Incorporating free-flowing rivers into global biodiversity targets: Prioritisation and targeted interventions to maintain ecological integrity

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Abstract

1. Free-flowing rivers are important surrogates for freshwater biodiversity as there are increasingly fewer rivers that reflect intact habitat and species diversity from source to sea. The status and changes in the ecological condition or protection of free-flowing rivers (FFRs) is not explicitly reported on in global biodiversity targets. Indices are proposed for reporting such changes to the Sustainable Development Goals (SDG) 6, SDG 15, Aichi Target 11 and post-2020 Global Biodiversity Framework.
2. Free-flowing rivers were identified at a countrywide scale in South Africa for protection, planning, monitoring and assessing changes in their ecological condition and protection status and were selected and prioritised using criteria co-produced with national, provincial and local river managers and policy makers. Given the high competition for water resources and the unlikely possibility for strictly protecting all FFRs, a subset of FFRs, termed 'flagship FFRs', were identified.
3. Methods for reporting changes in the protection levels of prioritised FFRs at a countrywide scale were developed, which included indices of FFRs related to global targets: the loss of the extent of FFRs in a natural and largely natural ecological condition for SDG 6; changes in the connectivity of FFRs included in the post-2020

Global Biodiversity Framework targets; and changes in protection levels of FFRs for Aichi Target 11 and SDG 15.1.2.

4. Flagship FFRs attracted targeted management initiatives and thus maintained their connectivity and ecological condition. This was not true when all FFRs were considered; in the broader set of FFRs, longitudinal fragmentation increased and ecological condition declined during 2011 to 2018.
5. Considering the increasing pressures rivers are likely to experience from anthropogenic and climate change impacts, particularly in semi-arid to temperate environments, urgent prioritisation and monitoring of FFRs is called for so that a targeted set of protection and management strategies can be applied.

KEYWORDS

Aichi Target 11, ecological condition, freshwater ecosystems, post-2020 Global Biodiversity Framework, river fragmentation, Sustainable Development Goals

1. Introduction

Degradation and losses in the biodiversity of freshwater ecosystems have been one of the key concerns of global reports since the 1970's, with increasing evidence thereof published in the past two decades (MEA, 2005; Darwall et al., 2009; Bunn, 2016; Díaz et al., 2019; IPBES, 2019). It is estimated that these habitat losses resulted in the decrease of 81% of monitored freshwater species populations between 1990 and 2012 (Abell et al., 2019). At a global scale, 70% of rivers occur outside protected areas and only 11.1% are protected in their entirety (Abell et al., 2017; Perry al., 2021).

Global targets for freshwater biodiversity and ecosystems are agreed upon by signatories to the Convention on Biological Diversity (CBD), including the Aichi targets (CBD, 2016) and post-2020 Global Biodiversity Framework targets (CBD, 2016; 2021), as well as to the United Nations, as part of the Sustainable Development Goals (UN, 2021). Aichi Target 11 focused on the extent of protection afforded to water-related ecosystems (CBD, 2016). SDGs 6 and 15 have also been applied since 2015 to monitor and report on changes in extent of ecosystem protection, including freshwater ecosystems (UN, 2021). SDG target 6.6 focuses on protection and restoration of water-related ecosystems. The SDG 15 is more broadly related to 'Life on Land' (UN, 2020). Targets of the post-2020 Global Biodiversity Framework focus on changes in the extent, connectivity and integrity of ecosystems, listing twenty-one action-orientated targets to be achieved by 2030 aiming to reach outcome-orientated goals by 2050.

Monitoring and reporting on declining river ecosystem extent needs to be complemented with documenting changing trends in river ecological condition. This is because changes in river ecosystems are less likely to be quantified as changes in extent (e.g. complete loss of a river), but rather as changes in their ecological condition or integrity. Factors affecting river ecological condition include alteration in water quantity (flow), quality (e.g. nutrient load and pH) and levels of connectivity (Harvey et al., 2019).

Given that water is such a scarce commodity in arid and semi-arid ecosystems, the more permanently-flowing, large mainstem rivers are particularly vulnerable to damming, with subsequent loss of river connectivity and ecological condition (Nel et al., 2007). Tracking changes in the ecological condition and protection levels of FFRs can offer indices for reporting changes in river ecosystems to the global targets. Abell et al. (2017) used a river protection metric to measure progress reporting to the Aichi Target 11, where the extent of formal protection of inland waters is poorly known due to inadequate, accurate and comprehensive spatial datasets for freshwater systems. At a global scale, 70% of the upper catchments of rivers occur outside protected areas and only 11.1% are protected in their entirety, therefore falling short of the Aichi target (Abell et al., 2017). Opperman et al. (2021) assessed FFRs in protected areas and found that globally, the level of FFRs in protected areas equalled the Aichi Target 11, however concluded that global protection levels across river catchments varied widely and noted that certain factors should be considered. These included, specific countries that allow dam construction within protected area borders, or protected area boundaries that are shifted to accommodate development (Opperman et al., 2021).

Globally, very few countries have river systems that have remained in their natural ecological condition with a high level of connectivity from source to sea, and thus representing functional biodiversity along their latitudinal and longitudinal zones. These so-called free-flowing rivers (FFRs) can be defined as rivers where the ecosystem services and functions are largely unaffected by changes in fluvial connectivity, thereby allowing continuing movement and exchange of water, energy, material and species within the river system and surrounding landscape (Grill et al., 2019; Opperman et al., 2021). A global analysis of changes in FFRs has shown that > 50% of river connectivity has been lost, and by number, > 63% of the FFRs (Grill et al., 2019).

Prioritising areas for management and targeted restoration and intervention of FFRs is necessary because the utilisation of rivers is likely to result in their degradation, which can have negative consequences for biodiversity and ecosystem services (Bernhardt & Palmer, 2011; Speed et al., 2016). The identification and prioritisation of FFRs offers an opportunity for potential improvement in monitoring, management and restoration interventions. This would also allow the reporting of their associated ecological condition and protection levels, thus making a valuable contribution to reporting on global biodiversity targets, such as the Aichi Target 11, which was aimed at 17% of the extent of freshwater ecosystems in protected areas by 2020, the post-2020 global biodiversity framework targets, and SDG 6 and 15.1 by 2030.

The intent of the study was to demonstrate the approach and methodology for assessing changes in the integrity (or status) of FFR condition and protection levels for use as two sub-indices in reporting to SDG 6, 15.1, Aichi Target 11 and indicators of change in Goal A of the post-2020 Global Biodiversity Framework. This study proposed that the loss of the extent of FFRs in a natural and largely natural ecological condition be reported to SDG 6 and changes in protection levels of FFRs to Aichi Target 11 and SDG 15.1.2. The objectives were to 1) assess and identify changes in the ecological condition of the FFRs identified in 2011 and how these changes have affected their status; and 2) to determine the changes in protection levels of FFRs between 2011 and 2018. The intent is to illustrate how these approaches and methods can be implemented for global reporting as indices related to FFRs. The methods applied to track changes in extent, condition and protection in the FFRs are explicit for the refinement of the criteria and selection for FFRs at a countrywide scale, highlight areas to improve in global datasets and are easily replicable in other countries, especially those that are data-poor.

2. Methods

A case study approach was used to demonstrate the methods that can be applied in reporting changes in the ecological condition and protection levels of FFRs to global reporting indices. South Africa is located in the temperate climatic region, with approximately 72% of the extent of the landmass (Van Deventer, Smith-Adao & Kotze, unpublished data) ranging from arid to semi-arid regions. A total length of 222 river ecosystems have been mapped (1:500 000 scale) (Van Deventer et al., 2019a) with a total of 164 018 km, encompassing permanent, seasonal, and intermittently (or episodic) inundated rivers (Smith-Adao et al., 2018; Keith et al., 2020; Keith et al., 2022).

A total of 62 FFRs were mapped by the National Freshwater Priority Areas (NFEPA) project in 2011 (Nel et al., 2011b). FFRs were defined as long (at least 50 km) reaches of rivers that have no in-channel dams and therefore flow undisturbed from their source to the confluence with a larger river or to the sea; permanent or seasonal flowing rivers and at least 50 km of river length was in a natural or largely natural state (Nel et al., 2011b). The mainstem FFRs identified included the major tributaries that formed part of each system. The status of the 62 FFRs were reassessed after seven years, using data related to their ecological condition and connectivity, thereafter protection levels were also assessed. Figure 1 describes the flow of the methods followed to achieving the ecological categories and protection levels for FFRs and supplementary information I, Table S1 describes the datasets and use thereof during the different phases of the study to achieve the identified objectives. The processes and linked outputs illustrated in Figure 1 are described in further detail in the following subsections.

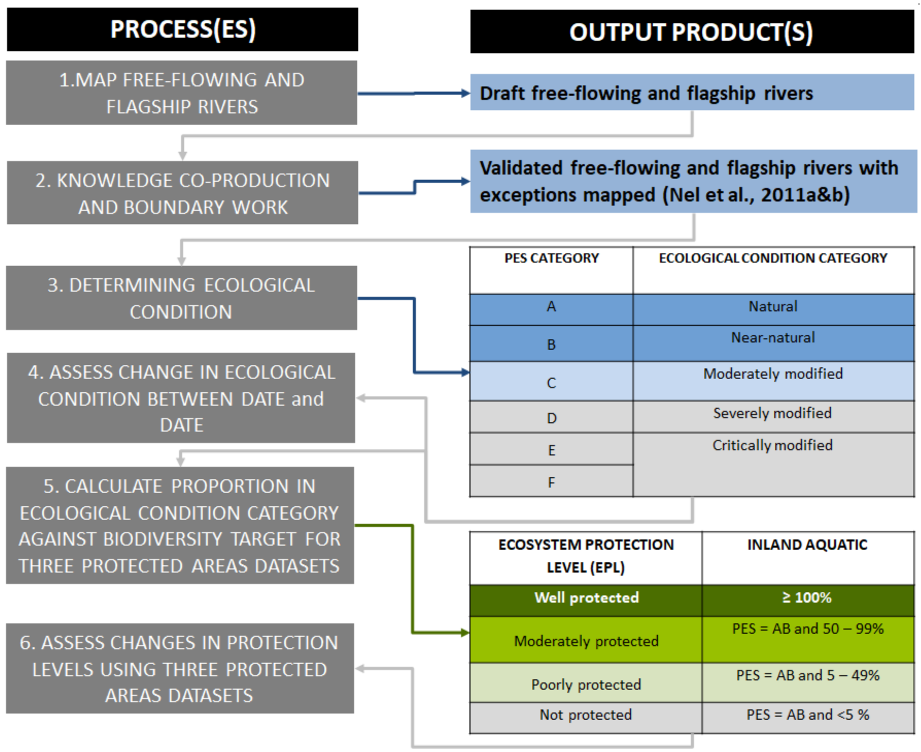

Figure 1. Flow diagram of the methods followed to achieving the ecological condition categories and protection levels for free-flowing rivers. Present Ecological State (PES) categories are driven by biotic response attributes of a river relative to the natural ecological condition.

2.1. Mapping of free-flowing and flagship rivers of South Africa

In addition to identifying FFRs, a subset of FFRs known as flagship free-flowing rivers, were selected based on representativeness and their importance to ecosystem processes and biodiversity value, which were prioritised for conservation (Nel et al., 2011b). Representativeness of FFRs ensured that the range of FFRs selected from ecoregions represented the full range of species, processes and ecosystems, which were selected from surrogates that served as proxies for biodiversity attributes (Linke, Turak & Nel, 2011). Flagship rivers represented different freshwater ecoregions of South Africa (SANBI, 2016) and continued effort is required for their formal protection due to their importance for ecosystem process and biodiversity value.

The South African 1:500 000 rivers layer (Supplementary information I, Table S1) was used for mapping of river ecosystem types (step 1, Figure 1). River ecosystem types represent the diversity of river ecosystems, grouped by physical features (such as climate, flow and geomorphology), and therefore assumed biological response potential. River ecosystem types are therefore coarse-filter biodiversity surrogates (Roux et al., 2006) and the goal of the conservation plan was to keep at least 20% of each river ecosystem type in a good ecological condition (Figure 2). Ninety-seven additional coastal rivers were included during the National Biodiversity Assessment (NBA) in 2011 from the 1:50 000 rivers network (DLA:CDSM, 2005-2007) to ensure alignment with all estuaries during these two assessments (NBA 2011-NBA 2018). During the NBA in 2018 the NFEPA rivers dataset was topologically corrected with a small number of duplicated river line errors removed (resulting in a slight river extent decrease of 0.1% or 242 km). The ecosystem typology that was assigned to the layer during the NFEPA (Nel et al., 2011b) and NBA projects (Skowno et al., 2019b), were expanded to the newly added coastal rivers. The FFRs and flagship rivers were selected from the river ecosystem type layer and were identified as a separate attribute field, with coding to distinguish between them.

DWS ecological condition categories [Present Ecological State (PES)]	A Natural	B Largely natural	C Moderately modified	D Largely modified	E Highly degraded	F Extremely degraded
IUCN RLE ecosystem degradation categories	Natural or near natural (≤50% degr.)		Moderately degraded (>50 - ≤70% degr.)	Severely degraded (>70 - ≤90% degr.)		Very severely degraded (>90% degr.)
NBA ecological condition categories	Natural	Near natural	Moderately modified	Heavily modified	Severely modified	Critically modified
	Decreasing ecosystem function & increasing ecosystem restoration cost →					

Figure 2. The ecological condition categories used in the National Biodiversity Assessment of 2018, modified from the original South African Department of Water and Sanitation (DWS) framework (Present Ecological State) applied to the rivers layer. The International Union for Conservation of Nature (IUCN) Red List of Ecosystems approach of percentage degradation of ecosystems or percentage disruption of biotic processes is also presented.

2.2. Validation of FFRs through knowledge co-production and boundary work

During the NFEPA project, an approach of knowledge co-production and boundary work in conservation planning, which included an array of researchers, decision makers, and other stakeholders in the water sector, was applied (step 2 in Figure 1). This approach allowed a range of different levels of relevant information through several stakeholders from diverse knowledge systems to be transformed into co-produced knowledge. The boundary work refers to the creation of permeable knowledge boundaries to satisfy multiple social group needs but still guards the functional integrity of these contributing knowledge systems (Nel et al., 2016). During the consultation process, the 31 Level 1 ecoregions were aggregated to represent 10 regions, in which 62 FFRs rivers were selected (Nel et al., 2011a; Nel et al., 2011b) (Figure 3). The process also informed the selection of 19 FFRs identified as flagship rivers, for focused management (Nel et al., 2016). The stakeholders validated the criteria for all FFRs.

Exceptions to the selection criteria were listed by the stakeholders, and included FFRs traversing the Highveld and Escarpment and Limpopo Mountains ecoregions, which do not reach the sea within the boundaries of South Africa (Figure 3). In addition, the minimum criterion of ≥ 50 km were also accepted where a river reached this target from its source to the first instream dam. The total length, and number of the final validated and knowledge co-produced FFRs, flagship rivers and those listed through the exception criteria, were summarised by the aggregated ecoregions.

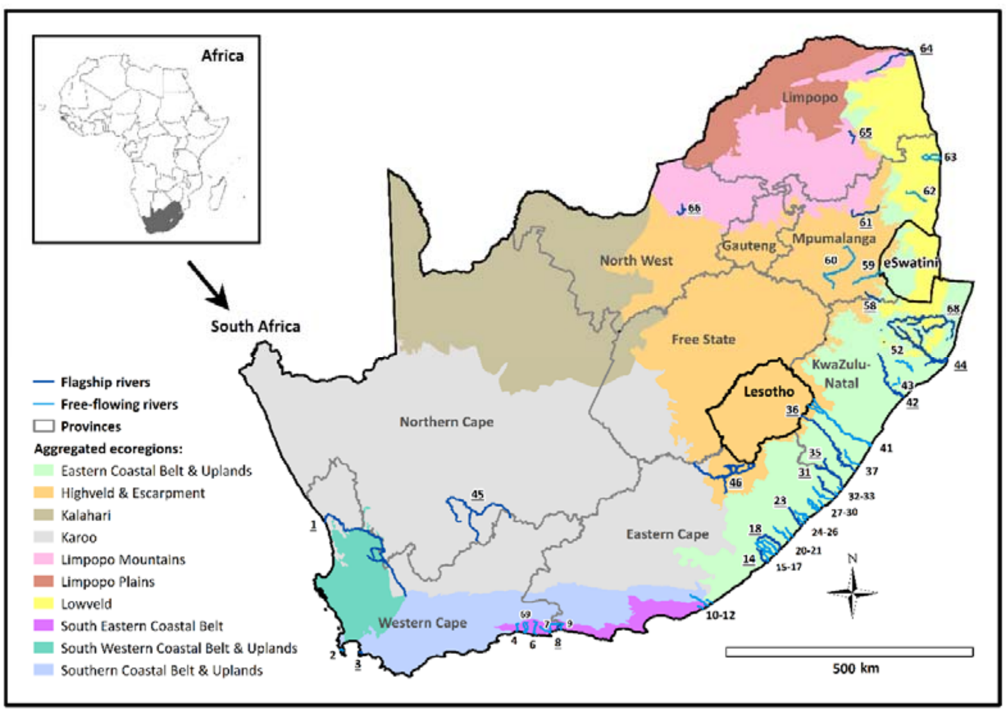

Figure 3. Location of free-flowing and flagship rivers relative to aggregated Level 1 ecoregions after Kleynhans, Thirion & Moolman (2005) (see supplementary information II, Table S2 for FFR names and IDs. Labels that are underlined indicates flagship FFRs).

2.3. Determining and assessing change in the ecological condition and connectivity of free-flowing and flagship rivers

2.3.1. Assessing changes in ecological conditions of FFRs

Ecological condition refers to the assessment of the extent to which the composition, structure and function of a river has been modified from a reference condition of natural (SANBI, 2016). In South Africa, the national Department of Water and Sanitation (DWS) uses Present Ecological State (PES) categories (hereafter referred to as PES) for ranking the ecological condition of rivers (Kleynhans, 2000; DWS, 2014). The PES category is determined by various abiotic drivers and biotic response attributes of a river relative to its natural or reference ecological condition (Kleynhans, 2000). The *in situ* factors include flow modification, physical-chemical modification, instream habitat and modification, riparian/wetland habitat modification and geomorphological zonation (DWS, 2014). These factors serve as a surrogate for measuring river pattern, process and species distribution. Six ecological categories (A-F) determine the level of ecological degradation for rivers on a national scale from 'A' being in a 'natural' ecological condition to 'F' being 'extremely degraded' or critically modified (Figure 2).

During the NBA 2018 the PES categories were updated with the latest available data (step 3, Figure 1), which included mainstems and tributaries between the period of 2011 and 2018 per quaternary catchment (supplementary information I, Table S1). Either the PES ecological category remained unchanged or it was updated with the most recent *in situ* assessment data (DWS, 2014; Van Deventer et al., 2019a). The mainstem river's ecological condition was updated to reflect the upstream tributary's ecological condition and the International Union for Conservation of Nature (IUCN, 2012) Red List of Ecosystems (Bland, Keith, Miller et al., 2017) as indicated in Figure 2.

Changes in FFR and flagship rivers were quantified by a comparison between 2011 and 2018 using differences in the ecological condition and connectivity of rivers (step 4 in Figure 1). Changes in the ecological condition of rivers, where applicable, were noted for river reaches and reported as percentages of the total length of the FFR.

2.3.2. Assessing changes in fragmentation of FFRs

For the connectivity analysis, the study only focused on the disruption of flow that results from instream dams in the mainstem and larger tributaries of the FFRs, making use of explicit national scale dam data as opposed to modelled data as sufficient spatial data was available. The artificial wetlands layer was updated for the NBA 2018 and included the extent of large and small dams, and the date of their construction. The construction date was used to validate the original selection of FFR and flagship rivers, to determine whether they were correctly selected as FFRs in the 2011 NFEPA project (supplementary information I, Table S1; Van Deventer et al., 2018). Dams intersecting tributaries of FFRs resulted in no change in FFR status. If a dam intersected the mainstem of the FFR and resulted in a split of < 50 km river segments, the status of these FFRs were considered lost. Thereafter, the dams were used in ArcGIS 10.6 (ESRI, 1999-2016) in an intersect with the rivers, to assess changes in longitudinal connectivity.

2.3.3. Assessing changes in protection levels of FFRs

Classification of protection levels of FFR and flagship rivers were quantified in ArcGIS 10.6 (ESRI, 1999-2016) using the intersect tool, according to the percentage of river length occurring in formally National Protected Areas (NPAs). This included the NPA layers of 2008, 2018, and the Protected Areas Expansion Strategy (NPAES) projected protected areas by 2024 (supplementary information I, Table S1; Figure 1, steps 5 & 6). The protected area layers were integrated for the purpose of assessing ecosystem protection levels in the NBA 2018 (Skowno et al., 2019b). Three layers of protected areas were used in the assessment: the first NPAES of 2008 (RSA, 2010) (Figure 4a), that of 2018 (Figure 4b) and the extent of protected areas envisaged for expansion within the next five years (2016-2020) as depicted in the revised NPAES for 2024 (DEA, 2016) (Figure 4c).

Protection levels for the FFRs were calculated using similar thresholds to the Ecosystem Protection Levels (EPLs) of river ecosystem types in the NBA 2018 (Table 1). Since the NBA 2018 found that < 10% of the extent of rivers often occur inside NPAs, and only those in a natural and largely-natural ecological condition contribute effectively to biodiversity processes and habitats, only FFRs in a good ecological condition (DWS ecological categories A & B, Figure 2), were used in the analysis. The percentage extent of the reaches of the FFRs in a good ecological condition was calculated from the total extent of each FFR, and depending on the range of the percentages, the protection levels were assigned according to the categories in Table 1. The total length of the river reaches in a good ecological condition was summarised per aggregated ecoregion, across the NPAs of 2008, 2018 and the NPAES for 2024. Since the ecological condition of the rivers are unknown for the NPAES 2024, the PES of 2018 was retained in the analysis for the NPAES 2024, and therefore assessed the impact of the expansion of protection area, rather than changes in ecological condition of the rivers.

Table 1. Ecosystem Protection Levels (EPLs) and ecological condition used for the assessment of river and inland wetland ecosystem types in the South African National Biodiversity Assessment of 2018, here translated to the protection level categories used in this study for free-flowing (FFR) and flagship rivers.

Protection Level	Extent of the reaches (km) of a river and inland wetland ecosystem type in a good (natural and largely-natural) ecological condition† and which were within the National Protected Areas (NBA 2018)	Extent of the reaches (km) of the FFRs in a good (natural and largely-natural) ecological condition† which were within the National Protected Areas
Well protected	≥100%	≥75%
Moderately protected	50-99%	50-74%
Poorly protected	5-49%	5-49%
Unprotected	< 5%	< 5%

† *Comparable to the A & B categories of the Department of Water and Sanitation for rivers*

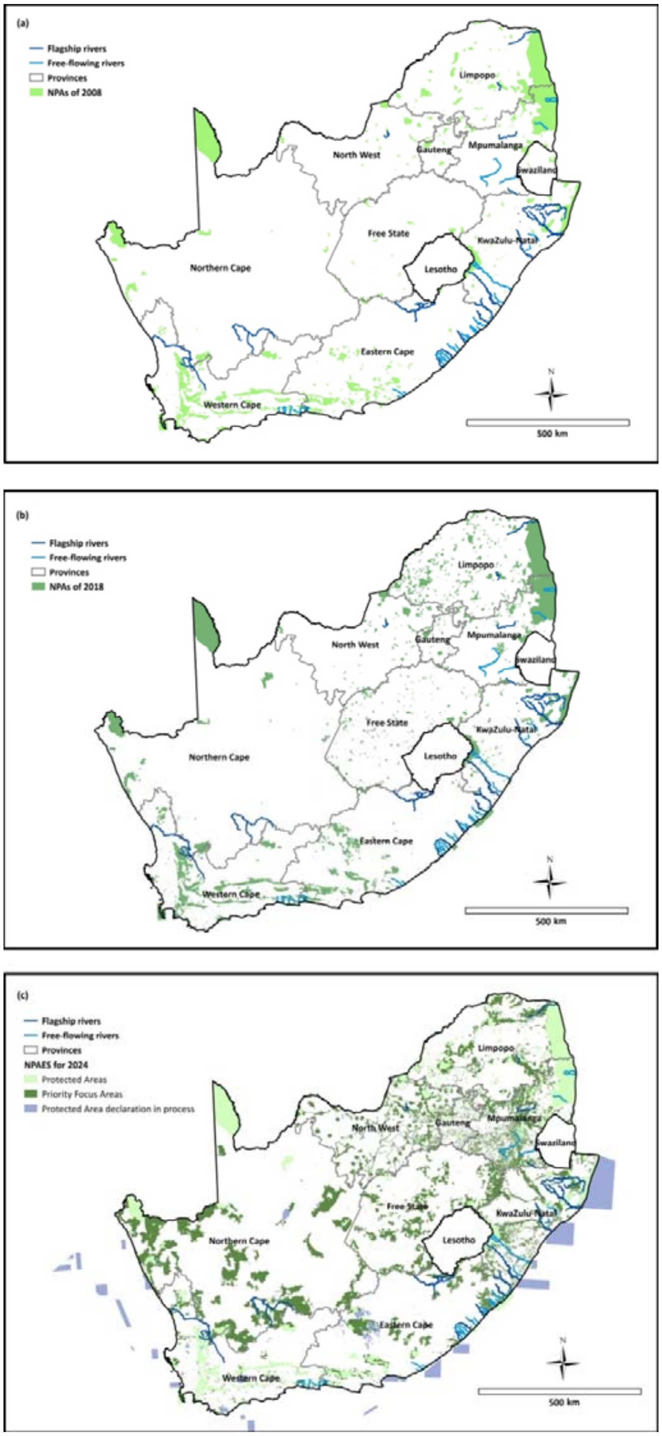

Figure 4. Extent and location of free-flowing rivers relative to the National Protected Areas of South Africa of (a) 2008, (b) 2018 and (c) the National Protected Areas Expansion Strategy (NPAES) plan for implementation in 2024.

3. Results

3.1. Spatial extent of free-flowing and flagship rivers in South Africa

Free-flowing rivers are unevenly distributed among ecoregions in South Africa, both in terms of extent of river length and number. The majority of FFR and flagship rivers are distributed in the eastern half of South Africa, with the exception of four FFRs, which are mainly in the central to western arid regions (see supplementary information II, Table S2 for FFR IDs 1, 45, 65 & 66) (Figure 3). The flagship rivers show similar patterns of distribution to all the FFRs. The Eastern Coastal Belt & Uplands aggregated ecoregion hosts the largest extent of the FFRs, with a total of 2 680 km (35.6%), though hosting less than a fifth (14) of the 62 FFRs (Table 2). The Southeastern Coastal Belt & Uplands aggregated ecoregion hosts the second-largest extent of FFR extent (1 939 km – 25.8%), almost double the number of FFRs (26), and the highest number of FFRs occur in this ecoregion. In contrast, the Southwestern Coastal Belt & Uplands aggregated ecoregion hosts the smallest extent of FFRs (18 km – 4.4%) and number (2) of FFRs of the eight aggregated ecoregions (Table 2).

Table 2. Extent (km) and number of free-flowing rivers (FFR) across aggregated ecoregions of South Africa (see supplementary information II, Table S2 for FFR names and IDs). FFR numbers which are flagship rivers are indicated in bold, with those listed under the exclusion conditions underlined.

Aggregated ecoregions numbers and names	Extent of the aggregated ecoregion (km²)	List of identity numbers of FFRs	Total extent of FFR (km) (Percentage of total FFR length)	Total extent of Flagship rivers (km) (Percentage of total Flagship river length)	Total number of FFR per aggregated ecoregion [exceptions] (flagship)
Eastern Coastal Belt & Uplands	136 630	**36**, 37, 38, 39, 40, 41, **42**, 43 **44**, 49, 50, 52, 56 & **68**	2 680.5 (34.9%)	1 632.9 (38.5%)	14 [3] (**4**)
Highveld & Escarpment	240 550	**46**, 51, **58**, 59, 60 & **61**	1 194.0 (15.6%)	731.3 (17.3%)	6 [2] (**3**)
Kalahari†	174 130				
Karoo	411 595	**1** & **45**	897.6 (11.7%)	897.6 (21.2%)	2 (**2**)
Limpopo Mountains	88 094	**65** & **66**	110.0 (1.4%)	110.0 (2.6%)	2 (**2**)
Limpopo Plains†	46 626				
Lowveld	62 216	62, 63 & **64**	507.6 (6.6%)	153.7 (3.6%)	3 (**1**)
Southeastern Coastal Belt & Uplands	13 080	10, 11, 12, 13, **14**, 15, 16, 17, **18**, 19, 20, 21, 22, **23**, 24, 25, 26, 27, 28, 29, 30, **31**, 32, 33, 34 & **35**	1 938.7 (25.3%)	682.1 (16.1%)	26 [3] (**5**)
Southern Coastal Belt & Uplands	64 785	4, 5, 6, 7, **8**, 9 & 69	331.3 (4.3%)	19.7 (0.5%)	7 [1] (**1**)
Southwestern Coastal Belt & Uplands	29 784	2 & **3**	17.8 (0.2%)	9.6 (0.2%)	2 (**1**)
Total	**1 267 490**	N.A.	**7 677.6**	**4 236.7**	62 [9] (**19**)

†*indicates the absence of free-flowing river*

3.2. *Changes in the status of free-flowing and flagship rivers*

Overall, the ecological condition of the FFRs showed a decrease in the natural/largely natural ecological condition and an increase in the moderately modified (C) and largely modified to extremely degraded (D, E and F respectively) ecological condition from PES 2011 to 2018 (Figure 5a & b). This represented 14% of the FFR length that remained in a natural/largely natural condition with 78% in a moderately modified condition (C ecological condition category of DWS) from 2011 to 2018.

In total, 14 FFRs have lost their status as FFRs, of which ten resulted from a deterioration in ecological condition and four were due to the presence of dams in the mainstem river (Table 3) (see supplementary information III for further details). Despite the deterioration and fragmentation observed in the FFRs, all flagship rivers remained intact in ecological condition and longitudinal connectivity. The Groot Marico and the Mutale Rivers, unique rivers from the arid regions, were listed as exceptions FFRs regardless of their ecological condition during both assessments in 2011 and 2018.

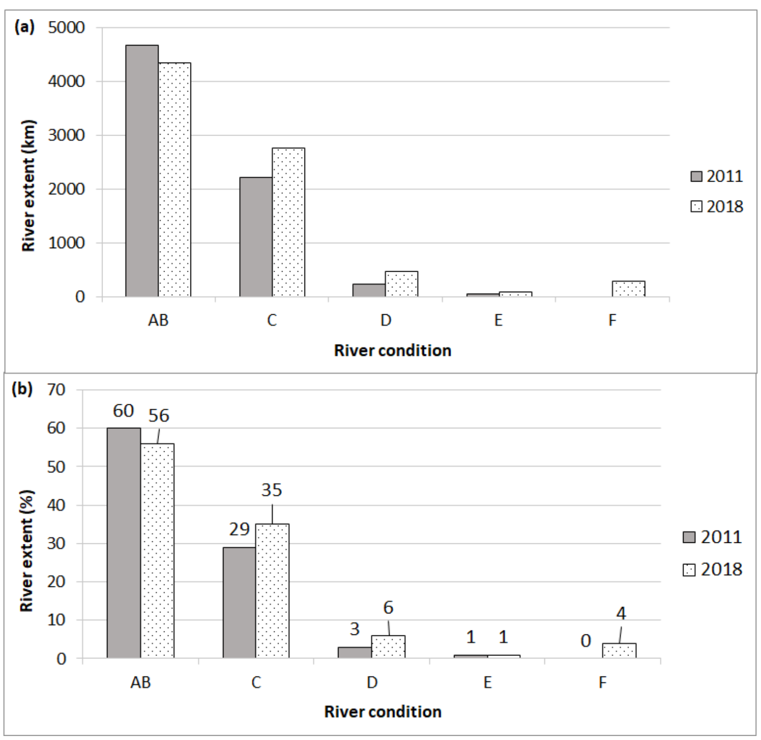

Figure 5. Summary of free-flowing rivers for river ecological condition (main rivers and tributaries) from PES in 2011 to PES in 2018; (a) river extent in km and (b) percentage of the total free-flowing river extent.

Table 3. Free-flowing rivers that lost their status as a result of changes in their ecological condition and/or loss of longitudinal connectivity (fragmentation resulting from new dam construction in the channel), between 2011-2018.

FFR ID	River	Province	Reason
5	Homtini	Western Cape	Change in ecological condition
13	Mgwalana	Eastern Cape	Change in ecological condition
19	Ntlonyane	Eastern Cape	Change in ecological condition
22	Mdumbi	Eastern Cape	Fragmentation and change in ecological condition
28	Mzintlava	Eastern Cape	Change in ecological condition
34	Mzamba	Eastern Cape	Change in ecological condition
38	Mpambanyoni	KwaZulu-Natal	Change in ecological condition
39	aMahlongwa	KwaZulu-Natal	Fragmentation and change in ecological condition
43	Matigulu	KwaZulu-Natal	Change in ecological condition
49	Nsonge	KwaZulu-Natal	Fragmentation and change in ecological condition
50	Nondweni	KwaZulu-Natal	Change in ecological condition
51	Ngogo	KwaZulu-Natal	Fragmentation and change in ecological condition
56	Nyalazi	KwaZulu-Natal	Change in ecological condition
60	Upper Vaal	Mpumalanga	Change in ecological condition

3.3. Changes in the protection levels of free-flowing and flagship rivers

Protection levels of FFRs were dependent on two criteria: the total length (i) in a good ecological condition and (ii) within a protected area. An increase in protected area does not necessarily imply an increase in the protection levels, as was evident from the changes in protected areas between 2008, 2018 and the future NPAES (Table 4, Figure 4). However, certain FFRs in the current study did show an improvement in ecological condition with an increase in the level of protection. Between 2008 and 2018, a three-fold increase in the extent of the FFRs and flagship rivers (km) in a natural/largely natural ecological condition and within protected areas have occurred, increasing from 517 km to 1 628 km.

Table 4. Extent of river length (km) according to the protection level categories listed for the aggregated level 1 ecoregions of South Africa. Protection levels were derived for free-flowing rivers, which are in a good ecological condition (natural and largely natural) and within a protected area. Abbreviations: WP = well protected; MP = moderately protected; PP = poorly protected & NP =not protected; NPA = National Protected Area; NPAES = National Protected Areas Expansion Strategy.

Protection extent scenario	Protection levels	Aggregated Level 1 ecoregions							Total extent (km)
		Eastern Coastal Belt & Uplands	Highveld & Escarpment	Karoo	Limpopo Mountains	Lowveld	Southeastern Coastal Belt & Uplands	Southern Coastal Belt & Uplands	
NPAs 2008	WP	-	-	-	-	213.1	-	63.0	**276.2**
	MP	-	-	-	-	-	-	101.7	**101.7**
	PP	-	-	29.2	23.5	32.5	8.8	37.8	**131.9**
	NP	-	-	-	1.7	-	5.5	-	**7.2**
	Total extent (km)	**-**	**-**	**29.2**	**25.2**	**245.6**	**14.4**	**202.6**	**517.0**
NPAs 2018	WP	-	-	-	-	300.0	-	280.4	**580.4**
	MP	58.0	54.5	-	-	-	-	58.2	**170.7**
	PP	92.9		11.3	47.5	-	21.9	86.1	**259.6**
	NP	361.3	165.7	-	-	-	31.6	58.2	**616.8**
	Total extent (km)	**512.2**	**220.2**	**11.3**	**47.5**	**300.0**	**53.5**	**482.8**	**1 627.5**
NPAES for 2024	WP	70.8	-	79.2	174.6	300.0	644.2	492.2	**1 761.0**
	MP	242.8	189.2	-	-	-	375.4	65.5	**872.9**
	PP	204.5	21.4	28.7	-	-	113.8	-	**368.5**
	NP	-	-	-	-	-	-	-	**-**
	Total extent (km)	**518.2**	**210.6**	**107.9**	**174.6**	**300.0**	**1 133.4**	**557.7**	**3 002.4**

Improvements in the extent and ecological condition of FFRs were also noted between 2008 and 2018 for the Lowveld and Southern Coastal Belt and Uplands ecoregions (Figure 6a & b), while the extent under protection doubled for the Southern Coastal Belt and Uplands ecoregion. A four-fold increase in the extent of FFRs in the well protected level was observed, following improvement in the ecological condition as well. The extent of FFRs in the aggregated Southwestern Coastal Belt & Uplands aggregated ecoregion increased > 8 times, while the extent in the well protected level category increased 5.5 times.

Three of the aggregated ecoregions; the Karoo, Limpopo Mountains & Southeastern Coastal Belt & Uplands, shows almost no improvement in the extent or ecological condition of FFRs within protected areas when comparing to those of 2008 and 2018 (Table 4, Figure 3).

Projecting the ecological condition of the NBA 2018 into the future NPAES of 2024, shows that the extent of FFRs within the NPAES will nearly double from 1 268 km in 2018 to 3 002 km in 2024 (Table 4). Increases range from a minimum of 1.4 times the extent of FFRs in the Southern Coastal Belt & Uplands aggregated ecoregion within NPAs to more than 7 times in the Highveld & Escarpment aggregated ecoregion (Figure 6b & c). The highest increase in extent is visible for the Southeastern Coastal Belt & Uplands aggregated ecoregion, with an increase of > 20 times the extent represented in a natural/largely natural ecological condition compared to what it was in the NPAs of 2018. Representation of the FFRs in the Karoo and Limpopo Mountains aggregated ecoregions will increase by > five times, and nearly three times their extent in 2018, respectively.

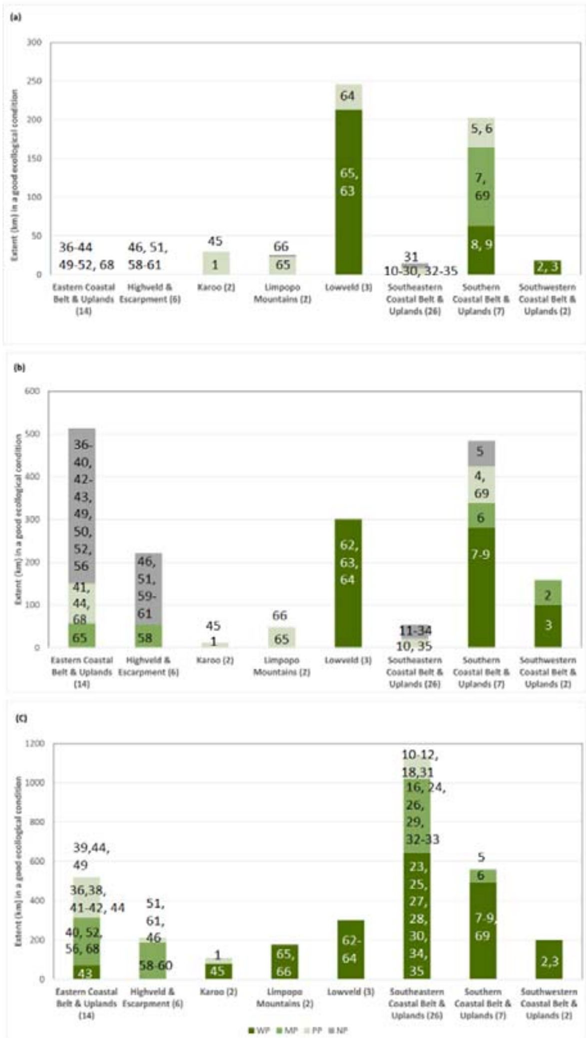

Figure 6. Extent (km) of free-flowing rivers in a good ecological condition and protection level category per aggregated ecoregion for (a) 2008, (b) 2018 and (c) 2024. Numbers on the graph show the FFR identity numbers per protection level and aggregated ecoregion (see supplementary information II, Table S2 for FFR names and IDs). Please note that the ranges of the y-axis differs across the three graphs to accommodate changes in the numbers/extent. WP = well protected; MP = moderately protected; PP = poorly protected & NP =not protected

4. Discussion

4.1 Changes in the ecological condition and protection of free-flowing rivers as a global biodiversity index

Considering the important role that FFRs play in the protection of biodiversity of river ecosystems under increasing negative influences of anthropogenic pressures and climate change influences, their selection, prioritisation, management and global reporting is of critical importance. Consequently, the refined reporting of three indices of FFRs to global targets is proposed:

i) Changes in the integrity of FFRs in a natural and largely natural ecological condition to SDG 6 and Goal A of the post-2020 Global Biodiversity Framework;
ii) Changes in the connectivity of FFRs to Goal A of the post-2020 Global Biodiversity Framework;
iii) Changes in protection levels of FFRs to the Aichi Target 11 and SDG 15.1.2

Changes in the extent of freshwater ecosystems are expected to be reported under the SDG sub-indicator 6.6.1a and Goal A of the post-2020 Global Biodiversity Framework, while changes in water quality are reported under SDG 6.3.2 and Goal A of the post-2020 Global Biodiversity Framework. While river ecosystems may not change in their extent, monitoring changes in the overall habitat, in addition to changes in water quality is critical. Currently rivers are poorly reported at global scale, and officiating these indices, could contribute to improved monitoring and reporting.

The natural capital accounting method reported by Nel & Driver (2015) serves as an example of an index for the improved reporting of the ecological condition of river ecosystems to SDG 6, and can potentially be used for reporting on FFRs, in addition to the methods proposed in the current study. The proposed method for assessing connectivity to Goal A in the future is an easily applied method by many data-poor countries, considering that global rivers and dams datasets are available. Inadequate representation hinders accurate reporting, however, a consistent assessment of river connectivity can offer a reasonable starting point, which can subsequently be improved upon.

To date, the general protection of river ecosystems is reported globally to the Aichi Target 11 that targeted 17% of the extent of freshwater ecosystems by 2020, while the post-2020 Global Biodiversity Framework calls for 30% representation (CBD, 2021). The proportion of important freshwater biodiversity sites that are covered by designated protected areas are collectively reported under the SDG 15.1.2 sub-indicator (Ritchie et al., 2018). This study offers a novel and expanded method for reporting quantifiable changes in the protection levels of FFRs, offering more detail than the current extent protection reporting of the Aichi Target 11 and post-2020 Global Biodiversity Frameworks.

4.2 Implementing a bottom-up approach in selection and reporting of FFRs at a countrywide scale

Using global datasets for the monitoring and reporting of FFRs presents several challenges. The extent of the free-flowing rivers identified by Grill et al. (2019) for South Africa shows a total extent of 225 192 km of FFRs, which is 27% more than the extent used to apply in South Africa's countrywide scale assessments, planning and monitoring (164 018 km in the most recent NBA 2018) (Smith-Adao et al., 2018; Van Deventer et al., 2019a). The extent of rivers in these global river datasets were modelled from digital elevation models and offer more extensive representation of tributaries and therefore increased river extent for South Africa (Grill et al., 2019; Linke, Hermoso, & Januchowski-Hartley, 2019). However, tracking changes in their ecological condition, managing and conserving all these river networks, particularly ephemeral rivers, would be challenging.

The methods applied in the current study are easily replicable by other countries for selecting and prioritising FFRs for focused management, prioritised conservation, and reporting to global indicators. Other countries can apply the same methods even when using global datasets. These datasets could be integrated with already available finer scale datasets at the country scale, which can be refined through knowledge co-production methods.

4.3. Incorporating free-flowing and flagship rivers in conservation planning at a countrywide scale

In 2008, the former Department of Environmental Affairs and Tourism (DEAT) implemented an NPAES (Jackelman, Holness, & Lechmere-Oertel, 2008), which did not include planning for freshwater ecosystems. Historically, protected areas were not established with freshwater ecosystems as key priority areas for protection and were only incidentally incorporated with terrestrial biodiversity area protection (Nel et al., 2009; Rivers-Moore, Goodman & Nel, 2011; Opperman et al., 2021). It was often assumed that rivers within protected areas would be adequately conserved without taking cognisance of river connectivity (i.e. longitudinal, lateral, vertical and temporal linkages) or catchment disturbances. In 2016, the NPAES was revised to identify additional priority areas and ecosystems towards achieving biodiversity targets under the CBD (DEA, 2016). The results from this study showed that including freshwater ecosystems and FFRs in particular in the implementation of the successive NPAES plans (2016 and 2024) resulted in progressive increase of FFRs representation throughout all ecoregions (Table 4). In fact, the future extent of protection may result in protecting 59% of FFRs in the well-protected category.

The adoption and championing of a priority list of free-flowing rivers by national, provincial and local government authorities provided some success of incorporating a prioritised selection of FFRs in conservation planning. After seven years of assessment since the NBA 2011 and NBA 2018, the 19 flagship rivers showed no major deterioration in ecological condition and no loss of connectivity in their extent. This can be directly attributed to the efforts of the NFEPA project (Nel et al., 2011b; Nel et al., 2016), the first countrywide freshwater conservation plan in South Africa, and the success of targeting attention and initiatives to manage these systems.

FFRs could contribute significantly to the improvement of protection levels and to global CBD targets. In South Africa, the NPAES for 2024 has the potential to allow for a substantial increase in the extent of the South African FFRs within protected and managed areas, with a possibility that the ecological condition could be rehabilitated and improved. The identification of FFRs and the inclusion of non-intact rivers, tributaries and their associated river ecosystems can contribute to improving connectivity and thereby contribute to broader conservation goals (Abell et al., 2017) as well as expanding freshwater ecosystem representation in protected area networks. The 19 flagship FFRs were included in the NPAES for 2024 (DEA, 2016), which ensured improved representation of freshwater ecosystems in a previously terrestrially biased conservation planning tool.

4.4 Challenges in the assessment of changes in the ecological condition and connectivity of FFRs

One of the main inconsistencies in PES assessments between 2011 and 2018 was that ecological condition for tributaries were modelled from land cover datasets in 2011 while in 2018 their ecological condition was based on *in situ* assessments where applicable. However, most of the FFRs where change was detected due to ecological condition were mainstem FFRs with only 1% of the FFRs influenced by change in tributary ecological condition. Despite the inconsistencies, the outcome of both assessments showed similar trends in overall river health where tributaries were generally in a better condition than mainstems (Van Deventer et al., 2019b). Furthermore, PES assessments consider biophysical aspects relating to the capacity of a river to function sustainably and attributes relating to the sensitivity of these aspects to environmental change (Van Deventer et al., 2019b). Species data, where available are also considered, which includes fish, macroinvertebrates and riparian vegetation. Where species data is lacking the river ecosystem types were used as a coarse-filter surrogate for diversity, especially for freshwater invertebrates (Dallas, 2004; Roux et al., 2007; Nel et al., 2011b). The fact remains that trends in changes for mainstem rivers showed a decline in ecological condition, whereas the use of modelled and *in situ* ecological condition data for the tributaries, reflected similar degradation.

Global and large-scale data sets will inevitably contain errors or omissions and the aim is to keep such errors to a minimum. This should be achieved through dedicated programmes at countrywide scale, to improve representation and accuracy. In the current study, the use of the original underrepresented Geographical Information System dams data set represented an error of 6.5% in river extent in the selection of FFRs, which means that the error was low enough to adequately represent changes in connectivity. Knowledge through co-production and boundary work assisted by refining and improving the accuracy of data layers as well as in selecting the 19 free-flowing flagship rivers for prioritisation and focused management and conservation (Nel et al., 2011b). By developing the criteria applied for mapping FFRs through knowledge co-production, exceptions to the selection of FFRs was possible. Living data layers, which are continually updated, will also assist to improve the accuracy of analyses and will ensure that the best available data at the time of use is applied.

5. Acknowledgements

This study was funded by the Parliamentary Grant funding of the Council for Scientific & Industrial Research (CSIR) (Project EEEO053) and funding allocated by the South African National Biodiversity Institute (SANBI) for the National Biodiversity Assessment for 2018 (NBA 2018). We are thankful to Prof Dirk Roux from the South African National Parks (SANParks) and Nelson Mandela University who provided an initial review of the changes in the free-flowing and flagship rivers as part of the review of the NBA 2018. Lastly, we are grateful to the reviewers who provided comments and suggestions to the improvement of this

manuscript. The authors have no conflicts of interest to disclose, and all authors approved the article and this submission. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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