BR, Weyl OLF, Britz PJ. 2012. The use of water resources for inland fisheries in South Africa. <i>Water SA</i> <b>38</b>: 327–344.</p> |                           |                  |
| <b>BAC14 Primary (introduction) pathways</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                           |                  |
| Release                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | fishery in the wild       | Confidence: High |
| Escape                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | aquaculture / mariculture | Confidence: High |
| Contaminant                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | None                      | Confidence: Low  |
| Stowaway                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | None                      | Confidence: Low  |
| Corridor                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | None                      | Confidence: Low  |
| Unaided                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | None                      | Confidence: Low  |
| <p>Comments: <i>Oncorhynchus mykiss</i> was first introduced to South Africa in 1897 for angling (de Moor and Bruton 1988). There was a sustained and widespread effort to stock <i>O. mykiss</i> initially by government agencies for aquaculture and later by angling societies and private individuals (Van Rensburg et al. 2011; McCafferty et al. 2012).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                           |                  |
| <p>References:</p> <p>de Moor IJ, Bruton MN. 1988. Atlas of alien and translocated indigenous aquatic animals in southern Africa, Pretoria: South African National Scientific Programmes Report no.144. CSIR, Pretoria, pp 78–133.</p> <p>van Rensburg BJ, Weyl OLF, Davies SJ, van Wilgen NJ, Spear D, Chimimba CT, Peacock F. 2011. Invasive vertebrates of South Africa. In Pimentel, D. (Ed). <i>Biological invasions: Economic and environmental costs of alien plant, animal, and microbe species</i>, 325–380. Taylor &amp; Francis Group.</p> <p>McCafferty JR, Ellender BR, Weyl OLF, Britz PJ. 2012. The use of water resources for inland fisheries in South Africa. <i>Water SA</i> <b>38</b>: 327–344.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                           |                  |

## 2. Likelihood

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |
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| <b>LIK1 Likelihood of entry via unaided primary pathways</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                  |
| Response: Present in the country (p = 1)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Confidence: High |
| <p>Rationale: <i>Oncorhynchus mykiss</i> is present in the country and has established self-sustaining populations in headwaters of several catchments (Weyl et al. 2020). In terms of the likelihood of future introductions, <i>O. mykiss</i> occurs in three neighbouring countries (Eswatini, Lesotho and Zimbabwe) (CABI 2021; GBIF 2021). It is possible that <i>O. mykiss</i> could enter South Africa unaided from Eswatini and Lesotho through interconnected waterways. However, dispersal of <i>O. mykiss</i> from Zimbabwe to South Africa will likely be prevented by unsuitably high water temperatures (Rivers-Moore et al. 2019).</p> |                  |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                  |

CABI .2021. *Oncorhynchus mykiss* (rainbow trout). In: Invasive Species Compendium, viewed 19 August 2021, from <https://www.cabi.org/isc/datasheet/71813>.

GBIF. 2021. *Oncorhynchus mykiss* (Walbaum, 1792). In: GBIF Backbone Taxonomy Checklist dataset, viewed 20 August 2021, from <https://www.gbif.org/species/5204019>.

Rivers-Moore NA, Ellender BR, Weyl OLF. 2019. Modelling expected trout ranges under current and future water temperature regimes in the Eastern Cape, South Africa. *African Journal of Aquatic Science* **44**: 35–42.

Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds) *Biological invasions in South Africa*. Springer, Berlin, pp 153-183.

#### LIK2 Likelihood of entry via human aided primary pathways

|                                          |                  |
|------------------------------------------|------------------|
| Response: Present in the country (p = 1) | Confidence: High |
|------------------------------------------|------------------|

Rationale: *Oncorhynchus mykiss* is already present in the country. It is probable that further introductions could occur to augment angling and aquaculture through stocking (McCafferty et al. 2012; Ellender et al. 2014).

References:  
Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non-native fishes in southern Africa. *Journal of Fish Biology* **85**: 1890-1906.  
McCafferty JR, Ellender BR, Weyl OLF, Britz PJ. 2012. The use of water resources for inland fisheries in South Africa. *Water SA* **38**: 327-344.

#### LIK3 Habitat suitability

|                            |                  |
|----------------------------|------------------|
| Response: Probable (p = 1) | Confidence: High |
|----------------------------|------------------|

Rationale: *Oncorhynchus mykiss* can be found in streams, ponds, rivers, and lakes (Page and Burr 1991). *Oncorhynchus mykiss* prefer cold and well-oxygenated waters where the maximum temperature does not exceed 25°C (Rowe and Chisnall 1995; Froese and Pauly 2021). In South Africa, suitable habitats are found in mountain headwater-streams in several provinces such as Limpopo, Mpumalanga, Free State, Western Cape and Kwa-Zulu Natal (Rivers-Moore et al. 2019).

References:  
Froese R, Pauly D (eds). 2021. *Oncorhynchus mykiss* (Walbaum, 1792) *Rainbow trout*, viewed 20 August 2021, from <https://www.fishbase.in/Summary/SpeciesSummary.php?ID=239&AT=Rainbow+trout>.  
Page LM, Burr BM. 1991. A field guide to freshwater fishes of North America north of Mexico. Houghton Mifflin Company, Boston. 432 p.  
Rivers-Moore NA, Ellender BR, Weyl OLF. 2019. Modelling expected trout ranges under current and future water temperature regimes in the Eastern Cape, South Africa. *African Journal of Aquatic Science* **44**: 35–42.  
Rowe RK, Chisnall BL. 1995. Effects of oxygen, temperature and light gradients on the vertical distribution of rainbow trout, *Oncorhynchus mykiss*, in two North Island, New Zealand, lakes differing in trophic status. *New Zealand Journal of Marine and Freshwater Research*, **29**: 421–434.

#### LIK4 Climate suitability

|                            |                  |
|----------------------------|------------------|
| Response: Probable (p = 1) | Confidence: High |
|----------------------------|------------------|

Rationale: Due to specific temperature requirements, *O. mykiss* only occurs in cooler environments with the optimal temperature being in the range 14 to 26.5°C (Brungs and Jones 1977). These climatic conditions can be found in the headwaters of many rivers in South Africa, especially the eastern escarpment stretching from the south-western Cape to Northern Kwa-Zulu Natal as indicated by systematic climate modelling studies (Picker and Griffiths 2011; Weyl and Keevey 2012; Ellender et al. 2016; Rivers-Moore et al. 2019).

References:  
Brungs WA, Jones BR. 1977. *Temperature Criteria for Freshwater Fish: Protocol and Procedures*, US Environmental Protection Agency Environmental Research Laboratory, Duluth, Minn. EPA-600/3-77-061.  
Ellender BR, Rivers-Moore NA, Coppinger CR, Bellingan TA, Weyl OLF. 2016. Towards using thermal stress thresholds to predict salmonid invasion potential. *Biological Invasions* **18**: 3513–3525.

- Picker MD, Griffiths CL. 2011. *Alien and invasive animals – A South African Perspective*, Randomhouse/Struik, Cape Town, South Africa, 240 pp.
- Rivers-Moore NA, Ellender BR, Weyl, OLF. 2019. Modelling expected trout ranges under current and future water temperature regimes in the Eastern Cape, South Africa. *African Journal of Aquatic Science* **44**: 35–42.
- Weyl OLF, Keevey G. 2012. Deliverable 17. Report on GIS mapping and bibliography of dams with inland fisheries potential. Water Research Commission, Baseline and scoping study on the development and sustainable utilisation of storage dams for inland fisheries and their contribution to rural livelihoods Project Title: K5/1957/4.

**LIK5 Unaided secondary (dispersal) pathways**

Response: Unlikely ( $p = 0.027$ )

Confidence: High

Rationale: In South Africa, naturalised populations of *O. mykiss* are mainly restricted to isolated headwater streams and dispersal is limited by warm temperatures as well as natural and manmade geographic barriers (Shelton et al. 2018; Rivers-Moore et al. 2019; Maimela et al. 2021). Therefore, the dispersal capabilities of *O. mykiss* through unaided pathways are slow and only possible over short distances.

References:

- Maimela LT, Chimimba CT, Zengeya TA. 2021. The effect of rainbow trout (*Oncorhynchus mykiss*) invasions on native fish communities in the subtropical Blyde River, Mpumalanga province, South Africa. *African Journal of Aquatic Science* 1–10.
- Rivers-Moore NA, Ellender BR, Weyl OLF. 2019. Modelling expected trout ranges under current and future water temperature regimes in the Eastern Cape, South Africa. *African Journal of Aquatic Science* **44**: 35–42.
- Shelton JM, Weyl OL, Esler KJ, Paxton BR, Impson ND, Dallas HF. 2018. Temperature mediates the impact of non-native rainbow trout on native freshwater fishes in South Africa's Cape Fold Ecoregion. *Biological Invasions* **20**: 2927–2944.

| LIK6 Human aided secondary (dispersal) pathways                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                  |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Response: Probable (p = 1)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Confidence: High |
| <p>Rationale: <i>Oncorhynchus mykiss</i> is cultured in hatcheries and is often stocked into ponds, rivers and lakes to support recreational anglers (McCafferty et al. 2012; Ellender and Weyl 2014; Ellender et al. 2014; Weyl et al. 2020). Therefore, it is probable that it will disperse through human aided secondary pathways for angling and aquaculture purposes.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                  |
| <p>References:</p> <p>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b>: 117–132.</p> <p>Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. <i>Journal of Fish Biology</i> <b>85</b>: 1890–1906.</p> <p>McCafferty JR, Ellender BR, Weyl OLF, Britz PJ. 2012. The use of water resources for inland fisheries in South Africa. <i>Water SA</i> <b>38</b>: 327–344.</p> <p>Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), <i>Biological invasions in South Africa</i>. Springer, Berlin, pp 153–183.</p> |                  |

### 3. Consequences

| CON1 Environmental impact                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| CON1a: Competition                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                  |
| Response: Major (MR)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Confidence: High |
| <p>Rationale: Evidence from across the invaded range including Australia, eastern North America, Japan, Peru, and South Africa show that <i>O. mykiss</i> competes with native fauna for habitat and food resources (Rosenthal 1980; Crowl et al. 1992; Fausch 1988; Taniguchi et al. 2000; Ellender 2013; Jackson et al. 2016; Marr et al. 2017). For example, the release of <i>O. mykiss</i> into Lake Titicaca, Peru, to provide a fishery, caused the local extinction of several native fish due to competition for spawning microhabitats and food resources (Rosenthal 1980). In South Africa, <i>O. mykiss</i> have been implicated in the decline in abundance of river minnows in several mountain headwater catchments such as Breede River (Shelton et al. 2015) and Blyde River (Maimela et al. 2021). Competition is one of the possible mechanisms of impact as there is usually high overlap in resource use (food and habitats) between <i>O. mykiss</i> and native minnows (Dörgeloh 1994, 1996). In addition, trout invasions (<i>O. mykiss</i> and <i>S. trutta</i>) have been shown to modify aquatic-terrestrial food-web linkages by competing for resources with indigenous riparian consumers such as spiders in several river systems such as the Keiskamma, Thukela, and the uMngeni (Jackson et al. 2016). There have been no recorded instances of <i>O. mykiss</i> causing a global extinction through competition (i.e., an irreversible change) and for this reason the impact was scored major rather than massive.</p>                                                                        |                  |
| <p>References:</p> <p>Crowl TA, Townsend CR, McIntosh AR. 1992. The impact of introduced brown and rainbow trout on native fish: the case of Australasia. <i>Reviews in Fish Biology and Fisheries</i> <b>2</b>: 217–241.</p> <p>Dörgeloh WG. 1994. Diet and food selection of <i>Barbus aeneus</i>, <i>Clarias gariepinus</i> and <i>Oncorhynchus mykiss</i> in a clear man-made lake, South Africa. <i>Water SA</i> <b>20</b>: 91–98.</p> <p>Dörgeloh WG. 1996. Food overlap between the alien <i>Oncorhynchus mykiss</i> and the indigenous fish species <i>Barbus aeneus</i> and <i>Clarias gariepinus</i> in a man-made lake, South Africa. <i>Water SA</i> <b>22</b>: 79–83.</p> <p>Ellender BR. 2013. Ecological consequences of non-native fish invasions in Eastern Cape headwater streams, PhD Thesis, Rhodes University, 215 pp.</p> <p>Fausch KD. 1988. Tests of Competition between Native and Introduced Salmonids in Streams: What Have We Learned? <i>Canadian Journal of Fisheries and Aquatic Sciences</i> <b>45</b>: 2238–2246.</p> <p>Jackson MC, Woodford DJ, Bellingan TA, Weyl OLF, Potgieter MJ, Rivers-Moore NA, Ellender BR, Fourie HE, Chimimba CT. 2016. Trophic overlap between fish and riparian spiders: potential impacts of an invasive fish on terrestrial consumers. <i>Ecology and Evolution</i> <b>6</b>: 1745–1752.</p> <p>Maimela LT, Chimimba CT, Zengeya TA. 2021. The effect of rainbow trout (<i>Oncorhynchus mykiss</i>) invasions on native fish communities in the subtropical Blyde River, Mpumalanga province, South Africa. <i>African Journal of Aquatic Science</i> 1–10.</p> |                  |



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- Shelton JM, Samways MJ, Day JA. 2015. Non-native rainbow trout change the structure of benthic communities in headwater streams of the Cape Floristic Region, South Africa. *Hydrobiologia* **745**: 1–15.
- Taniguchi Y, Miyake Y, Saito T, Urabe H, Nakano S. 2000. Redd superimposition by introduced rainbow trout, *Oncorhynchus mykiss*, on native charrs in a Japanese stream. *Ichthyological Research* **47**: 149–156.

#### CON1b: Predation

Response: Major (MR)

Confidence: High

Rationale: *Oncorhynchus mykiss* is a generalist predator and often the recorded negative impacts in the invasive global range are as a result of predation on native fauna (Crowl et al. 1992; Lintermans 2000; Dunham et al. 2004; Kitano 2004; McDowall 2006; McIntosh et al. 2010; Young et al. 2010; Habit et al. 2010; Marr et al. 2017). In South Africa, *O. mykiss* has led to a decline and in some cases local extirpation of native invertebrates, frogs, and fish (Weyl et al. 2020). For example, *O. mykiss* has caused a decline in abundance of populations of native river minnows such as Cape galaxias (*Galaxias zebratus*), Breede River redbin (*Pseudobarbus burchelli*) and Cape kurper (*Sandelia capensis*) (Woodford and Impson 2004; Shelton et al. 2015), Maloti minnow (*Pseudobarbus quathlambae*) (Jubb 1966; de Moor and Bruton 1988), endangered border barb (*Amatolacypis trevelyani*) (Ellender 2013), and the critically endangered Treur River barb (*Enteromius treurensis*) (Maimela et al. 2021). The presence of *O. mykiss* has also been implicated in the decline of several amphibian species such as Natal ghost frog (*Hadromophryne natalensis*) (Karssing 2010; Karssing et al. 2012) and the Cederberg ghost frog (*Heleophryne depressa*) (Avidon et al. 2018). In addition, *O. mykiss* invasions have induced trophic cascades by releasing some herbivorous invertebrates from predation, leading to an increase in grazing pressure and lower algal biomass at invaded sites (Shelton et al. 2015). There have been no recorded instances of *O. mykiss* causing a global extinction through predation (i.e., an irreversible change) and for this reason the impact was scored major rather than massive.

#### References:

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- Ellender BR. 2013. Ecological consequences of non-native fish invasion in Eastern Cape headwater streams, PhD thesis, Rhodes University.
- Engelbrecht J, Bills R. 2007. *Barbus treurensis*. In: IUCN Red List of Threatened Species. Version 2012.1, viewed 20 August, from [www.iucnredlist.org](http://www.iucnredlist.org).
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- Kitano S. 2004. Ecological impacts of rainbow, brown and brook trout in Japanese inland waters. *Global Environment Research* **8**: 41–50.
- Lintermans M. 2000. Recolonization by the mountain galaxias *Galaxias olidus* of a montane stream after the eradication of rainbow trout *Oncorhynchus mykiss*. *Marine Freshwater Research* **51**: 799–804.
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- McIntosh AR, McHugh PA, Dunn NR, Goodman JM, Howard SW, Jellyman PG, Brien LKO, Nyström P, Woodford DJ. 2010. The impact of trout on galaxiid fishes in New Zealand. *New Zealand Journal of Ecology* **34**: 195–206.
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- Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), *Biological invasions in South Africa*. Springer, Berlin, pp 153–183.
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#### CON1c: Hybridisation

|                                                                                                                                |                  |
|--------------------------------------------------------------------------------------------------------------------------------|------------------|
| Response: Data deficient (DD)                                                                                                  | Confidence: High |
| Rationale: There are no native Salmonidae species in South Africa, therefore there is no risk of hybridisation (Skelton 2001). |                  |
| References:<br>Skelton P. 2001. A complete guide to the freshwater fishes of Southern Africa. Struik Publishers, Cape Town.    |                  |

#### CON1d: Transmission of disease

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| Response: Minimal Concern (MC)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Confidence: Medium |
| Rationale: <i>Oncorhynchus mykiss</i> has been shown to carry whirling disease myxosporean parasite <i>Myxobolus cerebralis</i> and <i>Enterococcus</i> -like bacterium (Carson et al. 1993; Bartholomew and Reno 2002; Bartholomew et al. 2005). However, these diseases are of minimal concern in South Africa, since they are salmonid-specific diseases (Carson et al. 1993; Bartholomew et al. 2005) and therefore unlikely to have adverse effects on native fishes in South Africa. In addition, to date, all the diseases/parasites listed by FAO (2012) which commonly infect <i>O. mykiss</i> have not been found in South African salmonids (despite regular testing of imported ova and cultured adults for Viral Haemorrhagic Septicaemia and Infectious Haemopoietic Necrosis) (Anchor Environmental Consulting 2012).                                                                                                 |                    |
| References:<br>Bartholomew JL, Kerans BL, Hedrick RP, Macdiarmid SC, Winton JR. 2005. A risk assessment based approach for the management of whirling disease. <i>Reviews in Fisheries Science</i> <b>13</b> : 205–230.<br>Bartholomew JL, Reno PW. 2002. The history and dissemination of whirling disease. In: Bartholomew JL, Wilson JC (eds), <i>Whirling disease: reviews and current topics, Symposium 29</i> . American Fisheries Society, Maryland, USA, pp 3–24.<br>Baxter CV, Fausch KD, Murakami M, Chapman PL. 2004. Fish invasion restructures stream and forest food webs by interrupting reciprocal prey subsidies. <i>Ecology</i> <b>85</b> : 2656–2663.<br>Carson J, Gudkovs N, Austin B. 1993. Characteristics of an <i>Enterococcus</i> -like bacterium from Australia and South Africa, pathogenic for rainbow trout, <i>Oncorhynchus mykiss</i> (Walbaum). <i>Journal of Fish Diseases</i> <b>16</b> : 381–388. |                    |

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|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
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| FAO. 2012. <i>Oncorhynchus mykiss</i> . In: Cowx IG. (Ed), Cultured Aquatic Species Information Programme, FAO Fisheries and Aquaculture Department, Rome.                                                                                                                                                                                      |                    |
| <b>CON1e: Parasitism</b>                                                                                                                                                                                                                                                                                                                        |                    |
| Response: Data Deficient (DD)                                                                                                                                                                                                                                                                                                                   | Confidence: Medium |
| Rationale: No documented information available to assess the level of impact.                                                                                                                                                                                                                                                                   |                    |
| References:                                                                                                                                                                                                                                                                                                                                     |                    |
| <b>CON1f: Poisoning/toxicity</b>                                                                                                                                                                                                                                                                                                                |                    |
| Response: Data Deficient (DD)                                                                                                                                                                                                                                                                                                                   | Confidence: Medium |
| Rationale: No documented information available to assess the level of impact                                                                                                                                                                                                                                                                    |                    |
| References:                                                                                                                                                                                                                                                                                                                                     |                    |
| <b>CON1g: Bio-fouling or other direct physical disturbance</b>                                                                                                                                                                                                                                                                                  |                    |
| Response: Data Deficient (DD)                                                                                                                                                                                                                                                                                                                   | Confidence: Medium |
| Rationale: No documented information available to assess the level of impact                                                                                                                                                                                                                                                                    |                    |
| References:                                                                                                                                                                                                                                                                                                                                     |                    |
| <b>CON1h: Grazing/herbivory/browsing</b>                                                                                                                                                                                                                                                                                                        |                    |
| Response: Data Deficient (DD)                                                                                                                                                                                                                                                                                                                   | Confidence: Medium |
| Rationale: No documented information available to assess the level of impact                                                                                                                                                                                                                                                                    |                    |
| References:                                                                                                                                                                                                                                                                                                                                     |                    |
| <b>CON1i: Chemical, physical or structural impact on ecosystem</b>                                                                                                                                                                                                                                                                              |                    |
| Response: : Data Deficient (DD)                                                                                                                                                                                                                                                                                                                 | Confidence: Medium |
| Rationale: No documented information available to assess the level of impact                                                                                                                                                                                                                                                                    |                    |
| References:                                                                                                                                                                                                                                                                                                                                     |                    |
| <b>CON1k: Indirect impacts through interactions with other species</b>                                                                                                                                                                                                                                                                          |                    |
| Response: Data Deficient (DD)                                                                                                                                                                                                                                                                                                                   | Confidence: Low    |
| Rationale: No documented information available to assess the level of impact                                                                                                                                                                                                                                                                    |                    |
| References:                                                                                                                                                                                                                                                                                                                                     |                    |
| <b>CON1 Maximum environmental impact</b>                                                                                                                                                                                                                                                                                                        |                    |
| Response: Major (MR)                                                                                                                                                                                                                                                                                                                            | Confidence: High   |
| Rationale: In South Africa, a national level Environmental Impact Classification of Alien Taxa (EICAT) assessment classified impacts caused by <i>O. mykiss</i> as Major (MR) as is it known to cause declines and in some cases local extinction of native invertebrates, frogs and fish through predation and competition (Marr et al. 2017). |                    |
| References:<br>Marr S, Ellender B, Woodford D, Alexander M, Wasserman R, Ivey P, Zengeya T, Weyl O. 2017. Evaluating invasion risk for freshwater fishes in South Africa. <i>Bothalia</i> <b>47</b> : 1–10.                                                                                                                                     |                    |

|                                                                              |                 |
|------------------------------------------------------------------------------|-----------------|
| <b>CON2 Socio-economic impact</b>                                            |                 |
| <b>CON2a: Safety</b>                                                         |                 |
| Response: Data Deficient (DD)                                                | Confidence: Low |
| Rationale: No documented information available to assess the level of impact |                 |
| References:                                                                  |                 |
| <b>CON2b: Material and immaterial assets</b>                                 |                 |
| Response: Data Deficient (DD)                                                | Confidence: Low |
| Rationale: No documented information available to assess the level of impact |                 |
| References:                                                                  |                 |
| <b>CON2c: Health</b>                                                         |                 |
| Response: Data Deficient (DD)                                                | Confidence: Low |
| Rationale: No documented information available to assess the level of impact |                 |
| References:                                                                  |                 |
| <b>CON2d: Social, spiritual and cultural relations</b>                       |                 |
| Response: Data Deficient (DD)                                                | Confidence: Low |
| Rationale: No documented information available to assess the level of impact |                 |
| References:                                                                  |                 |



| CON2 Maximum socio-economic impact                                           |                 |
|------------------------------------------------------------------------------|-----------------|
| Response: Data Deficient (DD)                                                | Confidence: Low |
| Rationale: No documented information available to assess the level of impact |                 |
| References:                                                                  |                 |

| CON3 Closely related species' environmental impact                                                      |             |
|---------------------------------------------------------------------------------------------------------|-------------|
| Response: Not Scored as CON1 scored                                                                     | Confidence: |
| Rationale: There is information to score CON1, so CON3 does not need to be scored as per the framework. |             |
| References:                                                                                             |             |

| CON4 Closely related species' socio-economic impact                                  |                 |
|--------------------------------------------------------------------------------------|-----------------|
| Response: Data Deficient (DD)                                                        | Confidence: Low |
| Rationale: There are no relevant records of the socio-economic impacts of salmonids. |                 |
| References:                                                                          |                 |

| CON5 Potential impact                                                                                                                                                                                                                                                                                                                                                                                                                 |                 |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|
| Response: Massive (MV)                                                                                                                                                                                                                                                                                                                                                                                                                | Confidence: Low |
| <p>Rationale:<br/>Potential impacts through predation and competition might be massive as, if no interventions are implemented, endemic and range restricted species only known to occur in discrete catchments in South Africa could be driven to extinction (e.g. see Marr et al. 2017; Chakona et al. 2022).</p>                                                                                                                   |                 |
| <p>References:<br/>Marr S, Ellender B, Woodford D, Alexander M, Wasserman R, Ivey P, Zengeya T, Weyl O. 2017. Evaluating invasion risk for freshwater fishes in South Africa. <i>Bothalia</i> <b>47</b>: 1–10.<br/>Chakona A, Jordaan MS, Raimondo DC, Bills RI, Skelton PH, van der Colff D. 2022. Diversity, distribution and extinction risk of native freshwater fishes of South Africa. <i>Journal of Fish Biology</i> 1–18.</p> |                 |

#### 4. Management

| MAN1 What is the feasibility to stop future immigration?                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Response: Low                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Confidence: High |
| <p>Rationale: <i>Oncorhynchus mykiss</i> is already present in South Africa where it is cultured in hatcheries and is often stocked into ponds, rivers and lakes to support recreational angling (Ellender and Weyl 2014; Ellender et al. 2014; Weyl et al. 2020). Therefore, it is probable that it will disperse through human aided secondary pathways for angling and aquaculture purposes. <i>Oncorhynchus mykiss</i> is present in neighbouring countries (CABI 2021; GBIF 2021) and could spread unaided through interconnected waterways.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                  |
| <p>References:<br/>CABI. 2021. <i>Oncorhynchus mykiss</i> (rainbow trout). In: Invasive Species Compendium, viewed 19 August 2021, from <a href="https://www.cabi.org/isc/datasheet/71813">https://www.cabi.org/isc/datasheet/71813</a><br/>GBIF. 2021. <i>Oncorhynchus mykiss</i> (Walbaum, 1792)', in GBIF Backbone Taxonomy Checklist dataset, viewed 20 August 2021, from <a href="https://www.gbif.org/species/5204019">https://www.gbif.org/species/5204019</a><br/>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b>: 117–132.<br/>Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. <i>Journal of Fish Biology</i> <b>85</b>: 1890–1906.<br/>Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), <i>Biological invasions in South Africa</i>. Springer, Berlin, pp 153-183.</p> |                  |

| MAN2 Benefits of the Taxon                 |
|--------------------------------------------|
| MAN2a Socio-economic benefits of the Taxon |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Response: High                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Confidence: High |
| <p>Rationale: <i>Oncorhynchus mykiss</i> has high socio-economic value and is utilised in aquaculture and recreational fisheries (McCafferty et al. 2012). There are several studies that have assessed the economic benefits derived from <i>O. mykiss</i> such as recreational fishery and tourism, and aquaculture (Britz et al. 2009; Anchor Environmental Consultanting 2010; Britz and Venter 2016; Du-Preez and Lee 2010; McCafferty et al. 2012). Trout farming (primarily <i>O. mykiss</i>) is regarded as the second largest aquaculture sector in terms of production in South Africa (Britz and Venter 2016). These studies strengthen the evidence base for quantifying the benefits derived from introduced fish species, but there were done using different methods and at small scales (e.g. towns, and discrete catchments), and the results still have to be extrapolated to larger scales (e.g. national).</p>         |                  |
| <p>References:</p> <p>Anchor Environmental Consultanting. 2010. The nature, distribution and value of aquatic ecosystem services of the Olifants, Inkomati and Usutu to Mhlathuze Water Management Areas, Contract report for Department: Water Affairs and Forestry, 378 pp.</p> <p>Britz PJ, Lee B, Botes L. 2009. AISA 2009 Aquaculture Benchmarking Survey: Primary Production and Markets, AISA report produced by Enviro-Fish Africa (Pty) Ltd, 117 pp.</p> <p>Britz P, Venter S. 2016. Aquaculture review: South Africa. <i>World Aquaculture</i> <b>47</b>: 20–28.</p> <p>Du-Preez M, Lee DE. 2010. The contribution of trout fly fishing to the economy of Rhodes, North Eastern Cape, South Africa. <i>Development Southern Africa</i> <b>27</b>: 241–253.</p> <p>McCafferty JR, Ellender BR, Weyl OLF, Britz PJ. 2012. The use of water resources for inland fisheries in South Africa. <i>Water SA</i> <b>38</b>: 327–344.</p> |                  |
| <b>MAN2b Environmental benefits of the Taxon</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                  |
| Response: Low                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Confidence: Low  |
| <p>Rationale: There are no environmental benefits documented for <i>Oncorhynchus mykiss</i> in South Africa.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                  |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                  |
| <b>MAN3 Ease of management</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  |
| <b>MAN3a How accessible are populations?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                  |
| Response: 2 (difficult to access)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Confidence: High |
| <p>Rationale: Naturalised populations of <i>Oncorhynchus mykiss</i> can be found in the mountainous headwater reaches that can be difficult to access (de Moor and Bruton 1988). Populations in streams and dams are often on private land and require land owner permission for access.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                  |
| <p>References:</p> <p>de Moor IJ, Bruton MN. 1988. Atlas of alien and translocated indigenous aquatic animals in southern Africa. Pretoria: South African National Scientific Programmes Report no.144.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                  |
| <b>MAN3b Is detectability critically time-dependent?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                  |
| Response: 2 (yes)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Confidence: High |
| <p>Rationale: <i>Oncorhynchus mykiss</i> is difficult to detect all of the time as it lives underwater. <i>Oncorhynchus mykiss</i> tends to display a seasonal range expansion and contraction that follows water temperature in all the river systems it invades though this does not specifically affect detectability (Dallas and Rivers-Moore 2014; Shelton et al. 2018).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                  |
| <p>References:</p> <p>Dallas HF, Rivers-Moore NA. 2014. Ecological consequences of global climate change for freshwater ecosystems in South Africa. <i>South African Journal of Science</i> <b>110</b>: 1–11.</p> <p>Shelton JM, Weyl OLF, Impson ND, Dallas HF, Esler KJ, Paxton BR. 2018. Temperature mediates the impact of non-native rainbow trout on native freshwater fishes in South Africa's Cape Fold Ecoregion. <i>Biological Invasions</i> <b>20</b>: 2927–2944.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                  |
| <b>MAN3c Time to reproduction</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                  |
| Response: 1 (1–3 years)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Confidence: High |
| <p>Rationale: <i>Oncorhynchus mykiss</i> is a short-lived species (generally 5 years) that reaches sexual maturity between one and four years of age (Gall and Crandall 1992).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                  |
| <p>References:</p> <p>Gall GAE, Crandall PA. 1992. The rainbow trout. <i>Aquaculture</i> <b>100</b>: 1–10.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  |
| <b>MAN3d Propagule persistence</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                  |
| Response: 0 (< 1 year)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Confidence: High |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                  |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Rationale: The eggs of <i>O. mykiss</i> can only survive for short periods e.g. eggs can be stored up to approximately one week in an ordinary household refrigerator and for more extended storage periods lower temperatures are advised (Ginatullina et al. 2018).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                  |
| References:<br>Ginatullina E, Komrakova M, Holtz W. 2018. Chilled storage of unfertilized and fertilized rainbow trout ( <i>Oncorhynchus mykiss</i> ) eggs in sealed polyethylene bags at different temperatures. <i>Aquaculture</i> <b>484</b> : 214–218.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                  |
| <b>MAN3 Ease of management</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                  |
| Response: Medium                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Confidence: High |
| Rationale: Management of <i>Oncorhynchus mykiss</i> is complicated given the logistical challenges of finding and treating populations. Many control options harm native species (though subsequent recovery may be good), and control operations have been met with resistance from some stakeholders (Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                  |
| References:<br>Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. <i>Journal of Fish Biology</i> <b>85</b> : 1890–1906.<br>Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. <i>Bothalia</i> <b>47</b> : 1–9.<br>Woodford DJ, Richardson DM, MacIsaac HJ, Mandrak N, van Wilgen BW, Wilson JR, Weyl OLF. 2016. Confronting the wicked problem of managing invasive species. <i>Neobiota</i> <b>31</b> : 63–86.<br>Zengeya T, Ivey P, Woodford DJ, Weyl O, Novoa A, Shackleton R, Richardson DM, van Wilgen B. 2017. Managing conflict-generating invasive species in South Africa: challenges and trade-offs. <i>Bothalia</i> <b>47</b> : 1–11. |                  |

|                                                                                                                                                                                                                                                                                                                                                                      |                  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| <b>MAN4 Has the feasibility of eradication been evaluated?</b>                                                                                                                                                                                                                                                                                                       |                  |
| Response: No                                                                                                                                                                                                                                                                                                                                                         | Confidence: High |
| Rationale: There have been no studies that have addressed the country-wide eradication of <i>O. mykiss</i> in South Africa. An attempt to extirpate <i>O. mykiss</i> from a discrete catchment of the Kroom River in the Cederberg was unsuccessful because of gear selectivity and budgetary constraints (Shelton et al. 2017).                                     |                  |
| References:<br>Shelton J, Weyl O, Van Der Walt J, Marr S, Impson D, Maciejewski K, Tye D, Dallas H, Esler K. 2017. Effect of an intensive mechanical removal effort on a population of non-native rainbow trout <i>Oncorhynchus mykiss</i> in a South African headwater stream. <i>Aquatic Conservation: Marine and Freshwater Ecosystems</i> <b>27</b> : 1051–1055. |                  |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |  |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|
| <b>MAN5 Control options and monitoring approaches available for the Taxon</b>                                                                                                                                                                                                                                                                                                                                                                                    |  |
| Response: Part of the proposed management initiatives for <i>O. mykiss</i> includes managing it by area where utilisation is to be allowed in areas where it has naturalised and in areas where it has been historically utilised by constant re-stocking. However, the need for broader consultations and transparency on the evidence used to assess the risks posed by trout to biodiversity and the benefits derived from their utilisation has been raised. |  |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                      |  |

|                                                               |                         |
|---------------------------------------------------------------|-------------------------|
| <b>MAN6 Any other management considerations to highlight?</b> |                         |
| Response                                                      | Yes (see Appendix MAN6) |

## 5. Calculations

Likelihood = Probable

| Parameter | Likelihood | Stages               | Final assessment |
|-----------|------------|----------------------|------------------|
| LIK1      | 1          | P(entry) = 1         | P (invasion) = 1 |
| LIK2      | 1          |                      |                  |
| LIK3      | 1          | P(establishment) = 1 |                  |

|      |       |                |  |
|------|-------|----------------|--|
| LIK4 | 1     | P (spread) = 1 |  |
| LIK5 | 0.027 |                |  |
| LIK6 | 1     |                |  |

**Consequence** = Massive (MV)

| Parameter | Mechanism/sector                                         | Response                  |
|-----------|----------------------------------------------------------|---------------------------|
| CON1a     | Competition                                              | MR                        |
| CON1b     | Predation                                                | MR                        |
| CON1c     | Hybridisation                                            | DD                        |
| CON1d     | Disease transmission                                     | MC                        |
| CON1e     | Parasitism                                               | DD                        |
| CON1f     | Poisoning/toxicity                                       | DD                        |
| CON1g     | Bio-fouling or other direct physical disturbance         | DD                        |
| CON1h     | Grazing/herbivory/browsing                               | DD                        |
| CON1i     | Chemical, physical, structural impact                    | MO                        |
| CON1k     | Indirect impacts through interactions with other species | DD                        |
| CON1      | Maximum environmental impact                             | MR                        |
| CON2a     | Safety                                                   | DD                        |
| CON2b     | Material and immaterial assets                           | DD                        |
| CON2c     | Health                                                   | DD                        |
| CON2d     | Social, spiritual and cultural relations                 | DD                        |
| CON2      | Maximum socio-economic impact                            | DD                        |
| CON3      | Environmental impact of closely related taxa             | Not scored as CON1 scored |
| CON4      | Socio-economic impact of closely related taxa            | DD                        |
| CON5      | Potential impact based on traits, experiments, or models | MV                        |

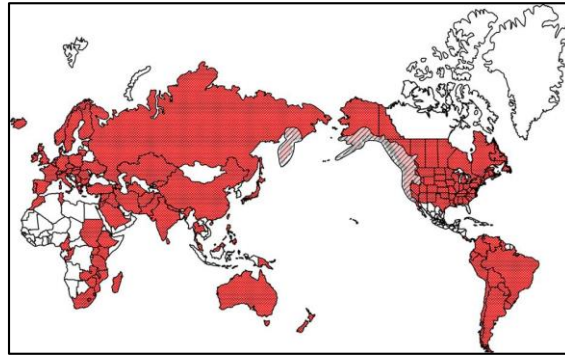
**Risk score** = High

|            |                    | Consequences |        |        |        |        |
|------------|--------------------|--------------|--------|--------|--------|--------|
|            |                    | MC           | MN     | MO     | MR     | MV     |
| Likelihood | Extremely unlikely | low          | low    | low    | medium | medium |
|            | Very unlikely      | low          | low    | low    | medium | high   |
|            | Unlikely           | low          | low    | medium | high   | high   |
|            | Fairly probable    | medium       | medium | high   | high   | high   |
|            | Probable           | medium       | high   | high   | high   | high   |

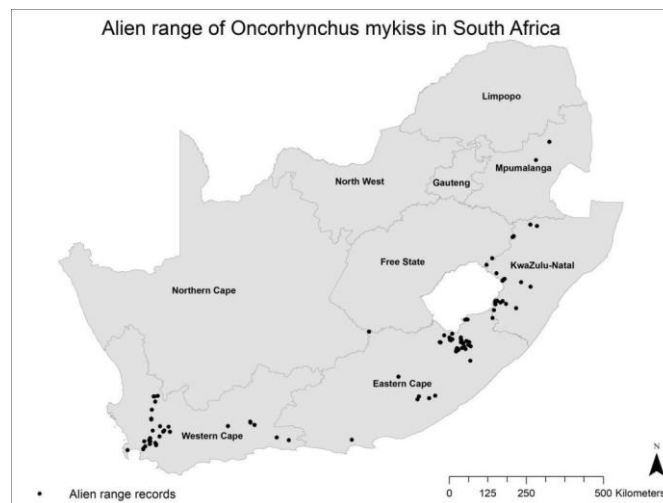
**Ease of management** = Medium

| Parameter   | Question                                    | Response |
|-------------|---------------------------------------------|----------|
| MAN3a       | How accessible are populations?             | 2        |
| MAN3b       | Is detectability critically time-dependent? | 2        |
| MAN3c       | Time to reproduction                        | 1        |
| MAN3d       | Propagule persistence                       | 0        |
| <b>MAN3</b> | <b>SUM</b>                                  | <b>5</b> |

**Appendix BAC7 & Appendix BAC8 (a):** Native range of *Oncorhynchus mykiss* (Walbaum, 1792) (hatched shading) and countries, states, or provinces into which this species has been introduced (red shading). Source: Crawford SS, Muir AM. 2008. Global introductions of salmon and trout in the genus *Oncorhynchus*: 1870–2007. *Reviews in Fish Biology and Fisheries* **18**: 313–344.



**Appendix BAC8 (b):** Distribution of *Oncorhynchus mykiss* (Walbaum, 1792) in South Africa. Source: GBIF.org (26/07/2021) GBIF Occurrence Download <https://doi.org/10.15468/dl.q8dh3t>.



## **Appendix MAN6:** Proposed listing options for *Oncorhynchus mykiss* under the NEM:BA A&IS Regulations

|                                    |
|------------------------------------|
| <b>Current listing:</b> Not listed |
|------------------------------------|

*Oncorhynchus mykiss* was published for listing as an invasive species in the South African Government Gazette on 18 September 2020, but the promulgation of the lists was delayed because of ongoing consultation with stakeholders. New lists (without *Oncorhynchus mykiss*) were published on 24 Feb 2021 and promulgated on 1 March 2021.

The proposed listing of *Oncorhynchus mykiss* was category 2 with “All persons are exempted from requiring a permit for restricted activities “b” and “j” under Notice 1. Activity b is “having in possession or exercising physical control over any specimen of a listed invasive species”, and activity “j” is “Catch and release of a specimen of a listed invasive fresh-water fish or listed invasive fresh-water invertebrate species”.

Although *O. mykiss* is not listed at a national-level, under the NEM:BA A&IS lists, *O. mykiss* is managed in some regions (e.g. the Western Cape province) under provincial legislation (Woodford et al. 2017).

### **Rationale**

*Oncorhynchus mykiss* in South Africa has both major negative environmental impacts and high socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts.

### **Potential criteria for permits and exemptions**

Two key aims for the management of *O. mykiss* should be to: a) prevent the spread of *O. mykiss* to new areas; and b) limit the negative environmental impacts by controlling *O. mykiss* populations in key fish conservation areas. To this end, those catchments where *O. mykiss* does not yet occur but where suitable habitat exists, and key fish conservation areas (with and without *O. mykiss* populations) would need to be identified in a National Management Plan that contains appropriate maps. The inclusion of maps outlining areas where permits may be granted would greatly facilitate the application and processing of permits.

The beneficial uses of *O. mykiss* could then be managed as follows:

- Permits for existing or new aquaculture facilities could be granted, but only if such activities do not result in new sites becoming invaded or spread of *O. mykiss* into key fish conservation areas. As such permits would not be issued for aquaculture facilities in discrete catchment systems in which *O. mykiss* does not yet occur or that include key fish conservation areas. Permits could, however, be granted for aquaculture facilities in part of a discrete catchment system where *O. mykiss* occurs, providing there are natural or artificial habitat barriers (for example waterfalls, dams or weirs) that prevents the spread of *O. mykiss* to other parts of the catchment system where *O. mykiss* is currently absent, but where suitable habitat exists.
- In terms of restocking the same considerations as for aquaculture facilities would apply.
- In terms of angling, catch-and-release (i.e. the practice of anglers to return a fish to the water where it was caught) is exempt in any discrete-catchments that are specified on maps produced as per the National Management Plan. At all other sites catch-and-kill should be practised. This provision could be incorporated into provincial freshwater angling licences.
- The transport of live fish or eggs would always require a permit, but any dead specimens (e.g. for personal consumption or commercial trade) would, of course, be exempt.

### **National Management Plan**

To facilitate the implementation of these criteria and to ensure the process is transparent, it would be important to draw up a National Management Plan for *O. mykiss*. The plan would need to include maps of the catchments where permits may be issued for commercial production purposes, where permits

may be issued for restocking, and where catch-and-release angling is exempt. Maps of key fish conservation areas would also be useful to indicate areas where catch-and-kill would need to be practised.

The National Management Plan would also need to specify the standards that should be met to limit the risk of escape or unintentional or illegal re-distribution to new areas.

#### **Overall recommendation**

**Proposed listing:** Category 2

**Taxon:** *Oncorhynchus mykiss* (Walbaum, 1792)

**Category:** 2

**Exemption:** catch-and-release is exempt in areas specified in maps produced as part of a National Management Plan for *O. mykiss*.

Permits may only be issued for the situations as outlined above.

#### **Reference**

Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. *Bothalia* **47**: a2138.



### Appendix 5.3<sup>6</sup>: Chinook salmon (*Oncorhynchus tshawytscha*)

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                                                                                                                                                                                                                                                                                                                            |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Taxon:</b> <i>Oncorhynchus tshawytscha</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | <b>Area:</b> South Africa                                                                                                                                                                                                                                                                                                                  |
| <b>Compiled by:</b> Lerato Maimela                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | <b>Approved by:</b>                                                                                                                                                                                                                                                                                                                        |
| <b>Picture of Taxon</b><br><br><a href="http://robinbarefield.com/king-chinook-salmon-oncorhynchus-tshawytscha/">http://robinbarefield.com/king-chinook-salmon-oncorhynchus-tshawytscha/</a>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | <b>Alien distribution map (BAC8)</b><br><b>6</b><br><br><small>CABI, 2021. <i>Oncorhynchus tshawytscha</i>. In: Invasive Species Compendium. Wallingford, UK: CAB International. <a href="https://www.cabi.org/isc">https://www.cabi.org/isc</a></small> |
| <b>Risk Assessment summary:</b><br><i>Oncorhynchus tshawytscha</i> is native to the west coast of North America from southern California to Alaska, and north-eastern Asia from northern Japan to Kamchatka. It has been introduced to several countries in Europe, south America, Asia and Oceania. It has been introduced in South Africa (date of first introduction uncertain) for angling and aquaculture. Evidence from elsewhere, suggests that <i>O. tshawytscha</i> can cause minimal environmental impacts through competition with native fish, predation of native fish, amphibians and macroinvertebrates, and has potential to cause moderate non-environmental impacts through declines in economic returns from stock farming.                                                                                                                                                                                                                                                                | <b>Risk score:</b><br>High                                                                                                                                                                                                                                                                                                                 |
| <b>Management options summary:</b><br>Management of trout species in South Africa is difficult. This is because trout are a conflict-generating invasive species that have major negative environmental impacts, but also have socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Part of the proposed management initiatives for <i>O. tshawytscha</i> is to restrict importation through permitting and implement post border intervention measures similar to those proposed for other trout species in South Africa. This includes managing the species by area where utilisation is to be allowed in areas where trout species have naturalised and in areas where they have been historically utilised for stocking. However, concerned stakeholders have highlighted the need for broader consultations and transparency on the evidence used to assess the risks posed by trout to biodiversity and the benefits derived from their utilisation. | <b>Ease of management:</b><br>Medium                                                                                                                                                                                                                                                                                                       |
| <b>Recommendations:</b><br>Given that <i>O. tshawytscha</i> has both major negative environmental impacts and high socio-economic benefits, the recommendation is retain the listing of <i>O. tshawytscha</i> as category 2 (with limitations and exemptions as outlined in Appendix MAN6). In particular, to facilitate the regulation of <i>O. tshawytscha</i> it is recommended that a National Management Plan be developed with appropriate maps. It will be important to ensure there is broad consultation and transparency both on the evidence of the impact <i>O. tshawytscha</i> invasions cause to biodiversity, and on the benefits derived from the use of <i>O. tshawytscha</i> .                                                                                                                                                                                                                                                                                                              | <b>Listing under NEM:BA A&amp;IS lists of 2014 as amended 2021:</b><br>2<br><b>Recommended listing category:</b><br>No change                                                                                                                                                                                                              |

<sup>6</sup> This risk analyses report for *Oncorhynchus tshawytscha* (Chinook salmon) is presented as submitted to the South African Alien Species Risk Analysis Review Panel (ASRARP), a committee that is tasked with reviewing risk analyses attached to import applications and listing of species under national legislation to ensure they are scientifically robust and take into account the best available evidence (see Kumschick et al. 2020 for details). ASRARP is an independent body and its members consist of scientists and taxon experts working on various issues on biological invasions. The committee provides recommendations to an interdepartmental panel set up by the Department of Forestry, Fisheries and the Environment tasked with granting import permits and/or approving changes to regulations on biological invasions.



## 1. Background

|                                                                                                                                                                                                                                                      |                                                                           |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|
| <b>BAC1 Name of assessor(s)</b>                                                                                                                                                                                                                      |                                                                           |
| Name of lead assessor                                                                                                                                                                                                                                | Lerato T Maimela                                                          |
| Additional assessor (1)                                                                                                                                                                                                                              | Tsungai A Zengeya                                                         |
| Additional assessor (2)                                                                                                                                                                                                                              | Christian T Chimimba                                                      |
| <b>BAC2 Contact details of assessor (s)</b>                                                                                                                                                                                                          |                                                                           |
| Lead assessor                                                                                                                                                                                                                                        | Organisational affiliation: University of Pretoria                        |
|                                                                                                                                                                                                                                                      | email: lerato.maimela@zoology.up.ac.za                                    |
|                                                                                                                                                                                                                                                      | Phone: 0124204315                                                         |
| Additional assessor (1)                                                                                                                                                                                                                              | Organisational affiliation: South African National Biodiversity Institute |
|                                                                                                                                                                                                                                                      | email: t.zengeya@sanbi.org                                                |
|                                                                                                                                                                                                                                                      | Phone: 021 799 8408                                                       |
| Additional assessor (2)                                                                                                                                                                                                                              | Organisational affiliation: University of Pretoria                        |
|                                                                                                                                                                                                                                                      | email: chris.chimimba@up.ac.za                                            |
|                                                                                                                                                                                                                                                      | Phone: 012 429 0838                                                       |
| <b>BAC3 Name(s) and contact details of expert(s) consulted</b>                                                                                                                                                                                       |                                                                           |
| Expert (1)                                                                                                                                                                                                                                           | Name:                                                                     |
|                                                                                                                                                                                                                                                      | email:                                                                    |
|                                                                                                                                                                                                                                                      | Phone:                                                                    |
| Expert (2)                                                                                                                                                                                                                                           | Name:                                                                     |
|                                                                                                                                                                                                                                                      | email:                                                                    |
|                                                                                                                                                                                                                                                      | Phone:                                                                    |
| Comments:                                                                                                                                                                                                                                            |                                                                           |
| <b>BAC4 Scientific name of <i>Taxon</i> under assessment</b>                                                                                                                                                                                         |                                                                           |
| <i>Taxon</i> name: <i>Oncorhynchus tshawytscha</i>                                                                                                                                                                                                   | Authority: Walbaum, 1972                                                  |
| Comments:<br><i>Oncorhynchus tshawytscha</i> is the accepted taxonomic name for this fish in the family Salmonidae (GBIF 2021).                                                                                                                      |                                                                           |
| References:<br><br>GBIF. 2021. <i>Oncorhynchus tshawytscha</i> (Walbaum, 1792). In: GBIF Backbone Taxonomy, Checklist dataset, viewed 16 November 2021, from <a href="https://www.gbif.org/species/5204024">https://www.gbif.org/species/5204024</a> |                                                                           |
| <b>BAC5 Synonym(s) considered</b>                                                                                                                                                                                                                    |                                                                           |
| Synonyms: There are 13 synonyms of <i>O. tshawytscha</i> listed on FishBase (Froese and Pauly 2022). However, in this assessment, only <i>O. tshawytscha</i> was used in the literature searches                                                     |                                                                           |
| Comments:                                                                                                                                                                                                                                            |                                                                           |
| References:<br>Froese R, Pauly D (Editors). 2022. FishBase. World Wide Web electronic publication. <a href="http://www.fishbase.org">www.fishbase.org</a> , ( 06/2022 )                                                                              |                                                                           |
| <b>BAC6 Common name(s) considered</b>                                                                                                                                                                                                                |                                                                           |
| Common names: Chinook salmon                                                                                                                                                                                                                         |                                                                           |
| Comments: Other common names include King salmon and Quinnsat salmon                                                                                                                                                                                 |                                                                           |
| References:<br>Froese R, Pauly D (Editors). 2022. FishBase. World Wide Web electronic publication. <a href="http://www.fishbase.org">www.fishbase.org</a> , ( 06/2022 )                                                                              |                                                                           |
| <b>BAC7 What is the native range of the <i>Taxon</i>? (add map in Appendix BAC7)</b>                                                                                                                                                                 |                                                                           |

|                                                                                                                                                                                                                                                                                                                                                                                       |     |                    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|--------------------|
| Response:<br>Chinook salmon is native to the west coast of North America from southern California to Alaska, and north-eastern Asia from northern Japan to Kamchatka (Page and Buir 1991; Crawford and Muir 2008);                                                                                                                                                                    |     | Confidence: High   |
| Comments:                                                                                                                                                                                                                                                                                                                                                                             |     |                    |
| References:<br>Crawford SS, Muir AM. 2008. Global introductions of salmon and trout in the genus <i>Oncorhynchus</i> : 1870-2007. <i>Reviews in Fish Biology and Fisheries</i> <b>18</b> : 313–344.<br>Page LM, Burr BM. 2011. A field guide to freshwater fishes of North America north of Mexico. Boston: Houghton Mifflin Harcourt, 663 p.                                         |     |                    |
| <b>BAC8 What is the global alien range of the <i>Taxon</i>? (add map in Appendix BAC8)</b>                                                                                                                                                                                                                                                                                            |     |                    |
| Response:<br>It has been introduced into several countries that include Argentina, Australia, Brazil, Chile, Denmark, Finland, France, Germany, Hawaii, , Ireland, Italy, Japan, Madagascar, Mexico, Nicaragua Netherlands, New Zealand, and United Kingdom (Froese and Pauly 2022)                                                                                                   |     | Confidence: High   |
| Comments:                                                                                                                                                                                                                                                                                                                                                                             |     |                    |
| References:<br>Froese R, Pauly D (Editors). 2022. FishBase. World Wide Web electronic publication. <a href="http://www.fishbase.org">www.fishbase.org</a> , ( 06/2022)                                                                                                                                                                                                                |     |                    |
| <b>BAC9 Geographic scope = the Area under consideration</b>                                                                                                                                                                                                                                                                                                                           |     |                    |
| Area of assessment: South Africa                                                                                                                                                                                                                                                                                                                                                      |     |                    |
| Comments:                                                                                                                                                                                                                                                                                                                                                                             |     |                    |
| <b>BAC10 Is the <i>Taxon</i> present in the Area?</b>                                                                                                                                                                                                                                                                                                                                 |     |                    |
| Response: Yes                                                                                                                                                                                                                                                                                                                                                                         |     | Confidence: medium |
| Comments:<br>There are several import permit records <i>O. tshawytscha</i> into South Africa and it is likely present in aquaculture facilities (SANBI and CIB 2020).                                                                                                                                                                                                                 |     |                    |
| References:<br>SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <a href="http://dx.doi.org/10.5281/zenodo.3947810">http://dx.doi.org/10.5281/zenodo.3947810</a> |     |                    |
| <b>BAC11 Availability of physical specimen</b>                                                                                                                                                                                                                                                                                                                                        |     |                    |
| Response: N/A                                                                                                                                                                                                                                                                                                                                                                         |     | Confidence in ID:  |
| Herbarium or museum accession number:                                                                                                                                                                                                                                                                                                                                                 |     |                    |
| References:                                                                                                                                                                                                                                                                                                                                                                           |     |                    |
| <b>BAC12 Is the <i>Taxon</i> native to the Area or part of the Area?</b>                                                                                                                                                                                                                                                                                                              |     |                    |
| The <i>Taxon</i> is native to (part of) the Area.                                                                                                                                                                                                                                                                                                                                     | No  | Confidence: High   |
| The <i>Taxon</i> is alien in (part of) the Area.                                                                                                                                                                                                                                                                                                                                      | Yes | Confidence: High   |
| Comments: Chinook salmon is native to the west coast of North America from southern California to Alaska, and north-eastern Asia from northern Japan to Kamchatka (Page and Buir 1991; Crawford and Muir 2008);                                                                                                                                                                       |     |                    |
| References:<br>Crawford SS, Muir AM. 2008. Global introductions of salmon and trout in the genus <i>Oncorhynchus</i> : 1870-2007. <i>Reviews in Fish Biology and Fisheries</i> <b>18</b> : 313–344.<br>Page LM, Burr BM. 2011. A field guide to freshwater fishes of North America north of Mexico. Boston : Houghton Mifflin Harcourt, 663 p.                                        |     |                    |
| <b>BAC13 What is the <i>Taxon</i>'s introduction status in the Area?</b>                                                                                                                                                                                                                                                                                                              |     |                    |
| The <i>Taxon</i> is in cultivation/containment.                                                                                                                                                                                                                                                                                                                                       | yes | Confidence: medium |

|                                                                                                                                                                                                                                                                                                                                                                        |                     |                  |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|------------------|
| The <i>Taxon</i> is present outside of cultivation/containment.                                                                                                                                                                                                                                                                                                        | No                  | Confidence: High |
| The <i>Taxon</i> has established/naturalised.                                                                                                                                                                                                                                                                                                                          | No                  | Confidence: High |
| The <i>Taxon</i> is invasive.                                                                                                                                                                                                                                                                                                                                          | No                  | Confidence: High |
| Comments:                                                                                                                                                                                                                                                                                                                                                              |                     |                  |
| References:                                                                                                                                                                                                                                                                                                                                                            |                     |                  |
| <b>BAC14 Primary (introduction) pathways</b>                                                                                                                                                                                                                                                                                                                           |                     |                  |
| Release                                                                                                                                                                                                                                                                                                                                                                | fishery in the wild | Confidence: High |
| Escape                                                                                                                                                                                                                                                                                                                                                                 | N/A                 | Confidence: High |
| Contaminant                                                                                                                                                                                                                                                                                                                                                            | N/A                 | Confidence: High |
| Stowaway                                                                                                                                                                                                                                                                                                                                                               | N/A                 | Confidence: High |
| Corridor                                                                                                                                                                                                                                                                                                                                                               | N/A                 | Confidence: High |
| Unaided                                                                                                                                                                                                                                                                                                                                                                | N/A                 | Confidence: High |
| Comments:                                                                                                                                                                                                                                                                                                                                                              |                     |                  |
| There are several import permit records <i>O. tshawytscha</i> into South Africa and it is likely present in aquaculture facilities (SANBI and CIB 2020).                                                                                                                                                                                                               |                     |                  |
| References:                                                                                                                                                                                                                                                                                                                                                            |                     |                  |
| SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <a href="http://dx.doi.org/10.5281/zenodo.3947810">http://dx.doi.org/10.5281/zenodo.3947810</a> |                     |                  |

## 2. Likelihood

|                                                                                                                                                                                                                                                                                                                                                                                          |                    |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| <b>LIK1 Likelihood of entry via unaided primary pathways</b>                                                                                                                                                                                                                                                                                                                             |                    |
| Response: present in the country (p=1)                                                                                                                                                                                                                                                                                                                                                   | Confidence: medium |
| <i>Oncorhynchus tshawytscha</i> is present in the country and has is likely confined to aquaculture facilities (SANBI and CIB 2020). There are no population that are known to have established in the wild and there are no introduction records in neighboring countries                                                                                                               |                    |
| References:<br>SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch.<br><a href="http://dx.doi.org/10.5281/zenodo.3947810">http://dx.doi.org/10.5281/zenodo.3947810</a> |                    |

|                                                                                                                                                                                                                                                                                                                                                                                          |                    |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| <b>LIK2 Likelihood of entry via human aided primary pathways</b>                                                                                                                                                                                                                                                                                                                         |                    |
| Response: present in the country (p=1)                                                                                                                                                                                                                                                                                                                                                   | Confidence: medium |
| Rationale:<br><i>Oncorhynchus tshawytscha</i> is present in the country and has is likely confined to aquaculture facilities (SANBI and CIB 2020).                                                                                                                                                                                                                                       |                    |
| References:<br>SANBI and CIB .2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch.<br><a href="http://dx.doi.org/10.5281/zenodo.3947810">http://dx.doi.org/10.5281/zenodo.3947810</a> |                    |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                  |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| <b>LIK3 Habitat suitability</b>                                                                                                                                                                                                                                                                                                                                                                                                                                   |                  |
| Response: Fairly probable (p=0.5)                                                                                                                                                                                                                                                                                                                                                                                                                                 | Confidence: High |
| Rationale:<br>Similar to rainbow trout and brown trout, Chinook salmon prefer clear, cool, well-oxygenated creeks, small to medium rivers, and lakes (prefer streams with cool, flowing waters and rocky substrate (Page and Burr 2011). These habitat are found in several headwater mountain streams in South Africa. However confidence is marked as medium because previous introduction attempts in the wild were not successful (see Ellender et al. 2014). |                  |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |

Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. *Aquatic Invasions* **9**: 117–132. <http://dx.doi.org/10.3391/ai.2014.9.2.01>

Page LM, Burr BM. 2011. A field guide to freshwater fishes of North America north of Mexico. Boston : Houghton Mifflin Harcourt, 663p

#### LIK4 Climate suitability

Response: Probable (p=1)

Confidence: High

##### Rationale:

Chinook salmon thrive in cool, fast flowing streams (<14 °C) (National Wildlife Federation 1996-2002; NOAA 2002; Pacific States Marine Fisheries Commission 1996). These climatic conditions can be found in the headwaters of many rivers in South Africa, especially the eastern escarpment stretching from the south-western Cape to Northern Kwa-Zulu Natal as indicated by systematic climate modelling studies (Picker and Griffiths 2011; Weyl and Keevey 2012; Ellender et al. 2016; Rivers-Moore et al. 2019).

##### References:

Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. *Aquatic Invasions* **9**: 117–132.

Ellender BR, Rivers-Moore NA, Coppinger CR, Bellingan TA, Weyl OLF. 2016. Towards using thermal stress thresholds to predict salmonid invasion potential. *Biological Invasions* **18**: 3513–3525.

National Wildlife Federation. 1996-2002. "Chinook Salmon" (On-line). Accessed October 21, 2002 at <http://www.nwf.org/keepthewildalive/salmon>.

NOAA. 2002. "Where do salmon go in the ocean?" (On-line). Accessed October 23, 2002 at <http://www.nefsc.noaa.gov/faq/fishfaq2d.html>.

Pacific States Marine Fisheries Commission. 1996. "Chinook Salmon" (On-line). Accessed October 21, 2002 at [http://www.psmfc.org/habitat/edu\\_chinook\\_facts.html](http://www.psmfc.org/habitat/edu_chinook_facts.html).

Picker MD, Griffiths CL. 2011. Alien and invasive animals – A South African Perspective, Randomhouse/Struik, Cape Town, South Africa, 240 pp.

Rivers-Moore NA, Ellender BR, Weyl OLF. 2019. Modelling expected trout ranges under current and future water temperature regimes in the Eastern Cape, South Africa. *African Journal of Aquatic Science* **44**: 35–42.

Weyl OLF, Keevey G. 2012 Deliverable 17. Report on GIS mapping and bibliography of dams with inland fisheries potential. Water Research Commission, Baseline and scoping study on the development and sustainable utilisation of storage dams for inland fisheries and their contribution to rural livelihoods Project Title: K5/1957/4.

#### LIK5 Unaided secondary (dispersal) pathways

Response: Unlikely (P=0.027)

Confidence: Medium

##### Rationale:

In South Africa, populations of *O. tshawytscha* are mainly aquaculture facilities and there are no known naturalised populations (SANBI and CIB 2020). Therefore, the dispersal capabilities of *O. tshawytscha* through unaided pathways are limited.

##### References:

SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <http://dx.doi.org/10.5281/zenodo.3947810>

#### LIK6 Human aided secondary (dispersal) pathways

Response: probable (p=1)

Confidence: Medium

##### Rationale:

*Oncorhynchus tshawytscha* is stocked in aquaculture facilities (SANBI and CIB 2020). Therefore, it is probable that it will disperse through human aided secondary pathways for angling and aquaculture purposes.

##### References:

SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <http://dx.doi.org/10.5281/zenodo.3947810>

### 3. Consequences

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                    |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| <b>CON1 Environmental impact</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                    |
| <b>CON1a: Competition</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |
| Response: MC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Confidence: Medium |
| <p>Rationale:<br/>Evidence from across the invaded range including eastern North America that <i>O. tshawytscha</i> competes with native fauna for habitat and food resources (Crawford 2001; Hansen et al. 2014)..</p> <p>References:<br/>Crawford SS. 2001. Salmonine Introductions to the Laurentian Great Lakes: An Historical Review and Evaluation of Ecological Effects. Salmon report.<br/>Hansen MJ, Holey ME. 2014. Ecological Factors Affecting the Sustainability of Chinook and Coho Salmon Populations in the Great Lakes, Especially Lake Michigan. In: Lynch KD, Jones ML, Taylor WW (eds), <i>Sustaining North American salmon: perspectives across regions and disciplines</i>. American Fisheries Society. <a href="https://doi.org/10.47886/9781888569254">https://doi.org/10.47886/9781888569254</a></p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                    |
| <b>CON1b: Predation</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                    |
| Response: MC                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Confidence: medium |
| <p>Rationale:<br/>Salmon, particularly chinook and coho, in their natural habitats are placed as top predators in pelagic food webs where they act mostly as piscivorous fish (Welch and Parsons 1993). In Lake Michigan and Lake Ontario, a decline in populations of native species such as alewife (<i>Alosa pseudoharengus</i>) has been linked to predation by introduced chinook salmon (Elliott 1993; Rybicki and Clapp 1996; Holey et al. 1998). Predation by both chinook salmon and rainbow trout has also been implicated in the decline of <i>G. maculatus</i> in Lake Purrumbete in Australia and in streams in New Zealand (Cadwallader and Eden 1982; Glova and Sagar 1993).</p> <p>References:<br/>Cadwallader PL, Eden AK. 1982. Observations on the food -of rainbow trout, <i>Salmo gairdneri</i> Richardson, in Lake Purrumbete, Victoria. -Australian Society for Limnology, Bulletin No. 8: 17-21.<br/>Elliott RF. 1993. Feeding habits of chinook salmon in eastern Lake Michigan. Master's thesis. Michigan State University, East Lansing.<br/>Glova GJ, Sagar PM. 1993. A further assessment of trophic and spatial interrelations of galaxiids and salmonids in New Zealand. <i>Ecology of Freshwater Fish</i> 2: 132-140.<br/><br/>Hansen MJ, Holey ME. 2014. Ecological Factors Affecting the Sustainability of Chinook and Coho Salmon Populations in the Great Lakes, Especially Lake Michigan. In KD Lynch, ML Jones, WW Taylor (eds), <i>Sustaining North American salmon: perspectives across regions and disciplines</i>. American Fisheries Society. <a href="https://doi.org/10.47886/9781888569254">https://doi.org/10.47886/9781888569254</a><br/><br/>Holey ME, Elliott RF, Marcquenski SV, Hnath JG, Smith KD.1998. Chinook salmon epizootics in Lake Michigan: possible contributing factors and management implications. <i>Journal of Aquatic Animal Health</i> 10: 202–210.<br/>Rybicki RW, Clapp DF. 1996. Diet of chinook salmon in eastern Lake Michigan, 1991-1993. Michigan Department of Natural Resources, Research Report 2027, Lansing, Michigan.<br/>Welch D, Parsons T. 1993. bl3C-bl3N values as indicators of trophic position and competitive overlap for Pacific salmon (<i>Oncorhynchus</i> spp.). <i>Fisheries Oceanography</i> 2:11-23.</p> |                    |
| <b>CON1c: Hybridisation</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                    |
| Response: MO                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Confidence: medium |
| <p>Rationale:<br/>Hybridsation is common among salmonid species (Moyle 2002). For example, deleterious genetic interactions have been particularly well documented for Atlantic (McGinnity et al. 2003; Naylor et al. 2005) and chinook salmon (Waples 1991), including irreversible loss of genetic diversity leading to</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                    |



reduced environmental adaptability, significant fitness reduction and potential local extinction of wild populations. Genetic alteration of native species by introduced chinook salmon in the Great Lakes can be either direct or indirect. There is evidence of direct alteration effects, such as hybridisation and introgression with native species (Crawford 2001). There are no native Salmonidae species in South Africa, therefore there is no risk of hybridisation (Skelton 2001).

**References:**

- Crawford SS. 2001. Salmonine Introductions to the Laurentian Great Lakes: An Historical Review and Evaluation of Ecological Effects. Salmon report.
- McGinnity P, Prodohl P, Ferguson A, Hynes R, Maoiléidigh N, Baker N, Cotter D, O'Hea B, Cooke D, Rogan G. 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. *Proceedings of the Royal Society of London. Series B, Biological Sciences* **270**: 2443-2450.
- Moyle P. 2002. Inland Fishes of California, 2nd Edition, Berkeley, University of California Press.
- Naylor R, Hindar K, Fleming IA, Goldburg R, Williams S, Volpe J, Whoriskey F, Eagle J, Kelso D, Mangel M. 2005. Fugitive salmon: assessing the risks of escaped fish from net-pen aquaculture. *Bioscience* **55**: 427-437.
- Skelton P. 2001. A complete guide to the freshwater fishes of Southern Africa. Struik Publishers, Cape Town.
- Waples RS. 1991. Genetic interactions between hatchery and wild salmonids: lessons from the Pacific Northwest. *Canadian Journal Fisheries and Aquatic Science* **48**: 124-133.

**CON1d: Transmission of disease**

Response: MC

Confidence: medium

**Rationale:**

Studies in several countries (e.g., Ireland, Scotland, Norway, Canada, the USA, and Chile) suggest the occurrence of several diseases is often correlated introduction of alien salmonids (Krkosek et al. 2005; Naylor et al. 2005; Sepulveda et al. 2013; van der Veer and Nentwig 2015). These include diseases such as rickettsial septicemia, sea lice (*Caligus* spp.), pancreatic necrosis virus, and salmon anemia virus (Rodríguez Saint Jean et al. 2003, Asche et al. 2010; Niklitschek et al. 2013).

**References:**

- Asche F, Hansen H, Tveteras R, Tveteras S. 2010. The salmon disease crisis in Chile. *Marine Resource Economics* **24**: 405-411.
- Krkosek M, Lewis MA, Volpe JP (2005) Transmission dynamics of parasitic sea lice from farms to wild salmon. *Proceedings of the Royal Society* **272**: 689-696
- Naylor R, Hindar K, Fleming IA, Goldburg R, Williams S, Volpe J, Whoriskey F, Eagle J, Kelso D, Mangel M. 2005. Fugitive salmon: assessing the risks of escaped fish from net-pen aquaculture. *Bioscience* **55**: 427-437.
- Niklitschek EJ, Soto D, Lafon A, Molinet C, Toledo P. 2013. Southward expansion of the Chilean salmon industry in the Patagonian Fjords: main environmental challenges. *Reviews in Aquaculture* **4**: 1-24.
- Rodríguez Saint-Jean S, Borrego J, Pérez-Prieto S. 2003. Infectious pancreatic necrosis virus: biology, pathogenesis and diagnostic methods. *Advances in Virus Research* **62**: 113-165.
- Sepulveda M, Arismendi I, Soto D, Jara F, Farias F. 2013. Escaped farmed salmon and trout in Chile: incidence, impacts, and the need for an ecosystem view. *Aquaculture Environment Interactions* **4**: 273-283.

**CON1e: Parasitism**

Response: MC

Confidence: Low

**Rationale:**

Chinook salmon are infected by numerous parasite species (Hoffman 1999; Love and Moser 1983; McDonald and Margolis 1995; Bravo et al. 2011). For example, Non-native diseases (e.g. furunculosis, whirling disease) and parasites (e.g. *Philonema oncorhynchi*, *Ergasilus nerkae*) may have been introduced to the Great Lakes along with the introduced salmonines (Crawford 2001, Hansen and Holey 2014).

**References:**

- Bravo S, Boxshall G, Conroy G. 2011. New cultured host and a significant expansion in the known geographical range of the sea louse *Caligus rogercresseyi*. *Bulletin of the European Association of Fish Pathologists* **31**:156-160.

Hansen MJ, Holey ME. 2014. Ecological Factors Affecting the Sustainability of Chinook and Coho Salmon Populations in the Great Lakes, Especially Lake Michigan. Research Gate.  
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McDonald T, Margolis L. 1995. Synopsis of the parasites of fishes of Canada: supplement (1978–1993). *Canadian Special Publication of Fisheries and Aquatic Sciences* **122**: 265 p.  
Sepulveda M, Arismendi I, Soto D, Jara F, Farias F. 2013. Escaped farmed salmon and trout in Chile: incidence, impacts, and the need for an ecosystem view. *Aquaculture Environment Interactions* **4**: 273-283.

#### **CON1f: Poisoning/toxicity**

Response: DD | Confidence: Low

Rationale: No documented information available to assess the level of impact

References:

#### **CON1g: Bio-fouling or other direct physical disturbance**

Response: DD | Confidence: Low

Rationale: No documented information available to assess the level of impact

References:

#### **CON1h: Grazing/herbivory/browsing**

Response: DD | Confidence: Low

Rationale: No documented information available to assess the level of impact

References:

#### **CON1i: Chemical, physical or structural impact on ecosystem**

Response: DD | Confidence: Low

Rationale: No documented information available to assess the level of impact

References:

#### **CON1k: Indirect impacts through interactions with other species**

Response: DD | Confidence: Medium

Rationale: No documented information available to assess the level of impact

References:

#### **CON1 Maximum environmental impact (Figure S3)**

Response: MO | Confidence:

Rationale:

In its introduced range, Chinook salmon has been reported to impact native species mainly through predation and transmission of diseases (Crawford 2001; Hansen et al. 2014).

References:

Crawford SS. 2001. Salmonine Introductions to the Laurentian Great Lakes: An Historical Review and Evaluation of Ecological Effects. Salmon report.  
Hansen MJ, Holey ME. 2014. Ecological Factors Affecting the Sustainability of Chinook and Coho Salmon Populations in the Great Lakes, Especially Lake Michigan. In KD Lynch, ML Jones, WW Taylor (eds), *Sustaining North American salmon: perspectives across regions and disciplines*. American Fisheries Society.  
<https://doi.org/10.47886/9781888569254>

#### **CON2 Socio-economic impact**

##### **CON2a: Safety**

Response: DD | Confidence: Low

Rationale: No documented information available to assess the level of impact

References:

##### **CON2b: Material and immaterial assets**

Response: DD | Confidence: Low

Rationale: No documented information available to assess the level of impact

References:

|                                                                              |                 |
|------------------------------------------------------------------------------|-----------------|
| <b>CON2c: Health</b>                                                         |                 |
| Response: DD                                                                 | Confidence: Low |
| Rationale: No documented information available to assess the level of impact |                 |
| References:                                                                  |                 |
| <b>CON2d: Social, spiritual and cultural relations</b>                       |                 |
| Response: DD                                                                 | Confidence: Low |
| Rationale: No documented information available to assess the level of impact |                 |
| References:                                                                  |                 |
| <b>CON2 Maximum socio-economic impact (Figure S3)</b>                        |                 |
| Response: DD                                                                 | Confidence: Low |
| Rationale: No documented information available to assess the level of impact |                 |
| References:                                                                  |                 |

|                                                                                                        |             |
|--------------------------------------------------------------------------------------------------------|-------------|
| <b>CON3 Closely related species' environmental impact</b>                                              |             |
| Response: Not scored as CON1 scored                                                                    | Confidence: |
| Rationale: There is information to score CON1, so CON3 does not need to be scored as per the framework |             |
| References:                                                                                            |             |

|                                                                                                                                                                                                                                             |                    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| <b>CON4 Closely related species' socio-economic impact</b>                                                                                                                                                                                  |                    |
| Response: MO                                                                                                                                                                                                                                | Confidence: medium |
| Rationale:<br>Alien salmonid species can affect animal production (usually aquacultures) through the transmission of pathogens, which may cause relatively high expenses (van der Veer and Nentwig 2015).                                   |                    |
| References:<br>van der Veer G, Nentwig W. 2015. Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system. <i>Ecology of Freshwater Fishes</i> <b>24</b> : 646-656. |                    |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                    |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| <b>CON5 Potential impact</b>                                                                                                                                                                                                                                                                                                                                                                                                                                               |                    |
| Response: MR                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Confidence: medium |
| Rationale:<br>In South Africa, a national-level EICAT assessment classified impacts caused by closely related species ( <i>Salmo trutta</i> and <i>Oncorhynchus mykiss</i> ) as Major (MR) as they are known to cause declines, and in some cases local extinction of native invertebrates, frogs and fish through predation and competition (Marr et al. 2017). If <i>Oncorhynchus tshawytschais</i> introduced and becomes invasive, it likely to cause similar impacts. |                    |
| References:<br>Marr S, Ellender B, Woodford D, Alexander M, Wasserman R, Ivey P, Zengeya T, Weyl O. 2017. Evaluating invasion risk for freshwater fishes in South Africa. <i>Bothalia</i> <b>47</b> : 1–10.                                                                                                                                                                                                                                                                |                    |

#### 4. Management

|                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                  |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| <b>MAN1 What is the feasibility to stop future immigration?</b>                                                                                                                                                                                                                                                                                                                                                                                 |                  |
| Response: Low                                                                                                                                                                                                                                                                                                                                                                                                                                   | Confidence: High |
| Rationale: <i>Oncorhynchus tshawytscha</i> is already present in South Africa in aquaculture facilities SANBI and CIB 2020). Therefore, it is probable that it may be dispersed through human-aided secondary pathways for angling purposes, as observed for other salmonid species (Ellender and Weyl 2014; Ellender et al. 2014, Weyl et al. 2020).                                                                                           |                  |
| References:<br>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b> : 117–132.<br>Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non-native fishes in southern Africa. <i>Journal of Fish Biology</i> <b>85</b> : 1890–1906. |                  |



SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <http://dx.doi.org/10.5281/zenodo.3947810>

Weyl OLF, Ellender BR, Ivey P, Jackson MC, Tweddle D, Wasserman RJ, Woodford DJ, Zengeya TA. 2017. Africa: Brown trout introductions, establishment, current status, impacts and conflicts. In: Lobón-Cerviá J, Sanz N (eds), *Brown Trout: Biology, Ecology and Management*, Wiley, Oxford, pp 623–639.

## MAN2 Benefits of the Taxon

### MAN2a Socio-economic benefits of the Taxon

Response: High

Confidence: medium

#### Rationale:

Trout species have socio-economic value and are utilised in recreational fisheries in their global invasive range (e.g., Muhlfeld et al. 2019). In South Africa, there are several studies that have assessed the economic benefits of trout (mainly for *Oncorhynchus mykiss*) and these strengthen the evidence base for quantifying the benefits derived from introduced fish species (Britz et al. 2009; Britz and Venter 2016; Du-Preez and Lee 2010; Anchor Environmental Consulting 2010). However, the studies were done using different methods and at small scales (e.g. towns, and discrete catchments), and the results still have to be extrapolated to larger scales (e.g. national). *Salmo trutta* is of lower importance than *O. mykiss* (rainbow trout) as it is currently used exclusively for recreational fishing, and not for commercial production (Stander and Brink 2009). No studies have been done for *O. tshawytscha*. In addition, native fish species are also available as alternatives for recreational angling (e.g. various yellowfish species, Hoogendoorn 2014).

#### References:

Anchor Environmental Consulting. 2010. The nature, distribution and value of aquatic ecosystem services of the Olifants, Inkomati and Usutu to Mhlathuze Water Management Areas. Contract report for Department: Water Affairs and Forestry, 378 pp.

Britz P, Venter S. 2016. Aquaculture review: South Africa. *World Aquaculture* **47**: 20–28.

Britz PJ, Lee B, Botes L. 2009 AISA 2009 Aquaculture Benchmarking Survey: Primary Production and Markets. AISA report produced by Enviro-Fish Africa (Pty) Ltd, 117 pp.

Du-Preez M, Lee DE. 2010. The contribution of trout fly fishing to the economy of Rhodes, North Eastern Cape, South Africa. *Development Southern Africa* **27**: 241–253.

Hoogendoorn G. 2014. Mapping fly-Fishing Tourism in Southern Africa. *African Journal of Hospitality, Tourism and Leisure* **3**: 13 pp.

Muhlfeld CC, Dauwalter DC, D'Angelo VS, Ferguson A, Giersch JJ, Impson D, Koizumi I, Kovach R, McGinnity P, Schöffmann J, Vøllestad LA. 2019. Global status of trout and char: Conservation challenges in the twenty-first century. Trout and char of the world, pp 717-60.

Stander H, Brink D. 2009. Trout farming In South Africa: Expanding local markets work with ecotourism. Global Aquaculture Advocate, November/December 2009.

### MAN2b Environmental benefits of the Taxon

Response: DD

Confidence: Medium

#### Rationale:

There are currently no known environmental benefits of the species.

#### References:

## MAN3 Ease of management

### MAN3a How accessible are populations?

Response: 1 (moderately accessible)

Confidence: High

#### Rationale:

*Oncorhynchus tshawytscha* is present in South Africa in aquaculture facilities (SANBI and CIB 2020). These facilities are often on private land and permission would be needed to access these areas.

#### References:

SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute,

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch.<br><a href="http://dx.doi.org/10.5281/zenodo.3947810">http://dx.doi.org/10.5281/zenodo.3947810</a>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |
| <b>MAN3b Is detectability critically time-dependent?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                    |
| Response: 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Confidence:        |
| <p>Rationale:<br/>Trout can be detected at any time, but it does require special equipment (e.g. electrofishing gear) and trained specialists to operate such equipment. Detection is thus logistically challenging, but not time-dependent</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                    |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                    |
| <b>MAN3c Time to reproduction</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                    |
| Response: 0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Confidence: High   |
| <p>Rationale:<br/>Chinook salmon are capable of spawning in both mainstream rivers and small tributaries and headwaters. Freshwater populations are also known but most are anadromous, utilizing rivers for spawning and early juvenile development and marine waters for growth to adulthood (Healey 1991; Behnke 2002). Spawning time varies among populations and is most often in the fall with late spring and summer runs (Correa and Gross 2008). Sexual maturity is reached between 2-7 years.</p>                                                                                                                                                                                                                                                                                                                                                                           |                    |
| <p>References:<br/>Behnke RJ. 2002. Trout and salmon of North America. The Free Press, New York.<br/>Correa C, Gross MR. 2008. Chinook salmon invade southern South America. <i>Biological Invasions</i> <b>10</b>: 615-639.<br/>Healey MC. 1991. Life history of chinook salmon (<i>Oncorhynchus tshawytscha</i>). In: Groot C, Margolis L (eds), <i>Pacific salmon life histories</i>. UBC Press, Vancouver, BC, pp 311–396.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                    |
| <b>MAN3d Propagule persistence</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                    |
| Response: 0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Confidence: low    |
| <p>Rationale:<br/>The persistence of the introduced fry or juveniles is dependent on the suitability of the habitat for survival, which is mainly dependent on the climate of the environment (Healey 1991)</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                    |
| <p>References:<br/>Healey MC. 1991. Life history of chinook salmon (<i>Oncorhynchus tshawytscha</i>). In: Groot C, Margolis L (eds), <i>Pacific salmon life histories</i>. UBC Press, Vancouver, BC, pp 311–396.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |
| <b>MAN3 Ease of management (SUM from Table S4)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                    |
| Response: Medium                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Confidence: Medium |
| <p>Rationale: Management of <i>O. tshawytscha</i> is scored here as medium. However, several issues make management challenging. These include the fact that many control options could also harm native species, and that control operations would likely be met with resistance from certain interest groups (see Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                    |
| <p>References:<br/>Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. <i>Journal of Fish Biology</i> <b>85</b>: 1890–1906.<br/>Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. <i>Bothalia</i> <b>47</b>: 1–9.<br/>Woodford DJ, Richardson DM, MacIsaac HJ, Mandrak N, van Wilgen BW, Wilson JR, Weyl OLF. 2016. Confronting the wicked problem of managing invasive species. <i>Neobiota</i> <b>31</b>: 63–86.<br/>Zengeya T, Ivey P, Woodford DJ, Weyl O, Novoa A, Shackleton R, Richardson D, Van Wilgen B. 2017. Managing conflict-generating invasive species in South Africa: challenges and trade-offs. <i>Bothalia</i> <b>47</b>: 1–11.</p> |                    |
| <b>MAN4 Has the feasibility of eradication been evaluated?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                    |
| Response: No                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Confidence: High   |
| <p>Rationale:<br/>There have been no studies that have addressed the country-wide eradication of <i>O. tshawytscha</i> in South Africa. There was an attempt to extirpate another trout species, <i>O. mykiss</i>, from a discrete</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                    |

catchment of the Kroom River in the Cederberg was unsuccessful because of gear selectivity and budgetary constraints (Shelton et al. 2017).

**References:**

Shelton J, Weyl O, Van Der Walt J, Marr S, Impson D, Maciejewski K, Tye D, Dallas H, Esler K. 2017. Effect of an intensive mechanical removal effort on a population of non-native rainbow trout *Oncorhynchus mykiss* in a South African headwater stream. *Aquatic Conservation: Marine and Freshwater Ecosystems* **27**: 1051–1055.

**MAN5 Control options and monitoring approaches available for the Taxon**

**Response:**

Management of trout species in South Africa is relatively difficult. This because trout are conflict-generating invasive species that have major negative environmental impacts, but also some socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Known populations of *O. tshawytscha* in South Africa are restricted to aquaculture facilities and the recommended management option is to restrict utilisation through permitting with key conditions to prevent potential spread and impacts. For example, the proposed management initiatives could include managing it by area where utilisation is restricted to a few areas where trout species have been historically been stocked. Concerned stakeholders have highlighted the need for broader consultations and transparency on the evidence used to assess the risks posed by trout to biodiversity and the benefits derived from their utilisation see (Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017).

**References:**

Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. *Journal of Fish Biology* **85**: 1890–1906.

Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. *Bothalia* **47**: 1–9.

Woodford DJ, Richardson DM, MacIsaac HJ, Mandrak N, van Wilgen BW, Wilson JR, Weyl OLF. 2016. Confronting the wicked problem of managing invasive species. *Neobiota* **31**: 63–86.

Zengeya T, Ivey P, Woodford DJ, Weyl O, Novoa A, Shackleton R, Richardson D, Van Wilgen B. 2017. Managing conflict-generating invasive species in South Africa: challenges and trade-offs. *Bothalia* **47**: 1–11.

**MAN6 Any other management considerations to highlight? (if yes, fill in Appendix MAN6)**

|          |                        |
|----------|------------------------|
| Response | Yes, see Appendix MAN6 |
|----------|------------------------|

## 5. Calculations

**Likelihood** = Probable

| Parameter | Likelihood      | Stages                      | Final assessment        |
|-----------|-----------------|-----------------------------|-------------------------|
| LIK1      | Probable        | P(entry) = probable         | P (invasion) = Probable |
| LIK2      | Probable        |                             |                         |
| LIK3      | Fairly probable | P(establishment) = probable |                         |
| LIK4      | Probable        |                             |                         |
| LIK5      | Unlikely        | P (spread) = probable       |                         |
| LIK6      | Probable        |                             |                         |

**Consequence** = Moderate (MO)

| Parameter | Mechanism/sector     | Response |
|-----------|----------------------|----------|
| CON1a     | Competition          | MC       |
| CON1b     | Predation            | MC       |
| CON1c     | Hybridisation        | MO       |
| CON1d     | Disease transmission | MC       |
| CON1e     | Parasitism           | MC       |

|       |                                                                                                   |                              |
|-------|---------------------------------------------------------------------------------------------------|------------------------------|
| CON1f | Poisoning/toxicity                                                                                | DD                           |
| CON1g | Bio-fouling or other direct physical disturbance                                                  | DD                           |
| CON1h | Grazing/herbivory/browsing                                                                        | DD                           |
| CON1i | Chemical, physical, structural impact                                                             | DD                           |
| CON1k | Indirect impacts through interactions with other species                                          | DD                           |
| CON1  | Maximum environmental impact                                                                      | MO                           |
| CON2a | Safety                                                                                            | DD                           |
| CON2b | Material and immaterial assets                                                                    | DD                           |
| CON2c | Health                                                                                            | DD                           |
| CON2d | Social, spiritual and cultural relations                                                          | DD                           |
| CON2  | Maximum socio-economic impact                                                                     | DD                           |
| CON3  | Environmental impact of closely related taxa<br>(only score if CON1a-k are all DD, otherwise NA)  | Not scored as<br>CON1 scored |
| CON4  | Socio-economic impact of closely related taxa<br>(only score if CON2a-g are all DD, otherwise NA) | MO                           |
| CON5  | Potential impact based on traits, experiments, or models                                          | MR                           |

**Risk score = High**

|            |                    | Consequences |        |        |        |        |
|------------|--------------------|--------------|--------|--------|--------|--------|
|            |                    | MC           | MN     | MO     | MR     | MV     |
| Likelihood | Extremely unlikely | low          | low    | low    | medium | medium |
|            | Very unlikely      | low          | low    | low    | medium | high   |
|            | Unlikely           | low          | low    | medium | high   | high   |
|            | Fairly probable    | medium       | medium | high   | high   | high   |
|            | Probable           | medium       | high   | high   | high   | high   |

**Ease of management = Medium**

| Parameter   | Question                                    | Response |
|-------------|---------------------------------------------|----------|
| MAN3a       | How accessible are populations?             | 1        |
| MAN3b       | Is detectability critically time-dependent? | 2        |
| MAN3c       | Time to reproduction                        | 0        |
| MAN3d       | Propagule persistence                       | 0        |
| <b>MAN3</b> | <b>SUM</b>                                  | <b>3</b> |

**Appendix BAC7:** Native distribution of Chinook salmon (*Oncorhynchus tshawytscha*; black diagonal) and countries, states or provinces into which this species has been introduced (red stipple). Sources: Crawford and Muir 2007, <https://doi.org/DOI.10.1007/s11160-007-9079-1> Provide here a map of the native range, if possible. If the map is available in a file, please insert a low res copy (<1MB) and provide the file name and (if possible) a link to a higher resolution copy below.



## **Appendix MAN6:** Proposed listing options for *Oncorhynchus tshawytscha* under the NEM:BA A&IS Regulations

### **Current listing as per NEM:BA A&IS lists of 2020**

**Taxon:** *Oncorhynchus tshawytscha* (Walbaum, 1792)

**Common name:** Chinook salmon

**Category:** 2

*Oncorhynchus tshawytscha* (Walbaum, 1792) was listed as Category 2 invasive species in the South African Government Gazette on 18 September 2020, and in the NEM:BA A&IS Lists promulgated on 1 March 2021. There are no exemptions specified as per the provisions of section 71(3) / prohibition in terms of section 71a(1).

### **Rationale**

*Oncorhynchus tshawytscha* is present in South Africa and is likely confined to aquaculture facilities. There are no known naturalised populations. Management of trout species in South Africa is relatively difficult. This because trout are conflict-generating invasive species that have major negative environmental impacts, but also some socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Therefore, the recommended management option is to restrict importation through permitting and implement intervention measures similar to those proposed for other trout species in South Africa to prevent spread and minimise impacts (Woodford et al. 2017).

### **Potential criteria for permits and exemptions**

Two key aims for the management of trout species in South Africa should be to: a) prevent the spread to new areas; and b) limit the negative environmental impacts by controlling trout populations in key fish conservation areas. To this end, those catchments where trout does not yet occur but where suitable habitat exists, and key fish conservation areas (with and without trout populations) would need to be identified in a National Management Plan that contains appropriate maps. The inclusion of maps outlining areas where permits may be granted would greatly facilitate the application and processing of permits.

The beneficial uses of trout species could then be managed as follows:

- Permits for existing or new aquaculture facilities could be granted, but only if such activities do not result in new sites becoming invaded or spread of trout into key fish conservation areas. As such permits would not be issued for aquaculture facilities in discrete catchment systems in which trout does not yet occur or that include key fish conservation areas. Permits could, however, be granted for aquaculture facilities in part of a discrete catchment system where trout occurs, providing there are natural or artificial habitat barriers (for example waterfalls, dams or weirs) that would prevent the spread of trout to other parts of the catchment system where it is currently absent, but where suitable habitat exists.
- In terms of restocking the same considerations as for aquaculture facilities would apply.
- In terms of angling, catch-and-release (i.e. the practice of anglers to return a fish to the water where it was caught) is exempt in any discrete-catchments that are specified on maps produced as per the National Management Plan. At all other sites catch-and-kill should be practised. This provision could be incorporated into provincial freshwater angling licences.
- The transport of live fish or eggs would always require a permit, but any dead specimens (e.g. for personal consumption or commercial trade) would, of course, be exempt.

### **National Management Plan**

To facilitate the implementation of these criteria and to ensure the process is transparent, it would be important to draw up a National Management Plan for each trout species. The plan would need to



include maps of the catchments where permits may be issued for commercial production purposes, where permits may be issued for restocking, and where catch-and-release angling is exempt. Maps of key fish conservation areas would also be useful to indicate areas where catch-and-kill would need to be practised.

The National Management Plan would also need to specify the standards that should be met to limit the risk of escape or unintentional or illegal re-distribution to new areas.

### **Overall recommendation**

#### **Proposed listing**

**Taxon:** *Oncorhynchus tshawytscha* (Walbaum, 1792)

**Common name:** Chinook salmon

**Category:** no change

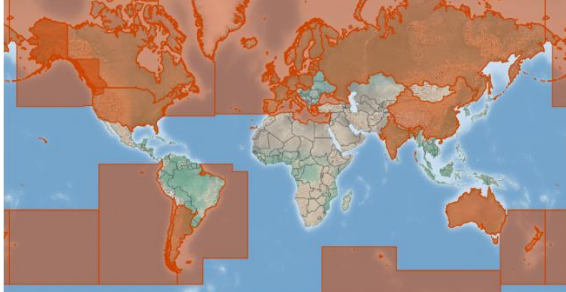
**Exemption:** catch-and-release is exempt in areas specified in maps produced as part of a National Management Plan for *O. tshawytscha*.

Permits may only be issued in line with the considerations discussed in the “Potential criteria for permits and exemptions” section above.

#### **Reference**

Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF.2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. *Bothalia* 4: a2138.

## Appendix 5.4<sup>7</sup>: Atlantic salmon (*Salmo salar*)

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                                                                                                                                                                                                                                                                                            |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Taxon:</b> <i>Salmo salar</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | <b>Area:</b> South Africa                                                                                                                                                                                                                                                                                  |
| <b>Compiled by:</b> Lerato Maimela                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | <b>Approved by:</b>                                                                                                                                                                                                                                                                                        |
| <b>Picture of Taxon</b><br><br><a href="https://www.fisheries.noaa.gov/species/atlantic-salmon-protected">https://www.fisheries.noaa.gov/species/atlantic-salmon-protected</a>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | <b>Alien distribution map</b><br><br><small>CABI, 2021. <i>Salmo salar</i>. In: Invasive Species Compendium. Wallingford, UK: CAB International. <a href="https://www.cabi.org/isc">https://www.cabi.org/isc</a></small> |
| <b>Risk Assessment summary:</b><br><i>Salmo salar</i> (Atlantic salmon) are native to North Atlantic on both the European (Portugal to Russia) and North American (Cape Cod to Labrador) sides. They also occur around North Atlantic islands (e.g., UK, Iceland, Greenland). It was introduced in South Africa in 1896 for angling but the introduction was not successful. Further intentional introductions unlikely as common pathways of introduction (e.g. angling and aquaculture) are infrequently used. Evidence from elsewhere, suggests that <i>S. salar</i> can cause moderate environmental impacts through hybridisation with native fish and predation of native fish, amphibians and macroinvertebrates.                                                                                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                                                                            |
| <b>Risk score:</b><br>Low                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                            |
| <b>Management options summary:</b><br>Management of trout species in South Africa is difficult. This is because trout are a conflict-generating invasive species that have major negative environmental impacts, but also have socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Part of the proposed management initiatives for <i>S. salar</i> is to restrict importation through permitting and implement post border intervention measures similar to those proposed for other trout species in South Africa. This includes managing the species by area where utilisation is to be allowed in areas where other trout species have naturalised and in areas where they have been historically utilised for stocking. However, concerned stakeholders have highlighted the need for broader consultations and transparency on the evidence used to assess the risks posed by trout to biodiversity and the benefits derived from their utilisation. |                                                                                                                                                                                                                                                                                                            |
| <b>Ease of management:</b><br>Medium                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                                                                                                                                                                                                                                                                                                            |
| <b>Recommendations:</b><br>Given that <i>S. salar</i> is not present in the country, and has moderate environmental impacts in its global introduction range it was assessed as a low risk. Therefore the recommendation is that it should be not be listed in the NEM:BA A&IS lists (see Appendix MAN6 for details).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                                                                                                                                                                                                                                                                                            |
| <b>Listing under NEM:BA A&amp;IS lists of 2014 as amended 2021:</b><br>Not listed                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                                                                                                                                                                                                                                                                                            |
| <b>Recommended listing category:</b><br>No change                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                                                                                                                                                                                                                                                                                            |

### 1. Background

<sup>7</sup> This risk analyses report for *Salmo salar* (Atlantic salmon) is presented as submitted to the South African Alien Species Risk Analysis Review Panel (ASRARP), a committee that is tasked with reviewing risk analyses attached to import applications and listing of species under national legislation to ensure they are scientifically robust and take into account the best available evidence (see Kumschick et al. 2020 for details). ASRARP is an independent body and its members consist of scientists and taxon experts working on various issues on biological invasions. The committee provides recommendations to an interdepartmental panel set up by the Department of Forestry, Fisheries and the Environment tasked with granting import permits and/or approving changes to regulations on biological invasions.



|                                                                                                                                                                                                                                                  |                                                                  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|
| <b>BAC1 Name of assessor(s)</b>                                                                                                                                                                                                                  |                                                                  |
| Name of lead assessor                                                                                                                                                                                                                            | Lerato Maimela                                                   |
| Additional assessor (1)                                                                                                                                                                                                                          | TA Zengeya                                                       |
| Additional assessor (2)                                                                                                                                                                                                                          | CT Chimimba                                                      |
| <b>BAC2 Contact details of assessor (s)</b>                                                                                                                                                                                                      |                                                                  |
| Lead assessor                                                                                                                                                                                                                                    | Organisational affiliation: University of Pretoria               |
|                                                                                                                                                                                                                                                  | email: lerato.maimela@zoology.up.ac.za                           |
|                                                                                                                                                                                                                                                  | Phone: 012 420 4315                                              |
| Additional assessor (1)                                                                                                                                                                                                                          | Organisational affiliation: South African Biodiversity institute |
|                                                                                                                                                                                                                                                  | email: t.zengeya@sanbi.org.za                                    |
|                                                                                                                                                                                                                                                  | Phone: 021 799 8408                                              |
| Additional assessor (2)                                                                                                                                                                                                                          | Organisational affiliation: University of Pretoria               |
|                                                                                                                                                                                                                                                  | email: chris.chimimba@up.ac.za                                   |
|                                                                                                                                                                                                                                                  | Phone: 012 420 3808                                              |
| <b>BAC3 Name(s) and contact details of expert(s) consulted</b>                                                                                                                                                                                   |                                                                  |
| Expert (1)                                                                                                                                                                                                                                       | Name:                                                            |
|                                                                                                                                                                                                                                                  | email:                                                           |
|                                                                                                                                                                                                                                                  | Phone:                                                           |
| Expert (2)                                                                                                                                                                                                                                       | Name:                                                            |
|                                                                                                                                                                                                                                                  | email:                                                           |
|                                                                                                                                                                                                                                                  | Phone:                                                           |
| Comments:                                                                                                                                                                                                                                        |                                                                  |
| <b>BAC4 Scientific name of <i>Taxon</i> under assessment</b>                                                                                                                                                                                     |                                                                  |
| <i>Taxon</i> name: <i>Salmo salar</i>                                                                                                                                                                                                            | Authority: Linnaeus, 1758                                        |
| Comments: <i>Salmo salar</i> is the accepted taxonomic name for this fish in the family Salmonidae (GBIF 2021).                                                                                                                                  |                                                                  |
| References:<br>GBIF. 2021. <i>Salmo salar</i> Linnaeus, 1758. In: <i>GBIF Backbone Taxonomy, Checklist dataset</i> , viewed 19 August 2021, <a href="https://www.gbif.org/species/7595433">https://www.gbif.org/species/7595433</a>              |                                                                  |
| <b>BAC5 Synonym(s) considered</b>                                                                                                                                                                                                                |                                                                  |
| Synonyms: There are 29 synonyms listed for <i>Salmo salar</i> in Fishbase (Froese and Pauly 2022).                                                                                                                                               |                                                                  |
| Comments:<br>This assessment only considered <i>S. salar</i> in its literature search.                                                                                                                                                           |                                                                  |
| References:<br>Froese R, Pauly D (Editors). 2022. FishBase. World Wide Web electronic publication. <a href="http://www.fishbase.org">www.fishbase.org</a> , ( 06/2022 )                                                                          |                                                                  |
| <b>BAC6 Common name(s) considered</b>                                                                                                                                                                                                            |                                                                  |
| Common names: Atlantic salmon                                                                                                                                                                                                                    |                                                                  |
| Comments:<br>There are over 50 vernacular names listed for <i>S. salar</i> on FishBase. Some of the common English names are Atlantic salmon, bay salmon, black salmon, Breedr, caplin-scul salmon, common atlantic salmon, fiddler and grayling |                                                                  |
| References:<br>Froese R, Pauly D (Editors). 2022. FishBase. World Wide Web electronic publication. <a href="http://www.fishbase.org">www.fishbase.org</a> , ( 06/2022 )                                                                          |                                                                  |
| <b>BAC7 What is the native range of the <i>Taxon</i>?</b> (add map in Appendix BAC7)                                                                                                                                                             |                                                                  |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |     |                        |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|------------------------|
| Response: Atlantic salmon are native to North Atlantic on both the European (Portugal to Russia) and North American (Cape Cod to Labrador) sides. They also occur around North Atlantic islands (e.g., UK, Iceland, Greenland). (Jones 1959, Scott and Crossman 1973, Mills 1980).                                                                                                                                                                                                                              |     | Confidence: High       |
| Comments:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |     |                        |
| References:<br>Jones JW. 1959. The Salmon. Collins, London, 192 pp.<br>Mills D. 1980. Scotland's King of Fish. Blackwood, Edinburgh. 74 pp.<br>Scott WB, Crossman EJ. 1973. Freshwater Fishes of Canada. Fisheries Research Board of Canada, Ottawa, Bulletin No. 184, 966 pp.                                                                                                                                                                                                                                  |     |                        |
| <b>BAC8 What is the global alien range of the <i>Taxon</i>? (add map in Appendix BAC8)</b>                                                                                                                                                                                                                                                                                                                                                                                                                      |     |                        |
| Response:<br>Atlantic salmon has been introduced introduced to New Zealand, Chile, southern Argentina and Australia (Kailola et al. 1993; Kottelat and Freyhof 2007).                                                                                                                                                                                                                                                                                                                                           |     | Confidence: High       |
| Comments:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |     |                        |
| References:<br>Kailola PJ, Williams MJ, Stewart PC, Reichelt RE, McNee A, Grieve C. 1993. Australian fisheries resources. Bureau of Resource Sciences, Canberra, Australia. 422 p.<br>Kottelat M, Freyhof J. 2007. Handbook of European freshwater fishes. Publications Kottelat, Cornol and Freyhof. Berlin, State of wild Atlantic salmon: A river by river assessment, WWF, 646 pp.                                                                                                                          |     |                        |
| <b>BAC9 Geographic scope = the Area under consideration</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                     |     |                        |
| Area of assessment: South Africa                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |     |                        |
| Comments:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |     |                        |
| <b>BAC10 Is the <i>Taxon</i> present in the Area?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                        |
| Response: yes                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |     | Confidence: High       |
| Comments: Atlantic salmon was introduced to South Africa in 1896 for angling but the introduction was not successful, probably due to lack of suitable habitats (Ellender et al. 2014; Weyl et al. 2020).                                                                                                                                                                                                                                                                                                       |     |                        |
| References:<br>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b> : 117–132.<br>Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), <i>Biological invasions in South Africa</i> . Springer, Berlin, pp 153-183. |     |                        |
| <b>BAC11 Availability of physical specimen</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |     |                        |
| Response: None                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |     | Confidence in ID: High |
| Herbarium or museum accession number:                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |                        |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |     |                        |
| <b>BAC12 Is the <i>Taxon</i> native to the Area or part of the Area?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                        |     |                        |
| The <i>Taxon</i> is native to (part of) the Area.                                                                                                                                                                                                                                                                                                                                                                                                                                                               | No  | Confidence: High       |
| The <i>Taxon</i> is alien in (part of) the Area.                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Yes | Confidence: High       |
| Comments: Atlantic salmon are native to North Atlantic on both the European (Portugal to Russia) and North American (Cape Cod to Labrador) sides. They also occur around North Atlantic islands (e.g., UK, Iceland, Greenland). (Jones 1959, Scott and Crossman 1973, Mills 1980).                                                                                                                                                                                                                              |     |                        |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                     |                  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|------------------|
| References:<br>Jones JW. 1959. The Salmon. Collins, London, 192 pp.<br>Mills D. 1980. Scotland's King of Fish. Blackwood, Edinburgh, 74 pp.<br>Scott WB, Crossman EJ. 1973. Freshwater Fishes of Canada. Fisheries Research Board of Canada, Ottawa, Bulletin No. 184, 966 pp.                                                                                                                                                                                                                                 |                     |                  |
| <b>BAC13 What is the <i>Taxon's</i> introduction status in the Area?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                       |                     |                  |
| The <i>Taxon</i> is in cultivation/containment.                                                                                                                                                                                                                                                                                                                                                                                                                                                                | No                  | Confidence: High |
| The <i>Taxon</i> is present outside of cultivation/containment.                                                                                                                                                                                                                                                                                                                                                                                                                                                | No                  | Confidence: High |
| The <i>Taxon</i> has established/naturalised.                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | No                  | Confidence: High |
| The <i>Taxon</i> is invasive.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | No                  | Confidence: High |
| Comments: Atlantic salmon was introduced to South Africa in 1896 for angling but the introduction was not successful, probably due to lack of suitable habitats (Ellender et al. 2014; Weyl et al. 2020).                                                                                                                                                                                                                                                                                                      |                     |                  |
| References:<br>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b> : 117–132.<br>Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), <i>Biological invasions in South Africa</i> . Springer, Berlin, pp153-183. |                     |                  |
| <b>BAC14 Primary (introduction) pathways</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                     |                  |
| Release                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Fishery in the wild | Confidence: High |
| Escape                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | N/A                 | Confidence: High |
| Contaminant                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | N/A                 | Confidence: High |
| Stowaway                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | N/A                 | Confidence: High |
| Corridor                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | N/A                 | Confidence: High |
| Unaided                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | N/A                 | Confidence: High |
| Comments:<br>Introduced to areas outside its native range for angling (Vøllestad et al 2014).                                                                                                                                                                                                                                                                                                                                                                                                                  |                     |                  |
| References:<br>Vøllestad LA, Skurdal, L'Abée-Lund JH. 2014. Evaluation of a new management scheme for Norwegian Atlantic Salmon <i>Salmo salar</i> . <i>Fisheries Management and Ecology</i> <b>21</b> :133–139.                                                                                                                                                                                                                                                                                               |                     |                  |

## 2. Likelihood

| <b>LIK1 Likelihood of entry via unaided primary pathways</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Response: Unlikely                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Confidence: High |
| <p><b>Rationale:</b><br/>Atlantic salmon were introduced into South Africa in 1896, however these introductions were not successful (Ellender et al. 2014; Marshall 2011). No recent import record of the species into the country (SANBI and CIB 2020).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                  |
| <p><b>References:</b><br/>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> 9:117–132.<br/>SANBI and CIB. 2020. Appendix 6 to "The Status of Biological Invasions and their Management in South Africa in 2019"—Permit database. South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch. <a href="http://dx.doi.org/10.5281/zenodo.3947810">http://dx.doi.org/10.5281/zenodo.3947810</a><br/>Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), <i>Biological invasions in South Africa</i>. Springer, Berlin, pp 153-183.</p> |                  |
| <b>LIK2 Likelihood of entry via human aided primary pathways</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                  |
| Response: Unlikely                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Confidence: High |
| <p><b>Rationale:</b><br/>There is no known evidence of atlantic salmon occurrence in the neighbouring countries, so the only possible introduction via human aided primary pathway is from other continents which is currently unlikely (Ellender et al. 2014; Marshall et al. 2011).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |
| <p><b>References:</b><br/>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> 9: 117–132.<br/>Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), <i>Biological invasions in South Africa</i>. Springer, Berlin, pp 153-183.</p>                                                                                                                                                                                                                                                                                                                                                                           |                  |
| <b>LIK3 Habitat suitability</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                  |
| Response: probable                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Confidence: High |
| <p><b>Rationale:</b><br/>Similar to rainbow trout and brown trout, Atlantic salmon prefer clear, cool, well-oxygenated creeks, small to medium rivers, and lakes (prefer streams with cool, flowing waters and rocky substrate (Page and Burr 2011). These habitat are found in several headwater mountain streams in South Africa. However confidence is marked as medium because previous introduction attempts in the wild were not successful (see Ellender and Weyl 2014).</p>                                                                                                                                                                                                                                                                                                                                                                                                              |                  |
| <p><b>References:</b><br/>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> 9: 117–132.<br/>Page LM, Burr BM. 2011. A field guide to freshwater fishes of North America north of Mexico. Boston: Houghton Mifflin Harcourt, 663 p.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                  |
| <b>LIK4 Climate suitability</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                  |
| Response: probable                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Confidence: High |
| <p><b>Rationale:</b><br/>Atlantic salmon is a cold water species that prefer streams with temperature range between 10 -18° (Mills 1989; Bjorn and Reiser 1991). These climatic conditions can be found in the headwaters of many rivers in South Africa, especially the eastern escarpment stretching from the south-western Cape to Northern Kwa-Zulu Natal as indicated by systematic climate modelling studies (Picker and</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                  |

Griffiths 2011; Weyl and Keevey 2012; Ellender et al. 2016; Rivers-Moore et al. 2019). However confidence is marked as medium because previous introduction attempts in the wild were not successful (see Ellender et al. 2014).

**References:**

- Bjorn TC, Reiser DW. 1991. Habitat Requirements of Salmonids in Streams. In: Influences of forest management on salmonid fishes and their habitats. Meehan, W.R. (ed.), Bethesda: American Fisheries Society.
- Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. *Aquatic Invasions* **9**: 117–132.
- Ellender BR, Rivers-Moore NA, Coppinger CR, Bellingan TA, Weyl OLF. 2016. Towards using thermal stress thresholds to predict salmonid invasion potential. *Biological Invasions* **18**: 3513–3525.
- Mills D. 1989. Ecology and Management of Atlantic Salmon. Department of Forestry and Natural Resources, University of Edinburgh, London: Chapman and Hall.
- Picker MD, Griffiths CL. 2011. Alien and invasive animals – A South African Perspective, Randomhouse/Struik, Cape Town, South Africa, 240 pp.
- Rivers-Moore NA, Ellender BR, Weyl OLF. 2019. Modelling expected trout ranges under current and future water temperature regimes in the Eastern Cape, South Africa. *African Journal of Aquatic Science* **44**: 35–42.
- Weyl OLF, Keevey G. 2012. Deliverable 17. Report on GIS mapping and bibliography of dams with inland fisheries potential. Water Research Commission, Baseline and scoping study on the development and sustainable utilisation of storage dams for inland fisheries and their contribution to rural livelihoods Project Title: K5/1957/4.

**LIK5 Unaided secondary (dispersal) pathways**

Response: Very unlikely

Confidence: High

**Rationale:**

There is no known populations of Atlantic salmon (in captivity or in the wild) in the South Africa or neighbouring countries which may facilitate its dispersal into the country via interconnected catchments (Ellender et al. 2014; Marshal 2011).

**References:**

- Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. *Aquatic Invasions* **9**: 117–132.
- Marshall BE. 2011. The Fishes of Zimbabwe and their Biology. Smithiana Monography 3, The South Africa Institute for Aquatic Biodiversity, Grahamstown, South Africa

**LIK6 Human aided secondary (dispersal) pathways**

Response: Very unlikely

Confidence: High

**Rationale:**

There is no recent records of introduction and utilisation of the brook trout for aquaculture and or angling (Ellender et al. 2014; Weyl et al. 2020). Therefore, the likelihood of human-aided dispersal of brook trout through human aided secondary (dispersal) pathways is unlikely

**References:**

- Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. *Aquatic Invasions* **9**: 117–132.
- Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), *Biological invasions in South Africa*. Springer, Berlin, pp 153-183.

### 3. Consequences

**CON1 Environmental impact**

**CON1a: Competition**

Response: MO

Confidence: Medium

**Rationale:**

Evidence from across the invaded range including Argentina and Chile shows that *S. salar* have adverse impacts on the population of native fishes through competition and predation (Whitley

1935; Andrews 1976; Glova 1990; Glova 1989; Soto et al. 2001; Buschmann et al. 2009; De Leaniz et al. 2010; Niklitschek et al. 2013).

**References:**

- Andrews AP. 1976. A revision of the family Galaxiidae (Pisces) in Tasmania. *Australian Journal of Marine and Freshwater Research* **27**: 297-349.
- Buschmann A, Costa-Pierce BA, Cross S, Iriarte J, Olsen LY, Reid G. 2009. Nutrient Impacts of Farmed Atlantic Salmon (*Salmo Salar*) On Pelagic Ecosystems And Implications For Carrying Capacity. Salmon Aquaculture Dialogue, WWF.
- De Leaniz CG, Gajardo G, Consuegra S. 2010. From Best to Pest: changing perspectives on the impact of exotic salmonids in the southern hemisphere. *Systematics and Biodiversity* **8**: 447-459.
- Glova GJ. 1989. Native and salmonid fishes: are they compatible? *Freshwater Catch* **40**: 12-13.
- Glova GJ. 1990. Galaxiids more vulnerable than bullies to trout predation. *Freshwater Catch* **43**: 19 p.
- Niklitschek EJ, Soto D, Lafon A, Molinet C, Toledo P. 2013. Southward expansion of the Chilean salmon industry in the Patagonian fjords: main environmental challenges. *Reviews in Aquaculture* **5**: 172-195.
- Soto D, Norambuena F. 2001. Evaluation of salmon farming effects on marine systems in the inner seas of southern Chile: a large-scale mensurative experiment. *Journal of Applied Ichthyology* **20**: 493-501.
- Whitley GP. 1935. Whitebait. *Victorian Naturalist* **52**: 41-5 1.

**CON1b: Predation**

Response: MO

Confidence: Medium

**Rationale:**

Evidence from across the invaded range including Argentina and Chile shows that *S. salar* have adverse impacts on population of native fishes through competition and predation (Soto et al. 2001; Buschmann et al. 2009; De Leaniz et al. 2010; Niklitschek et al. 2013).  
In South Africa, there are no reported impacts from *S. salar*.

**References:**

- De Leaniz CG, Gajardo G, Consuegra S. 2010. From Best to Pest: changing perspectives on the impact of exotic salmonids in the southern hemisphere. *Systematics and Biodiversity* **8**: 447-459.
- Buschmann A, Costa-Pierce BA, Cross S, Iriarte J, Olsen LY, Reid G. 2009. Nutrient Impacts of Farmed Atlantic Salmon (*Salmo Salar*) On Pelagic Ecosystems And Implications For Carrying Capacity. Salmon Aquaculture Dialogue, WWF.
- Soto D, Norambuena F. 2001. Evaluation of salmon farming effects on marine systems in the inner seas of southern Chile: a large-scale mensurative experiment. *Journal of Applied Ichthyology* **20**: 493-501.
- Niklitschek EJ, Soto D, Lafon A, Molinet C, Toledo P. 2013. Southward expansion of the Chilean salmon industry in the Patagonian fjords: main environmental challenges. *Reviews in Aquaculture* **5**: 172-195.

**CON1c: Hybridisation**

Response: MO

Confidence: High

**Rationale:**

Deleterious genetic interactions have been particularly well documented for Atlantic salmon (McGinnity et al. 2003; Naylor et al. 2005) and chinook salmon (Waples 1991), including irreversible loss of genetic diversity leading to reduced environmental adaptability, significant fitness reduction and potential local extinction of wild populations.  
There are no native species in the family Salmonidae in South Africa, therefore there is no risk of hybridisation (Skelton 2001)

**References:**

- McGinnity P, Prodohl P, Ferguson A, Hynes R, Maoiléidigh Nó, Baker N, Cotter D, O'Hea B, Cooke D, Rogan G. 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. *Proceedings of the Royal Society of London. Series B, Biological Sciences* **270**: 2443-2450.
- Naylor R, Hindar K, Fleming IA, Goldberg R, Williams S, Volpe J, Whoriskey F, Eagle J, Kelso D, Mangel M. 2005. Fugitive salmon: assessing the risks of escaped fish from net-pen aquaculture. *Bioscience* **55**: 427-437.



Waples RS. 1991. Genetic interactions between hatchery and wild salmonids: lessons from the Pacific Northwest. *Canadian Journal of Fisheries and Aquatic Sciences* **48**: 124-133.  
Skelton PH. 2001. A complete guide to the freshwater fishes of Southern Africa, Struik Publishers, Cape Town, South Africa.

#### CON1d: Transmission of disease

Response: MN

Confidence: Medium

##### Rationale:

Studies in several countries (e.g., Ireland, Scotland, Norway, Canada, the USA, and Chile) suggest the occurrence of several diseases is often correlated introduction of alien salmonids (Krkosek et al. 2005; Naylor et al. 2005; Sepulveda et al. 2013; van der Veer and Nentwig 2015). These include diseases such as rickettsial septicemia, sea lice (*Caligus* spp.), pancreatic necrosis virus, and salmon anemia virus (Rodríguez Saint Jean et al. 2003, Asche et al. 2010; Niklitschek et al. 2013). For example, while the presence of the ISA virus in Chile is broadly considered to be associated with the development of salmon farming in the region (Kibenge 2011), the virus itself was not identified in 502 samples of local fish, mollusks, crustaceans, sea lion feces, and microplankton, and the only positive result was from a free-living Atlantic salmon escapee (Gonzalez et al. 2011). ISA is also not known to have caused mortalities in any wild populations of salmon (NOAA 2012). On this basis, it seems unlikely that this particular virus has any significant impact on wild fish populations.

##### References:

- Asche F, Hansen H, Tveteras R, Tveteras S (2010) The salmon disease crisis in Chile. *Marine Resource Economics* **24**: 405–411.
- Bridson P. 2014. Montero Bay Aquarium Seafood Watch. Chile, Net pens.
- Gonzalez RR, Ruiz P, Llanos-Rivera A, Cruzat F, Silva J, Astuya A, Grandon M, Jara D, Aburto C. 2011. ISA virus outside the cage: Ichthyofauna and other possible reservoirs to be considered for marine biosafety management in the far-southern ecosystems of Chile. *Aquaculture* **318**: 37-42.
- Kibenge FSB. 2011. The Recovery of the Chilean Salmon Industry: The ISA crisis and its consequences and lessons. GAA GOAL Conference, Santiago Chile, November 2011.
- Krkosek M, Lewis MA, Volpe JP. 2005. Transmission dynamics of parasitic sea lice from farms to wild salmon. *Proceedings of the Royal Society B: Biological Sciences* **272**: 689–696.
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- Niklitschek EJ, Soto D, Lafon A, Molinet C, Toledo P. 2013. Southward expansion of the Chilean salmon industry in the Patagonian Fjords: main environmental challenges. *Reviews in Aquaculture* **4**: 1–24.
- Norwegian salmon farming in 2010. Report 53/2011, Published December 2011.
- Rodríguez Saint-Jean S, Borrego J, Pérez-Prieto S. 2003. Infectious pancreatic necrosis virus: biology, pathogenesis and diagnostic methods. *Advances in Virus Research* **62**: 113–165.
- Sepulveda M, Arismendi I, Soto D, Jara F, Farias F. 2013. Escaped farmed salmon and trout in Chile: incidence, impacts, and the need for an ecosystem view. *Aquaculture Environment Interactions* **4**: 273-283.

#### CON1e: Parasitism

Response: MN

Confidence: Medium

##### Rationale:

Even though, in many cases the mechanisms for pathogen transmission are unknown and highly unpredictable, there are several examples where escapees served as vectors of transmission of parasites, virus and bacterial diseases, particularly in salmon (Naylor et al. 2005). For instance, escapes of farmed salmonids have been linked to outbreaks of parasitic sea lice in several farming regions (Naylor et al. 2005; Costello 2006). In many cases, salmon in open net pen farms are initially infected by pathogens or parasites associated with local native fish populations, but due to the scale of farm operations they do have the potential to be a substantial point source of retransmission of the same pathogens (and potentially more virulent strains of those pathogens) to the same, or other, wild species (Rimstad 2011). Wild fish populations may carry these pathogens but be less susceptible to clinical disease

outbreak without the stress associated with the farm environment. Rimstad (2011) stated, "With the possible exception of salmon lice, there are few reliable data sets on the distribution of fish pathogens in wild populations, and the knowledge of interactions with wild reservoirs is thus limited."

Sepulveda et al. (2004) which compared the parasites of wild and farmed fish and the potential infection vectors between them. Of nine species of ectoparasites (external) and 21 species of endoparasites (internal), an overlap between wild fish and farmed salmon was only demonstrated for two parasites (the sea lice *Caligus rogercresseyi*, and the nematode worm *Hysterothylacium aduncum*). While it is assumed that native fish species such as the rock cod "Roballo" (*Eleginops maclovinus*) were the original source of the sea lice infections on the farm, this species sheds this parasite during migration to estuaries and rivers in the fall and regains the infection when returning to the sea in spring. While this means Roballo may be able to avoid serious impacts, it is farmed salmonids that have now become the source of infection of sea lice in this native species (Sepulveda et al. 2004).

Bravo et al. (2011) reported that *C. rogercresseyi* was recorded for the first time in Chile on Atlantic salmon in the Puerto Montt area but are now widely distributed in other areas.

**References:**

Bravo S, Boxshall G, Conroy G. 2011. New cultured host and a significant expansion in the known geographical range of the sea louse *Caligus rogercresseyi*. *Bulletin of the European Association of Fish Pathologists* **31**:156-160.

Bridson P. 2014. Montero Bay Aquarium Seafood Watch. Chile, Net pens.

Naylor R, Hindar K, Fleming IA, Goldburg R, Williams S, Volpe J, Whoriskey F, Eagle J, Kelso D, Mangel M. 2005. Fugitive salmon: assessing the risks of escaped fish from net-pen aquaculture. *Bioscience* **55**: 427-437.

Costello MJ. 2006. Ecology of sea lice parasitic on farmed and wild fish. *Trends Parasitol* **22**: 475-483.

Rimstad E. 2011. Examples of emerging virus diseases in salmonid aquaculture. *Aquaculture Research* **42**: 86-89.

Sernapesca. 2011. Resultados Diagnóstico General por Jaula Anual de Caligidosis en Chile (DGJA) de 2011. Servicio Nacional de Pesca Septiembre 2011.

Sepulveda F, Marin S, Carvajal J. 2004. Metazoan parasites in wild fish and farmed salmon from aquaculture sites in southern Chile. *Aquaculture* **235**: 89-100.

**CON1f: Poisoning/toxicity**

Response: DD Confidence: Low

Rationale: No documented information available to assess the level of impact

**References:**

**CON1g: Bio-fouling or other direct physical disturbance**

Response: DD Confidence: Low

Rationale: No documented information available to assess the level of impact

**References:**

**CON1h: Grazing/herbivory/browsing**

Response: DD Confidence: Low

Rationale: No documented information available to assess the level of impact

**References:**

**CON1i: Chemical, physical or structural impact on ecosystem**

Response: DD Confidence: Low

Rationale: No documented information available to assess the level of impact

**References:**

**CON1k: Indirect impacts through interactions with other species**

Response: MO Confidence:

Rationale: No documented information available to assess the level of impact

**References:**

**CON1 Maximum environmental impact (Figure S3)**

Response: MO Confidence: High

**Rationale:**



Atlantic salmon have been reported to impact native species through competition, predation and hybridisation leading to a reduced population of native species (e.g. de Leaniz et al. 2010).

References:

De Leaniz CG, Gajardo G, Consuegra S. 2010. From Best to Pest: changing perspectives on the impact of exotic salmonids in the southern hemisphere. *Systematics and Biodiversity* **8**: 447-459.

## CON2 Socio-economic impact

### CON2a: Safety

Response: DD

Confidence:

Rationale: No documented information available to assess the level of impact

References:

### CON2b: Material and immaterial assets

Response: DD

Confidence:

Rationale: No documented information available to assess the level of impact

References:

### CON2c: Health

Response: DD

Confidence:

Rationale: No documented information available to assess the level of impact

References:

### CON2d: Social, spiritual and cultural relations

Response: DD

Confidence:

Rationale: No documented information available to assess the level of impact

References:

### CON2 Maximum socio-economic impact (Figure S3)

Response: DD

Confidence:

Rationale: No documented information available to assess the level of impact

References:

## CON3 Closely related species' environmental impact

Response: Response: Not Scored as CON1 scored

Confidence:

Rationale: There is information to score CON1, so CON3 does not need to be scored as per the framework.

References:

## CON4 Closely related species' socio-economic impact

Response: MO

Confidence: medium

Rationale: Alien salmonid species can affect animal production (usually aquacultures) through the transmission of pathogens, which may cause relatively high expenses (van der and Nentwig 2015).

References:

van der Veer G, Nentwig, W. 2015. Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system. *Ecology of Freshwater Fishes* **24**: 646-656.

## CON5 Potential impact

Response: MR

Confidence: Medium

Rationale:

In South Africa, a national-level EICAT assessment classified impacts caused by closely related species (*Salmo trutta* and *Oncorhynchus mykiss*) as Major (MR) as they are known to cause declines, and in some cases local extinction of native invertebrates, frogs and fish through predation and competition (Marr et al. 2017). If *Salmo salar* is introduced and becomes invasive, it likely to cause similar impacts

References:

Marr S, Ellender B, Woodford D, Alexander M, Wasserman R, Ivey P, Zengeya T, Weyl O. 2017. Evaluating invasion risk for freshwater fishes in South Africa. *Bothalia* 47: 1–10.

#### 4. Management

##### MAN1 What is the feasibility to stop future immigration?

Response: High

Confidence: High

##### Rationale:

There are currently no recent records of *S. salar* occurring in South Africa and in neighbouring countries. This implies that its introduction into the country can be controlled through use of import restrictions and permitting to manage new introductions (Woodford et al. 2017).

##### References:

Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. *Bothalia* 47: a2138.

##### MAN2 Benefits of the Taxon

##### MAN2a Socio-economic benefits of the Taxon

Response: High

Confidence: Medium

##### Rationale:

Trout species have socio-economic value and are utilised in recreational fisheries in their global invasive range (e.g., Kailola et al. 1993; Muhlfeld et al. 2019). In South Africa, there are several studies that have assessed the economic benefits of trout (mainly for *Oncorhynchus mykiss*) and these strengthen the evidence base for quantifying the benefits derived from introduced fish species (Britz et al. 2009; Britz and Venter 2016; Du-Preez and Lee 2010; Anchor Environmental Consulting 2010). However, the studies were done using different methods and at small scales (e.g. towns, and discrete catchments), and the results still have to be extrapolated to larger scales (e.g. national). *Salmo trutta* is of lower importance than *O. mykiss* (rainbow trout) as it is currently used exclusively for recreational fishing, and not for commercial production (Stander and Brink 2009). No studies have been done for *S. salar*. In addition, native fish species are also available as alternatives for recreational angling (e.g. various yellowfish species, Hoogendoorn 2014).

##### References:

Anchor Environmental Consulting. 2010. The nature, distribution and value of aquatic ecosystem services of the Olifants, Inkomati and Usutu to Mhlathuze Water Management Areas, Contract report for Department: Water Affairs and Forestry, 378 pp.

Britz P, Venter S. 2016. Aquaculture review: South Africa. *World Aquaculture* 47: 20–28.

Britz PJ, Lee B, Botes L. 2009 AISA 2009 Aquaculture Benchmarking Survey: Primary Production and Markets, AISA report produced by Enviro-Fish Africa (Pty) Ltd, 117 pp.

Du-Preez M, Lee DE. 2010. The contribution of trout fly fishing to the economy of Rhodes, North Eastern Cape, South Africa. *Development Southern Africa* 27: 241–253.

Hoogendoorn G. 2014. Mapping fly-Fishing Tourism in Southern Africa. *African Journal of Hospitality, Tourism and Leisure* 3: 13 pp.

Kailola PJ, Williams MJ, Stewart PC, McNee A, Grieve C. 1993. Australian Fisheries Resources. Bureau of Resource Sciences (Department of Primary Industries and Energy) and Fisheries Research and Development Corporation, Canberra, 422 pp.

Muhlfeld CC, Dauwalter DC, D'Angelo VS, Ferguson A, Giersch JJ, Impson D, Koizumi I, Kovach R, McGinnity P, Schöffmann J, Vøllestad LA. 2019. Global status of trout and char: Conservation challenges in the twenty-first century. Trout and char of the world, pp 717-60.

Stander H, Brink D. 2009. Trout farming In South Africa: Expanding local markets work with ecotourism. *Global Aquaculture Advocate*, November/December 2009.

##### MAN2b Environmental benefits of the Taxon

Response: DD

Confidence:

Rationale: There are currently no known environmental benefits on record.

##### References:

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                  |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| <b>MAN3 Ease of management</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                  |
| <b>MAN3a How accessible are populations?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                  |
| Response: 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Confidence: High |
| Rationale:<br>There are no known populations of <i>S. salar</i> in the country (Weyl et al. 2020)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                  |
| References:<br>Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), <i>Biological invasions in South Africa</i> . Springer, Berlin, pp 151–182.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                  |
| <b>MAN3b Is detectability critically time-dependent?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |
| Response: 2 (difficult)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Confidence: High |
| Rationale: Trout can be detected at any time, but it does require special equipment (e.g. electrofishing gear) and trained specialists to operate such equipment. Detection is thus logistically challenging, but not time-dependent                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                  |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                  |
| <b>MAN3c Time to reproduction</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                  |
| Response: 1                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Confidence: High |
| Rationale:<br>In its natural habitat, it is a migratory species, with adult moving into rivers in winter to spawn. Spawning and hatching success depend upon favourable substrate and water quality. Sexual maturity reached between 1-5 years (Good and Davidson 2016)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |
| References:<br>The Status of Wild Atlantic Salmon. 2001. A River by River Assessment, WWF.<br>Good C, Davidson J. 2016. A Review of Factors Influencing Maturation of Atlantic Salmon, <i>Salmo salar</i> , with Focus on Water Recirculation Aquaculture System Environments. <i>Journal of the World Aquaculture Society</i> 47: 605-632.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                  |
| <b>MAN3d Propagate persistence</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  |
| Response: 0                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Confidence: low  |
| Rationale:<br>The total time of incubation period (60-100 days) depends on factors such as temperature and oxygen (Scott and Crossman 1985).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                  |
| References:<br>Scott W, Crossman E. 1985. Freshwater Fishes of Canada. Ottawa, Canada: Minister of Supply and Services Canada.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                  |
| <b>MAN3 Ease of management (SUM from Table S4)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  |
| Response: Medium                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Confidence: High |
| Rationale:<br>Management of <i>S. salar</i> is scored here as medium. There are no known naturalised populations or in captivity of <i>S. salar</i> in South Africa. Introductions can be managed through import restrictions and permitting. However, several issues make management challenging. These include the fact that control operations would likely be met with resistance from certain interest groups (see Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017)                                                                                                                                                                                                                                                                                                                                 |                  |
| References:<br>Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. <i>Journal of Fish Biology</i> 85: 1890–1906.<br>Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. <i>Bothalia</i> 47: 1–9.<br>Woodford DJ, Richardson DM, MacIsaac HJ, Mandrak N, van Wilgen BW, Wilson JR, Weyl OLF. 2016. Confronting the wicked problem of managing invasive species. <i>Neobiota</i> 31: 63–86.<br>Zengeya T, Ivey P, Woodford DJ, Weyl O, Novoa A, Shackleton R, Richardson D, Van Wilgen B. 2017. Managing conflict-generating invasive species in South Africa: challenges and trade-offs. <i>Bothalia</i> 47: 1–11. |                  |

**MAN4 Has the feasibility of eradication been evaluated?**

Response: No

Confidence: High

Rationale:

The species was never introduced in the country.

References:

**MAN5 Control options and monitoring approaches available for the Taxon**

Rationale:

Management of *S. salar* is scored here as medium. There are no known naturalised populations or in captivity of *S. salar* in South Africa. Introductions can be managed through import restrictions and permitting. However, several issues make management challenging. These include the fact that control operations would likely be met with resistance from certain interest groups (see Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017)

References:

Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. *Journal of Fish Biology* **85**: 1890–1906.

Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. *Bothalia* **47**: 1–9.

Woodford DJ, Richardson DM, MacIsaac HJ, Mandrak N, van Wilgen BW, Wilson JR, Weyl OLF. 2016. Confronting the wicked problem of managing invasive species. *Neobiota* **31**: 63–86.

Zengeya T, Ivey P, Woodford DJ, Weyl O, Novoa A, Shackleton R, Richardson D, Van Wilgen B. 2017. Managing conflict-generating invasive species in South Africa: challenges and trade-offs. *Bothalia* **47**: 1–11.

**MAN6 Any other management considerations to highlight? (if yes, fill in Appendix MAN6)**

Response

Yes, see Appendix MAN6

## 5. Calculations

**Likelihood** = Very unlikely

| Parameter | Likelihood    | Stages                      | Final assessment             |
|-----------|---------------|-----------------------------|------------------------------|
| LIK1      | Unlikely      | P(entry) = Unlikely         | P (invasion) = Very unlikely |
| LIK2      | Unlikely      |                             |                              |
| LIK3      | Probable      | P(establishment) = Probable |                              |
| LIK4      | Probable      |                             |                              |
| LIK5      | Very unlikely | P (spread) = Very unlikely  |                              |
| LIK6      | Very unlikely |                             |                              |

**Consequence** = Moderate (MO)

| Parameter | Mechanism/sector                                         | Response |
|-----------|----------------------------------------------------------|----------|
| CON1a     | Competition                                              | MO       |
| CON1b     | Predation                                                | MO       |
| CON1c     | Hybridisation                                            | MO       |
| CON1d     | Disease transmission                                     | MN       |
| CON1e     | Parasitism                                               | MN       |
| CON1f     | Poisoning/toxicity                                       | DD       |
| CON1g     | Bio-fouling or other direct physical disturbance         | DD       |
| CON1h     | Grazing/herbivory/browsing                               | DD       |
| CON1i     | Chemical, physical, structural impact                    | DD       |
| CON1k     | Indirect impacts through interactions with other species | DD       |
| CON1      | Maximum environmental impact                             | MO       |

|       |                                                                                                   |                                     |
|-------|---------------------------------------------------------------------------------------------------|-------------------------------------|
| CON2a | Safety                                                                                            | DD                                  |
| CON2b | Material and immaterial assets                                                                    | DD                                  |
| CON2c | Health                                                                                            | DD                                  |
| CON2d | Social, spiritual and cultural relations                                                          | DD                                  |
| CON2  | Maximum socio-economic impact                                                                     | DD                                  |
| CON3  | Environmental impact of closely related taxa<br>(only score if CON1a-k are all DD, otherwise NA)  | Not scored as<br>CON1 was<br>scored |
| CON4  | Socio-economic impact of closely related taxa<br>(only score if CON2a-g are all DD, otherwise NA) | MO                                  |
| CON5  | Potential impact based on traits, experiments, or models                                          | MR                                  |

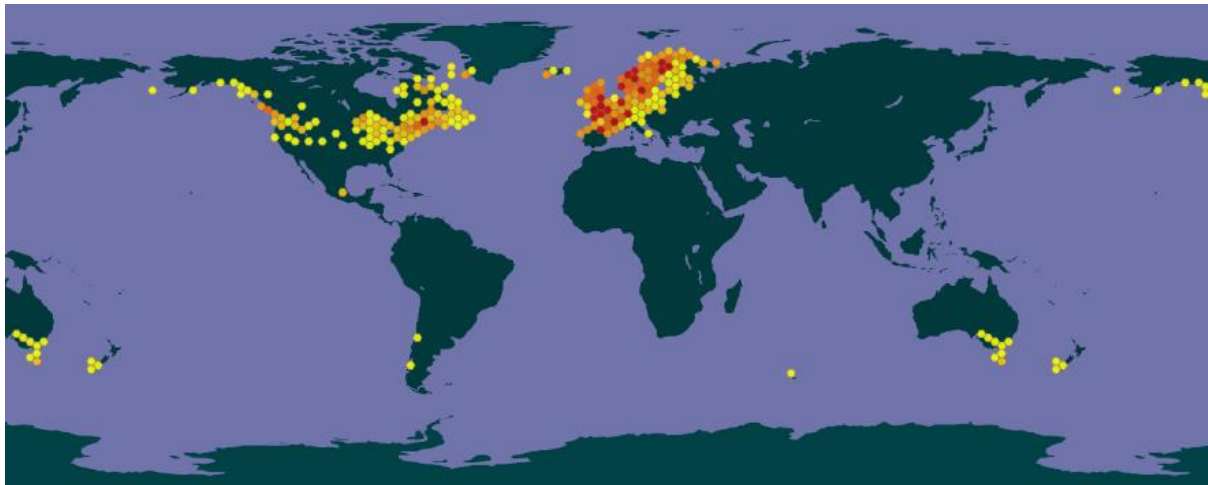
**Risk score = Low**

|                   |                    | Consequences |        |        |        |        |
|-------------------|--------------------|--------------|--------|--------|--------|--------|
|                   |                    | MC           | MN     | MO     | MR     | MV     |
| <b>Likelihood</b> | Extremely unlikely | low          | low    | low    | medium | medium |
|                   | Very unlikely      | low          | low    | low    | medium | high   |
|                   | Unlikely           | low          | low    | medium | high   | high   |
|                   | Fairly probable    | medium       | medium | high   | high   | high   |
|                   | Probable           | medium       | high   | high   | high   | high   |

**Ease of management = Medium**

| Parameter   | Question                                    | Response |
|-------------|---------------------------------------------|----------|
| MAN3a       | How accessible are populations?             | 2        |
| MAN3b       | Is detectability critically time-dependent? | 2        |
| MAN3c       | Time to reproduction                        | 1        |
| MAN3d       | Propagule persistence                       | 0        |
| <b>MAN3</b> | <b>SUM</b>                                  | 5        |

**Appendix BAC7:** Native and introduced range of *Salmo salar* with probabilities of occurrence ranging from yellow (lower) to red (higher) (GBIF Secretariat, 2020);



**Appendix MAN6:** Proposed listing options for *Salmo salar* under the NEM:BA A&IS Regulations

**Current listing as per NEM:BA A&IS lists of 2020**

**Taxon:** *Salmo salar* Linnaeus, 1758

**Common name:** Atlantic salmon

**Category:** not listed

*Salmo salar* Linnaeus, 1758 was not listed as an invasive species in the South African Government Gazette on 18 September 2020, and in the NEM:BA A&IS Lists promulgated on 1 March 2021.

#### **Rationale**

There are currently no recent records of *Salmo salar* occurring in South Africa and in neighbouring countries. Previous introduction attempts were unsuccessful. This implies that its introduction into the country can be controlled through use of import restrictions and permitting to manage new introductions (Woodford et al. 2017). Management of trout species in South Africa is relatively difficult. This because trout are conflict-generating invasive species that have major negative environmental impacts, but also some socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Therefore, the recommended management option is to restrict importation through permitting and implement intervention measures similar to those proposed for other trout species in South Africa.

#### **Potential criteria for permits and exemptions**

Two key aims for the management of trout species in South Africa should be to: a) prevent the spread to new areas; and b) limit the negative environmental impacts by controlling trout populations in key fish conservation areas. To this end, those catchments where trout does not yet occur but where suitable habitat exists, and key fish conservation areas (with and without trout populations) would need to be identified in a National Management Plan that contains appropriate maps. The inclusion of maps outlining areas where permits may be granted would greatly facilitate the application and processing of permits.

The beneficial uses of trout species could then be managed as follows:

- Permits for existing or new aquaculture facilities could be granted, but only if such activities do not result in new sites becoming invaded or spread of trout into key fish conservation areas. As such permits would not be issued for aquaculture facilities in discrete catchment systems in which trout does not yet occur or that include key fish conservation areas. Permits could, however, be granted for aquaculture facilities in part of a discrete catchment system where trout occurs, providing there are natural or artificial habitat barriers (for example waterfalls, dams or weirs) that would prevent the spread of trout to other parts of the catchment system where it is currently absent, but where suitable habitat exists.
- In terms of restocking the same considerations as for aquaculture facilities would apply.
- In terms of angling, catch-and-release (i.e. the practice of anglers to return a fish to the water where it was caught) is exempt in any discrete-catchments that are specified on maps produced as per the National Management Plan. At all other sites catch-and-kill should be practised. This provision could be incorporated into provincial freshwater angling licences.
- The transport of live fish or eggs would always require a permit, but any dead specimens (e.g. for personal consumption or commercial trade) would, of course, be exempt.

### **National Management Plan**

To facilitate the implementation of these criteria and to ensure the process is transparent, it would be important to draw up a National Management Plan for each trout species. The plan would need to include maps of the catchments where permits may be issued for commercial production purposes, where permits may be issued for restocking, and where catch-and-release angling is exempt. Maps of key fish conservation areas would also be useful to indicate areas where catch-and-kill would need to be practised.

The National Management Plan would also need to specify the standards that should be met to limit the risk of escape or unintentional or illegal re-distribution to new areas.

### **Overall recommendation**

#### **Proposed listing**

**Taxon:** *Salmo salar* Linnaeus, 1758

**Common name:** Atlantic salmon

**Category:** no change

**Exemption:** catch-and-release is exempt in areas specified in maps produced as part of a National Management Plan for *S. salar*

Permits may only be issued in line with the considerations discussed in the “Potential criteria for permits and exemptions” section above.

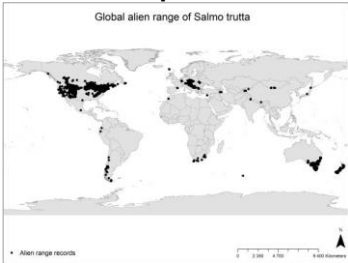
#### **Reference**

Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. *Bothalia* 47: a2138.



## Appendix 5.5<sup>8</sup>: Brown trout (*Salmo trutta*)

### Risk Analysis Report

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                            |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Taxon:</b> <i>Salmo trutta</i> Linnaeus, 1758                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | <b>Area:</b> South Africa                                                                                                                                                                                                                                  |
| <b>Compiled by:</b> Lerato T Maimela                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | <b>Approved by:</b>                                                                                                                                                                                                                                        |
| <b>Picture of Taxon</b><br><br>Photo: Agluper (from GBIF, accessed 30 July 2021)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | <b>Alien distribution map</b><br><br>Reference: GBIF, viewed 15 October 2021, from <a href="https://doi.org/10.15468/dl.7wrhav">https://doi.org/10.15468/dl.7wrhav</a> . |
| <b>Risk Assessment summary:</b><br><i>Salmo trutta</i> (Brown trout) is native to Europe, northern Africa and western Asia and was introduced to South Africa in the late nineteenth century for sport fishing and angling purposes. <i>Salmo trutta</i> also occurs in three neighbouring countries to South Africa. Therefore, <i>S. trutta</i> could potentially enter the country unaided through interconnected waterways from Eswatini and Lesotho but discontinuous habitat would prevent entry from Zimbabwe. Further intentional introductions to new areas within the country are also likely given the potential benefits of <i>S. trutta</i> . Evidence from elsewhere and from South Africa, suggests that <i>S. trutta</i> has major or massive environmental impacts through competition with native fish and predation of native fish, amphibians and macroinvertebrates. | <b>Risk score:</b><br><br>High                                                                                                                                                                                                                             |
| <b>Management summary:</b><br>Management of <i>Salmo trutta</i> in South Africa is medium. This is because <i>S. trutta</i> is a conflict-generating invasive species that has major negative environmental impacts, but also has socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Part of the proposed management initiatives for <i>S. trutta</i> includes managing it by area where utilisation is to be allowed in areas where it has naturalised and in areas where it has been historically utilised for stocking. However, concerned stakeholders have highlighted the need for broader consultations and transparency on the evidence used to assess the risks posed by trout to biodiversity and the benefits derived from their utilisation.                                                                             | <b>Ease of management:</b><br><br>Medium                                                                                                                                                                                                                   |
| <b>Recommendations:</b><br>Given that <i>S. trutta</i> has major negative environmental impacts, but also some socio-economic benefits the recommendation is that it should be listed as Category 2 species in the NEM:BA A&IS lists (see Appendix MAN6 for details).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | <b>Listing under NEM:BA A&amp;IS lists of 2014 as amended 2021:</b><br>Not listed <sup>9</sup>                                                                                                                                                             |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | <b>Recommended listing category:</b><br>2 (with exemption)                                                                                                                                                                                                 |

<sup>8</sup> This risk analyses report for *Salmo trutta* (brown trout) is presented as submitted to the South African Alien Species Risk Analysis Review Panel (ASRARP), a committee that is tasked with reviewing risk analyses attached to import applications and listing of species under national legislation to ensure they are scientifically robust and take into account the best available evidence (see Kumschick et al. 2020 for details). ASRARP is an independent body and its members consist of scientists and taxon experts working on various issues on biological invasions. The committee provides recommendations to an interdepartmental panel set up by the Department of Forestry, Fisheries and the Environment tasked with granting import permits and/or approving changes to regulations on biological invasions.

<sup>9</sup> A proposal for listing was published in the Government Gazette but not promulgated, see Appendix MAN6 for details.



## 1. Background

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                                                                   |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| <b>BAC1 Name of assessor(s)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                                                                   |
| Name of lead assessor                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | Lerato Maimela                                                                    |
| Additional assessor (1)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Tsungai Zengeya                                                                   |
| Additional assessor (2)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Anicia Malebajoa Maoela                                                           |
| Additional assessor (3)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Humbelani Felicia Thenga                                                          |
| <b>BAC2 Contact details of assessor (s)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                                                                                   |
| Lead assessor                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Organisational affiliation: University of Pretoria                                |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | email: lerato.maimela@zoology.up.ac.za                                            |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Phone:                                                                            |
| Additional assessor (1)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Organisational affiliation: Dr Tsungai Zengeya                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | email: T.Zengeya@sanbi .org.za                                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Phone 021 799 8408                                                                |
| Additional assessor (2)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Organisational affiliation: NA                                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | email: malebajoam@gmail.com                                                       |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Phone: +27 79 725 3786                                                            |
| Additional                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Organisational affiliation: Council for Scientific and Industrial Research (CSIR) |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | email: HThenga@csir.co.za                                                         |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Phone: +27 12 841 4112                                                            |
| <b>BAC3 Name(s) and contact details of expert(s) consulted</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                   |
| Expert (1)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Name: Dr Dalu Tatenda                                                             |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | email: dalutatenda@yahoo.co.uk                                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Phone: +27 13 002 0001                                                            |
| Comments: Dr Dalu Tatenda is a lecturer at the University of Mpumalanga. He provided information on the impacts of the taxon under assessment.                                                                                                                                                                                                                                                                                                                                                                                                                                |                                                                                   |
| <b>BAC4 Scientific name of <i>Taxon</i> under assessment</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                   |
| Taxon name: <i>Salmo trutta</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Authority: Linnaeus, 1758                                                         |
| Comments: <i>Salmo trutta</i> is the scientific name of the taxon under assessment. The taxonomic status of <i>S. trutta</i> has been resolved and accepted (GBIF 2021; ITIS 2021). <i>Salmo trutta</i> has three key morphs ( <i>Salmo trutta</i> morpha <i>trutta</i> ; <i>Salmo trutta</i> morpha <i>fario</i> and <i>Salmo trutta</i> morpha <i>lacustris</i> ), but has no distinct subspecies.                                                                                                                                                                          |                                                                                   |
| References:<br>GBIF. 2021. <i>Salmo trutta</i> Linnaeus, 1758. In: GBIF Backbone Taxonomy, Checklist dataset, viewed 19 August 2021, from <a href="https://www.gbif.org/species/5204019">https://www.gbif.org/species/5204019</a> .<br>Integrated Taxonomic Information System (ITIS), 2021, ' <i>Salmo trutta</i> Linnaeus, 1758', viewed 30 August 2021, from <a href="https://www.itis.gov/servlet/SingleRpt/SingleRpt?search_topic=TSN&amp;search_value=161997#null">https://www.itis.gov/servlet/SingleRpt/SingleRpt?search_topic=TSN&amp;search_value=161997#null</a> . |                                                                                   |
| <b>BAC5 Synonym(s) considered</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                                                                   |
| Synonyms: <i>Salmo trutta trutta</i> ; <i>Salmo trutta fario</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                   |
| Comments: More than ten synonyms of <i>S. trutta</i> are listed by CABI (2021) and GBIF (2021). This assessment only considered the above-mentioned synonyms of <i>S. trutta</i> in its literature search, given that they are widely used in scientific research (e.g., Vismara et al. 2001; Skrodenytė-Arbačiauskienė et al. 2008).                                                                                                                                                                                                                                         |                                                                                   |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                  |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| <p>References:</p> <p>CABI. 2021. <i>Salmo trutta</i> (sea trout). In: Invasive Species Compendium, viewed 30 August 2021, from <a href="https://www.cabi.org/isc/datasheet/65308">https://www.cabi.org/isc/datasheet/65308</a>.</p> <p>GBIF. 2021. <i>Salmo trutta</i> Linnaeus, 1758. In: GBIF Backbone Taxonomy, Checklist dataset, viewed 19 August 2021, from <a href="https://www.gbif.org/species/5204019">https://www.gbif.org/species/5204019</a>.</p> <p>Skrodenytė-Arbačiauskienė V, Sruoga A, Butkauskas D, Skrupskelis K. 2008. Phylogenetic analysis of intestinal bacteria of freshwater salmon <i>Salmo salar</i> and sea trout <i>Salmo trutta trutta</i> and diet. <i>Fisheries Science</i> <b>74</b>: 1307–1314.</p> <p>Vismara R, Azzellino A, Bosi R, Crosa G, Gentili G. 2001. Habitat suitability curves for brown trout (<i>Salmo trutta fario</i> L.) in the River Adda, Northern Italy: comparing univariate and multivariate approaches. <i>Regulated Rivers Research and Management</i> <b>17</b>: 37–50.</p>                                                                                                                                                                                                                                                                                                                                                                        |                  |
| <b>BAC6 Common name(s) considered</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                  |
| Common names: Brown trout; Sea trout                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  |
| <p>Comments: <i>Salmo trutta</i> has several vernacular common names in most countries it has been introduced (Froese and Pauly 2021). 'Brown trout' and 'Sea trout' are the most common English names of <i>S. trutta</i> (e.g., MacCrimmon and Marshall 1968; Cooper et al. 1992; Crowl et al. 1992; Weyl et al. 2017; CABI 2021). Therefore, this assessment only considered these two common names in its literature search.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  |
| <p>References:</p> <p>CABI. 2021. <i>Salmo trutta</i> (sea trout). In: Invasive Species Compendium, viewed 30 August 2021, from <a href="https://www.cabi.org/isc/datasheet/65308">https://www.cabi.org/isc/datasheet/65308</a>.</p> <p>Cooper J, Crafford JE, Hecht T. 1992. Introduction and extinction of brown trout (<i>Salmo trutta</i> L.) in an impoverished Subantarctic stream. <i>Antarctic Science</i> <b>4</b>: 9–14.</p> <p>Crowl TA, Townsend CR, McIntosh AR. 1992. The impact of introduced brown and rainbow trout on native fish: the case of Australasia. <i>Reviews in Fish Biology and Fisheries</i> <b>2</b>: 217–241.</p> <p>Froese R, Pauly D (Editors). 2021. FishBase. World Wide Web electronic publication. <a href="http://www.fishbase.org">www.fishbase.org</a>, (08/2021).</p> <p>MacCrimmon HR, Marshall TL. 1968. World distribution of brown trout, <i>Salmo trutta</i>. <i>Journal of the Fisheries Board of Canada</i> <b>25</b>: 2527–2548.</p> <p>Weyl OLF, Ellender BR, Ivey P, Jackson MC, Tweddle D, Wasserman RJ, Woodford DJ, Zengeya TA. 2017. Africa: Brown trout introductions, establishment, current status, impacts and conflicts. In: Lobón-Cerviá J, Sanz N (eds), <i>Brown Trout: Biology, Ecology and Management</i>, Wiley, Oxford, pp 623–639. <a href="https://doi.org/10.1002/9781119268352.ch24">https://doi.org/10.1002/9781119268352.ch24</a>.</p> |                  |
| <b>BAC7 What is the native range of the Taxon?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                  |
| Response: Parts of Europe, Western Asia and the Atlas Mountains in North Africa (see Appendix BAC7)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Confidence: High |
| <p>Comments: The native range of <i>S. trutta</i> includes parts of Europe along the Atlantic, North, White and Baltic Sea Basins (from Spain to Chosha Bay in Russia), Asia and the Atlas Mountains in North Africa (Picker and Griffiths 2011; McIntosh et al. 2012; Weyl et al. 2017, Froese and Pauly 2021).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  |
| <p>References:</p> <p>Froese R, Pauly D (Editors). 2021. FishBase. World Wide Web electronic publication. <a href="http://www.fishbase.org">www.fishbase.org</a>, (08/2021).</p> <p>McIntosh AR, McHugh PA, Budy P. 2012. <i>Salmo trutta</i> L. (brown trout). In: Francis, R.A. (Ed), A handbook of global invasive fishes. Earthscan, Oxon, UK.</p> <p>Picker MD, Griffiths CL. 2011. Alien and Invasive Animals - A South African Perspective, Randomhouse/Struik, Cape Town, South Africa.</p> <p>Weyl OLF, Ellender BR, Ivey P, Jackson MC, Tweddle D, Wasserman RJ, Woodford DJ, Zengeya TA. 2017. Africa: Brown trout introductions, establishment, current status, impacts and conflicts. In: Lobón-Cerviá J, Sanz N (eds), <i>Brown Trout: Biology, Ecology and Management</i>, Wiley, Oxford, pp 623–639. <a href="https://doi.org/10.1002/9781119268352.ch24">https://doi.org/10.1002/9781119268352.ch24</a>.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                  |
| <b>BAC8 What is the global alien range of the Taxon?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                  |
| Response: Africa, North and South America, Oceania and some parts of Europe and Asia (see Appendix BAC8a)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Confidence: High |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                        |                  |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|------------------|
| Comments: <i>Salmo trutta</i> is one of the most widely introduced fish species in the world that has successfully established populations in more than 30 countries (across 5 continents) outside of its native range (MacCrimmon and Marshall 1968; CABI 2021). <i>Salmo trutta</i> is listed among the world's top 30 worst invaders by the World Conservation Union (McIntosh et al. 2011).                                                                                                                                                                            |                        |                  |
| References:<br>CABI. 2021. <i>Salmo trutta</i> (sea trout). In: Invasive Species Compendium, viewed 30 August 2021, from <a href="https://www.cabi.org/isc/datasheet/65308">https://www.cabi.org/isc/datasheet/65308</a> .<br>MacCrimmon HR, Marshall TL. 1968. World Distribution of Brown Trout, <i>Salmo trutta</i> . <i>Journal of the Fisheries Research Board of Canada</i> <b>25</b> : 2527–2548.<br>McIntosh AR, McHugh PA, Budy P. 2012. <i>Salmo trutta</i> L. (brown trout). In: Francis, R.A. (Ed), A handbook of global invasive fishes, Earthscan, Oxon, UK. |                        |                  |
| <b>BAC9 Geographic scope = the Area under consideration</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                        |                  |
| Area of assessment: South Africa                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                        |                  |
| Comments: The geographic scope of the risk analysis is limited to South Africa.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                        |                  |
| <b>BAC10 Is the <i>Taxon</i> present in the Area?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                        |                  |
| Response: Yes                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Confidence: High       |                  |
| Comments: <i>Salmo trutta</i> have was introduced into South Africa from Scotland in 1890 for sport angling (Pike 1980; Weyl et al. 2017). It has naturalised in several mountain headwaters, but is not as widespread as rainbow trout (Weyl et al. 2017).                                                                                                                                                                                                                                                                                                                |                        |                  |
| References:<br>Pike T. 1980. An historical review of freshwater fish hatcheries in Natal. <i>Piscator</i> <b>106</b> : 49-53.<br>Weyl OLF, Ellender BR, Ivey P, Jackson MC, Tweddle D, Wasserman RJ, Woodford DJ, Zengeya TA. 2017. Africa: Brown trout introductions, establishment, current status, impacts and conflicts. In: Lobón-Cerviá J, Sanz N (eds), <i>Brown Trout: Biology, Ecology and Management</i> , Wiley, Oxford, pp 623–639.<br><a href="https://doi.org/10.1002/9781119268352.ch24">https://doi.org/10.1002/9781119268352.ch24</a> .                   |                        |                  |
| <b>BAC11 Availability of physical specimen</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                        |                  |
| Response: There are multiple specimens in the SAIAB collection including genetic samples in the biobank.                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Confidence in ID: High |                  |
| Catalogue numbers: 83134, 58387, 119865 and many more                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                        |                  |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                        |                  |
| <b>BAC12 Is the <i>Taxon</i> native to the Area or part of the Area?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                        |                  |
| The <i>Taxon</i> is native to (part of) the Area.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | No                     | Confidence: High |
| The <i>Taxon</i> is alien in (part of) the Area.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Yes                    | Confidence: High |
| Comments: <i>Salmo trutta</i> is native parts of Europe, western Asia, and the Atlas Mountains in North Africa (Reshetnikov et al. 1997; Gabrielyan 2001).                                                                                                                                                                                                                                                                                                                                                                                                                 |                        |                  |
| References:<br>Gabrielyan BK. 2001. An annotated checklist of freshwater fishes of Armenia. <i>Naga</i> <b>24</b> : 23–29.<br>Reshetnikov YS, Bogutskaya NG, Vasil'eva ED, Dorofeeva EA, Naseka AM, Popova OA, Savvaitova KA, Sideleva VG, Sokolov LI. 1997. An annotated check-list of the freshwater fishes of Russia. <i>Journal of Ichthyology</i> <b>37</b> : 687–736.                                                                                                                                                                                                |                        |                  |
| <b>BAC13 What is the <i>Taxon</i>'s introduction status in the Area?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                        |                  |
| The <i>Taxon</i> is in cultivation/containment.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Yes                    | Confidence: High |
| The <i>Taxon</i> is present outside of cultivation/containment.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Yes                    | Confidence: High |
| The <i>Taxon</i> has established/naturalised.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Yes                    | Confidence: High |
| The <i>Taxon</i> is invasive.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Yes                    | Confidence: High |

Comments: *Salmo trutta* is invasive and has established self-sustaining populations in several mountain headwater catchments. These include the Breede, Olifants-Doring and Keurbooms Rivers in the Cape Fold Ecoregion; the Buffalo and Keiskamma Rivers in the Amatola-Winterberg Ecoregion; the Mooi, Umkomaas, Umgemi, Umvuti, Orange and Tugela Rivers in the Drakensberg-Maloti Highlands Ecoregion; and the Phongolo, Blyde and Incomati catchments in the Southern Temperate Highveld freshwater ecoregion (Weyl et al. 2017). Populations are often re-stocked to maintain populations in rivers, lakes and impoundments. It is also present in containment in aquaculture farms and several hatcheries.

References:

Weyl OLF, Ellender BR, Ivey P, Jackson MC, Tweddle D, Wasserman RJ, Woodford DJ, Zengeya TA. 2017. Africa: Brown trout introductions, establishment, current status, impacts and conflicts. In: Lobón-Cerviá J, Sanz N (eds), *Brown Trout: Biology, Ecology and Management*, Wiley, Oxford, pp 623–639.  
<https://doi.org/10.1002/9781119268352.ch24>.

**BAC14 Primary (introduction) pathways**

|             |                           |                    |
|-------------|---------------------------|--------------------|
| Release     | fishery in the wild       | Confidence: High   |
| Escape      | aquaculture / mariculture | Confidence: Medium |
| Contaminant | none                      | Confidence: Low    |
| Stowaway    | none                      | Confidence: Low    |
| Corridor    | none                      | Confidence: Low    |
| Unaided     | none                      | Confidence: Low    |

Comments: *Salmo trutta* was first introduced to South Africa in 1890 from Scotland, mainly for sport fishing (de Moor and Bruton 1988) and has since been used in aquaculture (Britz and Venter 2016). There was a sustained and widespread effort to stock *S. trutta* initially by government agencies and later by angling societies and private individuals. As result they have established in headwaters of some river catchments. Some areas are re-stocked annually to artificially maintain populations in rivers, lakes and impoundments (Weyl et al. 2017).

References:

Britz P, Venter S. 2016. Aquaculture review: South Africa. *World Aquaculture* **47**: 20–28.  
de Moor IJ, Bruton MN. 1988. Atlas of alien and translocated indigenous aquatic animals in southern Africa, Pretoria: South African National Scientific Programmes Report no.144.  
Weyl OLF, Ellender BR, Ivey P, Jackson MC, Tweddle D, Wasserman RJ, Woodford DJ, Zengeya TA. 2017. Africa: Brown trout introductions, establishment, current status, impacts and conflicts. In: Lobón-Cerviá J, Sanz N (eds), *Brown Trout: Biology, Ecology and Management*. Wiley, Oxford, pp 623–639.  
<https://doi.org/10.1002/9781119268352.ch24>.

## 2. Likelihood

**LIK1 Likelihood of entry via unaided primary pathways**

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Response: Present in the country (p = 1)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Confidence: High |
| Rationale: <i>Salmo trutta</i> is already present in the country and has established self-sustaining populations in the headwaters of several catchments (Weyl et al. 2017). In terms of the likelihood of future introductions, <i>S. trutta</i> occurs in neighbouring countries to South Africa (i.e., Eswatini, Lesotho, and Zimbabwe) (CABI 2021). Therefore, it is possible that <i>S. trutta</i> could enter South Africa from Eswatini and Lesotho (due to the presence of continuous suitable habitat between countries) through interconnected waterways. Downstream dispersal of <i>S. trutta</i> is limited by temperature (Rivers-Moore et al. 2019), and it would not be possible for it to spread unaided through the Lowveld from Zimbabwe to South Africa. |                  |
| References:<br>CABI. 2021. <i>Salmo trutta</i> (sea trout). In: Invasive Species Compendium, viewed 30 August 2021, from <a href="https://www.cabi.org/isc/datasheet/65308">https://www.cabi.org/isc/datasheet/65308</a> .<br>Rivers-Moore NA, Ellender BR, Weyl OLF. 2019. Modelling expected trout ranges under current and future water temperature regimes in the Eastern Cape, South Africa. <i>African Journal of Aquatic Science</i> <b>44</b> : 35–42.<br>Weyl OLF, Ellender BR, Ivey P, Jackson MC, Tweddle D, Wasserman RJ, Woodford DJ, Zengeya TA. 2017. Africa: Brown trout introductions, establishment, current status, impacts and                                                                                                                          |                  |

conflicts. In: Lobón-Cerviá J, Sanz N (eds), *Brown Trout: Biology, Ecology and Management*, Wiley, Oxford, pp 623–639.

#### LIK2 Likelihood of entry via human aided primary pathways

Response: Present in the country (p = 1)

Confidence: Medium

Rationale: *Salmo trutta* is already present in the country and is utilised for angling (Ellender and Weyl 2014; Ellender et al. 2014; Weyl et al. 2017). It is probable that further introductions could occur to augment angling and aquaculture through stocking.

References:

Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. *Aquatic Invasions* **9**: 117–132.

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#### LIK3 Habitat suitability

Response: Probable (p = 1)

Confidence: High

Rationale: *Salmo trutta* can be found in streams, ponds, rivers and lakes (Scott and Scott 1988). They prefer cold, well-oxygenated headwater streams where the maximum temperature rarely exceeds 17 °C and there is adequate cover (submerged rocks, undercut banks, and overhanging vegetation (de Moor and Bruton 1988). *Salmo trutta* spawns in habitats with swift currents, usually characterized by downward movement of water into gravel (Kottelat and Freyhof 2007). In South Africa, *S. trutta* has established self-sustaining populations in headwaters of several catchments (Skelton 2001; Picker and Griffiths 2011). In other areas where conditions (habitat and climate) are partly ideal, populations are maintained by stocking (Weyl et al. 2017). They have a lower tolerance to high temperature and are not as widespread as *O. mykiss* (Weyl et al. 2017).

References:

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#### LIK4 Climate suitability

Response: Probable (p = 1)

Confidence: High

Rationale: Kleynhans et al. (2005) found that *S. trutta* could theoretically survive in 11 ecoregions across South Africa, based on correlations with ambient temperatures. These potentially suitable habitats range from the Northern Escarpment Mountains, the Eastern Escarpment Mountains and the South-eastern Uplands, and extend to the climatically marginal areas such as the South Eastern Coastal belt and the South Western Coastal Belt. A more recent climate model by Weyl et al. (2017) correctly predicted all areas with known or suspected established *S. trutta* populations in South Africa.

References:



Kleynhans CJ, Thirion C, Moolman J. 2005. A Level I River Ecoregion Classification System for South Africa, Lesotho and Swaziland. Resource Quality Services, Department of Water Affairs and Forestry, Pretoria, South Africa.

Weyl OLF, Ellender BR, Ivey P, Jackson MC, Tweddle D, Wasserman RJ, Woodford DJ, Zengeya TA. 2017. Africa: Brown trout introductions, establishment, current status, impacts and conflicts. In: Lobón-Cerviá J, Sanz N (eds), *Brown Trout: Biology, Ecology and Management*, Wiley, Oxford, pp 623–639.

#### LIK5 Unaided secondary (dispersal) pathways

Response: Unlikely ( $p = 0.027$ )

Confidence: Medium

Rationale: In South Africa, naturalised populations of *S. trutta* are restricted to isolated headwater streams and dispersal is limited by warm temperatures, and natural and manmade geographic barriers (Weyl et al. 2017, Ellender et al. 2016; Rivers-Moore et al. 2019). Therefore, the dispersal capabilities of *S. trutta* through unaided pathways are slow and short distance.

##### References:

Ellender BR, Rivers-Moore NA, Coppinger CR, Bellingan TA, Weyl OLF. 2016. Towards using thermal stress thresholds to predict salmonid invasion potential. *Biological Invasions* **18**: 3513–3525.

Rivers-Moore NA, Ellender BR, Weyl OLF. 2019. Modelling expected trout ranges under current and future water temperature regimes in the Eastern Cape, South Africa. *African Journal of Aquatic Science* **44**: 35–42.

Weyl OLF, Ellender BR, Ivey P, Jackson MC, Tweddle D, Wasserman RJ, Woodford DJ, Zengeya TA. 2017. Africa: Brown trout introductions, establishment, current status, impacts and conflicts. In: Lobón-Cerviá J, Sanz N (eds), *Brown Trout: Biology, Ecology and Management*, Wiley, Oxford, pp 623–639.

#### LIK6 Human aided secondary (dispersal) pathways

Response: Probable ( $p = 1$ )

Confidence: Medium

Rationale: There is evidence of regular restocking of *S. trutta* by angling societies and private individuals into areas that do not have self-sustaining populations (e.g., Woodford et al. 2017; Weyl et al. 2017). Therefore, the likelihood of human-aided dispersal of *S. trutta* to new areas in the country is probable.

##### References:

Weyl OLF, Ellender BR, Ivey P, Jackson MC, Tweddle D, Wasserman RJ, Woodford DJ, Zengeya TA. 2017. Africa: Brown trout introductions, establishment, current status, impacts and conflicts. In: Lobón-Cerviá J, Sanz N (eds), *Brown Trout: Biology, Ecology and Management*, Wiley, Oxford, pp 623–639.

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### 3. Consequences

| CON1 Environmental impact                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                    |
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| CON1a: Competition                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                    |
| Response: Major (MR)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Confidence: Medium |
| <p>Rationale: In its alien range, <i>S. trutta</i> has been implicated in outcompeting native fish species for resources such as food and habitats (Wang and White 1994; McHugh and Budy 2005, 2006). Its life history traits such as a rapid growth rate, large size and high fecundity predispose it outcompete with native fish species (Becker 1983; Elliot 1994; Townsend 1996). For example, <i>Salmo trutta</i> have caused the decline and local extinction of native fish species such as Brook trout (<i>Salvelinus fontinalis</i>) in many streams of eastern North America (Waters 1983; Sorensen et al. 1995; Grant et al. 2002).</p> <p>In South Africa, <i>S. trutta</i> have been implicated in causing major declines, and in some cases local extirpation, of native invertebrates, frogs and fish through competition and predation (Marr et al. 2017, Weyl et al. 2020). For example, broad food niche overlap between <i>S. trutta</i> and native fish species such as the mountain catfish <i>Amphilius natalensis</i> suggest that their present impact on native fish in Drakensberg Park streams is likely to come about through competition for resources (Potgieter 2014, Weyl et al. 2017). In addition, trout invasions (<i>Oncorhynchus mykiss</i> and <i>S. trutta</i>) in several river systems such as the Keiskamma River, and the Thukela and the uMngeni river systems have been shown to modify aquatic-terrestrial food-web linkages by competing for resources with riparian consumers such as spiders (Jackson et al. 2016).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                    |
| <p>References:</p> <p>Becker GC. 1983. Fishes of Wisconsin, The University of Wisconsin Press, Madison.</p> <p>Cambray JA. 2003. The global impact of alien trout species - a review; with reference to their impact in South Africa. <i>African Journal of Aquatic Science</i> <b>28</b>: 61–67.</p> <p>Ellender BR. 2013. Ecological consequences of non-native fish invasion in Eastern Cape headwater streams, PhD thesis, Rhodes University.</p> <p>Elliot JM. 1994. Quantitative ecology and the brown trout, Oxford University Press, Oxford.</p> <p>Grant GC, Vondracek B, Sorensen PW. 2002. Spawning interactions between sympatric brown and brook trout may contribute to species replacement. <i>Transactions of the American Fisheries Society</i> <b>131</b>: 569–576.</p> <p>Jackson MC, Woodford DJ, Bellingan TA, Weyl OLF, Potgieter MJ, Rivers-Moore NA, Ellender BR, Fourie HE, Chimimba CT. 2016. Diet overlap between fish and riparian spiders: potential impacts of an invasive fish on terrestrial consumers. <i>Ecology and Evolution</i> <b>6</b>: 1745–1752.</p> <p>Marr S, Ellender B, Woodford D, Alexander M, Wasserman R, Ivey P, Zengeya T, Weyl O. 2017. Evaluating invasion risk for freshwater fishes in South Africa. <i>Bothalia</i> <b>47</b>: 1–10.</p> <p>McHugh P, Budy P. 2005. An experimental evaluation of competitive and thermal effects on brown trout (<i>Salmo trutta</i>) and Bonneville cutthroat trout (<i>Oncorhynchus clarkii utah</i>) performance along an altitudinal gradient. <i>Canadian Journal of Fisheries and Aquatic Sciences</i> <b>62</b>: 2784–2795.</p> <p>McHugh P, Budy P. 2006. Experimental effects of nonnative brown trout on the individual- and population-level performance of native Bonneville cutthroat trout. <i>Transactions of the American Fisheries Society</i> <b>135</b>: 1441–1455.</p> <p>McIntosh AR, Townsend CR, Crowl TA. 1992. 'Competition for space between introduced brown trout (<i>Salmo trutta</i> L.) and a native galaxiid (<i>Galaxias vulgaris</i> Stokell) in a New Zealand stream. <i>Journal of Fish Biology</i> <b>41</b>: 63–81.</p> <p>Potgieter MJ. 2014. The impact of introduced trout on ecosystem structure and functioning in streams of the Drakensberg, South Africa, BSc (Hons) research report, University of Pretoria, South Africa, 32 pp.</p> <p>Skelton PH. 1987. South African Red Data Book. Fishes, South African National Scientific Programmes Report 137. Council for Scientific and Industrial Research, Pretoria, South Africa, 199 pp.</p> <p>Sorensen PW, Cardwell JR, Essington T, Weigel DE. 1995. Reproductive interactions between sympatric brook and brown trout in a small Minnesota stream. <i>Canadian Journal of Fisheries and Aquatic Sciences</i> <b>52</b>: 1958–1965.</p> <p>Townsend CR. 1996. Invasion biology and ecological impacts of brown trout <i>Salmo trutta</i> in New Zealand. <i>Biological Conservation</i> <b>78</b>: 13–22.</p> |                    |

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CON1b: Predation

Response: Major (MR)

Confidence: Medium

Rationale: *Salmo trutta* are aggressive predators (Nillson 1963), feeding primarily on aquatic invertebrates (Penczak 1999; Knapp and Matthews 2000; Freyhof 2011) and vertebrates such as freshwater fish, amphibians, reptiles and small mammals (Gillespie 2001; Budy et al. 2013). For example, *S. trutta* have been implicated in causing a decline in the abundance of amphibians in the USA and Australia (Kats and Ferrer 2003) and native *Galaxias* in New Zealand and Australia (Crowl et al. 1992; McIntosh et al. 1992; Townsend 2003). *Salmo trutta* have also been implicated in causing the local extinction and fragmented distribution of native fish species in Europe (Legalle et al. 2005; van Liefferinge et al. 2005; Lorenzoni et al. 2018), and Chile (Soto et al. 2006; Arismendi et al. 2009).

In South Africa, *S. trutta* has been linked to the decline and in some cases local extinction of native invertebrates, frogs and fish (Samways 1994; Karssing et al. 2012; Ellender 2013; Rivers-Moore et al. 2013; Potgieter 2014; Jackson et al., 2016). For example, trout invasions (*S. trutta* and co-occurring *Oncorhynchus mykiss*) in the uKhahlamba Drakensberg Park have been implicated in the reduction of macroinvertebrate communities and the abundance of amphibians probably due to predation (Karssing et al. 2012; Rivers-Moore et al. 2013). In addition, *S. trutta* invasions have been shown to induce trophic cascades by reducing the abundance of shredding invertebrates leading to a decline in the rate that leaf litter was shredded and decomposed (Potgieter 2014). *Salmo trutta* invasions have also been implicated in the decline of native species such as the Maloti minnow, *Pseudobarbus quathlambae* (de Moor and Bruton 1988) and the Border barb, *Barbus trevelyani* (Ellender et al. 2013).

References:

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#### CON1c: Hybridisation

Response: Data Deficient (DD)

Confidence: High

Rationale: There are no native species in the family Salmonidae in South Africa, therefore there is no risk of hybridisation.

#### References:

Skelton PH. 2001. A complete guide to the freshwater fishes of Southern Africa, Struik Publishers, Cape Town, South Africa.

#### CON1d: Transmission of disease

Response: Minimal Concern (MC)

Confidence: Medium

Rationale: The most common diseases and parasites that have been found internationally to infect *S. trutta* include furunculosis, bacterial kidney disease, vibriosis, viral haemorrhagic septicaemia, infectious haematopoietic necrosis, infectious pancreatic necrosis and costiasis (Ellis et al. 1985; Dawson 1998; Hendrick et al. 1999; Schmidt-Posthaus et al. 2001; Peeler et al. 2008). However, to date, none of these diseases has been found in alien salmonids in South Africa during regular testing of imported ova and cultured adults for Viral Haemorrhagic Septicaemia and Infectious Haematopoietic Necrosis (Anchor Environmental Consulting 2012).

#### References:

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| CON1e: Parasitism                                                                                                                                                                                                                                                                                                      |                    |
| Response: Data Deficient (DD)                                                                                                                                                                                                                                                                                          | Confidence: Medium |
| Rationale: No documented information available to assess the level of impact.                                                                                                                                                                                                                                          |                    |
| References:                                                                                                                                                                                                                                                                                                            |                    |
| CON1f: Poisoning/toxicity                                                                                                                                                                                                                                                                                              |                    |
| Response: Data Deficient (DD)                                                                                                                                                                                                                                                                                          | Confidence: Medium |
| Rationale: No documented information available to assess the level of impact.                                                                                                                                                                                                                                          |                    |
| References:                                                                                                                                                                                                                                                                                                            |                    |
| CON1g: Bio-fouling or other direct physical disturbance                                                                                                                                                                                                                                                                |                    |
| Response: Data Deficient (DD)                                                                                                                                                                                                                                                                                          | Confidence: Medium |
| Rationale: No documented information available to assess the level of impact.                                                                                                                                                                                                                                          |                    |
| References:                                                                                                                                                                                                                                                                                                            |                    |
| CON1h: Grazing/herbivory/browsing                                                                                                                                                                                                                                                                                      |                    |
| Response: Data Deficient (DD)                                                                                                                                                                                                                                                                                          | Confidence: Medium |
| Rationale: No documented information available to assess the level of impact.                                                                                                                                                                                                                                          |                    |
| References:                                                                                                                                                                                                                                                                                                            |                    |
| CON1i: Chemical, physical or structural impact on ecosystem                                                                                                                                                                                                                                                            |                    |
| Response: Data deficient (DD)                                                                                                                                                                                                                                                                                          | Confidence: Medium |
| Rationale: No documented information available to assess the level of impact.                                                                                                                                                                                                                                          |                    |
| References:                                                                                                                                                                                                                                                                                                            |                    |
| CON1k: Indirect impacts through interactions with other species                                                                                                                                                                                                                                                        |                    |
| Response: Data Deficient (DD)                                                                                                                                                                                                                                                                                          | Confidence: High   |
| Rationale: No documented information available to assess the level of impact.                                                                                                                                                                                                                                          |                    |
| References:                                                                                                                                                                                                                                                                                                            |                    |
| CON1 Maximum environmental impact                                                                                                                                                                                                                                                                                      |                    |
| Response: Major (MR)                                                                                                                                                                                                                                                                                                   | Confidence: High   |
| Rationale: In South Africa, a national level EICAT assessment classified impacts caused by <i>S. trutta</i> as Major (MR) as it is known to cause declines, and in some cases local extinction, of native invertebrates, frogs and fish through predation and competition (Marr et al. 2017).                          |                    |
| References:                                                                                                                                                                                                                                                                                                            |                    |
| Marr S, Ellender B, Woodford D, Alexander M, Wasserman R, Ivey P, Zengeya T, Weyl O. 2017. Evaluating invasion risk for freshwater fishes in South Africa. <i>Bothalia</i> <b>47</b> : 1–10.                                                                                                                           |                    |

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| CON2 Socio-economic impact (Note that CON2 classification only refers to negative impacts, and not to any potentially positive benefits) |                  |
| CON2a: Safety                                                                                                                            |                  |
| Response: Data Deficient (DD)                                                                                                            | Confidence: High |
| Rationale: No documented information available to assess the level of impact                                                             |                  |
| References:                                                                                                                              |                  |
| CON2b: Material and immaterial assets                                                                                                    |                  |
| Response: Data Deficient (DD)                                                                                                            | Confidence: High |
| Rationale: No documented information available to assess the level of impact                                                             |                  |
| References:                                                                                                                              |                  |
| CON2c: Health                                                                                                                            |                  |
| Response: Data Deficient (DD)                                                                                                            | Confidence: High |
| Rationale: No documented information available to assess the level of impact                                                             |                  |

|                                                                               |                 |
|-------------------------------------------------------------------------------|-----------------|
| References:                                                                   |                 |
| CON2d: Social, spiritual and cultural relations                               |                 |
| Response: Data Deficient (DD)                                                 | Confidence: Low |
| Rationale: No documented information available to assess the level of impact  |                 |
| References                                                                    |                 |
| CON2 Maximum socio-economic impact                                            |                 |
| Response: Data Deficient (DD)                                                 | Confidence: Low |
| Rationale: No documented information available to assess the level of impact. |                 |
| References:                                                                   |                 |

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|---------------------------------------------------------------------------------------------------------|--------------------|
| CON3 Closely related species' environmental impact                                                      |                    |
| Response: Not scored as CON1 scored                                                                     | Confidence: Medium |
| Rationale: There is information to score CON1, so CON3 does not need to be scored as per the framework. |                    |
| References:                                                                                             |                    |

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|----------------------------------------------------------------------------------|-----------------|
| CON4 Closely related species' socio-economic impact                              |                 |
| Response: Data Deficient (DD)                                                    | Confidence: Low |
| Rationale: There are no relevant records of socio-economic impacts of Salmonids. |                 |
| References:                                                                      |                 |

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| CON5 Potential impact                                                                                                                                                                                                                                                                        |                    |
| Response: Major (MR)                                                                                                                                                                                                                                                                         | Confidence: Medium |
| Rationale: In South Africa, a national-level EICAT assessment classified impacts caused by <i>S. trutta</i> as Major (MR) as it is known to cause declines, and in some cases local extinction of native invertebrates, frogs and fish through predation and competition (Marr et al. 2017). |                    |
| References:<br>Marr S, Ellender B, Woodford D, Alexander M, Wasserman R, Ivey P, Zengeya T, Weyl O. 2017. Evaluating invasion risk for freshwater fishes in South Africa. <i>Bothalia</i> <b>47</b> : 1–10.                                                                                  |                    |

#### 4. Management

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| MAN1 What is the feasibility to stop future immigration?                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                    |
| Response: Low                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Confidence: Medium |
| Rationale: <i>Salmo trutta</i> is already present in South Africa where it is cultured in hatcheries and is often stocked into ponds, rivers and lakes as a resource for use by recreational anglers (Ellender and Weyl 2014; Ellender et al. 2014; Weyl et al. 2020). Therefore, it is probable that <i>S. trutta</i> will be dispersed through human-aided secondary pathways for angling purposes. It is also present in neighbouring countries and could spread unaided through interconnected waterways.                                                                                                                                                                                                                                                     |                    |
| References:<br>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b> : 117–132.<br>Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non-native fishes in southern Africa. <i>Journal of Fish Biology</i> <b>85</b> : 1890–1906.<br>Weyl OLF, Ellender BR, Ivey P, Jackson MC, Tweddle D, Wasserman RJ, Woodford DJ, Zengeya TA. 2017. Africa: Brown trout introductions, establishment, current status, impacts and conflicts. In: Lobón-Cerviá J, Sanz N (eds), <i>Brown Trout: Biology, Ecology and Management</i> , Wiley, Oxford, pp 623–639. |                    |

|                                                   |  |
|---------------------------------------------------|--|
| <b>MAN2 Benefits of the Taxon</b>                 |  |
| MAN2a Socio-economic benefits of the <i>Taxon</i> |  |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| Response: Low                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Confidence: Medium |
| <p>Rationale: <i>Salmo trutta</i> has socio-economic value and is utilised in recreational fisheries. There are several studies that have assessed the economic benefits of trout (mainly for <i>Oncorhynchus mykiss</i>) and these strengthen the evidence base for quantifying the benefits derived from introduced fish species (Britz et al. 2009; Britz and Venter 2016; Du-Preez and Lee 2010; Anchor Environmental Consulting 2010). However, the studies were done using different methods and at small scales (e.g. towns, and discrete catchments), and the results still have to be extrapolated to larger scales (e.g. national). <i>Salmo trutta</i> is of lower importance than <i>O. mykiss</i> (rainbow trout) as it is currently used exclusively for recreational fishing, and not for commercial production (Stander and Brink 2009). In addition, native fish species are also available as alternatives for recreational angling (e.g. various yellowfish species, Hoogendoorn 2014).</p>                                                                                         |                    |
| <p>References:</p> <p>Anchor Environmental Consulting. 2010. The nature, distribution and value of aquatic ecosystem services of the Olifants, Inkomati and Usutu to Mhlathuze Water Management Areas. Contract report for Department: Water Affairs and Forestry, 378 pp.</p> <p>Britz PJ, Lee B, Botes L. 2009. AISA 2009 Aquaculture Benchmarking Survey: Primary Production and Markets, AISA report produced by Enviro-Fish Africa (Pty) Ltd, 117 pp.</p> <p>Britz P, Venter S. 2016. Aquaculture review: South Africa. <i>World Aquaculture</i> <b>47</b>: 20–28.</p> <p>Du-Preez M, Lee DE. 2010. The contribution of trout fly fishing to the economy of Rhodes, North Eastern Cape, South Africa. <i>Development Southern Africa</i> <b>27</b>: 241–253.</p> <p>Hoogendoorn G. 2014. Mapping fly-Fishing Tourism in Southern Africa. <i>African Journal of Hospitality, Tourism and Leisure</i> <b>3</b>: 13pp.</p> <p>Stander H, Brink D. 2009. Trout farming In South Africa: Expanding local markets work with ecotourism. <i>Global Aquaculture Advocate</i>, November/December 2009.</p> |                    |
| MAN2b Environmental benefits of the <i>Taxon</i>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                    |
| Response: Low                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Confidence: Low    |
| <p>Rationale: There are no environmental benefits documented for <i>Salmo trutta</i> in South Africa.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                    |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                    |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| <b>MAN3 Ease of management</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                    |
| MAN3a How accessible are populations?                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                    |
| Response: 1 (moderately accessible)                                                                                                                                                                                                                                                                                                                                                                                                                                                         | Confidence: Medium |
| <p>Rationale: Populations of <i>S. trutta</i> in South Africa can be found in several mountain rivers (Picker and Griffiths 2011) that may be difficult to access. Populations in containment are often on private land and permission would be needed to access these areas for control.</p>                                                                                                                                                                                               |                    |
| <p>References:</p> <p>Picker MD, Griffiths CL. 2011. Alien and Invasive Animals – A South African Perspective, Randomhouse/Struik, Cape Town, South Africa, 240 pp.</p>                                                                                                                                                                                                                                                                                                                     |                    |
| MAN3b Is detectability critically time-dependent?                                                                                                                                                                                                                                                                                                                                                                                                                                           |                    |
| Response: 2 (Difficult)                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Confidence: High   |
| <p>Rationale: Trout can be detected at any time, but it does require special equipment (e.g. electrofishing gear) and trained specialists to operate such equipment. Detection is thus logistically challenging, but not time-dependent.</p>                                                                                                                                                                                                                                                |                    |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                    |
| MAN3c Time to reproduction                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |
| Response: 1 (1–3 years)                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Confidence: Medium |
| <p>Rationale: The age at which <i>S. trutta</i> reaches sexual maturity can vary but is usually one to three years for males, and two to four years for females (Taube 1976; Maisse et al. 1991).</p>                                                                                                                                                                                                                                                                                       |                    |
| <p>References:</p> <p>Maisse G, Mourot B, Breton B, Fostier A, Marcuzzi O, Le Bail P-Y, Baglinière J-L, Richard A. 1991. Sexual maturity in sea trout, <i>Salmo trutta</i> L., running up the river Calonne (Normandy, France) at the "finnock" stage. <i>Journal of Fish Biology</i> <b>39</b>: 705–715.</p> <p>Taube CM. 1976. Sexual maturity and fecundity in Brown trout of the Platte River, Michigan. <i>Transactions of the American Fisheries Society</i> <b>105</b>: 529–533.</p> |                    |
| MAN3d Propagule persistence                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                    |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Response: 0 (< 1 year)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | Confidence: High |
| Rationale: Eggs of <i>S. trutta</i> hatch in approximately 3 weeks (Skelton 2001).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  |
| References:<br>Skelton P. 2001. A complete guide to the freshwater fishes of Southern Africa, Struik Publishers, Cape Town.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                  |
| <b>MAN3 Ease of management</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                  |
| Response: Medium                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Confidence: High |
| Rationale: Management of <i>S. trutta</i> is scored here as medium. However, several issues make management challenging. These include the fact that many control options could also harm native species, and that control operations would likely be met with resistance from certain interest groups (see Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017).                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                  |
| References:<br>Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. <i>Journal of Fish Biology</i> <b>85</b> : 1890–1906.<br>Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. <i>Bothalia</i> <b>47</b> : 1–9.<br>Woodford DJ, Richardson DM, MacIsaac HJ, Mandrak N, van Wilgen BW, Wilson JR, Weyl OLF. 2016. Confronting the wicked problem of managing invasive species. <i>Neobiota</i> <b>31</b> : 63–86.<br>Zengeya T, Ivey P, Woodford DJ, Weyl O, Novoa A, Shackleton R, Richardson D, Van Wilgen B. 2017. Managing conflict-generating invasive species in South Africa: challenges and trade-offs. <i>Bothalia</i> <b>47</b> : 1–11. |                  |

|                                                                                                                             |                  |
|-----------------------------------------------------------------------------------------------------------------------------|------------------|
| <b>MAN4 Has the feasibility of eradication been evaluated?</b>                                                              |                  |
| Response: No                                                                                                                | Confidence: High |
| Rationale: There have been no studies that have addressed the country-wide eradication of <i>S. trutta</i> in South Africa. |                  |
| References:                                                                                                                 |                  |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|
| <b>MAN5 Control options and monitoring approaches available for the Taxon</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |  |
| Response:<br>Management of <i>S. trutta</i> in South Africa is relatively difficult. This because <i>S. trutta</i> is a conflict-generating invasive species that has major negative environmental impacts, but also some socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Part of the proposed management initiatives for <i>Salmo trutta</i> includes managing it by area where utilisation is to be allowed in areas where it has naturalised and in areas where it has historically been stocked. Concerned stakeholders have highlighted the need for broader consultations and transparency on the evidence used to assess the risks posed by trout to biodiversity and the benefits derived from their utilisation see (Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017).  |  |
| References:<br>Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. <i>Journal of Fish Biology</i> <b>85</b> : 1890–1906.<br>Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. <i>Bothalia</i> <b>47</b> : 1–9.<br>Woodford DJ, Richardson DM, MacIsaac HJ, Mandrak N, van Wilgen BW, Wilson JR, Weyl OLF. 2016. Confronting the wicked problem of managing invasive species. <i>Neobiota</i> <b>31</b> : 63–86.<br>Zengeya T, Ivey P, Woodford DJ, Weyl O, Novoa A, Shackleton R, Richardson D, Van Wilgen B. 2017. Managing conflict-generating invasive species in South Africa: challenges and trade-offs. <i>Bothalia</i> <b>47</b> : 1–11. |  |

|                                                               |                         |
|---------------------------------------------------------------|-------------------------|
| <b>MAN6 Any other management considerations to highlight?</b> |                         |
| Response                                                      | Yes (see Appendix MAN6) |

## 5. Calculations

**Likelihood = Probable**

| Parameter | Likelihood | Stages               | Final assessment |
|-----------|------------|----------------------|------------------|
| LIK1      | 1          | P(entry) = 1         | P (invasion) = 1 |
| LIK2      | 1          |                      |                  |
| LIK3      | 1          |                      |                  |
| LIK4      | 1          | P(establishment) = 1 |                  |
| LIK5      | 0.027      | P (spread) = 1       |                  |
| LIK6      | 1          |                      |                  |

**Consequence = Major**

| Parameter | Mechanism/sector                                         | Response                  |
|-----------|----------------------------------------------------------|---------------------------|
| CON1a     | Competition                                              | MR                        |
| CON1b     | Predation                                                | MR                        |
| CON1c     | Hybridisation                                            | DD                        |
| CON1d     | Disease transmission                                     | MC                        |
| CON1e     | Parasitism                                               | DD                        |
| CON1f     | Poisoning/toxicity                                       | DD                        |
| CON1g     | Bio-fouling or other direct physical disturbance         | DD                        |
| CON1h     | Grazing/herbivory/browsing                               | DD                        |
| CON1i     | Chemical, physical, structural impact                    | DD                        |
| CON1k     | Indirect impacts through interactions with other species | DD                        |
| CON1      | Maximum environmental impact                             | MR                        |
| CON2a     | Safety                                                   | DD                        |
| CON2b     | Material and immaterial assets                           | DD                        |
| CON2c     | Health                                                   | DD                        |
| CON2d     | Social, spiritual and cultural relations                 | DD                        |
| CON2      | Maximum socio-economic impact                            | DD                        |
| CON3      | Environmental impact of closely related taxa             | Not scored as CON1 scored |
| CON4      | Socio-economic impact of closely related taxa            | DD                        |
| CON5      | Potential impact based on traits, experiments, or models | MR                        |

**Risk score = High**

|            |                    | Consequences |        |        |        |        |
|------------|--------------------|--------------|--------|--------|--------|--------|
|            |                    | MC           | MN     | MO     | MR     | MV     |
| Likelihood | Extremely unlikely | low          | low    | low    | medium | medium |
|            | Very unlikely      | low          | low    | low    | medium | high   |
|            | Unlikely           | low          | low    | medium | high   | high   |
|            | Fairly probable    | medium       | medium | high   | high   | high   |
|            | Probable           | medium       | high   | high   | high   | high   |

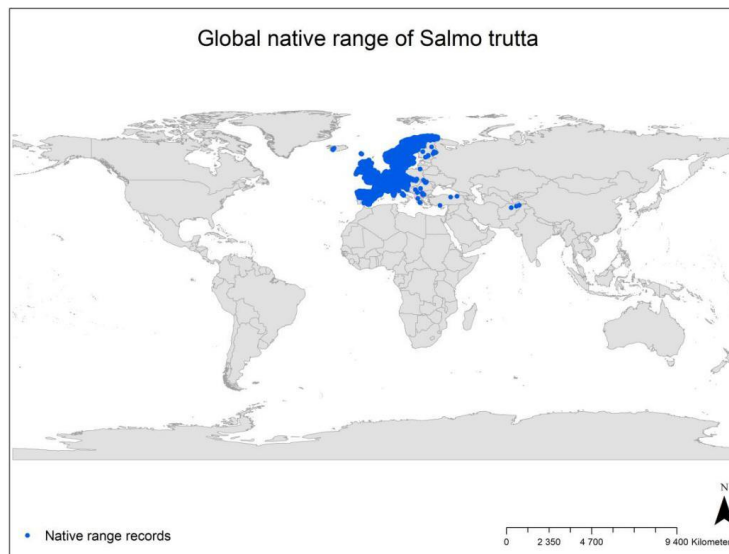
**Ease of management = Medium**

| Parameter | Question                                    | Response |
|-----------|---------------------------------------------|----------|
| MAN3a     | How accessible are populations?             | 1        |
| MAN3b     | Is detectability critically time-dependent? | 2        |
| MAN3c     | Time to reproduction                        | 1        |
| MAN3d     | Propagule persistence                       | 0        |

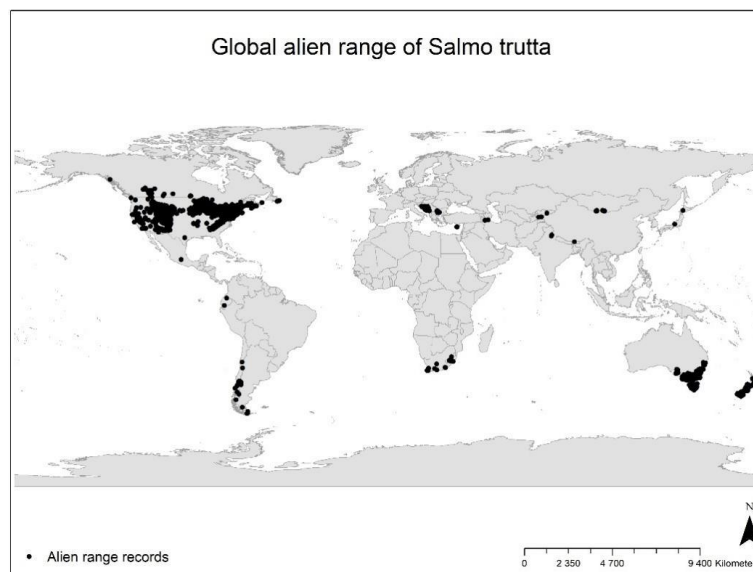


|      |     |   |
|------|-----|---|
| MAN3 | SUM | 4 |
|------|-----|---|

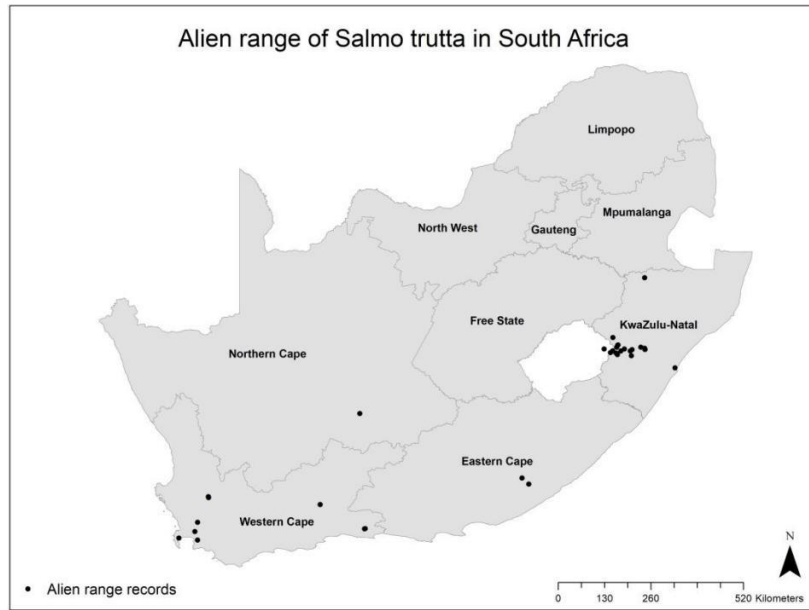
**Appendix BAC7:** Native range of *Salmo trutta* Linnaeus, 1758. GBIF.org (15 October 2021) GBIF Occurrence Download <https://doi.org/10.15468/dl.7wrhav>.



**Appendix BAC8(a):** Global alien range of *Salmo trutta* Linnaeus, 1758. GBIF.org (15 October 2021) GBIF Occurrence Download <https://doi.org/10.15468/dl.7wrhav>.



**Appendix BAC8(b):** Distribution of *Salmo trutta* Linnaeus, 1758 in South Africa. Source: GBIF.org (15 October 2021) GBIF Occurrence Download <https://doi.org/10.15468/dl.7wrhav>.





## **Appendix MAN6:** Proposed listing options for *Salmo trutta* under the NEM:BA A&IS Regulations

### **Current listing as per NEM:BA A&IS lists of 2020**

**Taxon:** *Salmo trutta* Linnaeus, 1758

**Common name:** brown trout

**Category:** not listed

*Salmo trutta* was published for listing as an invasive species in the South African Government Gazette on 18 September 2020, but the promulgation of the lists was delayed because of ongoing consultation with stakeholders. A note indicating the NEM:BA A&IS Lists would be promulgated without *Oncorhynchus mykiss* or *Salmo trutta* was published on 24 Feb 2021, and the lists were promulgated on 1 March 2021.

The proposed listing of *Salmo trutta* was category 2 with “All persons are exempted from requiring a permit for restricted activities “b” and “j” under Notice 1. Activity b is “having in possession or exercising physical control over any specimen of a listed invasive species”, and activity “j” is “Catch and release of a specimen of a listed invasive fresh-water fish or listed invasive fresh-water invertebrate species”.

Although *S. trutta* is not listed at a national-level, under the NEM:BA A&IS lists, *S. trutta* is managed in some regions (e.g. the Western Cape province) under provincial legislation (Woodford et al. 2017).

### **Rationale**

*Salmo trutta* in South Africa has both major negative environmental impacts and some socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts.

### **Potential criteria for permits and exemptions**

Two key aims for the management of *S. trutta* should be to: a) prevent the spread of *S. trutta* to new areas; and b) limit the negative environmental impacts by controlling *S. trutta* populations in key fish conservation areas. To this end, those catchments where *S. trutta* does not yet occur but where suitable habitat exists, and key fish conservation areas (with and without *S. trutta* populations) would need to be identified in a National Management Plan that contains appropriate maps. The inclusion of maps outlining areas where permits may be granted would greatly facilitate the application and processing of permits.

The beneficial uses of *S. trutta* could then be managed as follows:

- Permits for existing or new aquaculture facilities could be granted, but only if such activities do not result in new sites becoming invaded or spread of *S. trutta* into key fish conservation areas. As such permits would not be issued for aquaculture facilities in discrete catchment systems in which *S. trutta* does not yet occur or that include key fish conservation areas. Permits could, however, be granted for aquaculture facilities in part of a discrete catchment system where *S. trutta* occurs, providing there are natural or artificial habitat barriers (for example waterfalls, dams or weirs) that would prevent the spread of *S. trutta* to other parts of the catchment system where it is currently absent, but where suitable habitat exists.
- In terms of restocking the same considerations as for aquaculture facilities would apply.
- In terms of angling, catch-and-release (i.e. the practice of anglers to return a fish to the water where it was caught) is exempt in any discrete-catchments that are specified on maps produced as per the National Management Plan. At all other sites catch-and-kill should be practised. This provision could be incorporated into provincial freshwater angling licences.
- The transport of live fish or eggs would always require a permit, but any dead specimens (e.g. for personal consumption or commercial trade) would, of course, be exempt.

## National Management Plan

To facilitate the implementation of these criteria and to ensure the process is transparent, it would be important to draw up a National Management Plan for *S. trutta*. The plan would need to include maps of the catchments where permits may be issued for commercial production purposes, where permits may be issued for restocking, and where catch-and-release angling is exempt. Maps of key fish conservation areas would also be useful to indicate areas where catch-and-kill would need to be practised.

The National Management Plan would also need to specify the standards that should be met to limit the risk of escape or unintentional or illegal re-distribution to new areas.

## Overall recommendation

### Proposed listing

**Taxon:** *Salmo trutta* Linnaeus, 1758

**Common name:** brown trout

**Category:** 2

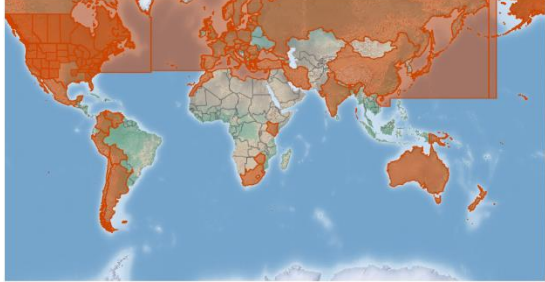
**Exemption:** catch-and-release is exempt in areas specified in maps produced as part of a National Management Plan for *S. trutta*.

Permits may only be issued in line with the considerations discussed in the “Potential criteria for permits and exemptions” section above.

## Reference

Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. *Bothalia* 47: a2138.

## Appendix 5.6<sup>10</sup>: Brook trout (*Salvelinus fontinalis*)

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                                                                             |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Taxon:</b> <i>Salvelinus fontinalis</i><br><b>Compiled by:</b> Lerato Maimela                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | <b>Area:</b> South Africa<br><b>Approved by:</b>                                                                                                                                                                                                                                                                            |
| <b>Picture of Taxon</b><br>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | <b>Alien distribution map (BAC8)</b><br><br><small>CABI, 2021. <i>Salvelinus fontinalis</i>. In: Invasive Species Compendium. Wallingford, UK: CAB International. <a href="https://www.cabi.org/isc">https://www.cabi.org/isc</a></small> |
| <b>Risk Assessment summary:</b><br><br><p><i>Salvelinus fontinalis</i> (brook trout) is native to North America and it has been introduced to several countries in Africa, Asia, Europe, South America, and Oceania. It was introduced in South Africa in 1890 for angling but the introduction was not successful. Similarly, introductions in neighboring were unsuccessful. Further intentional introductions unlikely as common pathways of introduction (e.g. angling and aquaculture) are infrequently used. Evidence from elsewhere, suggests that <i>S. fontinalis</i> can cause moderate environmental impacts through hybridisation with native fish and predation of native fish, amphibians and macroinvertebrates.</p>                                                                                                                                                                                                                                                                                       | <b>Risk score:</b><br><br>Low                                                                                                                                                                                                                                                                                               |
| <b>Management options summary:</b><br><p>Management of trout species in South Africa is difficult. This is because trout are a conflict-generating invasive species that have major negative environmental impacts, but also have socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Part of the proposed management initiatives for <i>S. fontinalis</i> is to restrict importation through permitting and implement post border intervention measures similar to those proposed for other trout species in South Africa. This includes managing the species by area where utilisation is to be allowed in areas where other trout species have naturalised and in areas where they have been historically utilised for stocking. However, concerned stakeholders have highlighted the need for broader consultations and transparency on the evidence used to assess the risks posed by trout to biodiversity and the benefits derived from their utilisation.</p> | <b>Ease of management:</b><br><br>Medium                                                                                                                                                                                                                                                                                    |
| <b>Recommendations:</b><br><p>Given that <i>S. fontinalis</i> is not present in the country, and has moderate environmental impacts in its global introduction range it was assessed as a low risk. Therefore the recommendation is that it should be not be listed in the NEM:BA A&amp;IS lists (see Appendix MAN6 for details).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | <b>Listing under NEM:BA A&amp;IS lists of 2014 as amended 2021:</b><br>Not listed<br><b>Recommended listing category:</b><br>No change                                                                                                                                                                                      |

<sup>10</sup> This risk analyses report for *Salvelinus fontinalis* (brook trout) is presented as submitted to the South African Alien Species Risk Analysis Review Panel (ASRARP), a committee that is tasked with reviewing risk analyses attached to import applications and listing of species under national legislation to ensure they are scientifically robust and take into account the best available evidence (see Kumschick et al. 2020 for details). ASRARP is an independent body and its members consist of scientists and taxon experts working on various issues on biological invasions. The committee provides recommendations to an interdepartmental panel set up by the Department of Forestry, Fisheries and the Environment tasked with granting import permits and/or approving changes to regulations on biological invasions.

## 1. Background

|                                                                                                                                                                                                                                                                                                                                                                                                            |                                                                  |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------|
| <b>BAC1 Name of assessor(s)</b>                                                                                                                                                                                                                                                                                                                                                                            |                                                                  |
| Name of lead assessor                                                                                                                                                                                                                                                                                                                                                                                      | Lerato Maimela                                                   |
| Additional assessor (1)                                                                                                                                                                                                                                                                                                                                                                                    | TA Zengeya                                                       |
| Additional assessor (2)                                                                                                                                                                                                                                                                                                                                                                                    | CT Chimimba                                                      |
| <b>BAC2 Contact details of assessor (s)</b>                                                                                                                                                                                                                                                                                                                                                                |                                                                  |
| Lead assessor                                                                                                                                                                                                                                                                                                                                                                                              | Organisational affiliation: University of Pretoria               |
|                                                                                                                                                                                                                                                                                                                                                                                                            | email: lerato.maimela@zoology.up.ac.za                           |
|                                                                                                                                                                                                                                                                                                                                                                                                            | Phone: 012 420 4315                                              |
| Additional assessor (1)                                                                                                                                                                                                                                                                                                                                                                                    | Organisational affiliation: South African Biodiversity institute |
|                                                                                                                                                                                                                                                                                                                                                                                                            | email: t.zengeya@sanbi.org.za                                    |
|                                                                                                                                                                                                                                                                                                                                                                                                            | Phone: 021 799 8408                                              |
| Additional assessor (2)                                                                                                                                                                                                                                                                                                                                                                                    | Organisational affiliation: University of Pretoria               |
|                                                                                                                                                                                                                                                                                                                                                                                                            | email: chris.chimimba@up.ac.za                                   |
|                                                                                                                                                                                                                                                                                                                                                                                                            | Phone: 012 420 3808                                              |
| <b>BAC3 Name(s) and contact details of expert(s) consulted</b>                                                                                                                                                                                                                                                                                                                                             |                                                                  |
| Expert (1)                                                                                                                                                                                                                                                                                                                                                                                                 | Name:                                                            |
|                                                                                                                                                                                                                                                                                                                                                                                                            | email:                                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                            | Phone:                                                           |
| Expert (2)                                                                                                                                                                                                                                                                                                                                                                                                 | Name: Darragh Woodford                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                            | email:                                                           |
|                                                                                                                                                                                                                                                                                                                                                                                                            | Phone:                                                           |
| Comments:                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                  |
| <b>BAC4 Scientific name of <i>Taxon</i> under assessment</b>                                                                                                                                                                                                                                                                                                                                               |                                                                  |
| <i>Taxon</i> name: <i>Salvelinus fontinalis</i>                                                                                                                                                                                                                                                                                                                                                            | Authority: Mitchill, 1814                                        |
| Comments: The two commonly known subspecies are <i>S. f. agassizii</i> (Garman, 1885) <i>S. f. timagamiensis</i> Henn and Rinckenbach, 1925                                                                                                                                                                                                                                                                |                                                                  |
| References:<br>Starnes WC. 2003. Research Curator of Fishes, North Carolina State Museum of Natural Sciences, Research Laboratory, 4301 Reedy Creek Rd., Raleigh, NC, 27607, USA.                                                                                                                                                                                                                          |                                                                  |
| <b>BAC5 Synonym(s) considered</b>                                                                                                                                                                                                                                                                                                                                                                          |                                                                  |
| Synonyms:<br>The synonyms include <i>Salmo fontinalis</i> Mitchill, 1814 <i>Baione fontinalis</i> (Mitchill, 1814) <i>Salmo canadensis</i> Griffith and Smith, 1834 <i>Salmo hudsonicus</i> Suckley, 1861                                                                                                                                                                                                  |                                                                  |
| Comments:                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                  |
| References:<br>Kocik JF, Kevin DF, Bruce B, Klein-MacPhee G. 2002. <i>Salmons and Trouts: Family Salmonidae</i> Bigelow and Schroeder's Fishes of the Gulf of Maine, Third Edition, Smithsonian Institution Press, Washington, DC, USA, 170-181. ISBN/ISSN: 1-56098-951-3.                                                                                                                                 |                                                                  |
| <b>BAC6 Common name(s) considered</b>                                                                                                                                                                                                                                                                                                                                                                      |                                                                  |
| Common names: The most common used common name for <i>Salvelinus fontinalis</i> is Brook trout                                                                                                                                                                                                                                                                                                             |                                                                  |
| Comments:<br>Other English common names used include aurora trout; baisers; breeder; brook char; brook charr; brookie; char; coaster; common brook trout; eastern brook trout; eastern speckled trout; humpbacked trout; lord-fish; mountain trout; mud trout; native trout; salter; sea trout; slob; speckled char; speckled trout; specks; squaretail; square-tail; squaretailed trout; trout; whitefin. |                                                                  |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                  |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| <p>References:<br/> <a href="https://www.itis.gov/servlet/SingleRpt/SingleRpt?search_topic=TSN&amp;search_value=162003#null">https://www.itis.gov/servlet/SingleRpt/SingleRpt?search_topic=TSN&amp;search_value=162003#null</a><br/>           Starnes WC. 2003. Research Curator of Fishes, North Carolina State Museum of Natural Sciences, Research Laboratory, 4301 Reedy Creek Rd., Raleigh, NC, 27607, USA.<br/> <a href="https://www.cabi.org/isc/datasheet/65325">https://www.cabi.org/isc/datasheet/65325</a></p>                                                                                                               |                  |
| <b>BAC7 What is the native range of the <i>Taxon</i>?</b> (add map in Appendix BAC7)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                  |
| <p>Response:<br/>           The brook trout's native range goes from the northern areas of Quebec down to the northern parts of South Carolina and Georgia and from the coasts of Newfoundland in the east to Manitoba down to Minnesota in the west (Karas 1997; Page and Burr 2011; Froese and Pauly 2022).</p>                                                                                                                                                                                                                                                                                                                        | Confidence: High |
| <p>Comments:</p> <p>References:<br/>           Froese R, Pauly D. (Editors). 2022. FishBase. World Wide Web electronic publication. <a href="http://www.fishbase.org">www.fishbase.org</a>, (06/2022).<br/>           Karas N. 1997. Brook Trout. Lyons and Buford, New York.<br/>           Page LM, Burr BM. 2011. A field guide to freshwater fishes of North America north of Mexico. Boston: Houghton Mifflin Harcourt, 663 p.</p>                                                                                                                                                                                                  |                  |
| <b>BAC8 What is the global alien range of the <i>Taxon</i>?</b> (add map in Appendix BAC8)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                  |
| <p>Response:<br/>           Alaska, Argentina, Australia, Austria, Belgium, Bolivia, British Columbia, Bulgaria, Chile, China, Colombia, Cyprus, Czech Republic, Denmark, Ecuador, Estonia, Falkland Islands, Finland, France, Germany, Greece, Hawaii, Hungary, India, Iran, Italy, Japan, Kenya, Latvia, Lebanon, Lithuania, Mexico, Morocco, Netherlands, New Zealand, Norway, Peru, Poland, Portugal, Romania, Russian Federation, Slovakia, South Africa, Spain, Sweden, Switzerland, Turkey, Venezuela, Zimbabwe.</p>                                                                                                              | Confidence: High |
| <p>Comments:<br/>           Global introductions of brook trout also began in the late 1800s and there are now established populations in many European countries, South America, Asia, Africa, and Oceania (Jansson 2013; Froese and Pauly 2022).</p>                                                                                                                                                                                                                                                                                                                                                                                   |                  |
| <p>References:<br/>           Froese R, Pauly D (Editors). 2022. FishBase. World Wide Web electronic publication. <a href="http://www.fishbase.org">www.fishbase.org</a>, (06/2022).<br/>           Jansson K. 2013. NOBANIS-Invasive Alien Fact Sheet-Salvelinus fontinalis. Online Database of the European Network on Invasive Alien Species.</p>                                                                                                                                                                                                                                                                                     |                  |
| <b>BAC9 Geographic scope = the Area under consideration</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                  |
| Area of assessment: South Africa                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                  |
| Comments:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                  |
| <b>BAC10 Is the <i>Taxon</i> present in the Area?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                  |
| Response: No                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Confidence: High |
| <p>Comments: Brook trout was introduced to South Africa in 1890 from the USA for angling but the introduction was not successful, probably due to lack of suitable habitats (Weaver R. 2008; Ellender et al. 2014; Weyl et al. 2020).</p>                                                                                                                                                                                                                                                                                                                                                                                                |                  |
| <p>References:<br/>           Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b>: 117–132.<br/>           Weaver R. 2008. The historical Jonkerhoek hatchery. <i>Piscator</i>, No 140.<br/>           Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), <i>Biological invasions in South Africa</i>. Springer, Berlin, pp 153-183.</p> |                  |

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                            |                        |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|------------------------|
| <b>BAC11 Availability of physical specimen</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                            |                        |
| Response: None                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                                            | Confidence in ID: High |
| Herbarium or museum accession number:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                            |                        |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                                            |                        |
| <b>BAC12 Is the <i>Taxon</i> native to the Area or part of the Area?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                            |                        |
| The <i>Taxon</i> is native to (part of) the Area.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | No                                         | Confidence: High       |
| The <i>Taxon</i> is alien in (part of) the Area.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Yes                                        | Confidence: High       |
| <p>Comments:</p> <p>Brook trout is native to North America and the range spans from the northern areas of Quebec down to the northern parts of South Carolina and Georgia and from the coasts of Newfoundland in the east to Manitoba down to Minnesota in the west (Karas 1997; Page and Burr 2011; Froese and Pauly 2022).</p> <p>References:</p> <p>Froese R, Pauly D (Editors). 2022. FishBase. World Wide Web electronic publication. <a href="http://www.fishbase.org">www.fishbase.org</a>, (06/2022).</p> <p>Karas N. 1997. Brook Trout. Lyons and Buford, New York.</p> <p>Page LM, Burr BM. 2011. A field guide to freshwater fishes of North America north of Mexico. Boston: Houghton Mifflin Harcourt, 663 p.</p>                                |                                            |                        |
| <b>BAC13 What is the <i>Taxon's</i> introduction status in the Area?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                            |                        |
| The <i>Taxon</i> is in cultivation/containment.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | No                                         | Confidence: High       |
| The <i>Taxon</i> is present outside of cultivation/containment.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | No                                         | Confidence: High       |
| The <i>Taxon</i> has established/naturalised.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | No                                         | Confidence: High       |
| The <i>Taxon</i> is invasive.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | No                                         | Confidence: High       |
| <p>Comments:</p> <p>Brook trout was introduced to South Africa in 1890 from the USA for angling but the introduction was not successful, probably due to lack of suitable habitats (Ellender et al. 2014; Weyl et al. 2022).</p> <p>References:</p> <p>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b>: 117–132.</p> <p>Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), <i>Biological invasions in South Africa</i>. Springer, Berlin, pp 153-183.</p> |                                            |                        |
| <b>BAC14 Primary (introduction) pathways</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                            |                        |
| Release                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | fishery in the wild                        | Confidence: High       |
| Escape                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | N/A                                        | Confidence: High       |
| Contaminant                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | N/A                                        | Confidence: High       |
| Stowaway                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | N/A                                        | Confidence: High       |
| Corridor                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | N/A                                        | Confidence: High       |
| Unaided                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Introduction via interconnected catchments | Confidence: low        |
| <p>Comments:</p> <p>Brook trout was also introduced in the neighbouring country (Zimbabwe), however, their establishment was not successful (Marshall 2011).</p> <p>References:</p> <p>Marshall BE. 2011. The Fishes of Zimbabwe and their Biology. Smithiana Monography 3, The South Africa Institute for Aquatic Biodiversity, Grahamstown, South Africa</p>                                                                                                                                                                                                                                                                                                                                                                                                |                                            |                        |



## 2. Likelihood

| <b>LIK1 Likelihood of entry via unaided primary pathways</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Response: Unlikely                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Confidence: low  |
| <p><b>Rationale:</b><br/>Brook trout were introduced into South Africa and neighbouring Zimbabwe. However, these introductions were not successful (Ellender et al. 2014; Marshall 2011). There were attempts to hybridise brook trout and brown trout (<i>Salmo trutta</i>) in South Africa and Zimbabwe to form the so-called 'tiger trout'. There is, however, no recent records of this this hybrids in South Africa and Zimbabwe.</p>                                                                                                                                                                                                             |                  |
| <p><b>References:</b><br/>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b>: 117–132.<br/>Marshall BE. 2011. The Fishes of Zimbabwe and their Biology. Smithiana Monography 3, The South Africa Institute for Aquatic Biodiversity, Grahamstown, South Africa.</p>                                                                                                                                                                                                                                   |                  |
| <b>LIK2 Likelihood of entry via human aided primary pathways</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |
| Response: Unlikely                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Confidence: low  |
| <p><b>Rationale:</b><br/>There is no known evidence of brook trout occurrence in the neighbouring countries, so the only possible introduction via human aided primary pathway is from other continents which is currently unlikely (Ellender et al. 2014; Marshall et al. 2011).</p>                                                                                                                                                                                                                                                                                                                                                                  |                  |
| <p><b>References:</b><br/>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b>: 117–132.<br/>Marshall BE. 2011. The Fishes of Zimbabwe and their Biology. Smithiana Monography 3, The South Africa Institute for Aquatic Biodiversity, Grahamstown, South Africa.</p>                                                                                                                                                                                                                                   |                  |
| <b>LIK3 Habitat suitability</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |
| Response: Probable                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Confidence: High |
| <p><b>Rationale:</b><br/>Similar to rainbow trout and brown trout, brook trout prefer clear, cool, well-oxygenated creeks, small to medium rivers, and lakes (prefer streams with cool, flowing waters and rocky substrate (Karas 1997; Page and Burr 2011). These habitat are found in several headwater mountain streams in South Africa. However confidence is marked as medium because previous introduction attempts in the wild were not successful (see Ellender et al. 2014).</p>                                                                                                                                                              |                  |
| <p><b>References:</b><br/>Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. <i>Aquatic Invasions</i> <b>9</b>: 117–132.<br/>Karas N. 1997. Brook Trout. Lyons and Buford, New York.<br/>Page LM, Burr BM. 2011. A field guide to freshwater fishes of North America north of Mexico. Boston: Houghton Mifflin Harcourt, 663 p.</p>                                                                                                                                                                                                     |                  |
| <b>LIK4 Climate suitability</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                  |
| Response: Probable                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Confidence: High |
| <p><b>Rationale:</b><br/>Brook trout is a cold water species that prefer streams with temperature range between 10 -18° (Scott and Crossman 1973). These climatic conditions can be found in the headwaters of many rivers in South Africa, especially the eastern escarpment stretching from the south-western Cape to Northern Kwa-Zulu Natal as indicated by systematic climate modelling studies (Picker and Griffiths 2011; Weyl and Keevey 2012; Ellender et al. 2016; Rivers-Moore et al. 2019). However, confidence is marked as medium because previous introduction attempts in the wild were not successful (see Ellender et al. 2014).</p> |                  |
| <p><b>References:</b><br/>Ellender BR, Rivers-Moore NA, Coppinger CR, Bellingan TA, Weyl OL. 2016. Towards using thermal stress thresholds to predict salmonid invasion potential. <i>Biological Invasions</i> <b>18</b>: 3513–3525.</p>                                                                                                                                                                                                                                                                                                                                                                                                               |                  |

Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. *Aquatic Invasions* **9**: 117–132.

Picker MD, Griffiths CL. 2011. Alien and invasive animals – A South African Perspective, Randomhouse/Struik, Cape Town, South Africa, 240 pp.

Rivers-Moore NA, Ellender BR, Weyl OLF. 2019. Modelling expected trout ranges under current and future water temperature regimes in the Eastern Cape, South Africa. *African Journal of Aquatic Science* **44**: 35–42.

Scott WB, Crossman EJ. 1973. Freshwater fishes of Canada. Fisheries Research Board of Canada, Bulletin, No. 184, 966 pp.

Weyl OLF, Keevey G. 2012. Deliverable 17. Report on GIS mapping and bibliography of dams with inland fisheries potential. Water Research Commission, Baseline and scoping study on the development and sustainable utilisation of storage dams for inland fisheries and their contribution to rural livelihoods Project Title: K5/1957/4.

#### LIK5 Unaided secondary (dispersal) pathways

Response: Very unlikely

Confidence: High

##### Rationale:

There is no known populations of brook trout (in captivity or in the wild) in the South Africa or neighbouring countries which may facilitate its dispersal into the country via interconnected catchments (Ellender et al. 2014; Marshal 2011).

##### References:

Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. *Aquatic Invasions* **9**: 117–132.

Marshall BE. 2011. The Fishes of Zimbabwe and their Biology. Smithiana Monography 3, The South Africa Institute for Aquatic Biodiversity, Grahamstown, South Africa.

#### LIK6 Human aided secondary (dispersal) pathways

Response: Extremely unlikely

Confidence: High

##### Rationale:

There is no recent records of introduction and utilisation of the brook trout for aquaculture and or angling (Ellender et al. 2014; Weyl et al. 2020). Therefore, the likelihood of human-aided dispersal of brook trout through human aided secondary (dispersal) pathways is unlikely

##### References:

Ellender BR, Weyl OLF. 2014. A review of current knowledge, risk and ecological impacts associated with non-native freshwater fish introductions in South Africa. *Aquatic Invasions* **9**: 117–132.

Weyl OLF, Ellender B, Wassermann RJ, Truter M, Dalu T, Zengeya TA, Smit NJ. 2020. Alien freshwater fauna in South Africa. In: van Wilgen BW, Measey J, Richardson DM, Wilson JR, Zengeya TA (eds), *Biological invasions in South Africa*. Springer, Berlin, pp 153-183.

### 3. Consequences

#### CON1 Environmental impact

##### CON1a: Competition

Response: MN

Confidence: High

##### Rationale:

In its alien range, *S. fontinalis* has been implicated in outcompeting native fish species for resources such as food and habitats (Levin et al. 2022; Copp et al. 2005; Rieman et al. 2006; Macneale et al. 2010; Nehring et al. 2010; Lepori et al. 2012; Warnock and Rasmussen 2013; van der Veer and Nentwig 2015, GISD 2022). Its life history traits such as a rapid growth rate, large size, and behavioral attributes (greater immigration, aggression, and piscivory) predispose it outcompete with native fish species (Dunham et al. 2002; Peterson and Fausch 2003; Peterson et al. 2004; McMahon et al. 2007; Benjamin and Baxter 2012). *Salvelinus fontinalis* is also known to affect other fauna such as aquatic and terrestrial invertebrates, amphibians, and even birds and bats (Benjamin et al. 2013). In South Africa, there are no known populations *S. fontinalis* and there is no evidence that the species has caused any negative environmental impacts.

##### References:



- Copp GH, Garthwaite R, Gozlan RE. 2005. Risk identification and assessment of non-native freshwater fishes: Concepts and perspectives on protocols for the UK. Cefas Science Technical Report. Lowestoft, UK.
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- McMahon TE, Zale AV, Barrows FT, Selong J, Danehy R. 2007. Temperature and competition between Bull Trout and Brook Trout: a test of the elevation refuge hypothesis. *Transactions of the American Fisheries Society* **136**:1313–1326.
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- Rieman BE, Peterson JT, Myers DL. 2006. Have brook trout (*Salvelinus fontinalis*) displaced bull trout (*Salvelinus confluentus*) along longitudinal gradients in central Idaho streams? *Canadian Journal of Fisheries and Aquatic Sciences* **63**: 63-78.
- van der Veer G, Nentwig W. 2015. Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system. *Ecology of Freshwater Fish* **24**: 646-656.
- Warnock WG, Rasmussen JB. 2013. Abiotic and biotic factors associated with brook trout invasiveness into bull trout streams in the Canadian Rockies. *Canadian Journal of Fisheries and Aquatic Sciences* **70**: 905-914.

#### CON1b: Predation

Response: MO

Confidence: High

##### Rationale:

*Salvelinus fontinalis* are opportunistic feeders and have been known to have a broad trophic niche that includes everything from insects to fish to small mammals and even plant matter (Karas 1997). In its alien range, *S. fontinalis* has been implicated in reducing the abundance of native species of invertebrates, amphibians and fishes through predation (Hikita et al. 1959; Gregory and Griffith 2000; Novinger 2000; Copp et al. 2005; Nehring et al. 2010; Lepori et al. 2012; Benjamin et al. 2013; van der Veer and Nentwig 2015; GISD 2022). *Salvelinus fontinalis* are known to cause top down cascading trophic interactions resulting in modifications of benthic zooplankton, macroinvertebrates, and algal communities e.g., Bechara et al. 2007; GISD 2022)

##### References:

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#### CON1c: Hybridisation

Response: MO

Confidence: High

##### Rationale:

Hybridisation between *S. fontinalis* and native trout species poses a risk to the genetic integrity of endemic fish. Hybridisation between *S. fontinalis* and other trout species has been observed in its alien range with species such as brown trout (*Salmo trutta*), Dolly Varden (*Salvelinus malma*), lake trout (*Salvelinus namaycush*), arctic char (*Salvelinus alpinus*), (white-spotted charr (*Salvelinus leucomaenis*), bull trout (*Salvelinus confluentus*) (Suzuki and Kato 1966; Leary et al. 1993; Kitano 2002; Copp et al. 2005; Kitano and Uehara 2002; Nehring et al. 2010; Jansson 2013; GISD 2022). There are no native species in the family Salmonidae in South Africa, therefore there is no risk of hybridisation.

##### References:

- Copp GH, Garthwaite R, Gozlan RE. 2005. Risk identification and assessment of non-native freshwater fishes: Concepts and perspectives on protocols for the UK. Cefas Science Technical Report. Lowestoft, UK.
- Global Invasive Species Database. 2022. Species profile: *Salvelinus fontinalis*. Downloaded from <http://www.iucngisd.org/gisd/speciesname/Salvelinus+fontinalis> on 10-11-2022.
- Jansson K. 2013. NOBANIS-Invasive Alien Fact Sheet-Salvelinus fontinalis. Online Database of the European Network on Invasive Alien Species.
- Kitano S. 2002. *Salvelinus fontinalis*. In: The ecological society of Japan, ed., Handbook of Alien Species in Japan. Chijinshokan Press, Tokyo, 114 p.
- Kitano S, Uehara T. 2002. Nest superimposition by exotic brook, brown trout and hybrids on native charrs in a Japanese stream. In: Proceeding of the VIII International Congress of Ecology (INTECOL), Seoul, Korea, 138 p.
- Leary RF, Allendorf FW. 1993. Conservation genetics of bull trout in the Columbia and Klamath River drainages. *Conservation Biology* **7**: 856-865.
- Nehring S, Essl F, Klingenstein F, Nowack C, Rabitsch W, Stohr O. 2010. Schwarze Liste invasiver Arten: Kriteriensystem und Schwarze Listen invasiver Fische für Deutschland und für Österreich. BfN-Skripten 285, Bonn-Bad Godesberg, 185 pp.

Suzuki R, Kato T. 1966. Hybridization in nature between salmonid fishes, *Salvelinus pluvius* x *Salvelinus fontinalis*. *Bulletin of the Freshwater Fisheries Research Laboratory* **17**: 83-90.  
van der Veer G, Nentwig W. 2015. Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system. *Ecology of Freshwater Fishes* **24**: 646-656.

#### CON1d: Transmission of disease

Response: MN

Confidence: High

##### Rationale:

*Salvelinus fontinalis* have been associated with a host of diseases and parasites such as *Myxobolus cerebralis*, most of which are typically associated with fish culture operations (Copp et al. 2005, Nehring et al. 2010; van der Veer and Nentwig 2015). For example, the Whirling disease (*Myxobolus cerebralis*) became of particular concern to several eastern states in the early 2000s when it was suspected to be introduced there by hatchery reared rainbow trout (*Oncorhynchus mykiss*) (Maryland DNR 2006). Whirling disease is an internal protozoan parasite that infects the cartilage of the head and spinal cord and can cause cranial-spinal deformations and mortalities (Warren 1991). More commonly seen parasites of brook trout are the external copepods often called lice. There are three types of copepods likely to be encountered on a brook trout: the *Salminicola* spp. or gill lice; the *Argulus* spp. or freshwater lice; and *Lepeophtheirus salmonis* or sea/salmon louse (Warren 1991, Trout Unlimited). These parasites rarely cause adverse effects or mortalities in host fish unless unusually large infestations occur (Warren 1991). Disease transmission from brook trout does not account for declines in greenback cutthroat trout (USFWS, unpublished data) or the closely related Colorado River cutthroat trout (*O. c. pleuriticus*; Peterson and Fausch 2002).

##### References:

Copp GH, Garthwaite R, Gozlan RE. 2005. Risk identification and assessment of non-native freshwater fishes: Concepts and perspectives on protocols for the UK. Cefas Science Technical Report. Lowestoft, UK.  
Maryland Department of Natural Resources. 2006. Maryland Brook Trout Fisheries Management Plan.  
Nehring S, Essl F, Klingenstein F, Nowack C, Rabitsch W, Stohr O. 2010. Schwarze Liste invasiver Arten: Kriteriensystem und Schwarze Listen invasiver Fische für Deutschland und für Österreich. BfN-Skripten 285, Bonn-Bad Godesberg, 185 pp.  
Peterson DP, Fausch KD. 2003. Upstream movement by non-native brook trout (*Salvelinus fontinalis*) promotes invasion of native cutthroat trout (*Oncorhynchus clarki*) habitat. *Canadian Journal of Fisheries and Aquatic Sciences* **60**:1502–1516.  
van der Veer G, Nentwig W. 2015. Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system. *Ecology of Freshwater Fishes* **24**: 646-656.  
Warren JW. 1991. Diseases of Hatchery Fish Sixth Edition. US Fish and Wildlife Service.

#### CON1e: Parasitism

Response: MN

Confidence: High

##### Rationale:

It is assumed that parasites such as *Ichthyophthirius multifiliis*, which causes white spot disease, and *Ichthyobodo necator* (formerly *Costia necatrix*) were brought into Australia with live fish sometime between 1880 and 1930 (Ashburner 1976). Whether they were introduced with salmonids or with other fish species, or with both salmonids and other species, is debatable and perhaps will never be known.

Hatcheries stocked with trout have been reported to spread parasites such as *I. multifiliis* and other pathogens widely throughout Tasmania, Victoria and New South Wales, then to South Australia and Western Australia. However, the role of salmonids as vectors for the dissemination of the wide range of protozoan, metazoan, bacterial and fungal pathogens typically found in Australian salmonid hatcheries is not known (Humphrey and Langdon 1985).

##### References:

Ashburner LD. 1976. Fish diseases and potential fish diseases in Australia. *Animal Quarantine* **5**: 1-7.  
Humphrey JD, Langdon JS. 1985. Proceedings of the Workshop on Diseases of Australian Fish and Shellfish, Australian Fish Health Reference Laboratory, Benalla. Department of Agriculture and Rural Affairs, Victoria, 277 pp.

#### CON1f: Poisoning/toxicity

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                    |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| Response: DD                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Confidence: medium |
| Rationale: No documented information available to assess the level of impact.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                    |
| <b>CON1g: Bio-fouling or other direct physical disturbance</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                    |
| Response: DD                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Confidence: medium |
| Rationale:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                    |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                    |
| <b>CON1h: Grazing/herbivory/browsing</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                    |
| Response: DD                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Confidence: medium |
| Rationale: No documented information available to assess the level of impact.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                    |
| <b>CON1i: Chemical, physical or structural impact on ecosystem</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                    |
| Response: DD                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Confidence: medium |
| Rationale: No documented information available to assess the level of impact.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                    |
| <b>CON1k: Indirect impacts through interactions with other species</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                    |
| Response: DD                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Confidence: medium |
| Rationale: No documented information available to assess the level of impact.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                    |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                    |
| <b>CON1 Maximum environmental impact (Figure S3)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                    |
| Response: MO                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Confidence: High   |
| Rationale:<br><i>Salvelinus fontinalis</i> were assessed as causing moderate impacts that have caused declines, and fragmentation of native populations of invertebrates, frogs and fish through predation and hybridisation (Copp et al. 2009; Nehring et al. 2010; van der Veer and Nentwig. 2015)                                                                                                                                                                                                                                                                                                                                                                                                           |                    |
| References:<br>Copp GH, Garthwaite R, Gozlan RE. 2005. Risk identification and assessment of non-native freshwater fishes: Concepts and perspectives on protocols for the UK. Cefas Science Technical Report. Lowestoft, UK.<br>Nehring S, Essl F, Klingenstein F, Nowack C, Rabitsch W, Stohr O. 2010. Schwarze Liste invasiver Arten: Kriteriensystem und Schwarze Listen invasiver Fische für Deutschland und für Österreich. BfN-Skripten 285, Bonn-Bad Godesberg, 185 pp.<br>van der Veer G, Nentwig W. 2015. Environmental and economic impact assessment of alien and invasive fish species in Europe using the generic impact scoring system. <i>Ecology of Freshwater Fishes</i> <b>24</b> : 646-656. |                    |

|                                                                              |                    |
|------------------------------------------------------------------------------|--------------------|
| <b>CON2 Socio-economic impact</b>                                            |                    |
| <b>CON2a: Safety</b>                                                         |                    |
| Response: DD                                                                 | Confidence: medium |
| Rationale: No documented information available to assess the level of impact |                    |
| References:                                                                  |                    |
| <b>CON2b: Material and immaterial assets</b>                                 |                    |
| Response: DD                                                                 | Confidence: medium |
| Rationale: No documented information available to assess the level of impact |                    |
| References:                                                                  |                    |
| <b>CON2c: Health</b>                                                         |                    |
| Response: DD                                                                 | Confidence: medium |
| Rationale: No documented information available to assess the level of impact |                    |
| References:                                                                  |                    |
| <b>CON2d: Social, spiritual and cultural relations</b>                       |                    |
| Response: DD                                                                 | Confidence: medium |
| Rationale: No documented information available to assess the level of impact |                    |
| References:                                                                  |                    |
| <b>CON2 Maximum socio-economic impact (Figure S3)</b>                        |                    |
| Response: DD                                                                 | Confidence: medium |

|                                                                              |
|------------------------------------------------------------------------------|
| Rationale: No documented information available to assess the level of impact |
| References:                                                                  |

### CON3 Closely related species' environmental impact

|                                                                                                         |                    |
|---------------------------------------------------------------------------------------------------------|--------------------|
| Response: Not scored as CON1 scored                                                                     | Confidence: medium |
| Rationale: There is information to score CON1, so CON3 does not need to be scored as per the framework. |                    |
| References:                                                                                             |                    |

### CON4 Closely related species' socio-economic impact

|                                                                                  |                 |
|----------------------------------------------------------------------------------|-----------------|
| Response: DD                                                                     | Confidence: low |
| Rationale: There are no relevant records of socio-economic impacts of Salmonids. |                 |
| References:                                                                      |                 |

### CON5 Potential impact

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Response: MO                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Confidence: High |
| Rationale: In South Africa, a national-level EICAT assessment classified impacts caused by closely related species ( <i>Salmo trutta</i> and <i>Oncorhynchus mykiss</i> ) as Major (MR) as they are known to cause declines, and in some cases local extinction of native invertebrates, frogs and fish through predation and competition (Marr et al. 2017). If <i>Salvelinus fontinalis</i> is introduced and becomes invasive, it likely to cause similar impacts. |                  |
| References:<br>Marr S, Ellender B, Woodford D, Alexander M, Wasserman R, Ivey P, Zengeya T, Weyl O. 2017. Evaluating invasion risk for freshwater fishes in South Africa. <i>Bothalia</i> <b>47</b> : 1–10.                                                                                                                                                                                                                                                           |                  |

## 4. Management

### MAN1 What is the feasibility to stop future immigration?

|                                                                                                                                                                                                                                                                                                                          |                  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| Response: High                                                                                                                                                                                                                                                                                                           | Confidence: High |
| Rationale:<br>There are currently no recent records of <i>Salvelinus fontinalis</i> occurring in South Africa and in neighbouring countries. This implies that its introduction into the country can be controlled through use of import restrictions and permitting to manage new introductions (Woodford et al. 2017). |                  |
| References:<br>Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. <i>Bothalia</i> <b>47</b> : a2138.                                                                                            |                  |

### MAN2 Benefits of the Taxon

#### MAN2a Socio-economic benefits of the Taxon

|                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| Response: High                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Confidence: Medium |
| Rationale:<br>The economic impacts of brook trout invasions are generally positive due to their desirability in the sport fishing community (Jansson 2013). Anglers spend money on bait, tackle, travel, lodging, dining, fishing licenses, guides, etc., all of which add to local economy (Jansson 2013). The culture and stocking of brook trout also provide job in the hatcheries themselves, in feed production, in the manufacture of hatchery related equipment. |                    |
| References:<br>Jansson K. 2013. NOBANIS-Invasive Alien Fact Sheet- <i>Salvelinus fontinalis</i> . Online Database of the European Network on Invasive Alien Species.                                                                                                                                                                                                                                                                                                     |                    |

#### MAN2b Environmental benefits of the Taxon

|                                                                               |                 |
|-------------------------------------------------------------------------------|-----------------|
| Response: DD                                                                  | Confidence: low |
| Rationale: No documented information available to assess the level of impact. |                 |



|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                  |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------|
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                  |
| <b>MAN3 Ease of management</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                  |
| <b>MAN3a How accessible are populations?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                  |
| Response: 2                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Confidence: High |
| Rationale: There are no known naturalised populations or in captivity of <i>S. fontinalis</i> in South Africa.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                  |
| <b>MAN3b Is detectability critically time-dependent?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |
| Response: 2 (difficult)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Confidence: High |
| Rationale: Trout can be detected at any time, but it does require special equipment (e.g. electrofishing gear) and trained specialists to operate such equipment. Detection is thus logistically challenging, but not time-dependent                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                  |
| References:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                  |
| <b>MAN3c Time to reproduction</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                  |
| Response: 1 (1-3 years)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Confidence: High |
| Rationale:<br><i>Salvelinus fontinalis</i> reach maturity on an average at the age of two and spawn every year, although their size at first maturity depends on growth rate and the productivity of thier habitat (Everhart, 1961)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                  |
| References:<br>Everhart W. 1961. Fishes of Maine. Augusta, Maine, USA: The Maine Department of Inland Fisheries and Game.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                  |
| <b>MAN3d Propagule persistence</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  |
| Response: 0 (< 1 year)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | Confidence: low  |
| Rationale:<br>The total time of incubation period (60-100 days) depends on factors such as temperature and oxygen (Scott and Crossman 1985).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                  |
| References:<br>Scott W, Crossman E. 1985. Freshwater Fishes of Canada. Ottawa, Canada: Minister of Supply and Services Canada.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                  |
| <b>MAN3 Ease of management (SUM from Table S4)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  |
| Response: Medium                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Confidence: High |
| Rationale:<br>Management of <i>S. fontinalis</i> is scored here as medium. There are no known naturalised populations or in captivity of <i>S. fontinalis</i> in South Africa. Introductions can be managed through import restrictions and permitting. However, several issues make management challenging. These include the fact that control operations would likely be met with resistance from certain interest groups (see Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017)                                                                                                                                                                                                                                                                                                                                                       |                  |
| References:<br>Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. <i>Journal of Fish Biology</i> <b>85</b> : 1890–1906.<br>Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. <i>Bothalia</i> <b>47</b> : 1–9.<br>Woodford DJ, Richardson DM, MacIsaac HJ, Mandrak N, van Wilgen BW, Wilson JR, Weyl OLF. 2016. Confronting the wicked problem of managing invasive species. <i>Neobiota</i> <b>31</b> : 63–86.<br>Zengeya T, Ivey P, Woodford DJ, Weyl O, Novoa A, Shackleton R, Richardson D, Van Wilgen B. 2017. Managing conflict-generating invasive species in South Africa: challenges and trade-offs. <i>Bothalia</i> <b>47</b> : 1–11. |                  |
| <b>MAN4 Has the feasibility of eradication been evaluated?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                  |
| Response: No                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Confidence: High |

**Rationale:**  
There have been no studies that have addressed the country-wide eradication of *S. fontinalis* in South Africa

**References:**

#### MAN5 Control options and monitoring approaches available for the Taxon

**Response:**  
Management of trout species in South Africa is relatively difficult. This because trout are conflict-generating invasive species that have major negative environmental impacts, but also some socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. There are no known *S. fontinalis* populations in South Africa and the first management option is to restrict importation through permitting with key conditions to prevent potential spread and impacts. For example, the proposed management initiatives could include managing it by area where utilisation is restricted to a few areas where it has historically been stocked. Concerned stakeholders have highlighted the need for broader consultations and transparency on the evidence used to assess the risks posed by trout to biodiversity and the benefits derived from their utilisation see (Ellender et al. 2014; Woodford et al. 2016; Woodford et al. 2017; Zengeya et al. 2017).

**References:**  
Ellender BR, Woodford DJ, Weyl OLF, Cowx IG. 2014. Managing conflicts arising from fisheries enhancements based on non native fishes in southern Africa. *Journal of Fish Biology* **85**: 1890–1906.  
Woodford DJ, Ivey P, Jordaan MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. *Bothalia* **47**: 1–9.  
Woodford DJ, Richardson DM, MacIsaac HJ, Mandrak N, van Wilgen BW, Wilson JR, Weyl OLF. 2016. Confronting the wicked problem of managing invasive species. *Neobiota* **31**: 63–86. <https://doi.org/10.3897/neobiota.31.10038>  
Zengeya T, Ivey P, Woodford DJ, Weyl O, Novoa A, Shackleton R, Richardson D, Van Wilgen B. 2017. Managing conflict-generating invasive species in South Africa: challenges and trade-offs. *Bothalia* **47**: 1–11.

#### MAN6 Any other management considerations to highlight? (if yes, fill in Appendix MAN6)

|                 |                         |
|-----------------|-------------------------|
| <b>Response</b> | Yes (see Appendix MAN6) |
|-----------------|-------------------------|

### 5. Calculations

**Likelihood** = Very unlikely

| Parameter | Likelihood    | Stages                      | Final assessment             |
|-----------|---------------|-----------------------------|------------------------------|
| LIK1      | Unlikely      | P(entry) = Unlikely         | P (invasion) = Very unlikely |
| LIK2      | Unlikely      |                             |                              |
| LIK3      | Probable      | P(establishment) = Probable |                              |
| LIK4      | Probable      |                             |                              |
| LIK5      | Very unlikely | P (spread) = Very unlikely  |                              |
| LIK6      | Very unlikely |                             |                              |

**Consequence** = Moderate (MO)

| Parameter | Mechanism/sector                                 | Response |
|-----------|--------------------------------------------------|----------|
| CON1a     | Competition                                      | MN       |
| CON1b     | Predation                                        | MO       |
| CON1c     | Hybridisation                                    | MO       |
| CON1d     | Disease transmission                             | MN       |
| CON1e     | Parasitism                                       | MN       |
| CON1f     | Poisoning/toxicity                               | DD       |
| CON1g     | Bio-fouling or other direct physical disturbance | DD       |

|       |                                                                                                   |                              |
|-------|---------------------------------------------------------------------------------------------------|------------------------------|
| CON1h | Grazing/herbivory/browsing                                                                        | DD                           |
| CON1i | Chemical, physical, structural impact                                                             | DD                           |
| CON1k | Indirect impacts through interactions with other species                                          | DD                           |
| CON1  | Maximum environmental impact                                                                      | MO                           |
| CON2a | Safety                                                                                            | DD                           |
| CON2b | Material and immaterial assets                                                                    | DD                           |
| CON2c | Health                                                                                            | DD                           |
| CON2d | Social, spiritual and cultural relations                                                          | DD                           |
| CON2  | Maximum socio-economic impact                                                                     | DD                           |
| CON3  | Environmental impact of closely related taxa<br>(only score if CON1a-k are all DD, otherwise NA)  | Not scored as<br>CON1 scored |
| CON4  | Socio-economic impact of closely related taxa<br>(only score if CON2a-g are all DD, otherwise NA) | DD                           |
| CON5  | Potential impact based on traits, experiments, or models                                          | MO                           |

**Risk score = Low**

|            |                    | Consequences |        |        |        |        |
|------------|--------------------|--------------|--------|--------|--------|--------|
|            |                    | MC           | MN     | MO     | MR     | MV     |
| Likelihood | Extremely unlikely | low          | low    | low    | medium | medium |
|            | Very unlikely      | low          | low    | low    | medium | high   |
|            | Unlikely           | low          | low    | medium | high   | high   |
|            | Fairly probable    | medium       | medium | high   | high   | high   |
|            | Probable           | medium       | high   | high   | high   | high   |

**Ease of management = Medium**

| Parameter   | Question                                    | Response |
|-------------|---------------------------------------------|----------|
| MAN3a       | How accessible are populations?             | 2        |
| MAN3b       | Is detectability critically time-dependent? | 1        |
| MAN3c       | Time to reproduction                        | 0        |
| MAN3d       | Propagule persistence                       | 0        |
| <b>MAN3</b> | <b>SUM</b>                                  | <b>3</b> |

**Appendix BAC7:** The global distribution of *Salvelinus fontinalis* (Brook trout) within their native and introduced range. Source: Muhlfeld et al. (2019), <https://doi.org/10.47886/9781934874547>.



**Appendix MAN6:** Proposed listing options for *Salvelinus fontinalis* under the NEM:BA A&IS Regulations

**Current listing as per NEM:BA A&IS lists of 2020**

**Taxon:** *Salvelinus fontinalis* (Mitchill, 1814)

**Common name:** brook trout



**Category:** not listed

*Salvelinus fontinalis* (Mitchill, 1814) was not listed as an invasive species in the South African Government Gazette on 18 September 2020, and in the NEM:BA A&IS Lists promulgated on 1 March 2021.

### **Rationale**

There are currently no recent records of *Salvelinus fontinalis* occurring in South Africa and in neighbouring countries. Previous introduction attempts were unsuccessful. This implies that its introduction into the country can be controlled through use of import restrictions and permitting to manage new introductions (Woodford et al. 2017). Management of trout species in South Africa is relatively difficult. This because trout are conflict-generating invasive species that have major negative environmental impacts, but also some socio-economic benefits. The challenge is to preserve the benefits while limiting the negative impacts. Therefore, the recommended management option is to restrict importation through permitting and implement intervention measures similar to those proposed for other trout species in South Africa.

### **Potential criteria for permits and exemptions**

Two key aims for the management of trout species in South Africa should be to: a) prevent the spread to new areas; and b) limit the negative environmental impacts by controlling trout populations in key fish conservation areas. To this end, those catchments where trout does not yet occur but where suitable habitat exists, and key fish conservation areas (with and without trout populations) would need to be identified in a National Management Plan that contains appropriate maps. The inclusion of maps outlining areas where permits may be granted would greatly facilitate the application and processing of permits.

The beneficial uses of trout species could then be managed as follows:

- Permits for existing or new aquaculture facilities could be granted, but only if such activities do not result in new sites becoming invaded or spread of trout into key fish conservation areas. As such permits would not be issued for aquaculture facilities in discrete catchment systems in which trout does not yet occur or that include key fish conservation areas. Permits could, however, be granted for aquaculture facilities in part of a discrete catchment system where trout occurs, providing there are natural or artificial habitat barriers (for example waterfalls, dams or weirs) that would prevent the spread of trout to other parts of the catchment system where it is currently absent, but where suitable habitat exists.
- In terms of restocking the same considerations as for aquaculture facilities would apply.
- In terms of angling, catch-and-release (i.e. the practice of anglers to return a fish to the water where it was caught) is exempt in any discrete-catchments that are specified on maps produced as per the National Management Plan. At all other sites catch-and-kill should be practised. This provision could be incorporated into provincial freshwater angling licences.
- The transport of live fish or eggs would always require a permit, but any dead specimens (e.g. for personal consumption or commercial trade) would, of course, be exempt.

### **National Management Plan**

To facilitate the implementation of these criteria and to ensure the process is transparent, it would be important to draw up a National Management Plan for each trout species. The plan would need to include maps of the catchments where permits may be issued for commercial production purposes, where permits may be issued for restocking, and where catch-and-release angling is exempt. Maps of key fish conservation areas would also be useful to indicate areas where catch-and-kill would need to be practised.

The National Management Plan would also need to specify the standards that should be met to limit the risk of escape or unintentional or illegal re-distribution to new areas.

### **Overall recommendation**

### **Proposed listing**

**Taxon:** *Salvelinus fontinalis* (Mitchill, 1814)

**Common name:** brook trout

**Category:** no change

**Exemption:** catch-and-release is exempt in areas specified in maps produced as part of a National Management Plan for *S. fontinalis*.

Permits may only be issued in line with the considerations discussed in the “Potential criteria for permits and exemptions” section above.

### **Reference**

Woodford DJ, Ivey P, Jordaan, MS, Kimberg PK, Zengeya T, Weyl OLF. 2017. Optimising invasive fish management in the context of invasive species legislation in South Africa. *Bothalia* **47**: a2138.

## Chapter 6: General discussion

The general objective of this study was to evaluate the impacts of rainbow trout (*Oncorhynchus mykiss*) on the ecology of indigenous fish communities in the headwater catchments of the Blyde River in Mpumalanga Province, South Africa. The thesis aimed at contributing toward a better understanding of factors that contribute to *O. mykiss* invasions in South Africa and its ecological implications. To achieve this objective, the study was separated into four components. Firstly, Chapter 2 applied the spread debt concept (an aspect of invasion debt concept) (Essl et al. 2011; Rouget et al. 2016) to highlight the potential increase in the area invaded by *O. mykiss* over time in Mpumalanga Province, South Africa. It specifically, assessed the extent of the invasion, identified areas that are climatically suitable for establishment but are still invasion-free, and evaluated how its potential invasive range may be affected by climate change scenarios. Secondly, Chapter 3 evaluated how *O. mykiss* invasions in the upper Blyde River have affected the community structure and function of indigenous species by evaluating the composition, relative abundance, and community structure. Thirdly, Chapter 4 assessed trophic interrelationships of fish communities in invaded and uninvaded river reaches within the catchment. Major concerns and implications for the conservation of indigenous congeners were highlighted. The last chapter (Chapter 5) assessed the risks associated with the introduction of several trout species (*O. mykiss*, *S. trutta*, *O. kisutch*, *O. tshawytscha*, *S. salar* and *S. fontinalis*) that are known to occur in South Africa using the recently developed Risk Analysis Framework for Alien Taxa. The RAAT framework offered a simple, objective, and transparent process of identifying risk associated with the introduction of alien species in South Africa and the development of appropriate management strategies.

*The current and predicted extent of *Oncorhynchus mykiss* invasions in Mpumalanga Province, South Africa*

Atlantic salmon (*Salmo salar*), and brook trout (*Salvelinus fontinalis*) The introduction of salmonid species in South African began over a century ago with the aim to improve recreational fisheries around the country (Weyl et al. 2020). Some of the introductions were successful (e.g., *O. mykiss* and *S. trutta*) but others such as *S. salar* and *Salvelinus fontinalis* failed probably due to lack of suitable habitats (de Moor and Bruton 1998; Ellender et al. 2014).. Despite its long history of introduction, naturalised populations of *O. mykiss* are still localised to a few areas with suitable habitats and climate (e.g., Ellender et al. 2016; Rivers-Moore et al. 2019). For cold-water species such as trout, climate change events such as global warming are likely to decrease habitat availability through range constriction of suitable areas. Climate change can, therefore, be a critical factor in determining the potential range of *O. mykiss*. It was, therefore, hypothesised that *O. mykiss* would have a low invasion debt because sustained and widespread stocking in pre-selected suitable receiving environments allowed it to establish in most of the areas where it has been introduced, but climate change would likely lead to a range contraction because of increasing temperatures. However, there was no evidence in the present study to support this hypothesis, instead, *O. mykiss* had a high invasion debt, and it has not established in most areas that were predicted as climatically suitable under current climatic conditions.

The spread debt of *O. mykiss* in Mpumalanga Province was estimated at over 60% of the suitable area. Several reasons may account for such a high estimate and these include natural and artificial in-stream barriers that can limit fish migration and management interventions such as protected areas where fish introductions are prohibited. In the upper Blyde River catchment, it is possible that *O. mykiss* was not introduced into all the suitable areas and natural dispersal may have been limited by natural biogeographic barriers. For

example, rainbow trout was introduced to some sections of the Blyde River below Christmas Pool falls but not in upper river sections above the falls (Engelbrecht and Roux 1998). The waterfalls act as a natural barrier to upstream fish migration and as a result the river sections above the falls, although suitable for trout are still invasion free. For example, Ellender et al. (2016) observed high spread debt for *O. mykiss* in Keiskamma River in the Eastern Cape Province, South Africa due to limited fish migration as a result of stream fragmentation by impoundments. In addition, these impoundments also have the potential to alter instream thermal regimes and create thermal gradients that limit the migration of cold-water species such as *O. mykiss* to downstream river sections that have warmer temperatures (e.g., Xie et al. 2017). Seasonal changes in river temperature have also been reported to affect the occurrence of *O. mykiss* in the Western Cape Province, South Africa, where warm temperatures during summer have resulted in low densities of *O. mykiss* (Shelton et al. 2018). In addition, the upper river section above Christmas Pool falls was also declared a natural heritage conservation area, so human-facilitated introductions are prohibited. Similarly, other areas that may be suitable for *O. mykiss* are located in conservation areas, where the introduction of *O. mykiss* is prohibited. For example, the Treur River catchment was declared a protected area because of the occurrence of the endangered and range-restricted Treur River barb (*Enteromius treurensis*) (Roux and Hoffman 2017).

The extent of the suitable area for *O. mykiss* in the Mpumalanga Province varied under different climate change scenarios where it was projected to decrease under the RCP 4.5 scenario and increase under the RCP 8.5 scenarios. The significant shifts in the extent of the suitable area for *O. mykiss* under the two scenarios were mainly attributed to changes in isothermality (a measure of how the diurnal temperature range fluctuates relative to the annual temperature range) and the mean temperature of the coldest quarter. There was a decline in the area predicted as suitable under the RCP 4.5 scenario when seasonality is projected to be high

and this is consistent with other studies elsewhere that have also predicted that *O. mykiss* distribution may be influenced by large seasonal temperature fluctuations (Ellender et al. 2016; Santiago et al. 2016; Shelton et al. 2018; Rivers-Moore et al. 2019). The increase in the suitable area under the RCP 8.5 scenario was unexpected and was largely due to a projected increase in the minimum temperature from 11° C to 15° C that resulted in a large proportion of the study area that occurs at lower altitudes and experiences warmer minimum water temperatures being predicted as suitable. This modelling artefact may be resolved by including mechanistic variables (e.g., thermal thresholds) in the models (e.g., Kearney and Porter 2009, Evans et al. 2015; Rivers-Moore et al. 2019).

While these data infer a large invasion debt, they are confounded by a lack of knowledge on sampling effort and verified true absence and should therefore be recognised as an estimate. The current records available on rainbow trout distribution in South Africa are limited and were mostly generated through stakeholder-government initiatives using expert opinion to map areas of occurrence. These records, however, have drawbacks that compromise their accuracy because they have not been verified and highlight the need for regular monitoring programmes to generate long term distribution data for alien species in freshwater systems in South Africa.

#### *Differences in community structure in the invaded and uninvaded sections of the upper Blyde River catchment*

The establishment of invasive predatory species within recipient systems is known to reduce native populations through various mechanisms such as predation and competitive exclusion for resources such as food and habitat (Eby et al. 2006). Salmonid fishes, particularly *O. mykiss* and *S. trutta* have caused major declines in native fish populations in areas of introduction around the world (e.g. McDowall 2006). This study assessed the effect of *O. mykiss* invasion on fish community structure in invaded and invasion-free reaches of the upper Blyde River,

Mpumalanga Province, South Africa. It specifically evaluated the hypotheses that the presence of *O. mykiss* would create specific differences in community structure such as a decline and fragmentation of native fish species populations in invaded areas. The study found some spatial differences in species composition, relative abundance, diversity, and community structure among sampling sites that may be a result of invasion status but there was also evidence that some of the differences might have been because of habitat differences among sites.

The invasion of *O. mykiss* in the upper catchments of the Blyde River was predominantly below the second waterfall where the abundance and diversity of indigenous species were significantly lower. The population of indigenous fish species that was most affected was the Treur River barb (96% lower) and this was probably due to predation and/or competition for habitat and food resources. *Oncorhynchus mykiss* is a predatory species that has been implicated in reducing the populations of indigenous species through selective predation of small-bodied fish species (McIntosh et al. 2010; Shelton et al. 2015). In South Africa alone, *O. mykiss* has been reported to have led to the extirpation of the endangered border barb (*Amatolacypris trevelyani*) (Ellender 2013), and in the decline of the Breede River redfin (*Pseudobarbus burchelli*), the Cape kurper (*Sandelia capensis*), and the Cape galaxias (*Galaxias zebratus*) (Shelton et al. 2015).

The present study also demonstrated that the impact of *O. mykiss* on indigenous fish community structure is density-dependent, implying that in areas where *O. mykiss* occurs in low densities, the population and diversity of indigenous fish species is often not affected, or the impact may be minimal as shown in other studies (e.g., Woodford and Impson 2004; McIntosh et al. 2010). The variation in the occurrence of *O. mykiss* along a river is often affected by the difference in water quality between the upstream and downstream which was probably the case in the current study. The water quality of the catchment downstream of the Blyde River is compromised by mining activities and sewage works which were reflected in

the increased concentrations of water chemistry parameters that included conductivity, total dissolved solids, and salinity. *Oncorhynchus mykiss* is often associated with high water quality rivers (Molony 2001), and that may have limited its migration downstream in the present study. In addition, water temperature downstream gets warmer with the decreasing altitude (Rivers-Moore et al. 2019), and in the present study, this may also explain the low occurrence of *O. mykiss* downstream of the Blyde River because it prefers cold water rivers.

In the present study, the fish species diversity downstream of the Blyde River was higher with over five species occurring at a sampled site. Apart from the low density of rainbow trout, the high fish species richness downstream may imply that the presence of omnivorous fish species (*Labeobarbus marequensis*) that is capable of piscivory may have also limited the impact of the invasive species. The low occurrence of *O. mykiss* downstream may have also resulted in the indigenous fish species using the catchments as a refuge to avoid predation. Similar results have previously been reported by Woodford and Impson (2004) in the Berg River in the Western Cape Province, South Africa where juveniles of the Berg River redbfin segregated from *O. mykiss*, probably to avoid predation.

The line-spotted barb (*Enteromius lineomaculatus*) showed a large distributional range occurring at > 50% of the surveyed sites, and it was the abundant species in catchments adjacent to the highly invaded areas. It was mainly sampled in deep pools under weeds, and this may represent a behavioural adaptation to avoid predation. Hindell et al. (2000) also reported that in the presence of a predatory fish, small body-sized fish tend to occupy vegetated sites to avoid predation. Baker et al. (2003) also found that Galaxias species were confined to shallower depths in rivers where *O. mykiss* was present than where it was absent. In addition, *E. lineomaculatus* is known to occur with facultative piscivores (e.g., African sharptooth catfish (*Clarias gariepinus*) and canary kurper (*Chetia flaviventris*)) in the Limpopo River Basin, Limpopo Province, South Africa suggesting that these species may not be as vulnerable to



predation as other river minnows such as the headwater endemic Treur River barb that evolved without large piscivores in the system and may experience predator naivety (e.g., Finke and Denno 2004).

The uninvasion catchments on Blyde River above the second waterfall in the Christmas Pools were mainly dominated by treur barb (*E. treurensis*) and the species richness in this catchment was also low. This may be attributed to the presence of the series of waterfalls that limited the upstream migration of both the invasive *O. mykiss* and indigenous fish species. Engelbrecht and Roux (1998) also found that *E. treurensis* was abundant above the second waterfall but absent in the catchments below. Other studies in South Africa have also shown that instream barriers such as waterfalls may conserve indigenous fish from predation by introduced predatory fish (Karssing et al. 2012; Rivers-Moore et al. 2013). The narrow river in the upper catchments of the Blyde River may also have contributed to the low fish species richness observed, because it has been reported that the river size has a direct relationship with species richness (Kadye and Marshall 2007). Unlike lower order streams, wider and larger river sections are often associated with high species richness because they provide a variety of habitats to accommodate different species (Weyl et al. 2013) as was the case in the present study.

The overall fish species composition between the Blyde and Treur Rivers was similar, with the exception of the banded tilapia (*T. sparrmanii*) and chubbyhead barb (*E. anoplus*) which mainly occurred in the Treur River. This may be attributed to the warmer temperatures in the Treur River which offers favourable conditions for the occurrence of *T. sparrmanii* (Nivelle et al. 2019). The Treur River catchments were wider, shallow and composed of rocky riverbeds that contributed to the high temperatures.

*The effect of Oncorhynchus mykiss on food web structure in the upper Blyde River catchment*

The present study investigated if the invasion of *O. mykiss* increased trophic functional diversity or changed the niche position and size of indigenous fish species in the upper Blyde River catchment. The results indicated that there was variation in the trophic length, centroid position, and the type and variety of food resources utilised by fish in the invaded and uninvaded sections of the Blyde River.

There were only two fish species that occurred in the invasion-free section of the Blyde River, and both fed at the same trophic level but there was no niche overlap observed between them. The stargazer mountain catfish (*Amphilius uranoscopus*), however, occupied a slightly higher trophic position than the Treur River barb possibly because its diet comprised of more animal-based food sources than the Treur River barb. *Amphilius uranoscopus* is known to prefer animal-based food resources such as insects as shown in other studies (Kimberg et al. 2014).

The trophic level of fish communities in the invaded section of the Blyde River varied significantly, probably because of the invasion status, the availability of different food resources and their isotopic value. The species with a high trophic position (*A. uranoscopus*) fed primarily on animal-based diet and those with a low trophic position (*E. treurensis*) fed on a variety of food resources that included both animal and plant-based diet. A similar study in the Wilge River in Mpumalanga and Gauteng Provinces also showed that fish that fed on a wider range of food sources occupied a lower level than those that fed mainly on animal-based diet (Lombard et al. 2018).

The Treur River had fish species that fed at more than two trophic levels and the food web length was longer than that of the species in the Blyde River. The species that occupied the top and middle trophic positions were mostly similar to those in the Blyde River, and the difference was observed in the banded tilapia (*Tilapia sparrmanii*) that occupied the lowest trophic position and primarily consumed plant-based food sources. The banded tilapia is a

herbivorous fish species that feeds mainly on plant material (Zengeya and Marshall 2007). Overall, the fish species in the Blyde River were enriched with nitrogen and those in the Treur River were Ccorr enriched. This may be attributed to the different organic matter deposited into the two rivers which determines the nitrogen and carbon sources based on the types of allochthonous and autochthonous resources (Britton et al. 2010). The nitrogen-enriched species in the Blyde River may be indicating that the river receives high autochthonous resources (Roach 2013).

The aquatic invertebrates were more abundant in the invaded catchments than the uninvaded ones. In the streams with a wide range of longitudinal changes, invertebrate abundance is often influenced by the different organic matter available across the stream (Finlay and Kendall 2007; Winemiller et al. 2011). In the current study, however, the high abundance of aquatic invertebrates in the invaded section of the river may be attributed to reduced predation pressure by indigenous species as a result of *O. mykiss* invasion. Congruent results were observed in Zimbabwe where increased abundance of aquatic invertebrates in the trout invaded areas may have been as a result of decreased predation pressure (Kadye et al. 2013).

*Oncorhynchus mykiss* occupied a trophic level similar to those of most of the indigenous species except for the one (*A. uranoscopus*) that occupied a higher trophic position. Implying that its impact on the indigenous species may not be through predation but competition for food. Similar results were reported in the Drakensberg streams and Cape Floristic Region of South Africa that showed that introduced trout occupied a similar trophic level as the indigenous species (Potgieter 2014; Shelton et al. 2017). The fish species in the uninvaded areas showed greater trophic redundancy and utilised smaller isotopic niche space than those in the invaded areas of the stream. This was mainly evident in the diet of *A.*

*uranoscopus* and *E. treurensis* which fed on a wide range of food resources in the invaded section and was mostly limited to crane flies, mayflies, and damselflies in the uninvaded section.

In this study *O. mykiss* primarily fed on aquatic invertebrates and utilised small niche space than indigenous fish species that occupied the same trophic level, implying that the impact of *O. mykiss* on the indigenous fish species in the Blyde River may be through competition for resources. A similar study has also shown that indigenous fish species utilised a wider trophic niche than the invasive *O. mykiss* in the same trophic level (Shelton et al. 2017). The wider niche space for indigenous fish species and the observed small overlap between *O. mykiss* and the indigenous species may indicate that the food web structure and function is also impacted by other factors such as habitat heterogeneity. The uninvaded Treur River consist more of boulders and it is much wider and warmer than the Blyde River. The differences in the habitat structure was also shown in the carbon isotope value which was more enriched in the uninvaded Treur River.

#### *The potential risk associated with the introduction of salmonids*

The potential risk associated with the six salmonid species that were introduced in South Africa were evaluated with the aim to provide recommendations on management strategies of the species based on the risks posed. The four (*O. mykiss*, *O. kisutch*, *O. tshawytscha*, and *S. trutta*) species that are currently present in the country were classified as high risk because their presence may result in adverse impacts, and the other two (*S. salar* and *S. fontinalis*) species were evaluated as low risk because they do not occur in the country.

The four species present in South Africa were given a high probability of likelihood of entry, establishment and spread in the country because two of the species (*O. mykiss* and *S. trutta*) already have thriving populations in the mountain streams (Weyl et al. 2020). Their successful introduction in the country can be credited to the continued stocking of the species by the government and angling societies into the carefully selected suitable sites in the

mountain stream (Ellender et al. 2014). *Oncorhynchus tshawytscha* and *O. kisutch* on the other hand are only known to be allowed through import permit (SANBI and CIB 2020) into the country but there are no records of naturalised populations in the rivers. There are currently no known occurrence records of *Salmo salar* and *Salvelinus fontinalis* in South Africa and therefore their likelihood score was assessed as very unlikely. Attempts to introduce the two species in the country was not successful probably due to lack of suitable habitats (Ellender et al. 2014; Weyl et al. 2017) as was the case in other countries (MacCrimmon and Gots 1979; Lever 1996).

The introduction and establishment of the salmonid species in South Africa may result in detrimental impacts on native species. A major (MR) consequence score was assigned to *O. mykiss* and *S. trutta* due to their known impacts in South Africa such as fragmentation and local extirpation of native fauna (Karssing et al. 2012; Jackson et al. 2016; Weyl et al. 2017; Weyl et al. 2020). A recent study in the Blyde River in Mpumalanga Province showed that the occurrence of *O. mykiss* in the stream have greatly affected the population of the threatened Treur River barb (*Enteromius treurensis*) (Maimela et al. 2021). In the Keiskamma River in the Eastern Cape Province, *O. mykiss* have been implicated in the extirpation of the endangered boarder barb (*Amatolacypris trevelyani*) probably due to predation (Ellender 2013). In other countries such as New Zealand, introduction of *O. mykiss* have had severe impacts more especially on the galaxoid species which have been reported threatened as the result of the invasion (McIntosh et al. 2010).

*Salmo trutta* have also been implicated in the decline and extirpation of native fauna through predation and competition in South Africa (Weyl et al. 2020). Impact of *S. trutta* through competition for resources was seen in uKhahlamba Drakensberg Park in KwaZulu-Natal where niche overlap with the native mountain catfish *Amphilius natalensis* was observed (Potgieter 2014; Weyl et al. 2017). A decline of native species such as Maloti minnow,

*Pseudobarbus quathlambae* and the Border barb, *Barbus trevelyani* were reported due to possible predation by the introduced *Salmo trutta* in South Africa (de Moor and Bruton 1988; Ellender 2013). Other studies elsewhere have also shown that the introduction of *S. trutta* have resulted in reduced population, fragmented distribution, and in some cases extinction of native species such as fish and amphibians (McIntosh et al. 1992; Kats and Ferrer 2003; Arismendi et al. 2009; Lorenzoni et al. 2018). For example, *S. trutta* have been implicated in causing a decline in the abundance of amphibians in the USA and Australia (Kats and Ferrer 2003) and native Galaxias in New Zealand and Australia (Crowl et al. 1992; McIntosh et al. 1992; Townsend 2003). In eastern North America, *S. trutta* have caused the decline and local extinction of native fish species such as brook trout (*Salvelinus fontinalis*) (Grant et al. 2002).

The reported impacts of the other four trout species (*O. kisutch*, *O. tshawytscha*, *Salmo salar* and *Salvelinus fontinalis*) in the introduced range where they have naturalised populations have been observed to range from minor to moderate through competition, predation and hybridisation (Muhlfeld et al. 2019). For example, the introduced *O. kisutch*, and *S. salar* have negatively affected the population of native fish in Chile (Young et al. 2009; Arismendi et al. 2012), *O. tshawytscha* resulted in a decline of the native alewife (*Alosa pseudoharengus*) through predation in Lake Michigan and Lake Ontario (Rybicki and Clapp 1996; Holey et al. 1998). Introduced *O. kisutch* on the other hand has been reported to affect the aquaculture productions through transmission of pathogens (van der Veer and Nentwig 2015).

Management of the introduced trout species have been a contentious journey over the years in South Africa due to the need to preserve the socio-economic benefits brought by the introduction of these species into the country. The socio-economic benefit studies conducted in South Africa have shown that *O. mykiss* aquaculture and recreation have improved the livelihoods of local communities in areas where invasion occurred (Britz and Venter 2016; Du-Preez and Lee 2010). Other aspects that are considered to be challenging in the management

of trout species that have naturalised populations (*O. mykiss* and *S. trutta*) in the country are the areas in which they occur in the inaccessible mountain streams and their co-occurrence with endangered river minnows which cannot be compromised in the process (Woodford et al. 2016; Zengeya et al. 2017). Attempts were, however, made to eradicate *O. mykiss* in other parts of the country but failed due to costs and lack of appropriate gear (Shelton et al. 2017).

Of the six species studied here, only two (*O. mykiss* and *S. trutta*) are not listed under NEM:BA A&IS list despite the call for their listing in recent years (Woodford et al. 2017). The two trout species are, however, managed under provincial legislation in other parts of the country (Woodford et al. 2017). Based on the risk analyses of the two species it is recommended that they should be relisted on the NEM:BA A&IS as Category 2 species. The two trout species that are currently listed on the NEM:BA A&IS are *O. kisutch* and *O. tshawytscha* as Category 2 invasive species but *Salvelinus fontinalis* and *Salmo salar* are not listed. For species that have no record of occurrence in the country, it is recommended that their importation should be restricted and for those that are currently present their utilisation should be confined to areas where they occur. This will ensure that their spread is limited to the current distribution and negative impacts are minimised. In addition, a National Management Plan for the species present in the country should be implemented to detail all the necessary measures applicable for each species based on their area of occurrence and use.

#### *Conservation implications and recommendations*

The current management strategies of conservation authorities in South Africa only allow the use of *O. mykiss* in areas where it is historically known to occur (Ellender et al. 2014). Implementation of this management plan is, however, still a challenge in some areas because some of the occurrence records for *O. mykiss* were produced through expert opinion and no ground-truthing was undertaken. Therefore, this area-based management plan can only be

made effective if the extent of the current distribution of *O. mykiss* in the country is verified and all the occurrence records are confirmed.

Verification of rainbow trout occurrence and distribution will assist in preventing new introductions and potential spread. In addition, suitable areas prone to invasion need to be identified to prevent new introductions. This study initiated the process of identifying the areas prone to invasion by projecting the potential suitable area for *O. mykiss* in Mpumalanga Province and found that there is a high invasion debt and large area that is suitable for *O. mykiss* establishment which remain free of invasion. The high invasion debt indicates that the distributional range of *O. mykiss* in South Africa has the potential to expand further. The large unoccupied projected suitable area may also imply that the range of current distribution of trout in Mpumalanga Province may be wider than indicated, given the lack of ground-truthing for verification of occurrence. This is of great concern given that several studies have shown that trout can have a significant effect on fish communities and that there is a need to prevent human-facilitated introductions in biodiversity sensitive areas such as mountain headwater streams that are inhabited by endemic and range restricted minnows (e.g., Weyl et al. 2020; Maimela et al. 2021).

The identification of the areas prone to invasion needs to be undertaken on a larger scale in order to develop management strategies with knowledge of specific areas to be protected in the country based on scientific evidence. The results on projected climate change scenarios in the present study showed potential contraction and expansion of predicted suitable areas under different climate change scenarios. The possible contraction of suitable areas may favour the conservation of indigenous fish species as the occurrence of *O. mykiss* may be limited to small areas, but this may also lead to strong arguments to amend trout-related regulations and allow the utilisation of all available suitable areas and consequently leading to new conflicts.



The survey conducted in the present study indicated that the invasion of *O. mykiss* in the Blyde River has affected the abundance and distribution of endemic river minnows, especially the Treur River barb. The series of waterfalls in the upper catchments of the Blyde River currently protects the remnant populations of the Treur River barb that occurs above the second waterfall. Alien fish species have often-circumscribed natural migration barriers through intentional stocking of upstream reaches by humans. This is of concern as stocking of trout in the upper Blyde River is still on going, as parts of the catchment are designated as trout angling areas. However, areas with remnant populations of *E. treurensis* have remained free of human facilitated alien fish introductions, because they were designated as natural heritage sites. This designation of areas where trout utilisation is allowed and prohibited appears to have diffused potential conflicts between utilisation of trout and conservation concerns, unlike other areas in the country (see Woodford et al. 2017 and Zengeya et al. 2017). It is therefore crucial that the conservation status of these alien-free areas is maintained and that they are regularly monitored and kept free of alien fish species for the conservation of endemic and range restricted minnows that occur in the system.

There are other river minnows that were not recorded in the current study but are known to occur in the Blyde River such as the shortfin barb (*E. brevipinnis*) and the side spot barb (*E. neefi*). *Enteromius brevipinnis* is listed as Near-threatened (NT) probably because of predation by the introduced invasive *O. mykiss* (Engelbrecht et al. 2017). This is a cause for concern because the *E. brevipinnis* along with other river minnows such as *E. neefi* and *E. pallidus* are range-restricted, and the occurrence of the invasive *O. mykiss* may be detrimental to the remnant populations (Engelbrecht et al. 2002; Chakona et al. 2015).

This study demonstrated that there are spatial differences in trophic functional diversity among the fish communities in the upper Blyde River catchment that are correlated to *O. mykiss* invasions. Fish communities in uninvaded areas had greater trophic redundancy than fish

communities in invaded areas. These spatial differences in trophic functional diversity are likely a result of top-down effects of *O. mykiss* invasion through predation on aquatic invertebrates and competition for resources with indigenous fish. This is consistent with observations elsewhere that have noted that *O. mykiss* invasions can influence the diet and trophic niches of indigenous fish by altering the structure and dynamics of food webs through an interaction of various mechanisms such as predation and competition. Although *O. mykiss* mainly fed on aquatic invertebrates, fish remains were found in their stomach which may imply that predation on native fish was also a contributing factor on the alteration of the trophic functional diversity in the invaded catchments. The niche overlap between *O. mykiss* and the endangered Treur River barb suggests an increased interaction and vulnerability to predation by *O. mykiss*. The conservation of the Treur River barb is vital because it represents the recovering populations from previous extirpations by the introduced *O. mykiss* and other predatory fish species (Engelbrecht and Roux 1998). In the Blyde River, the control measures needed include the prohibition of intentional introduction in invasion-free catchments because biogeographical barriers already limit their unaided spread.

The risk associated with the introduced alien invasive trout species is high because of the magnitude of their impacts that have the potential to result in local extirpation of indigenous fish species. The impact mechanism that has shown to cause more detrimental effects are predation and competition. This is a cause for concern because the South African mountain headwater streams do not have indigenous fish species that can out compete the introduced trout species (Ellender et al. 2014; Woodford et al. 2017). It is, therefore, recommended that their spread is controlled with strict regulations to preserve populations in invasion-free areas and the salmonid species that do not currently occur in the country should be restricted through importation permits.

*Limitations of the present study*

Although the present study provided insights into which catchments are at risk of invasion by *O. mykiss* based on current predicted suitable area, the study was only limited to Mpumalanga Province. Therefore, to provide a complete scope of catchments at risk of *O. mykiss* invasion in South Africa, an invasion debt on all catchments in South Africa needs to be estimated. This can also assist in identifying which catchments need to be monitored constantly through frequent surveys to avoid the spread of *O. mykiss* via interconnected catchments. The survey conducted in the present study was constrained by time and that may be why some of the species (e.g., shortfin barb (*Enteromius brevipinnis*) and sidespot barb (*Enteromius neefi*)) that are known to occur in the Blyde River were not recorded in the current study. This suggests that thorough surveys conducted over a longer period using various sampling methods need to be carried out to confirm the current species composition in the Blyde River.

### *Conclusions*

The large invasion debt estimated in the current study shows that if effective management plans are not implemented and adhered to, the freshwater systems may suffer a great loss of endemic fish species. In addition, the likelihood of the predicted suitable area for *O. mykiss* to expand or contract under different climate change scenarios may result in new considerable debates on trout-related issues that may cause new conflicts between stakeholders. The present study found impacts of *O. mykiss* to be detrimental to the indigenous river minnows in the Blyde River in Mpumalanga Province, South Africa especially the endangered Treur River barb (*Enteromius treurensis*). *Oncorhynchus mykiss* competes for resources with the indigenous fish species in the Blyde River and restrict their distribution to invasion-free sites. The management of the *O. mykiss* is, therefore, crucial to limit its potential spread and conserve the remaining indigenous fish populations in the river.

There were spatial differences in trophic functional diversity among the fish communities in the upper Blyde River catchment that could be attributed to *O. mykiss*

invasions. The study posits that these spatial differences are due to *O. mykiss* invasion reducing the indigenous fish abundance and thereby reducing predation pressure on aquatic invertebrates, with a knock-on effect on the structure of these assemblages. This suggests that their current impact on indigenous fish communities is mainly through competition for resources. The impact of *O. mykiss* on the food web structure of indigenous fish species is, however, made complex by the different factors that influence the trophic functionality of the fish communities. For better understanding, more detailed studies that focus on the impact of each factor (i.e., competition for resources and predation) on the food web structure and function need to be undertaken.

The conducted risk analyses of the trout species indicated that the occurrence of these invasive predatory species in South Africa poses a great threat on the conservation of the endangered river minnows. This presents a dire need for the management strategies of trout species to be concluded in order to avoid events of worst-case scenarios. The use of RAAT framework showed to provide sufficient science-based information that shows a true reflection of both the environmental impacts and socio-economic benefits of the introduced trout species. Generated reports can be used by policy decision-makers to formulate measures that will support both the conservation of native species and utilisation of trout species in South Africa. The main recommendations from the risk analyses is that *O. mykiss* and *S. trutta* should be included on the NEM:BA A&IS list as Category 2 species and that a National Management plan should be developed for each of the four species (*O. tshawytscha*, *O. kisutch*, *O. mykiss* and *S. trutta*) that are present in the country. This will allow appropriate utilisation of each species while ensuring conservation of native species in the invaded areas.

The findings of this study add to a growing body of work that has shown that introduced alien predatory fish such as *O. mykiss* can have a significant effect on indigenous fish communities and highlighted the need to prevent human-facilitated introductions in

biodiversity sensitive areas, such as mountain headwater streams, that are inhabited by endemic and range-restricted minnows.

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