River discharge dynamics, climate and land-use change: The Amatikulu-Nyoni Rivers, KwaZulu-Natal, South Africa

By

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DECLARATION OF ORIGINALITY
UNIVERSITY OF PRETORIA

I, Renate van Heerden, declare that the thesis/dissertation, which I hereby submit for the degree MSc Geography at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

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Abstract

Fluvial discharge dynamics, climate variability and land-use change: The Nyoni and Amatikulu Rivers

Land-use changes and climate variability are known to affect environmental processes, and fluvio-marine environments tend to be extremely sensitive to these impacts. Hydrological models have been introduced in numerous studies to explore the responses in catchment processes. Spatially distributed rainfall-runoff models provide a more holistic view of the hydrological behaviour under different environmental conditions. However, the use of hydrological models in South African studies which investigate the impacts of climate and land-use change on discharge are scarce, and only a limited number have investigated the impact of climate and land use on catchment processes. What is of more relevance and importance in real-world applications is the differentiation between the respective roles of climate and land use on specific catchments. This study implements Spatial Tools for River basin Environmental Analysis and Management (STREAM), a GIS-based water-balance model, to investigate the major causes in change of discharge volume in the Amatikulu and Nyoni catchments (KwaZulu-Natal, South Africa). River and coastal morphological changes have also been observed in the recent past. This study proposed that land-use changes and climate variability have the largest influence on the change in discharge volumes; however, the exact extent needs investigation. Climate and land-use data for the period 1964-2015 are used for the model simulations. It has been found that land-use changes have had no significant impact on the discharge for this period, while climate has had the larger effect. Climatic scenarios corresponding to projected climate change have been investigated, and have shown that a 5°C increase in temperature would have the largest influence on discharge compared to the observed changes in land use.

Keywords: River systems, discharge, climate, land use, hydrological modelling

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List of Abbreviations

ACRU: Agricultural Catchments Research Unit

DEM: Digital Elevation Model

GIS: Geospatial Information System

GTI: Geoterra Image

IPCC: Intergovernmental Panel on Climate Change

LULCC: Land-Use and Land Cover Changes

LUM: Land-Use Map

NSPECT: Non-Point Source Pollution and Erosion Comparison Tool

NGI: National Geospatial Information

RCP: Representative Concentration Pathways

STREAM: Spatial Tools for River Basins and Environment and Analysis of Management Options

SWAT: Soil and Water Assessment Tool

.txt: Textfile Extension

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Chapter 1: Introduction

The human and climate impact on the environment has been extensively studied. Several studies investigate the impact of humans, as well as the impact of climate, on the environment (see: Miller & Cruise, 1995; Scavia *et al.*, 2002; Jiang *et al.,* 2007; Longhitano & Colella, 2007; Paris & Chérubin, 2008; Grenfell *et al.*, 2009; Dosseto *et al*., 2010; Dymond *et al.,* 2010; Notebaert *et al.*, 2018). However, no definitive answer has been found as to whether climate or land-use and land use changes have been the larger drivers of environmental change (Longhitano & Colella, 2007; Dosseto *et al.,* 2010; Notebaert *et al.,* 2011a; Maina *et al.,* 2012, 2013). These environmental changes are likely due to the dynamic nature of the environment in combination with the unpredictable nature of the atmosphere. No two regions will experience the same environmental responses when exposed to the same land-use change and climate regime. Such uncertainty in exact regional responses to climate and land-use changes motivates for more studies on this topic.

1.1. Study background

From previous studies it has been established that humans have an impact on the environment and, more specifically, on different habitats, sediment dynamics and nutrient balance (see: Scavia *et al.*, 2002; Miller & Cruise, 1995; Paris & Chérubin, 2008; Grenfell *et al*., 2009; Dosseto *et al.*, 2010; Dymond *et al.,* 2010). The impact of climate on environmental processes has also been widely studied (e.g. Klein *et al.,* 2001; Scavia *et al.,* 2002; Jiang *et al.,* 2007; Grenfell *et al.*, 2009; Dosseto *et al.,* 2010). Both human and climate induced changes impact processes operating at the catchment scale (Longhitano & Colella, 2007). Investigations into the extent to which climate and human activities influence catchments, as well as the separate contributions of climate and land-use change, are necessary (Longhitano & Colella, 2007; Dosseto *et al.,* 2010). This is due to the argument that natural processes are no longer the only influence, and that anthropogenic causes not only influence, but also dominate (Bouwer *et al.*, 2006). However, disentangling the respective roles of natural or human-induced changes has proven difficult (Notebaert *et al.,* 2011a; 2011b).

Different studies describe the changes in land cover and climate that affected river systems during the Holocene (Coulthard & Macklin, 2001). Since river systems discharge into the sea to form fluvio-marine environments, it is important to consider both fluvial and coastal environmental changes. Coastal environments are dynamic systems that constantly adapt to new conditions to achieve a new state of equilibrium. These systems are especially susceptible to change because of being at the interface between land, sea and air (Klein *et al.,* 2001). Any slight alteration in land, sea or air would alter the presiding dynamics. Coastal water bodies, such as lagoons, estuaries and mangroves, show substantial morphological and dynamic variability and, as such, give essential insights into the processes that govern sediment dynamics in these environments (Cooper, 2001; Bouma *et al.,* 2007). Even then, the relationship between morphological modifications and the various coastal water bodies is poorly understood (Cooper, 2001). However, it is known that river-dominated estuaries are only likely to change if the discharge dynamics adapt to a different set of anthropogenic circumstances or climate conditions (Cooper, 2001). This follows the definition of river-dominated estuaries, where sedimentation processes and basin shape strive for equilibrium by maintaining a balance with fluvial discharge (Cooper, 1993).

River systems are disturbed by deforestation, changes in agriculture and hydro-climate variability. More specifically, deforestation, agriculture and climate variability affect valley floor sedimentation and erosion rates, which in turn affect sediment storage capabilities (Coulthard & Macklin, 2001). All these impacts are brought about by both climate and land-use shifts, but Coulthard and Macklin (2001) argue that river system change is primarily driven by climate change, although the combined effect is much greater. Bouwer *et al.* (2006) discuss the concept of human-induced climate change and natural climate variability, and the large impact that both may have on freshwater resources, which results in further impacts. The environment reacts to changes in land use which are reflected in hydrological responses (Schulze, 2000). Consequences of human-induced changes in the upper parts of drainage basins would thus be observed in the lower drainage basins and along the coastline (Longhitano & Colella, 2007).

Following Coulthard and Macklin's (2001) argument, these consequences would have an aggravated response as a result of the human-induced change, but would have also occurred due to climate change. Longhitano and Colella (2007) drew a similar conclusion, ultimately that the combined effect of natural and anthropogenic processes causes erosion. Variations in climate, such as precipitation, would influence discharge, which in turn would have an effect on the sediment dynamics of the catchment (for example see: Longhitano & Colella, 2007; Paris & Chérubin, 2008; Ward *et al.,* 2009; Moser *et al.,* 2012). Building on this, climate factors have relevance to the coastal environment and, together with other anthropogenic factors (such as resource overexploitation, pollution, increased nutrient fluxes, decreased freshwater availability, decreased sediment flux and urbanization), the hazard potential is likely to increase (e.g. Klein *et al.,* 2001; Scavia *et al.,* 2002; Dymond *et al.,* 2010). Hazard potential in this sense links with coastal environmental health (Klein *et al.,* 2001).

Sediment delivery to the coast has changed with the increase in human activities in the catchment area, since changes in surface runoff affect the transport agent of fluvial load (Syvitski *et al.,* 2005). Anthropogenic-driven changes simultaneously cause an increase in sediments transported by rivers, as well as a decrease in flux to the coast (Syvitski *et al.,* 2005). Increases in soil erosion causes increased sediment loads, however; these sediments are retained in reservoirs (Syvitski *et al.*, 2005). Since river discharges can be measured directly, discharge volumes and the changes therein are usually considered in catchment process studies. Hurkmans *et al.* (2008) thus consider discharge to incorporate hydrological processes at the catchment scale.

The nature and amount of riverine material are complex functions of hydraulic variables and are influenced by a combination of natural and anthropogenic processes within the catchment. Riverine material is therefore considered as an essential indicator of global hydrological change reflected in discharge dynamics (Yonggui *et al.,* 2013). The discharge dynamics of a river play a crucial role in catchments (Notebaert *et al.,* 2011a), because rivers are the primary link between land and ocean. As a result, influences in river environments are not restricted to the geomorphology of river channels, estuaries and deltas, but also influence the contribution of nutrients for the associated ecosystems (Liu *et al.,* 2014). Changes in freshwater discharges, as well as changes in temperature of coastal systems, will interact with changes in other atmospheric and oceanic conditions (Moser *et al.,* 2012). A new set of conditions is thus created that would effectively alter the coastal ecosystem (Moser *et al.,* 2012). With this in mind, understanding fluvial delivery of sediments to the coast, and how it will affect coastal dynamics, especially the way in which human interference has disturbed these systems, becomes vital (Syvitski & Milliman, 2007; Lui *et al.,* 2014).

Catchment hydrology is dependent on different factors, which include land use, climate and soil conditions (Tong & Chen, 2002; Ma *et al.,* 2008 & 2010). Fenicia *et al.* (2009) point out that land management practices could alter the hydrology of the catchment and van Rompaey *et al.* (2007) indicate that the spatial pattern of land-use change is more important than the overall percentage of land-cover change. Land-use changes are reflected in hydrological landform characteristics and increasing overland flow path length (Pelacani *et al.,* 2008; Germer *et al.,* 2010). The results of land management practices can be observed directly through reduced peak discharges, water volumes and increases in the base flow of rivers (Pelacani *et al.,* 2008; Germer *et al.,* 2010). Land management practices can further alter the presence and extent of perched water tables (Germer *et al.,* 2010).

Although catchment processes are influenced by several factors, land use and climate are the most dominant (see: Jansson,1988*;* Tong & Chen, 2002; Ma *et al.,* 2008). Verstraeten *et al.* (2009) support this notion by stating that fluvial system change is mainly brought on by climate and human induced land-use change. It is further shown by numerous studies that, although these studies specifically illustrate the responses of fluvial systems to land-use and land-cover changes, it is also necessary to understand the role of climate in erosion processes (e.g. Coulthard & Macklin, 2001; Vandenberghe, 2003; Verstraeten *et al.,* 2009; Dosseto *et al.,* 2010). The relationships between climate change, erosion and vegetation cover are complex and become even more complicated with land-cover changes because it involves interactions and feedbacks between the atmosphere, oceans and land surface (Jiang *et al.,* 2007; Dosseto *et al.,* 2010). Climate impacts on geomorphological processes, such as erosion, in some cases are considered more dominant than land-use change (see: Jansson, 1988; Coulthard & Macklin, 2001; Vandenberghe, 2003; Dosseto *et al.,* 2010; Park *et al.,* 2011).

Land use is a critical consideration in controlling soil erosion as it modifies the physicochemical and biological characteristics of the soil (Feng *et al.,* 2010). There is still uncertainty about the relative contributions each land-use type has on surface water systems (Tong & Chen, 2002). Soil erosion is also a serious global environmental problem (Feng *et al.,* 2010). Thus, knowing the relation of soil erosion processes to land-use practices is useful (Feng *et al.,* 2010). The continuous landscape transformation exerts a degree of control over soil erosion and sediment delivery to rivers and reservoirs (van Rompaey *et al.,* 2007). Increased sediment delivery to river systems could possibly be the most problematic consequence of soil erosion (van Rompaey *et al.,* 2007).

This highlights the fundamental question in fluvial geomorphology according to Coulthard and Macklin (2001:1) which is: “How sensitive are river systems in relation to either, or both, climate and land-use change?” Presently the question remains largely unanswered, particularly in a South African context. However, scientific consensus is that future increases in temperature will result in subsequent effects on precipitation, evapotranspiration and soil moisture (Park *et al.,* 2011). Different climate change scenarios also include predictions of change in the frequency and severity of floods and droughts (Park *et al.,* 2011). Flow regimes and sedimentation in streams and rivers are affected accordingly (Park *et al.,* 2011).

Even though there are a number of contradictory studies on the topic of climate and land-use change influences on catchment processes, Bouwer *et al.* (2006) consider that very few studies have given attention to the combined effect of natural climate variability, climate change and human impact. Knowledge of hydrological connectivity should be developed using a variety of techniques, with common understanding between studies with different perspectives (Bracken *et al.,* 2013). Understanding of the complex dynamics of a system is becoming more prevalent in studies. Coulthard *et al.* (2007) and Bracken *et al.* (2013) both consider that understanding the process is more important when formulating conclusions and giving recommendations. According to Coulthard *et al.* (2007) simulating the behaviour of fluvial systems to climate variability and human activities could be a first step in improving the understanding of fluvial systems and the management of water resources. Qualitative research allows more freedom when looking at processes holistically. It thus becomes possible to consider more concepts within a system without direct measurements. This type of approach is especially applicable in studies where attaining data is difficult or available data is of poor quality.

From the literature, it remains evident that investigating fluvial processes at a catchment scale as a whole remains difficult. Recent studies have become focused on developing models to simulate hydrological systems and the reactions to anthropogenic and climatic change (see: Kirkby *et al.,* 2000; Aerts *et al.,* 2006; Coulthard *et al.,* 2007; van Rompaey *et al.,* 2007; Maina *et al.,* 2013, Rebelo *et al.,* 2015). The intention of such models is effectively to simulate a system in a simple and understandable manner (van Griensven *et al.,* 2006). Modelling could enhance field observations (historical documentation and evidence of changes) while suggesting new areas to investigate and possible causations for environmental degradation (Coulthard & Macklin, 2001; Cooper & Pilkey, 2008). For example, incorporating a rainfall-runoff factor could possibly improve a model's ability to account for seasonal effects as well as accounting for the spatial variation of soil loss on hill slopes (Kinnel, 2010). Modelling provides the opportunity to study several impacts of land use and climate on catchment processes (Jordan *et al.,* 2005; Aerts *et al.,* 2006). However, more research is needed to determine how well model simulations reflect reality (Hessel *et al.,* 2003).

Currently, the application of hydrological modelling is largely concentrated in European countries and in the northern hemisphere. As noted by van Rompaey *et al.* (2005), it is not known how well these models would perform outside of northern and central Europe. Locally there have been only a few modelling studies, including Thomas *et al.* (2010) and Schulze (2000), and different hydrological models still need to be applied to different river catchments in South Africa. The intricate nature of processes operating in South Africa encourages further research into hydrological responses to land-use and climate changes. Schulze (2000) mentions several issues, including the idea that fluctuations in hydrology are exacerbated by fluctuations in climate.

What is intriguing is that the river-dominated estuaries on the east coast of South Africa are marked by unusual inlets and an abundance of ephemeral inlets (e.g. Cooper, 2001; Green *et al.,* 2013; Bond *et al.,* 2013). The east coast of South Africa provides ample ground for in-depth investigations because the dynamics of these inlets and transitional fluvio-marine environments are considered understudied (Cooper, 1993; Bond *et al.,* 2013). The coastline north of the Tugela River mouth has been specifically identified as one of two accreting sections of the South African coastline (Olivier & Garland, 2003). This section has further been described as an actively prograding, high energy coastline (Green *et al.,* 2013). The Amatikulu and Nyoni rivers are located on the prograding east coast and have river-dominated estuaries and, in time, the inlets go through open and closed phases (Green *et al.,* 2013).

Fluvial sedimentation extends to the coastal barrier in river-dominated estuaries (Green *et al.,* 2013). With this in mind, it is likely that the source of accumulating sediments along this coastal section is fluvial. It has been determined that the Tugela River is the major source of sediments; however, the Amatikulu River also contributes (Green *et al.,* 2013). The reasons for increasing sediments are still unclear. Since the sediment supply is affected, it seems fitting to investigate the relationship between anthropogenic and climatic factors and catchment processes, through simulating the river flow and sediment load. Certainly, part of the question to resolve is to what extent changes in river discharges in the past couple of decades would have influenced the hydrological balance. To acquire a complete understanding of the present landscape and geomorphic processes governing it, a study into past processes is necessary (Notebaert *et al.,* 2009).

Not only is the east coast a prograding coastline, but north-eastern longshore drift has also been identified to contribute sediments along the coast (Schoonees & Theron, 1993; Schoonees, 2000; Cooper & Pilkey, 2004; Schoonees *et al.,* 2006). In an attempt to explain these phenomena, it is suggested that the catchment has reacted to climate variability and land-use changes. A spatially distributed hydrological model is applied to investigate the sensitivity of the Amatikulu and Nyoni catchments to climate variability and land-use changes. The Spatial Tools for River Basins and Environment and Analysis of Management Options (STREAM) is a river-basin management instrument and a GIS-based rainfall-runoff model which is focused on climate change effects, land-use changes and the interaction between river discharges and coastal dynamics (Aerts *et al.,* 1999). STREAM enables the simulation of river discharge and water availability and facilitates scenario analysis (Aerts *et al.,* 1999). The input required for the application of the model consists of several spatially distributed layers, for example, a Digital Elevation Model (DEM), total monthly precipitation and average monthly temperature, crop factors and the maximum soil water holding capacity (Aerts *et al.,* 1999).

1.2. Aims and objectives

The aim of the study undertaken is to trace the changes through time in discharge dynamics (volume) as a result of either or both land-use change and climate. Several research objectives are highlighted:

- Data collection:
    - To obtain and modify the necessary input parameters for the modelling river discharge volume of the Amatikulu-Nyoni Catchment with the STREAM model. It is thus necessary to determine land-use and land-cover changes from digitised aerial photos and classified satellite images as well as determining annual climate variability for the same period. The model will be calibrated with measured discharge data of the catchment for the period between 1965-1992.
- Model simulations:
    - To determine past and present river discharge volumes through running model simulations for the study period (1965-2015). With these simulations, the sensitivity of the fluvial system to either climate variability, land-use change or both is determined.
    - To determine possible relationships between climate variability, land-use changes and river discharge dynamics. The model results are further analysed in clear and definite terms in order to answer the research problem.
- Scenario tests:
    - To test complete changes in land-use scenarios in order to test the impact of a single land use on discharge volumes.
    - To test different climate scenarios using Representative Concentration Pathways (RCP) according to the RCP2.6 and RCP8.5 temperature and precipitation

projections in order to determine the ‘worst case scenario’ in the projected climate trends.

This study will investigate the change in discharge volume of the Amatikulu-Nyoni River catchment as a result of land-use change and climate for the period from 1965 to 2015. Once past land use and climate have been investigated, a series of simulations will consider the likely change in discharge volumes as a result of scenario-based changes in land use and in projected climate change scenarios. Through the different simulations, the dominant driver of change for the Amatikulu-Nyoni catchment will be determined.

Chapter 2: Literature Review

There have been a number of studies into various hydrological changes as a result of climate and land-use forcings (e.g. Scavia *et al.*, 2002; Longhitano & Colella, 2007; Paris & Chérubin, 2008; Grenfell *et al.*, 2009; Dosseto *et al.*, 2010; Dymond *et al.,* 2010; Maina *et al.,* 2012, 2013; Notebaert *et al.,* 2018). Such studies are extremely important when looking into vulnerable ecosystems that function on the dynamic balance of chemical and physical processes. Changes in river discharge volumes, rate of flow and sediment load, for example, occur once an imbalance in these processes exists, thereby initiating landscape evolution (Walling, 2006). Ultimately, the dynamic nature of natural processes would force changes in discharge dynamics, such as the volume of water in a river, and a new equilibrium will be reached (Tinley, 1985; Kennish, 2001; Woodroffe, 2002). However, in some cases, climatic or land-use changes in river systems could cause natural disasters such as landslides, floods and droughts. Environmental studies can be divided into two schools of thought; some focus on what causes environmental change, and others look into the nature and consequences thereof (see: Klein *et al.,* 2001; Longhitano & Colella, 2007; Paris & Chérubin, 2008; Grenfell *et al.*, 2009; Dosseto *et al.*, 2010; Dymond *et al.,* 2010; Maina *et al.,* 2012, 2013). Landscape evolution is a visible consequence of several processes including changes in discharge dynamics. In order to understand how the landscape is changing as a result of rivers, it is necessary to look into the reason for different discharge regimes.

2.1. Environmental change

Some of the most dynamic landscapes would be those created by flowing water. River and coastal environments constantly change as a result of erosion and deposition processes within these environments (Tinley, 1985; Kennish, 2001; Woodroffe, 2002). Although naturally occurring, the rate and extent of erosional and depositional processes have been exacerbated by land-use changes and climatic events (Longhitano & Colella, 2007; Maina *et al.,* 2012, 2013; Notebaert *et al.,* 2018). Since climate change (such as increased or decreased precipitation) has been widely accepted as being largely driven by human activities, it is difficult to distinguish whether natural or anthropological forces have therefore shaped these environments (Sullivan *et al.,* 2004; Ma *et al.,* 2008; Notebaert *et al.,* 2011a; 2011b; Ahn & Merwade, 2017).

Global environmental changes and specifically human or climate induced environmental changes have received a lot of attention, with numerous studies looking into the extent of human and climate impacts on the environment (e.g. Syvitski & Milliman 2007; Verstraeten *et al.* 2009; Notebaert *et al.,* 2009; Notebaert *et al.,* 2018). Internal system dynamics and external forces control environmental system changes, where external forces are either through human or natural factors (Syvitski & Milliman, 2007; Dusar, *et al.,* 2011). Natural forces refer to changes in climate, vegetation cover, tectonics and sea-level change, for example (Milliman & Syvitski, 1992; Dusar *et al.,* 2011). Humans, however, have a remarkable influence on these factors as well (Ma *et al.*, 2008).

Human forces include the development of land for agricultural, industrial or residential uses. Human settlements in the past have developed in areas where shelter, security and food resources were abundant. With the development of civilization and increased population, the use of land changed and therefore the anthropological strain placed on the land increased. Several drivers have emerged in the more modern society, placing even more stress on the environment. Land-cover changes driven by humans, including deforestation, agriculture and mining, indirectly affect the natural forces (Ma *et al.*, 2008). It is considered that since the Neolithic, anthropogenic drivers have dramatically altered the hydrological regime and land forming processes (Dusar *et al.,* 2011).

The concept of environmental change as a result of climate and land-use change has been extensively debated in the literature, making it one of the most controversial themes in earth sciences (see: Klein *et al.,* 2001, Sullivan *et al.,* 2004; Jiang *et al.,* 2007; Syvitski & Milliman, 2007; Notebaert *et al.,* 2011a; 2011b; Maina *et al.,* 2012, 2013). Not only is the idea of change being investigated, but also the degree and nature of these changes (Ma *et al.,* 2008; Maina *et al.,* 2013). Interestingly, the debate is not whether or not the environment is changing, since a reasonable consensus has been reached that the environment has changed (Park *et al.,* 2011, Maina *et al.,* 2012). Disputes revolve around what causes the changes, to what extent the environment is changing and what the ideal solution would be (e.g. Sullivan *et al.,* 2004; Syvitski & Milliman, 2007; Notebaert *et al.,* 2011a; 2011b; Maina *et al.,* 2012, 2013; Ahn & Merwade, 2017).

Particular aspects of the environment are more prone or sensitive to changes. Sensitivity refers to how susceptible a system is to disturbances. Landscape degradation is the substantial reduction in an area’s biological yield or worth to humans, due to human activities. Studies into landscape sensitivity often involve three major questions, the first of which refers to what magnitude of environmental change would cause significant landscape modification (Dusar *et al.,* 2011). Since landscapes vary considerably, the second question is concerned with which landscape type is most affected by environmental changes (Dusar *et al.,* 2011). Triggers of changes could be regional or global and, accordingly, the spatial distribution of environmental changes is essential in understanding the outcomes (Peterson & Ver Hoef, 2010). The global pattern of changes shows large regional differences (Syvitski, *et al.,* 2005). However, timing of events should not be neglected, as both spatial and temporal scales are critical when investigating landscape change. This leads to the last question in landscape studies; at which timescale environmental changes impact the landscape (Dusar *et al.,* 2011)?

The combinations of factors that influence environmental change are infinite and most research is limited to what is seen to have affected the system. Tobler's first law of geography states: "Everything is related to everything else, but near things are more related than distant things" (Tobler, 1970 as cited in Peterson & Ver Hoef, 2010). Based on this, studies are commonly limited to explore "near things". Since all factors involved are not and cannot as yet be known and brought into consideration, understanding environmental changes is difficult. This means that no matter how well studied this theme is, more knowledge is always needed.

Since most research is limited to what can be seen, it follows that landscape evolution is one of the most well-studied themes in environmental studies (Peterson & Ver Hoef, 2010). However, to recreate a landform based on what is understood to have played a role is difficult. Therefore, a simulation of how the landscape has evolved cannot be created unless there is a grasp of what could have formed the landscape (Phillips, 2007; Notebaert *et al.,* 2009). Unfortunately, this is difficult, since not all conditions necessary to form a specific landscape are not always noticeable, or will exist again in that specific way (Phillips, 2007).

2.2. Landscape evolution

The available material and the conditions presiding within the system regulate landscape evolution (Walling, 2006). Landscape evolution occurs over varying periods, depending on the driving force behind the forming of a landscape. River systems evolve over centuries, while sections in a river could form in a single flood event. One of the fundamental goals of landscape science is to understand the redistribution of continental substrate through weathering and erosional processes and it follows that ongoing landscape dynamics have an extensive impact on erosion and eventual sediment delivery to rivers and oceans (van Rompaey *et al.,* 2007; Syvitski & Milliman, 2007; Yonggui *et al.*, 2013). Redistribution of material loads is known to impact landscape morphology and would reflect in several processes which could be investigated. Sediment is transported in numerous ways, such as water distributing sediment load within the drainage catchment towards the ocean (Milliman & Syvitski, 1992; Walling, 2006).

River systems form hydrological connections (see discussion below), through which these rivers become an important link for circulating material and energy (Kong *et al.*, 2016). By circulating earth materials or sediments through fluvial processes, rivers form and change landscapes. Understanding fluvial sediment dynamics is thus essential when attempting to understand landscape morphology and associated formation processes (Syvitski & Milliman, 2007; Verstraeten *et al.,* 2009). A thorough interpretation of the present landscape could give an indication of past processes (Notebaert *et al.,* 2009). It is thus probable to assume that the study of sediment and discharge dynamics of a catchment would contribute to explaining the processes currently forming the landscape, giving insight into the causes for the formation of certain features.

Landscape features refer to the physical linkage of sediments through channel systems, transporting matter and energy from one point to another, or to have the potential to do so (Bracken *et al.,* 2013). Freeman *et al.* (2007, p6) defined hydrological connectivity as the "water-mediated transport of matter, energy and organisms within or between elements of the hydrologic cycle". Thus the landscape features within a catchment cause hydrological connections. Furthermore, understanding the concept of connectivity in catchments provides a framework for investigating the spatial patterns associated with catchments (Bracken & Croke, 2007; Paris & Chérubin, 2008; Notebaert & Verstraeten, 2010; Bracken *et al.,* 2013). Hydrological connections are developed through surface and sub-surface flows, as a function of water volume (controlled by rainfall, infiltration and evaporation), and rate of transfer. These processes then interact with flow resistance, which would vary as a function of flow depth (Bracken *et al.,* 2013).

The concepts of hydrological connectivity can be understood as elements of structural (static) or functional (dynamic) connectivity (Bracken & Croke, 2007; Turnbull *et al.* 2008; Bracken *et al.,* 2013). This differentiation is made to describe the differences between spatial patterns of hydrological connectivity (discussed further below) and both the long-term landscape development and short-term variations (Bracken *et al.,* 2013). Elements of structural connectivity are more easily described and can be categorized, classified and estimated (Wainright *et al.,* 2011; Bracken, *et al.,* 2013). The spatial distribution of landscape features that would affect flow path is seen as the elements of structural connectivity, and acts as a topographical control (Turnbull *et al.,* 2008; Bracken *et al.,* 2013). The interaction between spatial patterns and catchment processes (runoff, connected flow) that produce water transfer in catchments represents elements of functional connectivity (Turnbull *et al.,* 2008; Wainright *et al.,* 2011; Bracken *et al.,* 2013). When referring to functional connectivity, the catchment processes are described, thus Bracken *et al.* (2013) propose the term process-based connectivity. This term more comprehensively describes the dynamics of hydrological connectivity as it specifically refers to the processes involved in forming these connections.

2.3. Hydrological connections and water resources

Since landscapes change over time, altering the processes, it is noted that understanding interactions between topographical controls and catchment processes is imperative in interpreting the dynamics associated with hydrological connectivity (Nijssen *et al.,* 2001; Bracken and Croke, 2007; Turnbull *et al.,* 2008; Bracken *et al.,* 2013). The topography of the landscape determines the path of water, but because the landscape changes with time, the path would change accordingly. However, this is only one example of the many complex process-topography interactions and it is clear that research cannot definitively isolate the elements of connectivity. Further investigations into the nature of process-topography interactions are necessary (Bracken *et al.,* 2013). Hydrological connections can be associated with process-topography interactions, which form rivers that comprise catchments, and act as the primary link between land and ocean (Milliman & Meade, 1983, Liu *et al.,* 2014). Rivers are fundamental in transporting sediments from land to the ocean, forming a clear link between land and ocean (e.g. Milliman & Syvitski, 1992; Walling, 2006; Paris & Chérubin, 2008; Liu *et al.,* 2014).

What is clear from the concept of hydrological connectivity is that streamflow acts as a spatial integrator (Nijssen *et al.,* 2001). Changes upland would have a ripple effect on fluvial and coastal environments (Syvitski *et al.,* 2005; Dymond *et al.*, 2010; Jackson, 2013). Water fluxes can transport increased concentrations of pollutants to the coast and changes in the amount of sediments and nutrients, which are caused by changes in land uses, precipitation and storm surges (e.g. Longhitano & Colella, 2007; Paris & Chérubin, 2008, Ward *et al.,* 2009; Moser *et al.,* 2012). The catchment dynamics, as well as the "connected" dynamics, are affected as the environment adjusts to new conditions (Syvitski *et al.,* 2005; Dymond *et al.*, 2010; Jackson, 2013). This means that what happens in the headwaters of the river, or lower down, will have effects at the coast. The dynamic balance between freshwater and ocean water will be adapted to account for changes in the freshwater source. Increased sediments or pollutants carried by the rivers can potentially destroy the sensitive chemical and physical equilibrium in fluvio-marine environments. This results in changes in the magnitude and rate of erosion and deposition that will then drive landscape evolution.

The coast and associated coastal environments act as buffer zones protecting the landmass from storms and sea-level changes (e.g. Tinley, 1985; Kennish, 2001; Woodroffe, 2002). These environments have unique ecosystems that perform vital chemical and physical functions (see e.g. Kennish, 2001; Scavia *et al.,* 2002; Jackson, 2013). Since the coast is mostly working towards a dynamic equilibrium, and because of hydrological connectivity, the changes in fluvial transport would cause change in the overall equilibrium state, forcing a new state of equilibrium (Woodroffe, 2002). It has been observed that coastal environments experience an inhibitory effect because of upland land uses (as seen in: Miller & Cruise, 1995; Longhitano & Colella, 2007; Paris & Chérubin, 2008; Dymond *et al.,* 2010; Moser *et al.*, 2012). Not only does the coast exhibit changes due to land-use changes, it also absorbs the extreme impacts of sea level changes and storms that are caused by climatic changes.

2.4. Climatic influences on water resources

Investigations into climatic change and its environmental effects have been prominent in past studies. It is almost unanimously considered that the climate is changing and that this would have certain effects on the environment (Park *et al.,* 2011; Fang *et al.*, 2012; Cuo *et al.*, 2013; Kong *et al.*, 2016). Since knowledge of how environmental systems would change is of utmost importance, it is reasonable that climate studies play an intricate role within the broader spectrum of earth system studies. The idea that climate could have a large impact on environmental processes only forms a small part of environmental studies. It has become even more important to quantify the extent to which climate affects the environment (Middelkoop *et al.,* 2001; Ma *et al.,* 2008). This is important on a global scale, as well as on a regional, even local scale.

A wide range of climate change studies has emerged recently, where these studies look at impacts on ecosystems, sustainable development and social impacts, including impacts on water resources. Water resource sustainability is essential for sustaining a healthy environment and living conditions, and relies on the availability and quality of water in the system. Inland water resources (such as rivers, lakes, wetlands, dams and subsurface aquifers) are vulnerable to over-exploitation and pollution, and should be protected and managed carefully (Department of Environmental Affairs and Tourism, 2006). Freshwater systems, such as streams and rivers, are more commonly considered as open systems (Townsend, 1996). Interactions between terrestrial and aquatic processes form part of these systems. Dusar *et al.* (2011) stated that larger-scale fluvial systems reflect environmental changes, though because of the complex nature of hydrological regimes, causal relationships are difficult to determine.

Wetlands and estuaries are some of the more sensitive systems and it is important to understand how climate would affect these systems. This is true not only for the conservation of the ecosystem, but also for the functions it performs, such as the purification of water (Grange *et al.*, 2000). With increasing population and increasing development, the demand on the natural environment is increasing. Observations indicate that coastal erosion has been accelerated by human interference with river systems, and has destructive effects on wetlands and other aquatic habitats (Syvitski *et al.,* 2005; Syvitski & Milliman, 2007). Knowledge of the stress that climate change places on these systems is, however, still necessary.

2.5. Land-use change influences on water resources

Apart from climate-focused studies, land use and land-use change have also become extremely intriguing concepts in more recent environmental change studies (Ahn & Merwade, 2017). Impacts on ecosystems, soil erosion, water runoff regimes, for example, have been evaluated in these studies (Ward *et al.,* 2009; Nejadhashemi *et al.,* 2011; Notebaert et al., 2011a, 2011b; Maina *et al.,* 2012; 2013). The general trend in the findings is that the different land uses have different degrees of impacts on the systems and it seems plausible to assume that there is scope for more detailed studies. Deforestation and urbanization are believed to cause increases in surface runoff and therefore increase erosion, sediment transport and flood frequency (Ward *et al.,* 2009; Notebaert *et al.,* 2011a; 2011b). Different agricultural schemes have various impacts; for example, when changing the land use from forests to agriculture, the soil structure is affected (Nejadhashemi *et al.,* 2011). Although the extent of impact is not quite clear, it is certain that past changes have transformed the natural environment. Following this idea, it is likely that future land-use changes would continue to alter the environment, but the exact extent is yet to be determined.

Given that upland land use impacts coastal zone environments, the morphologies of related landscapes are also affected (e.g. Milliman & Syvitski, 1992; Longhitano & Colella, 2007; Pelacani, *et al.,* 2008, Ward *et al.,* 2009). The established longshore drift of sediments on the east coast of South Africa is a response to sediments accumulating on the shoreline and the sea current (Schoonees, 2000; Smith *et al.,* 2010; Bond *et al.,* 2013; Green *et al.*, 2013). Upland land uses, together with the changes in climate, have been observed to affect erosion and sediment discharge in fluvial systems (Klein *et al.,* 2001; Scavia, *et al.,* 2002; Grenfell *et al.*, 2009; Moser *et al.,* 2012). Anticipated changes in precipitation and other climatic factors would only intensify expected environmental effects as a result of land-use changes (e.g. Milliman & Syvitski, 1992; Schulze, 2000; Scavia, *et al.,* 2002; Dymond *et al.*, 2010). Climate and land-use changes have been identified as two of the most important factors affecting soil erosion and sediment dynamics in river catchments and are expected to change even further because of ongoing human activities (Ward *et al.,* 2009).

Identifying and distinguishing between human impacts and climate on fluvial dynamics have proved to be challenging (Notebaert *et al.,* 2011a; 2011b; Maina *et al.,* 2012; 2013). It is difficult to separate the climate and land-use impacts, since there is no single factor operating in a system. Catchment management studies therefore investigate the roles that land use and climate play on the discharge dynamics (flow velocity and volume), sediment yield and surface runoff. It has been found that deforestation and afforestation particularly have affected the discharge dynamics of catchments (Hurkmans *et al.*, 2009; Germer *et al.*, 2010; Fang *et al.*, 2012; Cuo *et al.*, 2013). Creating impervious surfaces, as with urbanization, is also considered to affect the properties of fluvial systems significantly. The changing of fluvial system dynamics would change the original functioning of the system, causing the entities within the system to adapt to the new circumstances. This would ultimately lead to environmental change that would change the landscape. These changes were studied in the past; however, it still remains difficult to quantify, especially for different catchments.

2.6. Previous hydrological study methods

Considering the intricate nature of environmental changes specifically in catchment systems, it is not surprising that there are a large number of studies on hydrological processes. Within catchment studies, different methods have been applied which include hydrological modelling. Hydrological studies have been undertaken in various locations all over the world, including South Africa. Regardless of the number of studies done on the topic, information regarding the specific effects of land use and climate on specific river environments is still needed. Several methods have been implemented with which to study the climate and land-use impacts on fluvial sediment discharge (e.g. Miller & Cruise, 1995; Schulze, 2000; Hessel *et al.,* 2003; Grenfell. *et al.*, 2009). Curran and Novo (1988) have estimated the concentration of suspended sediment in lakes, reservoirs, rivers and other water bodies through remotely-sensed spectral radiance obtained by aircraft or satellite sensors. Another study analysed two hundred and eighty rivers around the world and found a log linear relationship between basin area and the maximum elevation of the river basin (Milliman & Syvitski, 1992). However, the study was focused on linking basin area with the elevation of the river basin, both of which are measurable entities in a river catchment.

Geomorphology as a science is largely dominated by the ‘measurability’ of an entity to indicate the processes forming the landscape (Wainright *et al.,* 2011). The current trend in geomorphic and hydrological studies advocates for the quantification of landscape-forming processes by measuring characteristics and attributes (Bracken *et al.,* 2013). Processes are inferred from extrapolating, interpolating and accumulating these measurements and attributes (Bracken, *et al.,* 2013). Obvious limitations associated with this approach include the lack of data available not only for regions difficult or even impossible to access, but also for global rivers, as shown by Nijssen *et al.* (2001). Even when there is data available, the entity measured does not necessarily measure the process directly, but rather the product of the process, from which the presiding processes are inferred. Bracken *et al.* (2013) best describe this scenario by stating that processes are observable while the dynamics of a system can be described by measuring entities (structural approach). Furthermore, with a purely structural approach in hydrological studies, only the potential runoff sources and potential hydrological connections are conjectured (Bracken *et al.,* 2013). The mechanisms for runoff generation tend to be more conceptual whereas the interaction between surface and atmosphere is based on physical principles (Nijssen *et al.,* 2001).

The intricate nature of the environment is so complex, however, that no number of measurements would begin to describe the dynamic nature of the processes that currently persist (Bracken, 2013). Faced with this issue, researchers have turned to theoretical conceptualizations of geomorphic processes (Hughes, 2004, Phillips, 2007). Away from the quantitative nature of landscape studies, conceptual analyses of processes are prevalent in an increasing number of surveys (Hughes, 2004; 2015). Conceptual analysis focuses on the qualitative nature of the processes in earth science and therefore gives a more descriptive understanding of what is currently happening. Descriptive assessments thus provide "step-back" views of landscape processes.

A controversial idea to investigate further is whether the changes in earth systems are actually detrimental or not. The dynamic nature of the environment makes it buoyant enough to adapt to new conditions, in order to reach a new equilibrium (Tinley, 1985; Kennish, 2001; Woodroffe, 2002). Landscape evolution is an example of how the environment works towards reaching a new equilibrium. In river systems, the rate and extent of erosion and deposition would adapt to the new conditions. This raises the issue of whether mitigation or adaptation is the answer. As the environment adapts, people should also adapt. Thus, understanding how systems adapt and will adapt in future is regarded as vital in order to manage water resources (Coulthard *et al.,* 2007; Bracken *et al.,* 2013). Even if mitigation is considered the solution, it is imperative to understand how a system would react.

To investigate changes in hydrological systems, different methods have been applied, adding to either quantitative or qualitative knowledge of these systems (Eum & Kim, 2010; Bracken *et al.*, 2013;). However, nothing can stand alone, thus combining quantitative and qualitative assessments is necessary. Since earth science is a more holistic science, descriptive along with empirical methods should be used in discovering how the earth processes and systems work (Cooper & Pilkey, 2008; Bracken *et al.*, 2013;). Quantitative data is necessary to validate and calibrate modelling approaches (Verstraeten *et al.,* 2009), whereas as a qualitative approach provides an understanding of complex interactions of the processes shaping the earth (Cooper & Pilkey, 2008). Modelling studies provide a platform for investigating and describing these processes and systems and provide possible solutions to vulnerable scenarios.

2.7. Hydrological modelling studies

In the past two decades, several advancements have been made in modelling natural systems (Miller & Cruise, 1995; Aerts *et al.,* 1999 Hessel *et al.,* 2003; Thomas *et al.,* 2010; Rebelo *et al.,* 2015). Environmental managers are becoming more dependent on modelling future scenarios to establish certain management options (see for example: Jiang *et al.,* 2007; Choi & Deal, 2008, de Vente *et al.*, 2008; Ma *et al.*, 2008). One of the first hydrological modelling methods used by Miller and Cruise (1995) involved multispectral data and the development of a geomorphic-hydrologic model. Since then, several hydrological models have been developed to include runoff volumes and sediment load in the calculations. The LISEM model is able to simulate erosion patterns and sediment yields, as well as calculating the discharge and erosion for the outlets of catchments as a time series (Hessel *et al.,* 2003).

Twenty-first century modelling studies have focused on impacts on a catchment scale (Coulthard & Macklin, 2001; Bao *et al.,* 2012). A number of arguments still persist with regard to the relative contribution of climate and land-use changes on hydrological regimes (Sullivan *et al.,* 2004; Ma *et al.,* 2008; Notebaert *et al.,* 2011a; 2011b, 2018; Ahn & Merwade, 2017). In attempting to resolve the issue, various methods have been applied to several catchments (Dymond *et al.*, 2010; Bracken *et al.,* 2013; Hughes, 2015). Some of these methods include field measurements of fluvial discharges and sediment yields, which is time consuming and, at times, difficult to obtain (Jansson,1988; Nijssen *et al.,* 2001; Walling, 2006).

Since hydrological studies conducted in the field require time and numerous and frequent samples, both of which are usually limited, hydrological modelling studies have consequently become more appealing (for example: Nijssen *et al.,* 2001; Coulthard & Macklin, 2001; Choi & Deal, 2008; Breuer *et al.,* 2009; Dusar *et al.,* 2011). Hydrological models are mathematical representations of the processes involved in river systems, which replace the need to take extensive numbers of samples to conduct detailed studies (Hughes, 2004). However, models are limited as well, especially in terms of the complexity at which the model operates. The more complex models can include more parameters in the calculations but would then sacrifice efficiency or even functionality. More simplistic models, on the other hand lose accuracy in the system’s holistic nature when ignoring several parameters (Cooper & Pilkey, 2008; Hughes, 2015). This has opened a debate as to whether modelling such dynamic systems is a viable method (Cooper & Pilkey, 2008; Mileham *et al.,* 2009; Breuer *et al.,* 2009).

The environment is complex, and it is difficult to disentangle the respective roles each factor plays in the evolution of the environment, therefore describing the system should be the first step in understanding hydrological systems (Phillips, 2007; Coulthard *et al.,* 2007; Bracken *et al.,* 2013). Modelling studies provide an understanding into the processes that govern hydrological systems. Therefore, to resolve the debate regarding the use of hydrological models, whether simplistic or more complex, it is important to consider the nature of the investigation. In many cases it is difficult to obtain field measurements and the data available is scarce and fragmented (Nijssen *et al.,* 2001; Kiptala *et al.,* 2014). Most hydrological modelling studies have focused on describing the processes driving the changes in discharge dynamics. However, with proper calibration of the hydrological models, simulated values become very accurate. It is therefore encouraged to combine field studies with hydrological modelling studies to improve the accuracy of the models (Kiptala *et al.*, 2014; Kling *et al.,* 2014).

An evolving trend in all these methods is the use of spatially distributed models facilitated by Geographic Information Systems to simulate catchment erosion and river discharge (e.g. Miller & Cruise, 1995; Hessel *et al.,* 2003; Dymond *et al.*, 2010, Hughes, 2015). Spatially distributed models use the terrain information to determine how the surface water will flow to the river. Since spatially distributed models account for terrain data, making it one of the more complex but accurate models (Cooper & Pilkey, 2008; Hughes, 2015). However, because of the complex nature of these models in some cases, the model is used to attain descriptive rather than empirical information (Cooper & Pilkey, 2008; Hughes, 2015). The descriptive nature of these models should not be disregarded as it gives important insight into the system. In some ways, using descriptive models can have more value in landscape evolution studies because of the intricate nature of these processes, making it difficult to define each contributing factor (Hughes, 2004, Phillips, 2007).

As a result of varying study objectives and the search for the perfect hydrological model, numerous water balance and rainfall-runoff models exist. Each of these models adds value to the study of hydrological systems; however, only a few apply directly to this study’s aims and objectives. Of these hydrological models, the more common models include the N-SPECT and SWAT models (e.g. Longhitano & Colella, 2007; Alansi *et al.,* 2009; Thomas *et al.*, 2010; Notebaert *et al.,* 2011a; 2011b; Maina *et al.,* 2012, 2013). STREAM has been more commonly applied in European studies in investigating the Rhine and the Meuse River catchments (see for example: Aerts & Bouwer, 2002; Aerts *et al.,* 2005; Aerts *et al.,* 2011). Since all of these models are very similar in the model outcomes, the models’ main aims as well as the input and output parameters are summarized in Table 1.

Table 1: Summary of spatially distributed rainfall-runoff models used globally.

Model	Description	Input Parameters	Output Parameters	Literature
ACRU Model Agricultural Catchments Research Unit	Conceptionally-physically based agro-hydrological modelling system	• Location • Catchment • Climatic • Hydrological • Land change • Agronomic • Soils • Reservoir • Land use • Irrigation supply & demand	• Reservoir status • Runoff components • Sediment yield • Irrigation demand • Irrigation supply • Land-use impacts • Climate change • Crop yield	Schulze (2000) Olivier *et al.* (2013) Rebelo *et al.* (2015)
NSPECT Non-Point Source Pollution and Erosion Comparison Tool	Geographic information system (GIS)-based, spatially distributed screening tool, modelling basic hydrological processes	• Land-use • DEM (topography) • Precipitation • Soil characteristics	• Accumulated runoff, pollutant and sediment load grids (event scale and annual) • Pollutant and sediment concentration grids • Pollutant assessment grid • Alternative land-use scenario analysis	Thomas *et al.* (2010) Maina *et al.* (2013)
STREAM Spatial Tools for River Basins and Environment and Analysis of Management options	Spatially distributed water balance model	• DEM (topography) • Climate (precipitation, temperature) • Crop factors (land use) • Soil type (water holding capacity)	• Runoff regime • Discharge • Sediment yield • Potential and actual evapotranspiration • Soil water regime • Aridity	Aerts *et al.* (1999; 2005) Aerts & Bouwer (2002) Aerts *et al.* (2011)
SWAT Soil and Water Assessment Tool	Predict the effect of management decisions on water, sediment, nutrient and pesticide yields with reasonable accuracy on large, ungauged river basins.	• DEM (topography) • Climate (daily measured and monthly statistical weather data) • Soil data (maps and physical parameters) • Land use (maps and physical parameters) • Nutrients and pesticides	• Daily time step-long term simulations • Reach routing command language to route and add flows • Hundreds of cells/sub basins simulated in spatially displayed outputs • Groundwater flow model • Nutrients and pesticide input/output	Alansi *et al.* (2009)

2.8. Similar studies in Africa and South Africa

There is a definite lack of hydrological modelling studies on African and South African catchments. Since Southern Africa is considered to exhibit considerable drought conditions within the climate change scenarios, this lack of knowledge is disconcerting. Major developments in hydrological assessments that have occurred over the past few decades are mostly seen in European countries. However, few hydrological studies have been undertaken in Africa focusing on climate variability and land-use change influencing the catchment.

In South Africa, some hydrological studies completed have combined remote-sensing techniques and field observation methods to determine discharge and the sediment load in the river, which will change the dynamics of the river morphology (Grenfell *et al.,* 2009; Green *et al.*, 2013; Bond *et al.*, 2013). It is, however, difficult and impractical to carry out studies requiring extensive sampling data and historical observations, because the information required to sufficiently quantify the resources available is lacking. Apart from data difficulties, the constant modification of human activities affects the accuracy and relevance of these studies. Therefore, there is a distinct necessity for hydrological modelling in South Africa (Hughes, 2015).

Despite limited resources compared to other countries, considerable advancements have been made in hydrological modelling in Africa and more specifically in South Africa. Nonetheless, the focus has not been on practical applicability of these models on real-world problems (Hughes, 2004). The focus of models also varies between the applications of studies and most earth scientists would focus on the conceptual and holistic nature of models (Hughes, 2004). In South Africa, the ACRU model has been used in some studies (Schulze, 2000; Rebelo, 2015). Although the STREAM model has been found to be a user-friendly spatially distributed rainfall-runoff model requiring limited input parameters (Maina *et al.*, 2013), it has never been used in a South African context.

Since Africa has a vastly different climate and land-use regime to that of Europe, so it is necessary to evaluate the successes and failures of different modelling studies applied in Africa. South Africa also differs in the climate and land-use patterns, therefore similar studies done in South Africa were also considered Table 2 illustrates research that is compatible with this study, which has been conducted in Africa and more locally, South Africa. These hydrological modelling studies either focus on only climate (Kabanda & Palamuleni, 2013; Nkhonjera, 2017), or only land use (Thomas *et al.*, 2010) and only a few consider the effect of both (Schulze, 2000; Rebelo *et al.*, 2015). The main ideas from all of the studies are also summarized along with suggestions for future research.

Table 2: Summary of recent hydrological studies in Africa and South Africa

Study Area	**Method used**	**Key ideas and suggested future research**	**Literature**
Pangani River (Kenya/ Tanzania)	Modified STREAM model	• Model was developed to be applied in heterogeneous, highly utilized but data-scarce areas, with a sub-humid and arid tropical climate. • Need to develop advanced methods to generate more accurate remotely sensed data, improved hydrological models, longer time-series investigations with stochastic and probabilistic techniques.	Kiptala *et al.* (2014)
Zambezi River (Southern Africa)	A river basin model (water balance & water allocation models)	• Modelled hydrological impact of water resource development, as well as impact of wetlands and reservoirs on discharge. • More detailed assessments are necessary within an ensemble modelling framework.	Kling *et al.* (2014)
Madagascar	STREAM and N-SPECT model	• Suggests that regional land-use management outweighs the effect of climate.	Maina *et al.* (2013)
Kromme River Catchment (South Africa)	ACRU model	• Land-use changes have resulted in the degradation of catchment. • There is an overall decline in water and a reduction in flood attenuation.	Rebelo *et al.* (2015)
Harts River Catchment (South Africa)	Integration of GIS, Remote sensing & Statistics	• A weak correlation between rainfall and discharge, suggesting a non-climatic time-dependent factor determining the fluctuations in discharge (land-use). • Improved understanding of the mechanisms through which land uses impact streams is needed.	Kabanda & Palamuleni (2013)
Kuils-Eerste River Catchment (South Africa)	N-SPECT model	• An increase in runoff discharge loads as a result of an increase in compacted, channelized and impervious land surfaces. • It is suggested to update land use and other important data continuously in order for models to simulate more accurately.	Thomas *et al.* (2010)
Lions River, Mgeni Catchment, Bivane Catchment (South Africa)	ACRU model	• Paper addressed issue of simulation modelling of land-use and climate change and hydrology. • From the questions raised two themes are identified: that of land-use change and climate variability and change and whether scientist are focusing enough on actual problems.	Schulze (2000)

Schulze (2000) addressed the issue of hydrology, land use and simulation modelling by employing the ACRU model within the context of the current conceptions of climate and climate change. The ACRU model was also used more recently in a study that investigated how land-use and land-cover changes (LULCC) have altered the responses in a hydrological landscape (Rebelo *et al.,* 2015). Rebelo *et al.* (2015) investigated how LULCC influenced the flow regulation of the Kromme catchment in the Eastern Cape. Thomas *et al.* (2010) applied the N-SPECT model as part of a comprehensive investigation into the effect of pollution and development on the Kuils-Eerste River catchments in the Western Cape. In terms of climate-change impacts on water resources, a recent study was conducted focusing on the Olifants River catchment (Nkhonjera, 2017).

An emerging field of water resource investigations in South Africa is focused mainly on the responses of the already-deteriorating water resources to climate change. Climate change is a major concern, especially regarding water resources and the adaptation to the possible consequences (Ziervogel *et al.* 2014; Nkhonjera, 2017). It is estimated that climate change could influence the runoff to rivers in a range of about 20% decreases in runoff to a 60% increase in runoff by 2050 (Ziervogel *et al.*, 2014). However, there is still a significant lack of empirical knowledge of the influence of climate change on water availability and management in Africa (Nkhonjera, 2017).

Coastal environments receive a lot of attention because coastal environments are important for the balance of certain physical and chemical processes, as well as for the protection of ecosystems along the coast. There have been numerous studies concentrating on the coastal environment of South Africa, particularly the east coast of South Africa (see for example: Cooper, 1993; Bond *et al.,* 2001; Cooper, 2001; Green *et al.*, 2013). However, a majority of coastal studies have focused on river mouths and estuaries rather than the catchment as a whole (e.g. Cooper, 1993; Bond *et al.,* 2001; Cooper, 2001; Green *et al.*, 2013). It has been established that the east coast of South Africa is a prograding coastline (Green *et al.*, 2013). River-dominated estuaries further characterize this particular part of the South African coast (see: Bond *et al.*, 2001; Cooper, 1993; Cooper, 2001; Green *et al.*, 2013). A further finding made by Cooper (2001) was that river-dominated estuaries are likely to maintain the inlet morphology unless the change occurs through human modification or climate change. This means that upland land-use changes may influence observed morphological changes at the coast.

Since most processes rely on the environmental controls that differ from region to region, it follows that studies should include location-specific investigations. It is important to investigate the processes that would be involved in the specific fluvio-marine environment under investigation because the need for identical interactions is not uniform (Grange *et al.*, 2000; Jackson, 2013). Fluvial input is recognised as being a critical component and could vary along all catchments in South Africa because of the physical environment, as well as human interference. The semi-arid climate and relatively low rainfall in some regions in South Africa, together with high evaporation rates, result in areas that have low conversions of rainfall to runoff. This means that the amount of water reaching a catchment is limited, variable and unpredictable. Added to this, an increasing population places more stress through impounding and regulating water resources where there is an increasing need for fresh water (Grange *et al.*, 2000). It is thus necessary to study the catchment location in terms of the physical environment as well as the anthropological environment.

Chapter 3: Study Area

According to the United Nations definition, South Africa is “water stressed, bordering on water scarce” with only 1100 m^3/person/annum water available (DEAT, 2006: 144). South Africa has an average annual rainfall of 450 mm/pa that is distributed unequally, where the eastern and southern parts of the country receive the majority of the rainfall (DEAT, 2006). The study area falls within the eastern part of the country (Figure 1) which receives approximately 845mm rainfall per year (Palmer *et al.*, 2011).

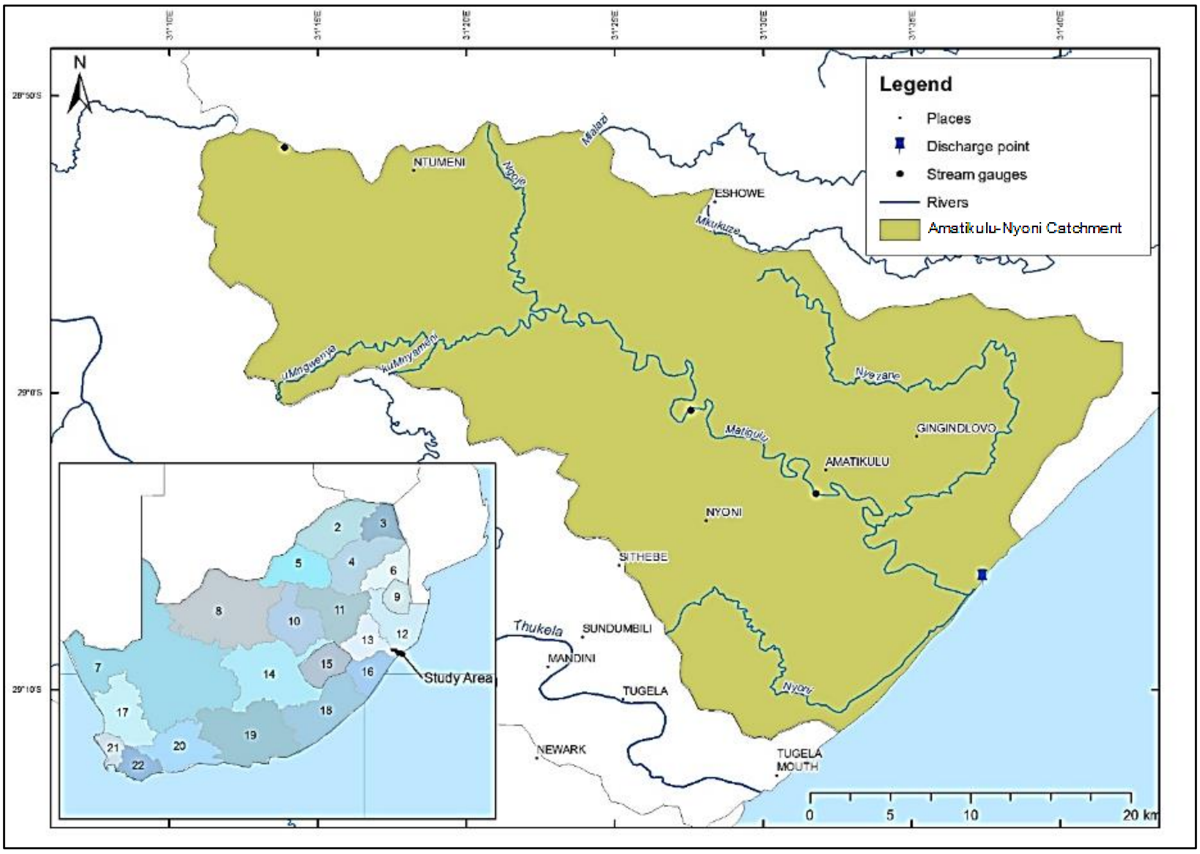

Figure 1: Location of the Amatikulu-Nyoni catchment, Kwa-Zulu Natal, South Africa (adapted from waterresourceswr2012.co.za, 2018)

The Drakensberg forms the boundary known as the Great Escarpment (a continuous elevated area that separates the coast from South Africa’s interior). With a highest elevation of 3450 m, the Drakensberg forms the western border of Kwa-Zulu Natal with the coast as the eastern border (Department of Environmental Affairs and Tourism, 2001; Partridge *et al.*, 2010). Since the Drakensberg forms the western border, all rivers in Kwa-Zulu Natal drain towards the east into the Indian Ocean. The east coast is mostly linear sandy beaches with intermittent rocky outcrops and few bays (Palmer *et al.*, 2011). This part of the South African coastline has a warm climate, enhancing the rich coastal biodiversity, which has encouraged the growth of the tourism sector and increased urban growth, resulting in higher population densities along the coast (DEAT, 2006; Palmer *et al.*, 2011).

3.1. Location

The Amatikulu-Nyoni catchment is located in northern Kwa-Zulu Natal and extends from the Ntumeni region approximately 50 km to the Indian Ocean. The Amatikulu River finds its course through an area defined by undulating hills and meanders its way to the outlet on the north-eastern coast (DEAT, 2001; Partridge *et al.*, 2010). In the middle course of the Amatikulu River the area becomes flatter and meanders become more prominent. Some records of the Amatikulu River refer to this river as the Matigulu River, which means “large water” or “large river” (Raper *et al.,* 1989). During a field visit in the winter season of 2014, very little discharge was observed in the Amatikulu River (Figure 2).

Figure 2: View of the lower-middle course of the Amatikulu River a few kilometres outside the town of Amatikulu, looking towards the upper valley

The Nyoni River starts its course between Sundumbili and Sithebe and is deflected 2 km from the coast in a north-east direction parallel with the coast towards the Amatikulu River (Figure 1). At the source the Nyoni River is narrow and the river banks are covered with thick bushes and shrubs (Figure 3).

Figure 3: View of the Nyoni River close to its source, covered by thick shrubbery and bush

This section of the coast, stretching from north of Durban to Mtunzini, is known as the Zululand coastal plain, where rivers are deflected and obstructed by the distinctively high dune ridges at the coast (Partridge *et al.*, 2010). As a result of this, the rivers run parallel to the shoreline, which is defined by long barrier dunes, estuaries, marshes and lagoons (Figure 4).

Figure 4: View of the Amatikulu-Nyoni estuary and coastline; Figure 4a: Coastal dunes at the Amatikulu-Nyoni outlet forming the barrier between the coast and the Nyoni River; Figure 4b and 4c: Vegetated dunes along the Amatikulu mouth; Figure 4d: The Amatikulu estuary looking from inland towards the coast

Several studies indicate a northerly longshore drift of coastal sediments on the east coast (Schoonees, 2000; Smith *et al.,* 2010; Bond *et al.,* 2013; Green *et al.,* 2013). Although most of the sediments are largely supplied by the Tugela River, it has been observed that the fluvial sediment yield of the Amatikulu River has, in part, contributed to the increased sediment along the east coast of South Africa (Schoonees, 2000; Smith *et al.,* 2010; Bond *et al.,* 2013; Green *et al.*, 2013).

3.2. Climate

The eastern part of South Africa falls into the humid, subtropical coastal climatic zone (Neumann *et al.*, 2012; Conradie, 2012). This area was further described by the Köppen-Geiger classification as being a warm, temperate, fully humid area with hot summers (Conradie, 2012). Kwa-Zulu Natal falls in a high rainfall zone, receiving up to 2000mm of rain on average per year (DEAT, 2001; weathersa.co.za, 2018). Most rain will fall in the summer period, as seen in Figure 5 (weathersa.co.za, 2018). This is a result of the humid monsoonal flow from the warm Aghulhas ocean current and the advection from the South Indian high-pressure system in the West Indian Ocean (Neumann *et al.*, 2012).

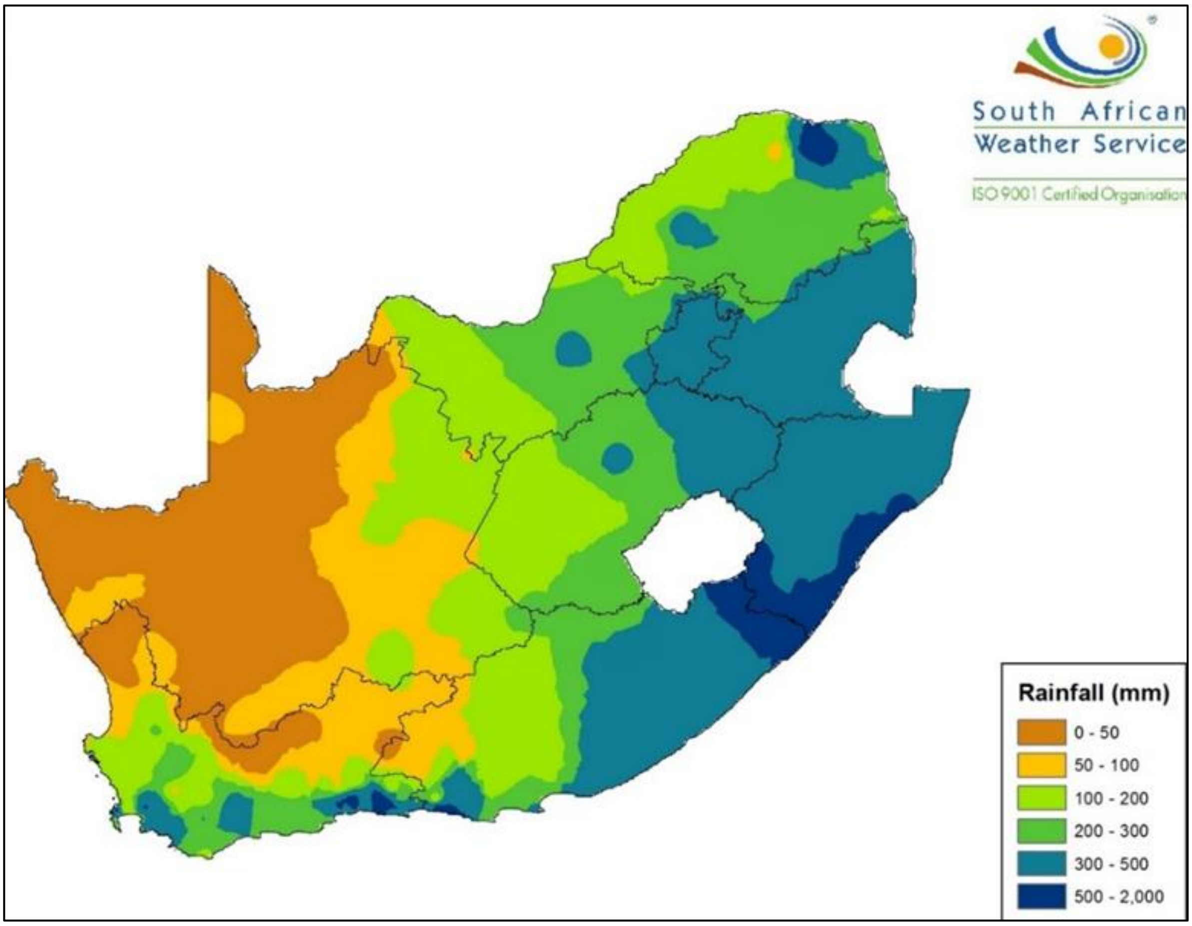

Figure 5: Rainfall zones for South Africa developed by South African Weather Services (weathersa.co.za, 2018)

In 1879, the temperature of the Tugela valley was described as “very great” (Blencowe, 1879:325). Summer is defined by the first rainfall, which usually falls between the start of September to mid-October. Rainfall in this area was defined by thunderstorms that mostly move in an easterly direction, only slightly deflected by the hills in the valley (Blencowe, 1879).

Presently the Amatikulu-Nyoni catchment receives most of its rain during the summer (Figure 6). The climate graph shows that even though the summer months receive most rainfall, there are quite significant volumes of rain falling in the winter as well. From this graph it is seen that the recent annual rainfall for the catchment is above 800mm. The summer months show average temperatures between 20°C - 25°C while in the winter it drops down to a low of 16°C such that the average annual temperature is calculated to be 18,6°C. With these climatic parameters, the catchment is classified within the warm subtropical coastal climate zone.

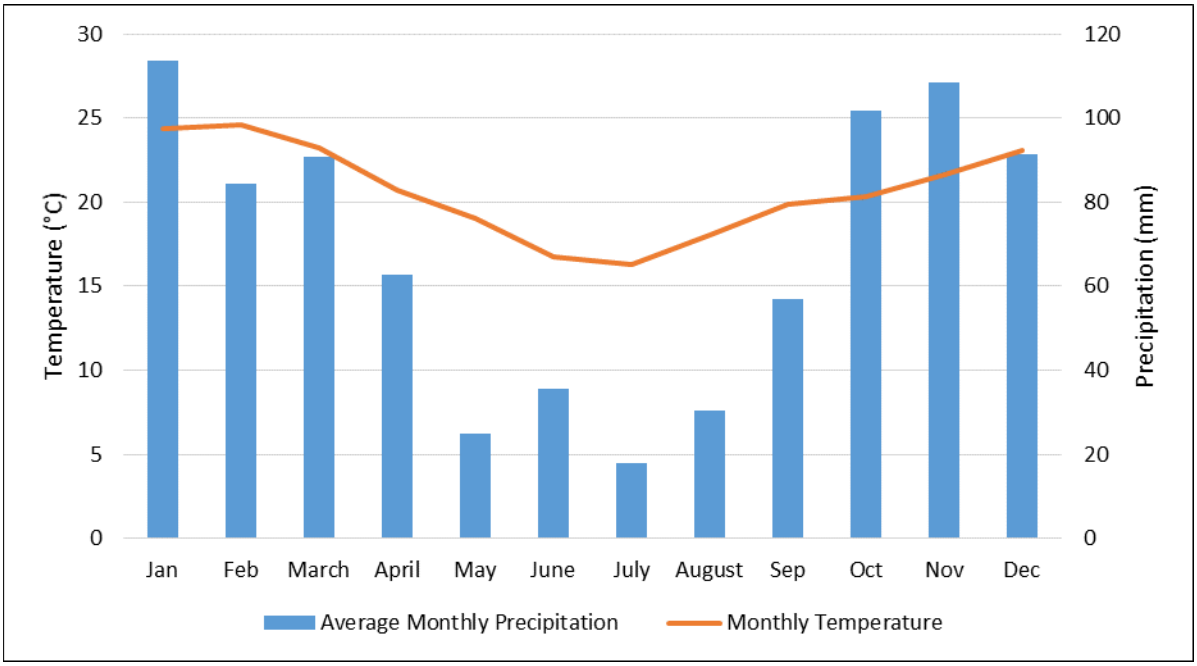

Figure 6: Climate graph for the Amatikulu-Nyoni catchment showing average monthly precipitation and average monthly temperature over the period from 2005-2015 (data from South African Weather Service)

The general climate change scenario (calculated using Representative Concentration Pathways) is applied to this catchment for the period from 2081–2100 relative to 1986–2005. These projections were calculated on a global scale, vary between regions. For South Africa, it is expected that there would between 10% and 20% less precipitation and the temperatures would rise between 2°C and 5°C (Pachauri *et al.*, 2014). This would mean that for the Amatikulu-Nyoni catchment, the volume of rainfall would drop to between 720mm and

660mm per annum and the temperatures would rise between 20,6°C and 23,6°C. This significant loss in annual rainfall and increase in temperature would force the environment to adapt and currently it is unclear how these changes in climate would affect the biodiversity (DEAT, 2006). What is known is that the fluctuations in rainfall will affect the amount of runoff in freshwater systems, which further influences the marine environment significantly (DEAT, 2006).

3.3. Catchment characteristics

A catchment is described in terms of its hydrological characteristics, the channel morphology, elevation, type of soil, geology and geomorphological characteristics. These aspects describe the nature of the catchment as an attempt to describe the processes that will govern in any catchment.

3.3.1. Hydrology

The Amatikulu catchment is 900km^2 with a mean annual runoff of 201.07×10^{6}m^3 and an annual runoff of 132-188m^3/s (Begg, 1978; Green *et al.,* 2013). River length is recorded to be roughly between 84km and 108km (Begg, 1978). The small, low-flowing Nyoni River is about 25km in length, and contributes an average 21,6×10^{6}m^3 runoff annually. It covers an area of 114km^2 (Begg, 1978). Since it is largely maintained by fluvial discharge, the Amatikulu inlet would go through open and closed phases (Green *et al.,* 2013). In the 1978 report, Begg (1978) stated that the mouth was very seldom closed. Concerns of this situation were mentioned, as it was just able to maintain the inlet allowing a sensitive and dynamic balance of salt and fresh water.

The Amatikulu-Nyoni estuary plays a cardinal role in the characteristics of the river. It covers an area of 1.22km^2 with a wide floodplain of 550 m. Saltwater influences are noted up to 7.5km upstream of the estuary. Extreme siltation in the estuary was noted in 1978, as well as infilling of the estuary by wind-blown sand (Begg, 1978). In several studies it is noted that sediments are brought up the coast from the Tugela River through longshore drift (Begg, 1978; Cooper, 1993; Green *et al.,* 2013). Apart from this, the condition of the estuary is deemed fair, indicating that the ecosystem health is of an acceptable standard (Begg, 1978; DEAT, 2006).

3.3.2. Estuary and channel morphology

The dynamic and unstable nature of the Nyoni and Amatikulu estuary features and channel migration has been extensively studied (Begg, 1978; Green *et al.,* 2013). Results from these studies show the migration of the Amatikulu-Nyoni mouth (Begg, 1978; Cooper, 1993; Green *et al.,* 2013). As a result of the longshore sediment transport, the channel seldom breaks through the barrier dunes (Green *et al.,* 2013). Before 1971, the Amatikulu and Nyoni rivers had separate inlets which joined as a result of this prolonged longshore drift and continuous deposition, pushing the Nyoni River mouth further northwards. This results in a channel parallel to the coast that joined the Amatikulu estuary after the floods in May 1971, 10km further north (Figure 7).

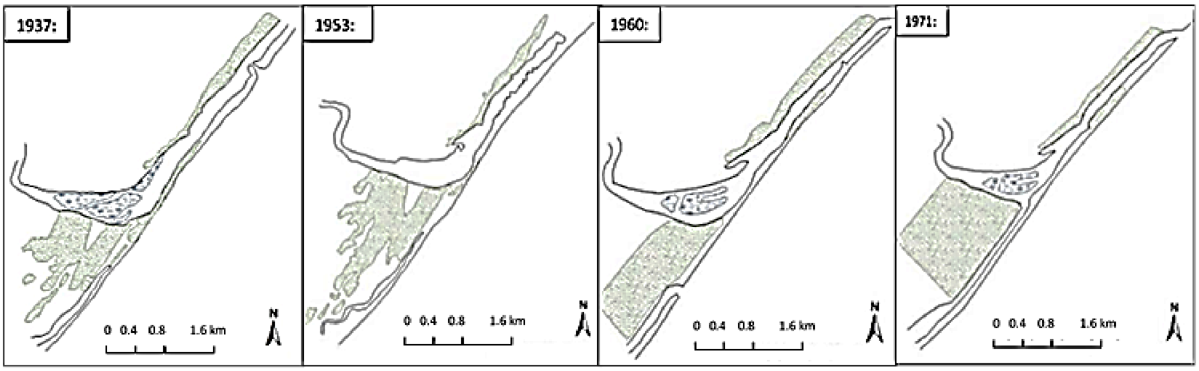

Figure 7: The Amatikulu-Nyoni mouth migration from 1937-1971 (adapted from: Engelbrecht, 2008)

Engelbrecht (2008) was of the opinion that the mouth would not migrate any further; however, a field observation revealed that it has since moved about 3m further north. The mouth still undergoes open and closed phases, with the most recent open phase observed in 2017. The inlets associated with the Amatikulu-Nyoni estuaries are located on the east coast of South Africa, which is an actively prograding section of the coast (Cooper, 1993; Green *et al.* 2013). River-dominated estuaries further characterize this particular part of the South African coast (Bond *et al.*, 2001; Cooper, 1993; Cooper, 2001; Green *et al.*, 2013).

A massive northward extending barrier defines the Amatikulu estuary and formed in response to the wave action from the south-east. Sediments largely supplied by the Tugela form a 4,5km long sandbar which ends close to the Amatikulu River mouth, as seen in Figure 8. This causes the coast-parallel barrier dunes, forcing the confluence of the Nyoni River into the Amatikulu River (Figure 9). Since the Amatikulu is a shallow, river-dominated estuary, it maintains an outlet due to the fluvial discharge and diminutive tidal exchange. It is further characterized by a braided channel pattern (Begg, 1978; Cooper, 1993; Green *et al.,* 2013).

Figure 8: Sandbar at the Amatikulu River mouth, dividing the river from the sea approximately 3 km northwards

Figure 9: The confluence of the deflected Nyoni River (short red arrow) entering into the Amatikulu River (longer blue arrow)

3.3.3. Elevation

The catchment stretches from just east of Ntumeni towards the east coast. At its western border the elevation ranges from approximately 800 m to 1000 m above sea level (Figure 10). Further west, the Drakensberg forms the escarpment that stretches roughly north to south and reaches a height of around 3000 m above sea level (Eeley *et al.*, 1999). From the Digital Elevation Model (DEM) the river valley is clearly visible, marking the paths for the Amatikulu and Nyoni rivers (Figure 10). Although the catchment reaches the higher inland areas, over a series of plateaus, most of the length of the river occupies a low-lying and gently sloping valley and makes its way through to the relatively flat coastal plain.

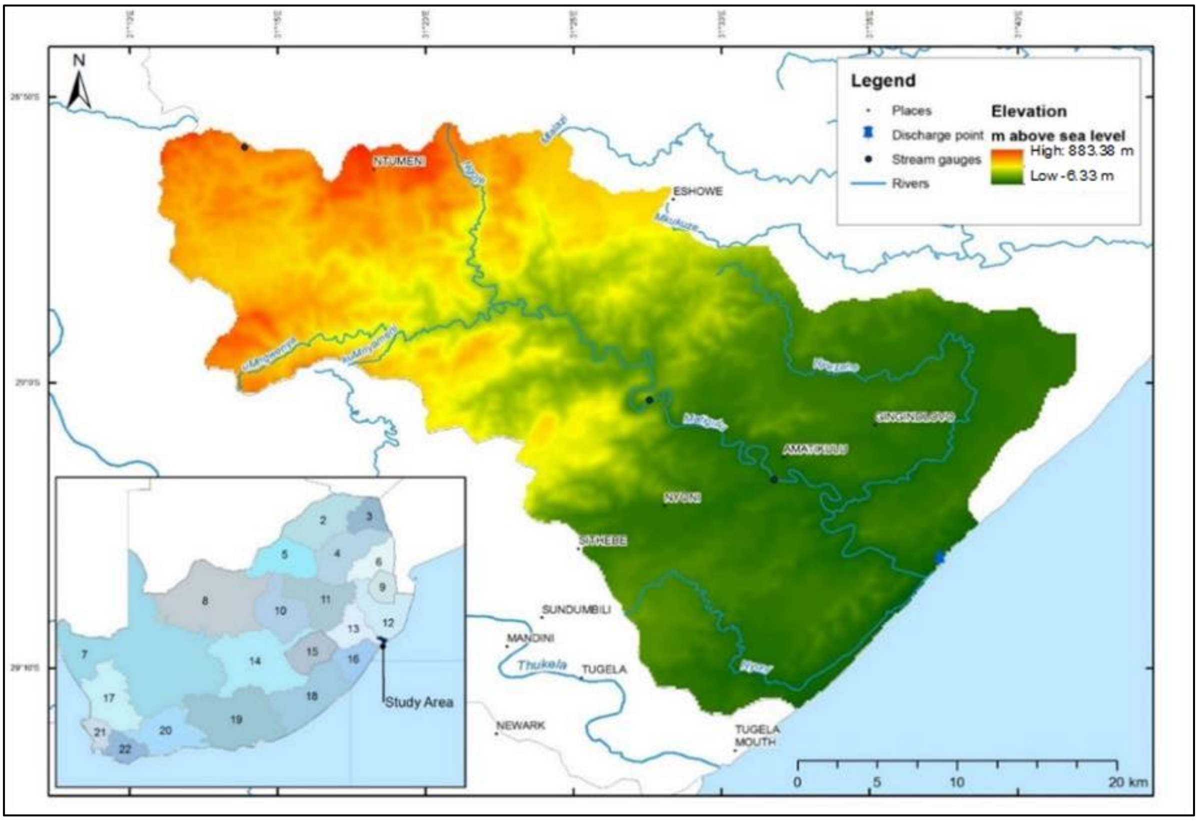

Figure 10: Digital Elevation Model (DEM) of the Amatikulu-Nyoni Catchment, Kwa-Zulu Natal, South Africa

3.3.4. Geology

Northern Kwa-Zulu Natal is underlain by Basement rocks of the Natal Metamorphic Province. This formation contains highly metamorphosed and intensely deformed sedimentary rocks and lavas, including intrusive granites and metamorphic gneisses, forming a section of compact sedimentary, extrusive and intrusive rocks (Figure 11). Closer to the coast, dunes of various ages are seen, with sands that are rich in titanium and zirconium. Richards Bay's sand dunes are considered to have one of the world's major deposits of these minerals, leading to the mining of these dunes. A large part of the Kwa-Zulu Natal coast is underlain by faulted rocks of the Dwyka and Ecca Groups, which are part of the Karoo Supergroup. Near the coast, an assemblage of tillite, shale and sandstones forms the underlying geology of the area and includes the Berea sandstones (Figure 11). The Berea Dune runs from south of Durban all the way up to Mtunzini and at intervals well beyond. It extends inland for 5km and are the characteristically red, compacted and well-vegetated dunes, more commonly known as the Berea Red Sand. This sediment is prime sugarcane land and, more recently, also serves as building land along the expanding Dolphin Coast (Norman & Whitfield, 2006).

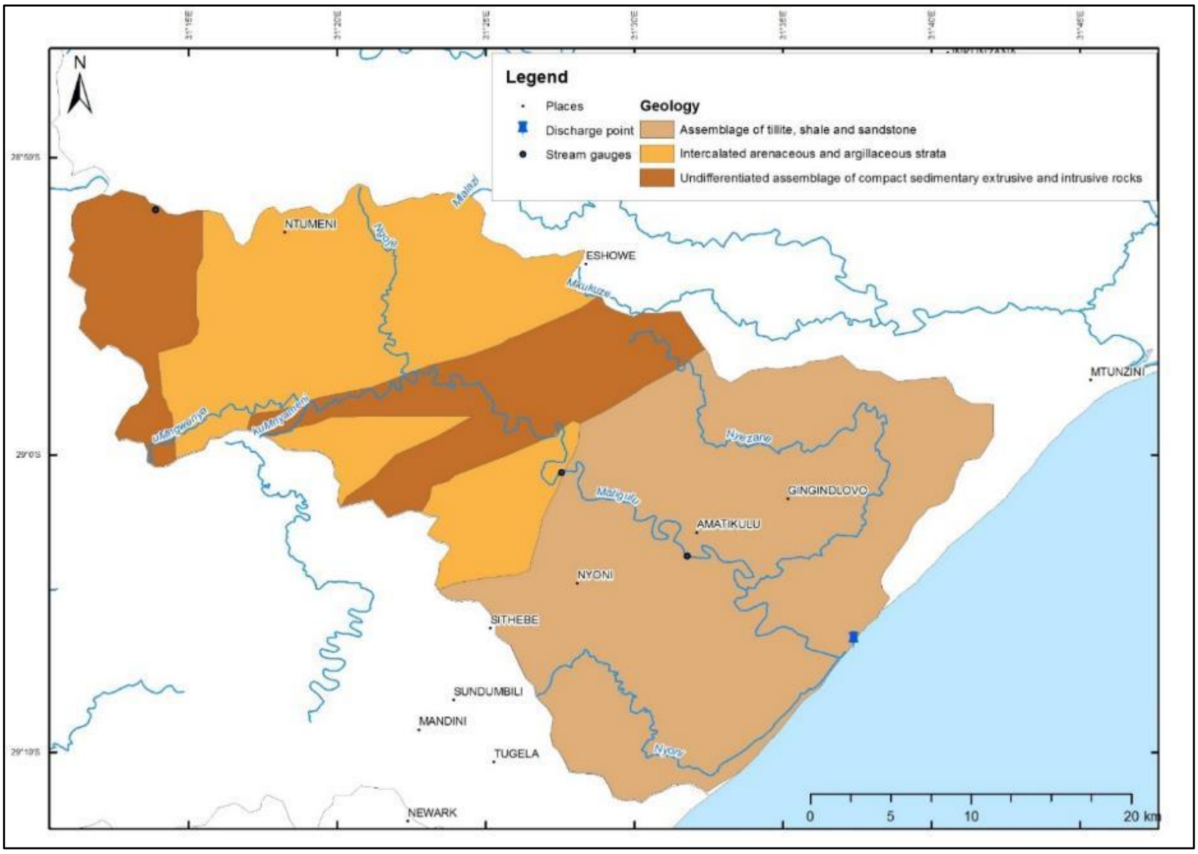

Figure 11: Geological map of the Amtikulu-Nyoni Catchment, Kwa-Zulu Natal, South Africa (derived from waterresourceswr2012.co.za, 2018)

3.3.5. Geomorphology and soils

Sandy and nutrient-poor soils are found on the coastal plain. Apart from the coast, meso- to eutrophic soils cover Kwa-Zulu Natal and are moderately to very productive. Material found in the Amatikulu-Nyoni river channels is dependent on its shape as well as the changes in the velocity of the water (Begg, 1978). Where the channels are wide and shallow, sand and gravelly sand can be found, while fine sediments with substantial nutrient and organic materials can be found in deeper parts of the channel. Tidal mudflats are formed as a result of the mouth migration and extended sand dunes (Begg, 1978).

Moderate to deep soils are found within the Amatikulu-Nyoni catchment. In terms of differentiating between the soil types, the catchment can be divided into three parts. The upper part of the catchment consists of clayey loam soils with a water-holding capacity of 305 mm/m (Figure 12). Sandy loam can be found in the southern coastal part of the catchment whilst sand is found at the northern coastal part of the catchment (Figure 12). Water-holding capacity values are 170 mm/m and 102 mm/m respectively (Figure 12).

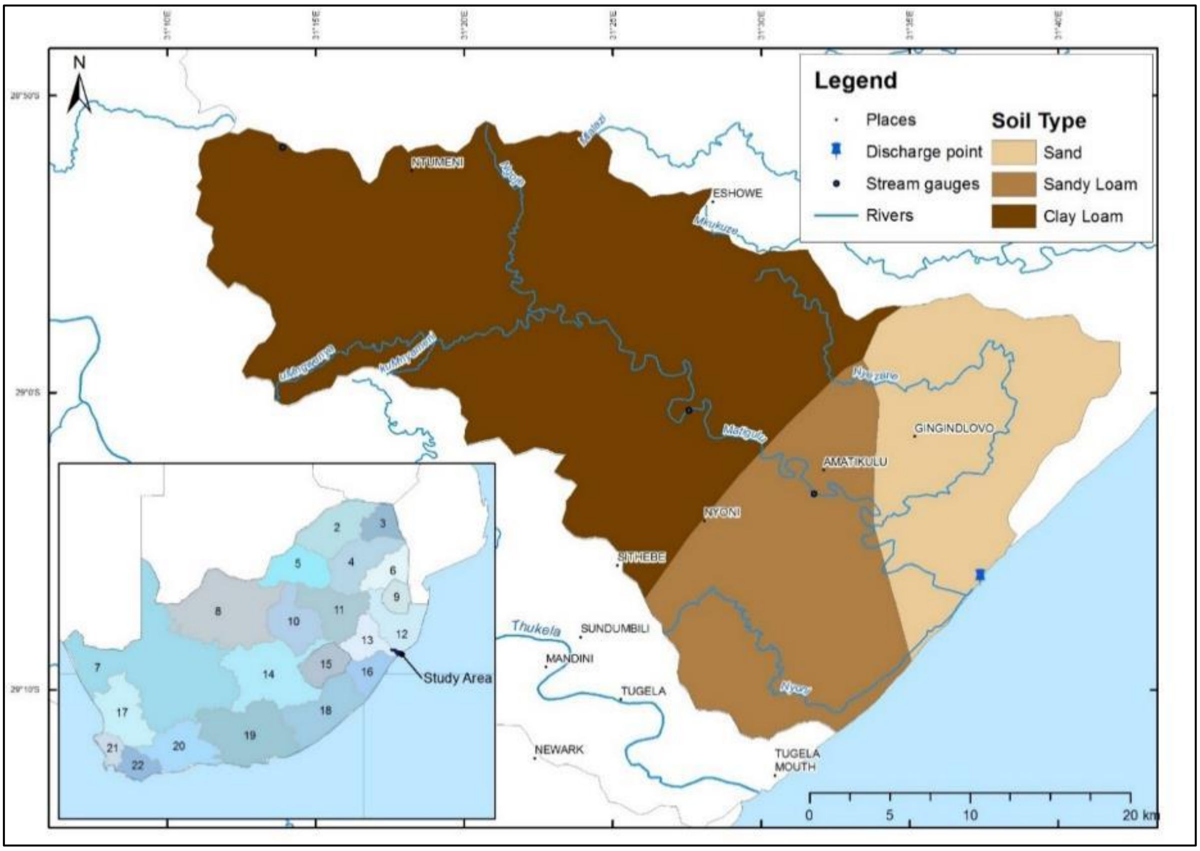

Figure 12: Distribution of soil in the Amatikulu-Nyoni River catchment (derived from waterresourceswr2012.co.za, 2018)

The catchment relief is described as undulating, except for the flat northern coastal part (Norman & Whitfield, 2006). Stretching from the relatively flat coastal plain and slightly inland, prominent hills define the landscape (Figure 13). The coastal plain widens northwards towards Mozambique (Figure 10). This sandy terrain is flat, with some undulating hills (Norman & Whitfield, 2006).

Figure 13: Prominent hills inland from the Kwa-Zulu Natal coast, South Africa photographed near the Amatikulu River mouth in Amatikulu Nature Reserve

Coastal dunes have migrated northwards from the Tugela mouth towards Richards Bay, because of longshore drift (Schoonees, 2000; Smith *et al.,* 2010; Bond *et al.,* 2013; Green *et al.,* 2013). The dunes on the beaches on the north eastern coast (from the Tugela mouth to Richards Bay) are noted as growing in size, due to the prograding nature of this coastline (Green *et al.*, 2013).

3.4. Land-use

Kwa-Zulu Natal is often described as rural (Figure 14), since over half of the population in the province live in rural areas (DEAT, 2001). The province also boasts the largest population in South Africa, whilst being the second most densely populated province in the country. Furthermore, it has the largest population growth of all provinces in the country. As a result, pressure placed on the environment is increasing, with an increase in demand for basic services and infrastructure.

Figure 14: Settlements in the Amatikulu-Nyoni catchment, Kwa-Zulu Natal, South Africa photographed between Gingindlovo and Nyoni

Blencowe (1879) noted that the only crops in the area at the time were maize and a species of millet grown by the Zulus. A century later, Begg (1978) reported that most of the catchment was used for sugarcane farming, with two sugar mills in the area (at Entumeni and Amatikulu). It is noted that because of the tidal exchange, no effects of the mills were detected at the time. Furthermore, Begg (1978) also stated that 56% of the catchment was then “Bantu” influenced as a result of the “Bantu Reserve” north of the estuary. Forests still cover the south bank of the Nyoni estuary and to the west of the Nyoni estuary, where the Amatikulu leper community was located, which closed in 1977. In 1970, the Prawn Research Unit used the estuary for a mariculture venture, where water from the estuary was pumped into artificial ponds.

By the year 2000, most of the land was designated for agricultural activities (Figure 15) and most of the land has been changed to host such activities. Forests are not dominant in Kwa-Zulu Natal, although one sixth of the country's indigenous forests are located there (DEAT, 2001). However, because of anthropological changes, the extent of the indigenous forest biome has decreased severely (Eeley *et al.*, 1999).

Figure 15: Sugarcane fields in the Amatikulu-Nyoni catchment between the coast and Amatikulu town, Kwa-Zulu Natal, South Africa

Grasslands are one of the most extensive biomes in the province, and savannahs are the second most abundant (Figure 16). Unfortunately, it is also one of the biomes that undergoes large percentages of transformation. Transformation results in the fragmentation of ecosystems, further forming patches of original biomes between transformed lands. A clear increase in transformed land use as well as an increase in degraded land, is observed for Kwa-Zulu Natal (DEAT, 2001).

Figure 16: Grasslands and some shrubbery close to the Amatikulu-Nyoni confluence

In Table 3 below the percentages of 1994 and 2000 land use and the percentage of land-use change between those years are given according to the South Africa Environment Outlook (DEAT, 2006). According to this report, there has been a decrease in cultivated land, sugarcane plantations, woodlands and the largest decrease of natural veld. Bushland or thicket shows the largest increase, far more than the second-largest increase in residential areas. It is not clear which land use has changed and to what it has changed, but it does seem that the cultivated land and sugarcane plantations could have been left abandoned, turning into bushland or thicket.

Table 3: Land cover and land-cover changes between 1994 and 2000 for Kwa-Zulu Natal (DEAT, 2006)

Land Cover Class	**Area 1994 (%)**	**Area 2000 (%)**	**Land cover change (%)**
Cultivated land	12.79	10.95	-1.84
Eroded areas	0.06	0.47	0.41
Bare rock / Soil	0.08	0.12	0.04
Plantations	6.79	7.06	0.27
Residential area	1.44	2.17	0.73
Sugarcane	4.34	3.25	-1.09
Bushland/ Thicket	17.14	22.63	5.49
Degraded lands	7.87	8.34	0.47
Indigenous Forests	1.33	1.57	0.24
Natural veld	39.12	35.58	-3.54
Waterbodies	1.29	1.31	0.02
Wetlands	0.79	1.46	0.67
Woodlands	6.33	5.09	-1.24

There have been numerous changes noted in the Amatikulu-Nyoni catchment over the years from 1994 to 2000, including an increase in degraded land and eroded areas (DEAT; 2006). Along with the other land-use changes, the increase in degraded land and eroded areas is a likely cause for a change in the fluvial discharge dynamics in the Amatikulu-Nyoni Rivers. However, several changes have occurred since the year 2000 that could further have contributed to the changes in the river discharge, and it is necessary to update land-cover information.

Chapter 4: Method

This study aims to determine the impact of land use, land-use change and climate variability over a period of five decades on the discharge dynamics of the Amatikulu-Nyoni River catchment. A grid-based spatial water balance model (STREAM) is used to determine changes in discharge volume. STREAM is a spatially distributed hydrological model that has been used to determine the effects of climate and land-use changes in several different catchments (Aerts & Bouwer, 2002; Maina *et al.,* 2013). This model calculates the discharge volume and various other parameters on an iterative basis, allowing a time-series calculation.

The studies that have used STREAM claim that the model is a user-friendly and easily applied hydrological model (Aerts *et al.,* 1999; Aerts & Bouwer, 2002, Maina *et al.*, 2013). It is internationally available and uses input parameters that can be attained from information freely available to users. The resolution of the model is determined by the quality of the input parameters. Therefore the higher the quality of data, the higher the resolution of the model simulations.

To calibrate the model is quite simple, and only requires knowledge of which parameters to change. As a result, the accuracy of the model is easily tested, depending only on the quality of discharge data available for the catchment. Iterations are calculated quickly, up to a thousand in a couple of minutes, thus running simulations over a long temporal scale is manageable. Since parameters can be changed between simulations, this allows scenario testing to be done quickly and effectively. By altering the parameters, singular influences can be determined, when all other parameters are kept constant and the parameter under investigation is changed accordingly. Furthermore, discharge volumes are calculated at a predetermined cell, permitting the alteration in discharge point to fit the aim of the study (Aerts *et al.,* 1999).

To acquire discharge volume information from STREAM, several input parameters are required, as listed in Table 4. In the following sections, each of these parameters will be discussed in detail, as well as the methods of obtaining the parameters. All input parameters were converted to numerical values to be imported into the model equations. The calibration parameters, as discussed later, are then defined in order to calculate the internally generated parameters accurately, which are then used to calculate discharge volumes of the catchment.

Table 4: Input parameters required for the STREAM model

Parameter	Required format	Data Source
Digital Elevation Model (Terrain / Topography map)	Text file (.txt)	Derived NGI, ENPAT
Crop factor map as multiple of 10 (Land use / Cover map)	Text file (.txt)	Derived NGI, CSIR, ARC, SANBI, GTI
Soil water holding capacity map (Soil Type)	Text file (.txt)	Derived WRC, DWAF
Monthly average precipitation	Matlab table (.mat)	SAWS
Monthly mean temperature	Matlab table (.mat)	SAWS
Mask (Catchment shape map)	Text file (.txt)	WRC- Water management areas
Calibration map	Text file (.txt)	Derived

To understand how the model works, a summary of the modelling process is shown in Figure 17. STREAM can be seen as a spatially distributed model that calculates the discharge volumes based on several mathematical equations (Aerts *et al.,* 1999; Schwanghart & Khun, 2010).

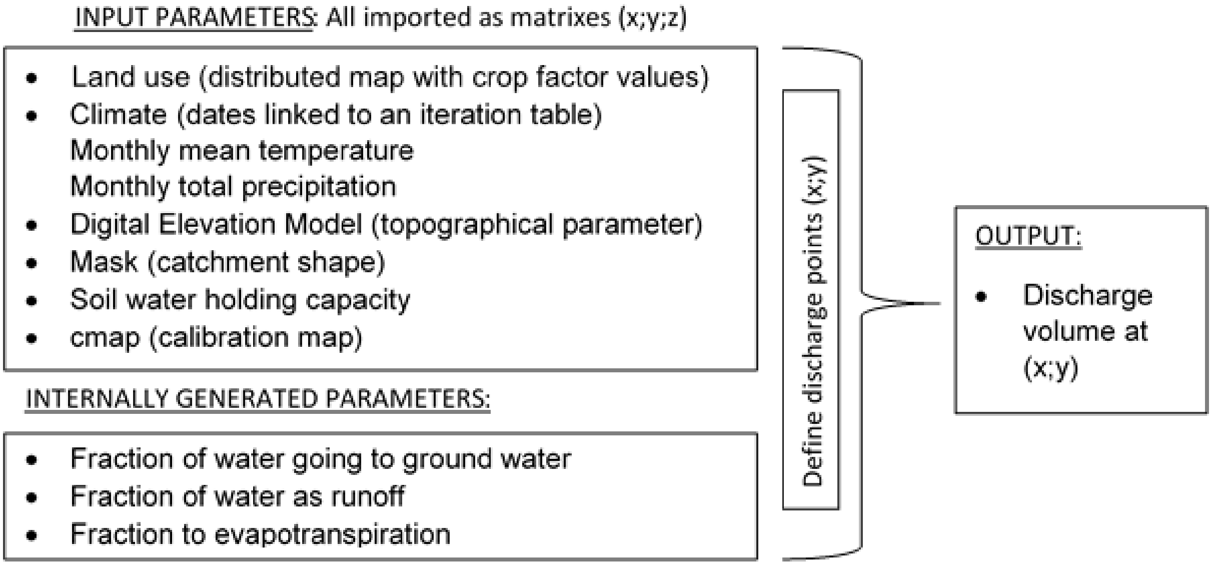

Figure 17: Simplified diagram illustrating how the STREAM model works (adapted from: Aerts et al. 1999)

Every input parameter as mentioned in the diagram (Figure 17) was developed as a map, but had to be imported as a .txt file because the model calculates per co-ordinate reference. When these maps are used in Matlab, what is seen as co-ordinates on the map is read as the row and column numbers. The input parameters are were derived from raster files, and when exporting these files as text files, all the raster cells were defined to be the same size. This meant that the exported text files maintained the characteristic of raster files, where the text file show the cells with information as numbered values in rows and columns. The position of the cell is used as the spatial reference while the input parameter value is represented as the cell value. If the number and size of cells are not the same for all input parameters, the number of columns and rows within the matrices do not correspond. As a result, the matrix dimensions would not match, and STREAM cannot run the simulations. Therefore, all input layers have corresponding columns numbers (x) and row numbers (y) as spatial references, where the z value would differ according to the specific input parameter. The matrix for each iteration (monthly time step) would then appear as:

(X) (Y) (Z)
Column/ Longitude : Row/ Latitude : Input Parameter

This enabled the model to take each cell reference to calculate for each iteration and corresponding cells whilst still keeping a spatial distribution. In order for the matrix dimensions to match, the input parameters were set at exactly the same spatial extent and exactly the same cell size. This was done by choosing a base layer, i.e. the DEM, and when converting the layer to ASCII, setting the spatial extent and cell size the same as the mask (Aerts *et al.,* 2005).

In order for STREAM to work accurately, a few set-up steps are required before simulating. These include defining an iteration pattern that follows the months of the year (for example, January 1965 would be iteration number 1 and the following January in 1966 would be iteration 13). Since the model's iteration numbers correspond with the monthly climate data, the model can simulate monthly discharge volumes and the changes in climatic data should be reflected in discharge volumes within a month. Since the model calculates per iteration, only climate data changes with the different iterations, whereas it is necessary to change the land-use map per simulation (Aerts *et al.,* 2005). Therefore, it was possible to simulate different scenarios in land use as opposed to the actual climatic data. This was an important step in order to be able to determine the actual influence of land-use change in the catchment.

Part of the calculation was to include the different climatic influences. This calculation was adjusted either to add temperature or subtract percentage rainfall per single iteration and not as an overall for the period in question. This meant that seasonal data was still reflected in the model, which was picked up in the discharge volumes and could be investigated further. The discharge point was defined to refer to the corresponding cell where the river mouth would be, so the values for discharge volumes were routed and determined at the point where the discharge point was set.

Each of the input parameters had a set importance for the model calculation. Some of these parameters could be kept constant throughout the simulation, while other parameters were calibrated according to the probable influence they would have on the routing of the water. The model had to be simulated through a calibration period as well, because of the internally-generated parameters. With the first simulation, all internally-generated parameters are equal to zero and, with each iteration, the output gets closer to the actual discharge volumes. This is referred to as the warm-up period and it is recommended that this period should be five years (Aerts *et al.,* 2005).

4.1. Data collection

The information required for the STREAM model was freely available from numerous sources such as weather data from the South African Weather Services and aerial photographs from National Geo-spatial Information (NGI). It was necessary to collect information on climate (precipitation and temperature), land-use cover, soil type and the elevation of the study area. The information was attained as either Excel Spreadsheets or ArcGIS-compatible shapefiles, which were necessary to convert as .txt files. The diagram below (Figure 18) shows how the dates were sorted and integrated into the different study periods.

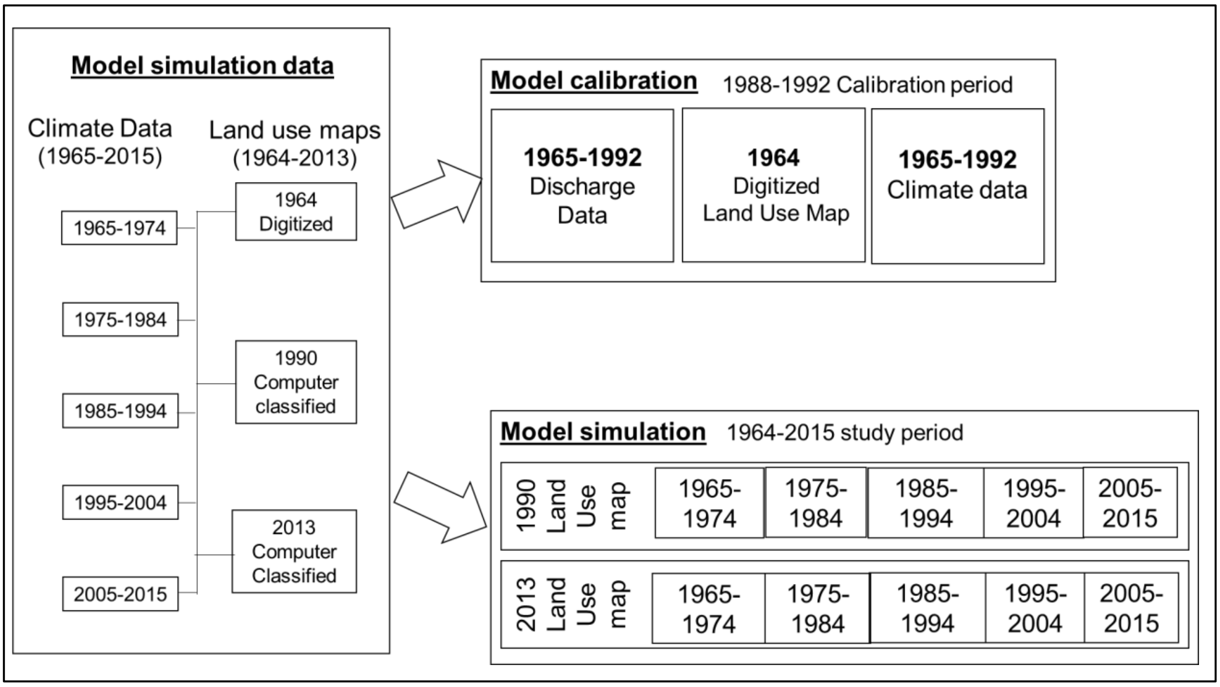

Figure 18: Flow chart illustrating the different dates for the climatic and land-use data used to simulate the discharge volumes of the Amatikulu-Nyoni catchment

This collection and conversion of data is described in Part A below. These files were used as the matrices in the model simulations. In Part B the model calibration is described along with the calibration parameters.

Part A: To obtain and modify the necessary input parameters for the modelling of discharge volume with the STREAM model.

Several input parameters were required for running STREAM, apart from land use and climate as listed in Table 4 and it was necessary to prepare all these input parameters in the required format. The data was obtained from the various sources as GIS shapefiles, text files, spreadsheets and images. All calculations in STREAM were made for each grid cell per month (Aerts *et al.,* 2005). Matlab calculates from matrices, thus all input parameters were required to be converted into matrices. All maps in ArcGIS 10.3 can be converted into ASCII files with the Conversion tool, From Raster to ASCII, which can then be opened as text files. In this process, the spatial distribution is converted from degrees latitude and longitude to rows and columns. It was vital that the spatial extents as well as the cell size for all maps were the same.

4.1.1. Digital Elevation Model (DEM)

Flow direction is determined from the DEM. Contour data is the only necessary information required to develop a DEM and 20m contours are available for South Africa as GIS shapefiles from the Department of Rural Development and Land Reform. When creating a DEM in ArcGIS, the “Topo to Raster” tool (Spatial Analyst- Interpolation) is used. The contour shapefile is set as the input feature and the output raster will be the DEM. Once the DEM is created, it is converted to an ASCII file format.

4.1.2. Crop factor maps

Crop factor maps were created from the catchment’s land-use maps. Land-use maps for the years 1964, 1990, and 2013 are used as shown in Table 5.

Table 5: Data sources for land-use maps

Date	**Source**	**Data Source**
1964	NGI	Aerial photographs (Digitized)
1990	GTI	Derived from Landsat 8 imagery
2013	GTI	Derived from Landsat 8 imagery

To obtain the land-use information for the year 1964 it was necessary to use aerial photos for that period. The National Geo-spatial Information (NGI), a component of the Department of Rural Development and Land Reform, provided the aerial photos without a spatial reference. The photos were georeferenced using the “Georeferencing Tool” in ArcGIS, the correct spatial reference was given to each photo. These photos were then mosaicked solely for the ease of the digitizing process. To mosaic several images, multiple steps were needed. First it was necessary to create a mosaic database. In ArcGIS, right click in the “Catalogue” window, select “New” then “New File Geodatabase”, after which a new mosaic dataset needs to be created and the images were added. In the ArcGIS toolbar, rasters can be added to the dataset by selecting “Data Management; Raster; Mosaic Dataset; Add Raster”. Once the rasters were added to the dataset, the mosaic can be stitched for a neater and more visible mosaic product. Stitching for this project was done on “Edge Detection”, where the boundaries of each image were determined on the basis of similar feature detected on the edges of the images. The “Stitching Tool” then trims the images on those boundary lines.

For the purpose of this study, the crop factors were determined from the table originally developed by Van Deursen and Kwadijk (1994). This table enables universal application of the model by reclassifying land-use types into crop factor values. Some detail may be lost in this method, since the crop factor value could be similar for several land-use types. However, it is important to note what the crop factor represents in this study. When using the RUSLE model to calculate erosion, from which crop factors are derived, the C-factor is the crop management factor. This factor is an index of the soil’s susceptibility to soil erosion. It calculates runoff and the potential soil loss through using the effectiveness of vegetation or mulch to prevent detachment and transport of soil particles (erosion control). Values closest to zero indicate well-protected soil, whereas values closer to 1.5 indicate soil that produces large volumes of runoff, leaving the soil highly exposed to erosion. Finely tilled and rigid soil, as usually found in cultivated lands, are highly erosive. The crop factor represents the soil loss for a given condition over a given period (Renard *et al.,* 1991). The table has been adapted to include only land-use types found in the study area (Table 6).

Table 6: Crop factor values for different types of land-use found in the Amatikulu-Nyoni catchment derived from Van Deursen and Kwadijk (1994)

Land-use category	**Crop factor**
Barren	0.5
Farmland, crop fields, sugarcane	1.0
Forests	1.1
Grassland	0.8
Mixed grassland and shrub land	0.8
Plantations	1.1
Shrub land (Bush)	0.8
Urban, Built-up land	0.8
Water	0.3
Wetlands	1.1

The land-use map for 1964 was a GIS shapefile and it was necessary to convert it to a raster file with the “Conversion Tool” (from Polygon to Raster). With the “Reclass Tool”, land-use categories were further reclassified according to the specified crop factor multiplied by 10. The multiple is to ensure that only whole numbers are inserted into STREAM and are accounted for within the model calculations. These crop factor maps were converted to ASCII files, after which the files were exported as .txt files.

4.1.3. Soil water holding capacity map

Based on a map of soil types from the WR2012 website, the soil water holding capacities were derived (waterresourceswr2012.co.za, 2018). This layer determines the amount of water that could be retained in the soil, which would influence the rate at which it would reach the discharge point. Water holding capacities were indicated as values of mm/m. The table below (Table 7) shows the water holding capacity for soil types found in the study area and is derived from the table given in the STREAM manual (Aerts *et al.,* 2005).

Table 7: Water holding capacity of soils found in the Amatikulu-Nyoni catchment derived from Aerts *et al.* (2005)

Soil Type	**Water Holding Capacity (S_{max}) in mm/m**
Sand	102
Sandy Loam	170
Clay Loam	305

There is a direct relationship between the different soil types and the water holding capacity of the soil; for example, sand has a lower water holding capacity than clay. Figure 19 shows the distribution of soil water holding capacity of the soils derived from the distribution of different soil types. The map was created by using the soil distribution map (Figure 12) and replacing the soil types with the water holding capacity values.

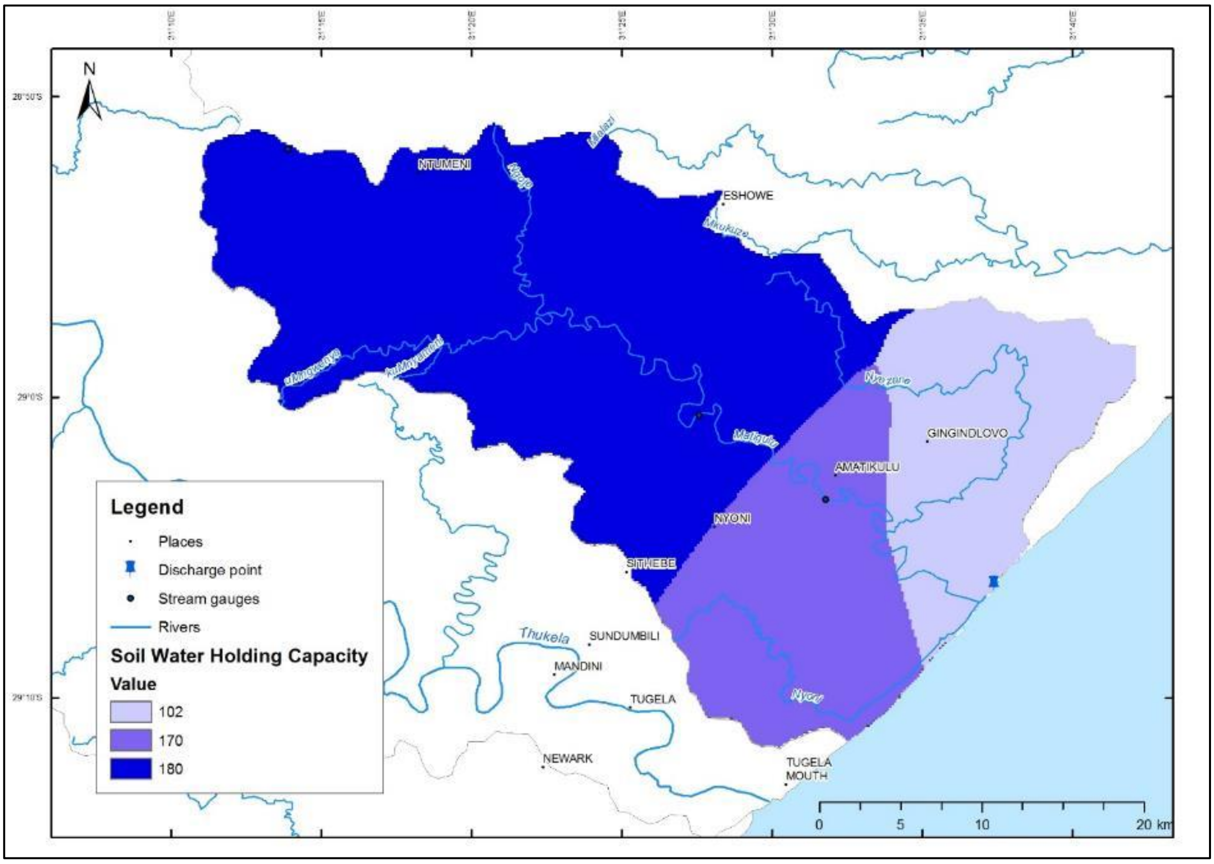

Figure 19: Soil water holding capacity map for the Amatikulu-Nyoni catchment (information waterresourceswr2012.co.za, 2018)

4.1.4. Climate matrices

Observed data for total monthly precipitation and the average monthly minimum and maximum temperatures for the period were obtained from the South African Weather Service (SAWS). The historical records were fragmented and several stations across the catchment area were included and listed in the table on the next page (Table 8). As a result of the fragmented data, all the station observations were used to create a more complete record of precipitation and temperature for the study period. The station observations were interpolated for the area surrounding the catchment, since the station's readings did not all include the complete study period. Interpolation was also needed to transpose the available data for areas within the catchment where no weather data was available. Once complete records for climate were obtained, the data was tabulated and imported into the STREAM model as a single source, covering the whole catchment.

Table 8: Station climate data surrounding the Amatikulu-Nyoni river catchment (source: South African Weather Service)

Station	**Observation period: Precipitation**	**Observation period: Temperature**
Mount Edgecombe	1930-2015	1930-2015
Greytown	1940-2015	1993-2015
Mandini	1983-2015	1983-2015
Richards Bay	1930-2015	1970-2015
Babanango	1930-2015	1982-2015
Ulundi	1993-2015	1993-2015
River View	1930-1990	1959-2015
Charters Creek	1950-2015	1993-2015
Eshowe	1959-2014	1959-1987
Mtunzini	1993-2014	1993-2014
Gingindlovu	1930-2014	-

The format of the climate parameter was slightly altered, since it had four dimensions instead of three (for example: latitude (y); longitude (x); monthly iteration (z) and climate data). It was imported into a Matlab table (month × year). A temporal matrix was created, with dimensions different from the other spatial input parameter matrices. Since a temporal scale is necessary, this matrix was used to create monthly iteration numbers. In order to assign a spatial characteristic to the temporal climate matrices, a custom Matlab script was created and run. The script enables the precipitation and temperature data to read as a matrix of row × column × iteration number. The row and column refer to spatial point, and the iteration number refers to the total monthly precipitation and average monthly temperature values for the corresponding month.

4.1.5. HEAT parameter

Since there are different factors that influence the amount of water that will eventually end up in the river and it was impossible to have actual measurements for all the factors, a couple of calculations were necessary. These calculations are specifically focused on the evapotranspiration of water within the catchment and include the A parameter and the HEAT parameter. The HEAT parameter in part determines the influence that surface temperature will have on the amount of water that will evaporate over the study period. To calculate the HEAT parameter, the equation below (Equation 1) is used (Aerts *et al.,* 2005).

Equation 1: HEAT parameter calculation

$$H = HEAT = \sum_{jan}^{dec} \left(\frac{T_m}{x}\right)^{1.514}$$

**T_m = Average monthly temperature*
x = number of years

The number of years used for the equation is the number of simulation years in STREAM. Once the HEAT value is calculated, a matrix with the same dimensions of the spatial input parameters was developed. There is no spatial variance for the H-value since it is calculated from temperature, which is a point source input for the purpose of this study.

4.1.6. A parameter

The HEAT parameter was used to determine the A parameter, which was used in the calculation of the total evapotranspiration for the catchment per iteration. The following equation (Equation 2) is used to calculate the A parameter (Aerts *et al.,* 2005):

Equation 2: A parameter calculation

$$A = 0.49239 + 0.01792H - 0.0000771771H^2 + 0.000000675H^3$$

**H= HEAT parameter*

A matrix for the A-value is developed with the dimensions for the spatial input parameters, once again with no spatial variation.

4.1.5. Mask

A mask was created for the model in order to read which areas should be included in the calculations and which should be ignored. The mask consisted of values of 1 (inside the catchment) and -9999 (outside the basin). From the WR2012 website, the water management areas were used to determine the catchment shapefile, which was further reclassified with the mask values and converted to an ASCII file.

4.1.6. Calibration map

The calibration map (cmap) reflects the duration of slow flow in months and is an important timing parameter for routing the flow towards the river. This parameter is calculated from the slope derived from the DEM and values range from 1 (steep slopes) to 3 (shallow slopes). Slope was calculated with the Spatial Analyst Tool, for which the DEM was the input raster.

The slope layer can be classified in three categories as percentage rises. The three categories were reclassified accordingly.

Since the DEM only gives information on the elevation of the catchment, it was necessary to have a parameter describing the nature of the slopes. By giving a numerical value to the type of slope, the speed at which water will flow was calculated. The values of the slope also affect the amount of water that infiltrates, as well as the amount that runs off towards the river. This map also influences the way the model is calibrated, since the calibration parameters also include the calculation for slow flow and the fraction of water going to groundwater and runoff.

4.1.7. Discharge points

A table containing instantaneous discharge (m^3/s) was created with each simulation. This discharge was calculated for a specific cell reference, defined as (column no. row no.). For accurate calibration, the cell reference should correspond with the position of the stream gauge measuring real-world discharge volume. Discharge data for the period 1965/11 – 1992/11 was obtained from stream gauge W1H0101@Amatikulu (29.0100°S; 31.4594°E).

When the input parameter maps are exported, the text file describes the information displayed in terms of the number of rows and columns, number of cells and the corresponding degrees latitude and longitude of the upper left corner of the exported map extent. The calculation below (Equation 3) was developed to calculate specific cell reference for specific degrees latitude and longitude.

Equation 3: Cell reference number calculation

$$C_R = \frac{(°PL - °L)}{C_S}$$

C_R= *Cell reference*
C_S= *Cell size*
PL= Point latitude or longitude (decimal degrees)
L= Top-left latitude or longitude (decimal degrees)

The cell reference should be calculated for latitude (row no.) and longitude (column no.) separately.

Part B: To calibrate the discharge volume for the study period.

Once all input parameter matrices are correctly inserted, STREAM will refer to the file location where it has been saved. Since STREAM is a Matlab script, the path to specific file locations can be edited. It is imperative for the path name to correspond to the file name. Model calibration was done manually by editing the calibration parameters systematically, testing

Pearson correlation coefficients (R-values) with the actual discharge data as each calibration parameter has been changed. The calibration parameters have a limited range over which it can be changed freely, so as not to affect the efficacy of its calculations. Along with determining the R-value, the calibrated simulations and actual discharge volumes were used to calculate the coefficient of determination (R^2-value).

4.1.8. Model calibration

For the calibration period, the period 1965/11 - 1992/11 was chosen. This is the same period for which there is observed discharge data for the catchment and will also later be referred to as the base period. Parameters that can be calibrated and the calibration range are listed in Table 9first . Since this catchment did not experience snow, the MELTcal parameter was kept constant at a value of one.

Table 9: Calibration parameters necessary for the STREAM model (Aerts *et al.,* 2005)

Calibration Parameter	**Parameter Description**	**Calibration Range**
HEATcal	A parameter controlling the influence of surface temperature	>0
WHOLDcal	Water holding capacity of the soil	>1
MELTcal	Parameter steering how fast snow melts	>1
CROPFcal	Parameter steering evapotranspiration	>0
TOGWcal	Parameter separating the fraction going to groundwater and direct runoff	0>1
Ccal	Parameter steering how fast groundwater flows	>1

Model calibration was checked using the Pearson correlation coefficient (R) and the coefficient of determination (R^2). The coefficient of determination illustrates the relationship between observed values and predicted values. Acceptable values of $R>0.8$ and $R^2>0.6$ illustrate satisfactory model forecasting ability. Model performance is considered unacceptable for R^2 values less than or very close to zero. The closer the value approaches one, the more perfect the relationship of simulated values to observed values (Alansi *et al.,* 2009).

For a couple of reasons, it was decided to calculate the coefficient of determination and Pearson correlation coefficient for the period between 1988-1992. The first of which is to allow the model a warm-up period, since this model is an iterative model, meaning that after each model calculation, new matrices were generated based on the previous calculations. Apart from the input matrices that the model used to simulate discharge, it generates other internally generated matrices for several other aspects in catchment processes (for example, groundwater flow, surface runoff, and evaporation). These matrices are given a value of zero for the first iteration, after which every iteration is averaged with the previous iteration to give the parameter values needed for the next iteration. It was advised to allow for a five-year warm-up period (Aerts *et al.*, 2005).

Another factor considered was the period of continuous measured discharge data. Unfortunately, there were gaps within the measured discharge data, and it was necessary to use a period with continuous data for the most accurate calculations. The longest period of continuous data was between 1988 and 1992 and this period was therefore used for the calibration of the model.

4.2. Model simulations

Considering that the model calibration was done over the period for which there was measured discharged data, the gaps can be filled in, future discharge volumes were calculated and the effects on discharge volumes as a result of different scenarios could be tested.

Part A: To determine past and present river discharge through running model simulations for the study period.

One of the largest difficulties in this investigation was the availability of continuous discharge data. Several methods were used to overcome this difficulty, one of which was to run simulations using past and present data to fill in the gaps. To be able to run these simulations, land-use maps and climate data for the study period were used.

4.2.1 Determine land use and land-use changes for the study period

As previously stated, the land-use information was determined according to land-use maps for the years as generated for 1964 and provided for 1990 and 2013. The area covered by each land-use type was calculated and tabulated. Land-use change was then determined by using the difference in area coverage between the years wherein land use has been mapped (LUM years). The methods of obtaining the land use information differ between the various years and it is therefore important to remember this when comparing the land areas. In order to avoid this discrepancy, land-use change in the area is described only between the periods where land use was determined or attained by the same source. For the 1990 and 2013 LUM years, land-use classification was obtained from maps from Geoterra Image (GTI) and were determined by using satellite imagery and remote sensing techniques.

Since the land-use data is determined by a similar method, 1990 and 2013 LUMs were used to determine changes within the land uses, while the map generated for 1964 was used to calibrate the model. To determine the land-use change within the catchment, the land-use maps were first reclassified, where after a raster calculation was done. Furthermore, for the purpose of this study, the land-use classes used for the reclassification were limited to the classes shown in Table 10.

Table 10: Land-use reclassification table

Land-use Class:	**Reclassified Value**	**Land-use Class:**	**Reclassified Value**
Urban/ Built-up	1	Forest/ Plantations	16
Grassland/ Bush	4	Water/ Wetland	25
Farmland/ Cultivated	9	Barren	36

The reclassification values were “squared values” so that each land use change over a given interval can be identified by a unique value after raster calculation. Once all the land-use classes were reclassified, a raster subtraction was done to determine land-use change between 1990 and 2013. Land use for 2013 was subtracted from the 1990 LUM in ArcGIS, where the raster calculation tool can be found under the “3D Analysis Tools > Raster Maths > Minus”. The following matrix was developed to identify how the land use has changed between these two maps (Table 11). These values were used to calculate the percentage area change of the respective land uses, in order to identify the major land-use change for the catchment.

Table 11: Reference table for types of land-use changes found in the Amatikulu-Nyoni catchment between 1990 and 2013

To: From:	Urban/ Built-up	Grassland /Bush	Farmland/ Cultivated	Forest/ Plantations	Water/ Wetland	Barren
Urban/ Built-up	0	-3	-8	-15	-24	-35
Grassland/ Bush	3	0	-5	-12	-21	-32
Farmland/ Cultivated	8	5	0	-7	-16	-27
Forest/ Plantations	15	12	7	0	-9	-20
Water/ Wetland	24	21	16	9	0	-11
Barren	35	32	27	20	11	0

The resultant raster calculation map was once again reclassified into values of “No change” when the result was zero and values of “Change” when the result was not equal to zero. This was done to detect areas of change versus areas of no change, and therefore the area of total land-use change could be determined. Furthermore, the percentage of specific changes was calculated to infer which land-use types had undergone the largest change to certain types of land use.

4.2.2 Determine annual climate variability for the study period

Graphs depicting the precipitation and temperature for the periods under investigation indicate the monthly and annual variability in these parameters. A trend line for each period was used to give an indication of whether the parameter is increasing or decreasing for the period. A standard deviation was further calculated between the study periods to determine how closely related the climate parameters were for each period. The statistical variation was calculated accordingly to further aid in describing the distribution of the climate parameters for each study period. The standard deviations of the different sets of climate parameters were compared in order to judge the deviation from the base period (1965-1992). In order to do this, z-scores were calculated for the data in the different study periods. Since precipitation, temperature and discharge have different units of measurements, a measure of relative variation (coefficient of variation) describes the variation between these parameters.

Part B: To determine possible relationships between climate variability, land-use changes and river discharge dynamics.

Simulations of the different scenarios allow for the investigation into the different effects of land-use change and climate change on the discharge regime of the catchment. This also allows for testing the influence of a single parameter or the combined effect of land use and climate on this system. By keeping all but one parameter constant, it was possible to determine the effect of this specific parameter on the catchment for a particular period.

4.2.3 Relationship tests

The climate parameters and model results are organised according to the specific study periods and the information is summarised as trends within these periods. The total monthly discharge volume is used as the discharge parameter, along with the total monthly precipitation and average monthly temperatures. Trends are calculated for the January and June months as summer and winter trends to account for the differences between these seasons.

Monthly discharge volume has also been simulated for the RCP scenarios as well as for different LUM years over the same period of climate, in order to determine possible differences between these scenarios. The simulated results are illustrated on line graphs for total monthly discharge volume for the study periods under investigation. To identify the differences between the scenarios, the peak discharges for the study periods were investigated. Further analysis includes tests for significant difference by means of Mann-Whitney U tests between the scenarios. By testing for a significant difference, the null hypothesis assumes that there will be no significant difference between the different scenarios. Thus, rejecting the null hypothesis would show that there is a significant difference between the scenarios.

Probability tests between precipitation and discharge volume were carried out to identify the probability of the influence that certain rainfall events have on the discharge volume. These tests are carried out on the assumption that a high rainfall event will cause high discharge volumes whilst low rainfall periods will cause low discharge volumes. The validity of this relationship is inferred from the value of the probability.

4.3. Scenario tests

The scenarios were based on the RCP (Representative Concentration Pathways) values determined by the Intergovernmental Panel on Climate Change (IPCC), and total land-cover changes in terms of crop factor values. These scenario tests enabled the investigation of either possible future discharge volumes or, in the case of the land use, the effect of each crop factor value on the discharge volumes.

4.3.1 To test complete changes in land-use scenarios to test the impact of a single land use on discharge volumes.

In order to test the impact of specific land uses, the model was set up to simulate discharge volumes for single crop factor values within the catchment. This enables the model to calculate the sensitivity of the catchment to each land use. Similar to creating the distributed crop factor maps, these single crop factor maps were developed by reclassifying all the raster cells to the crop factor value. These maps were converted to ASCII files and exported as .txt files.

4.3.2 To test different climate scenarios according to the RCP2.6 and RCP8.5 temperature and precipitation projections.

According to the Intergovernmental Panel on Climate Change (Pachauri *et al.*, 2014) Fifth Assessment Report (AR5), an integrated view of the current climate, anthropogenic causes for changes in the change and previous climate changes allowed several projections to be calculated. The global average surface temperature changes have been used in this study and the projection is shown in Figure 20 (Pachauri *et al.*, 2014). Since the actual climate trends in the catchment have been calculated and used in the simulations of the past five decades, it was not necessary to consider detailed regional climate projections. The general climate change trends for the study area were used to understand how future climate would affect the discharge volumes.

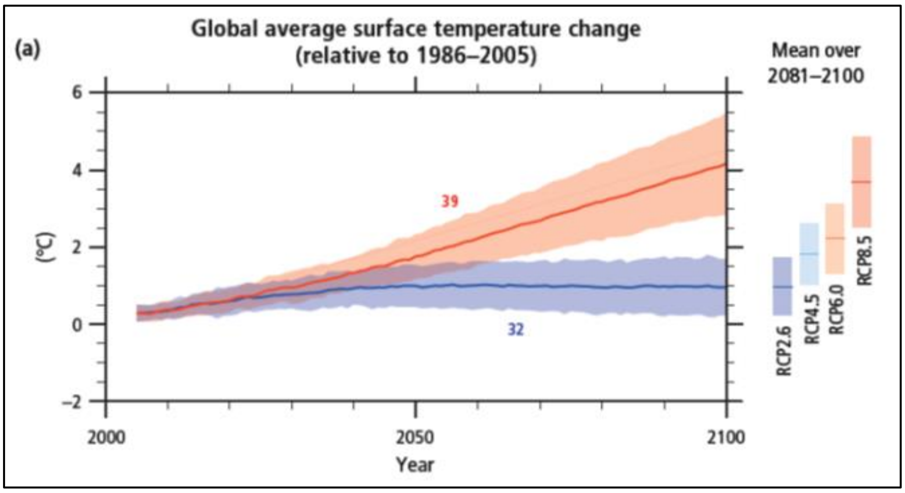

Figure 20: Projected global temperature changes taken from IPCC (Pachauri et al., 2014)

The global surface temperature changes by the end of the twenty-first century are projected using the RCPs, relative to 1986-2005, to be between 0.3°C and 1.7°C under RCP2.6 and between 2.6°C and 4.8°C under RCP8.5. (Pachauri *et al.*, 2014). For the purpose of this study, the mild RCP2.6 and extreme RCP8.5 projections are used in simulating possible effects of a changing climate on the discharge for the Amatikulu-Nyoni catchment. The distribution of global surface temperatures under the RCP2.6 and RCP8.5 projections are shown in the figure below (Figure 21a). The changes in average precipitation will not be uniform (Pachauri *et al.*, 2014) and the distribution of changes is shown below (Figure 21b).

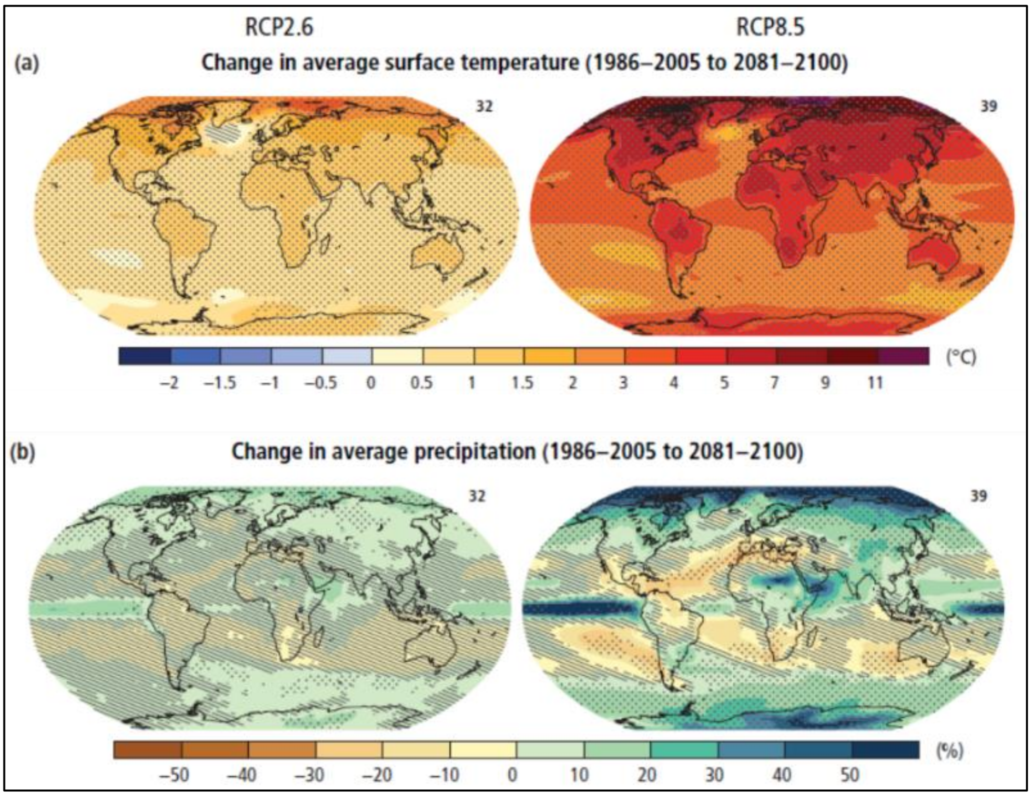

Figure 21: Global climate projections taken from IPCC (Pachauri et al., 2014)

The projection under RCP2.6 is a 2°C increase in average temperature and 10% decrease in precipitation, while the RCP8.5 predicts an increase of 5°C in average temperatures and a decrease of 20% in precipitation. When looking at the distribution of where extreme climate change can be expected, it is noted that the east coast of South Africa was somewhat protected. It can be seen in the figure above (Figure 21) that the interior towards the west of the country will experience even hotter and drier circumstances.

Chapter 5: Results

Land use and land-use changes in the catchment were determined, as well as climatic variation over the past fifty years. This information was used to simulate the discharge volumes in the catchment, to determine the various influences of the parameters over the study period. The same period was used to investigate different scenarios to establish whether land-use change or climate has had the largest influence on the catchment’s discharge. It was also established whether climate or land-use change in future would have the largest effect.

5.1. Land-use and crop factor maps

To investigate the influence of land-use change on the catchment’s discharge, it was necessary to create land-use maps as input for the STREAM model simulations. These maps were converted to crop factor maps to allow calculations to be made. The model used ASCII file format, whereas in the Figures below (Figure 22 - Figure 24) the distribution of crop factors is illustrated.

Figure 22 is a crop factor map generated from the digitized classification of the land use manually derived from the aerial photographs of 1964. From this map, it can be derived that

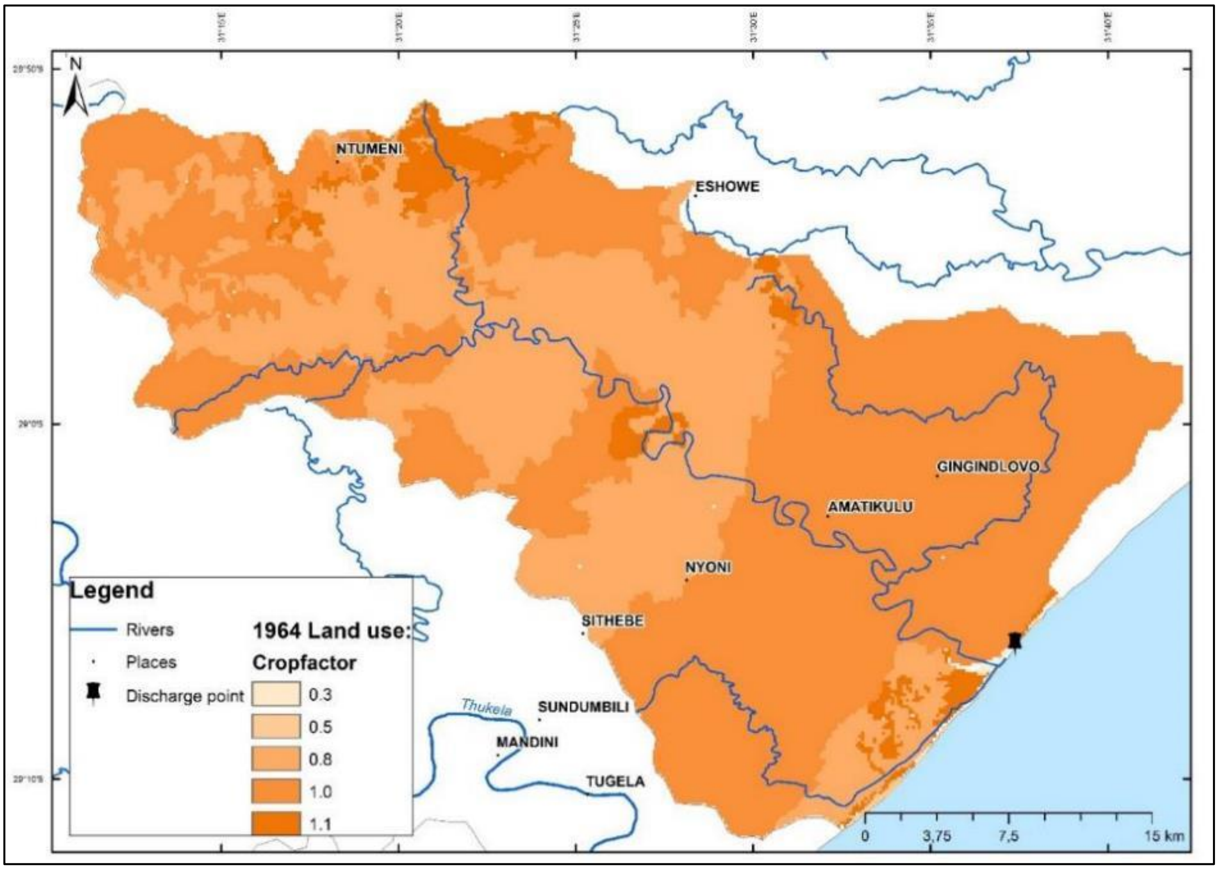

Figure 22: 1964 Crop factor map of the Amatikulu-Nyoni catchment, South Africa

cultivated land covered the largest area within the catchment in 1964. Cultivated land includes farmlands such as sugarcane and other crops as well as grazing land. Plantations and forests cover a large area of the upper north-western catchment while the cultivated land covers the lower south-eastern catchment.

The next study period dates from 1990, with a land-use classification map derived automatically from satellite imagery and then converted to a crop factor map (Figure 23). Since crop factor values are an index of the amount of runoff and particle detachment a specific land use would cause, the values for built-up land and bush or shrubbery are the same. It is thus hard to distinguish between these land classes from the map, therefore a detailed analysis of land-use change distinguishing between built-up land and shrubbery will follow. Although more pixelated, a similar pattern in cultivated land in 1964 is seen in the south-eastern lower catchment. Cultivated land, however, does not stretch to the coast as it did in 1964, but it seems to be replaced with either built-up land or bush and shrubbery. Plantations and forests have in part moved closer to the coast whilst still covering a part of the upper northern catchment. The middle catchment is covered by either built-up or bushes and shrubs.

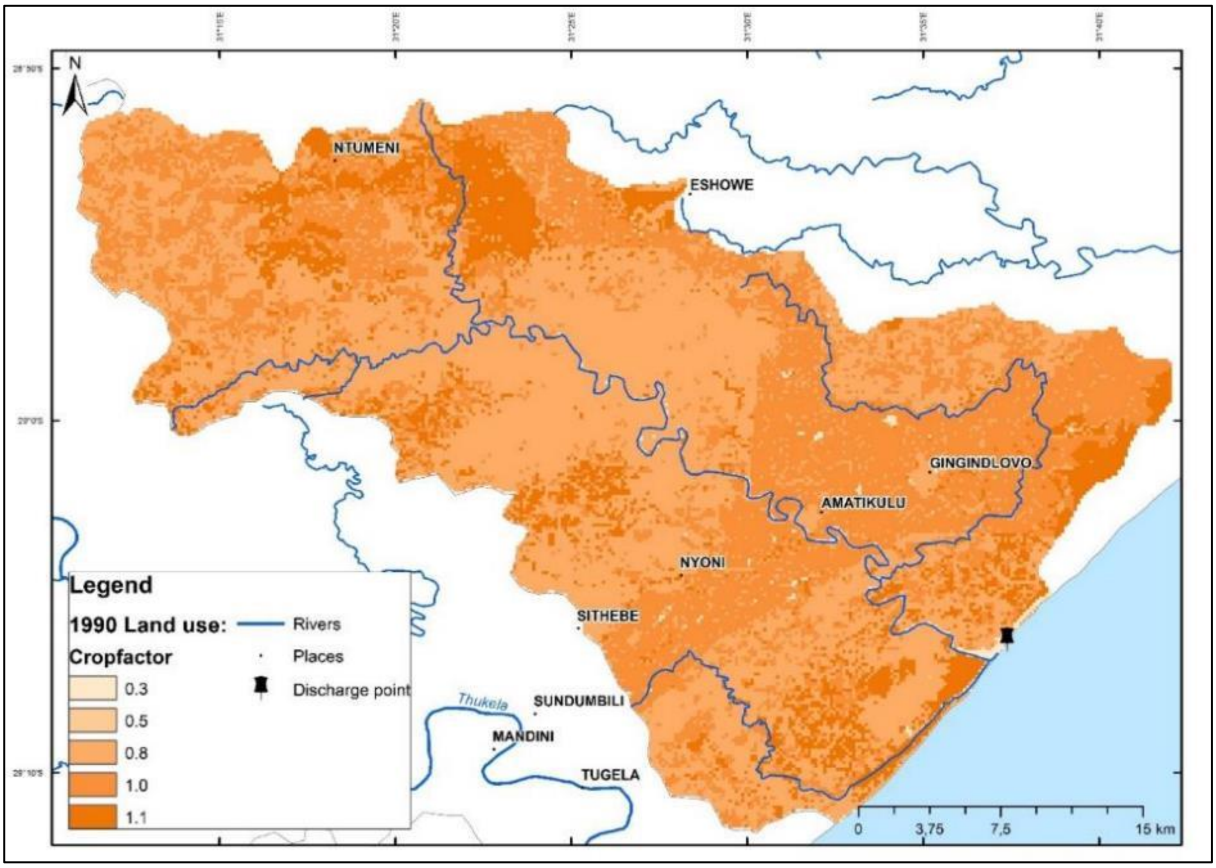

Figure 23: 1990 Crop factor map of the Amatikulu-Nyoni catchment, South Africa

Similar to the crop factor map of 1990, the crop factor map of 2013 was automatically classified from satellite imagery to land use classes, and then reclassified into the crop factor values (Figure 24). These two maps more closely resemble each other as they exhibit similar land-use patterns. The coastal areas are still largely covered by forests and plantations whilst cultivated land still covers most of the lower south-eastern catchment, although the area has increased somewhat. The middle catchment is still largely covered by crop factor 0.8, which could be built-up land, grassland or bush and shrubbery.

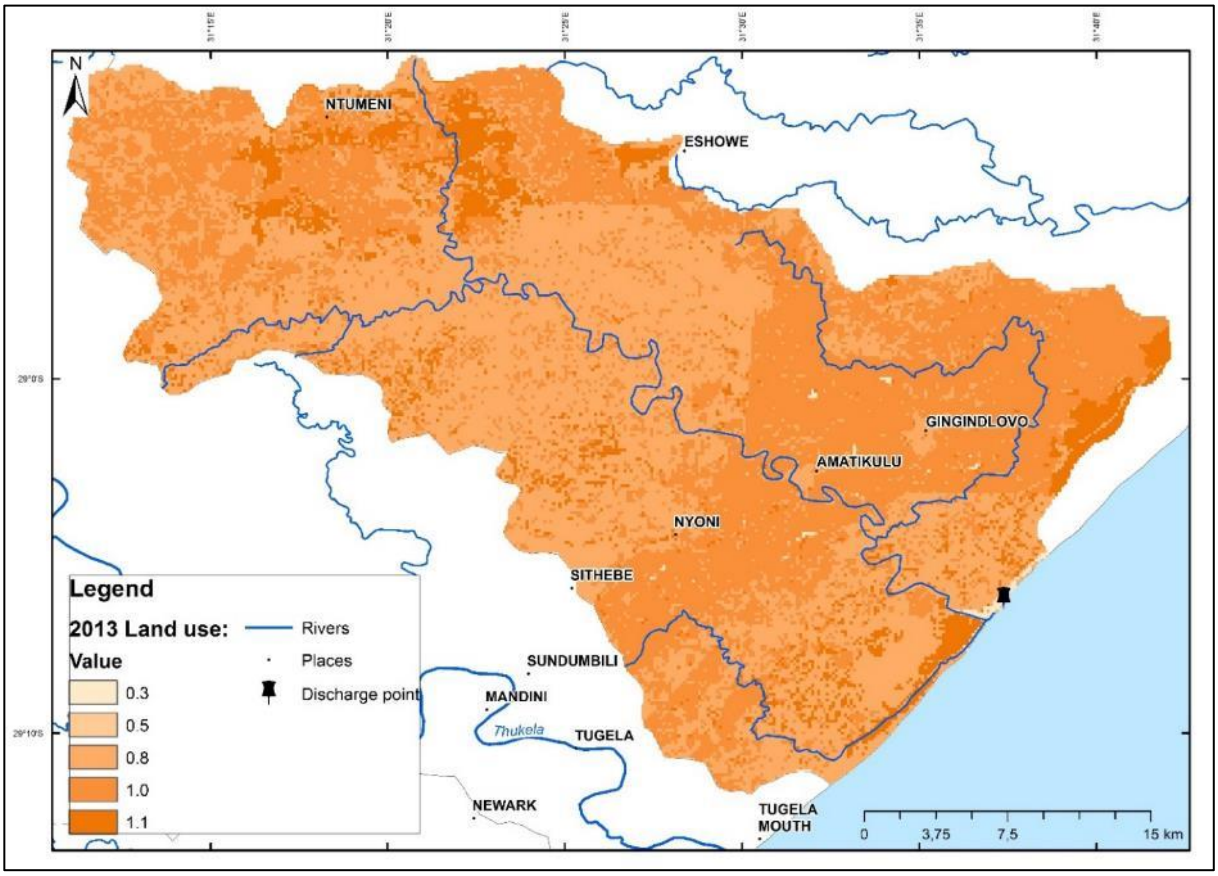

Figure 24: 2013 Crop factor map of the Amatikulu-Nyoni catchment, South Africa

The percentage area that the land-use types covers and the percentage change in land uses over the study period were calculated for the land-use map years (1964; 1990 and 2013). As previously mentioned, there are differences in the methods of acquiring the land-use classifications and as a result, only the 1990 and 2013 land-use map years are discussed. The land-use classification for these LUM years has been carried out in a similar fashion; therefore, discrepancies between the identification of land-use types are limited.

The percentage area covered by a certain land-use type in the Amatikulu-Nyoni catchment is summarised in Table 12. It is necessary to point out the surprising result that built-up areas have decreased from 1990 until 2013 by almost 4%. Another significant change in land use is the extent of cultivated land, which has increased by 8.22% whereas the area covered by plantations has decreased by 4.21%. Natural areas have seen an increase in percentage area, though quite small at 0.51%, and the area coverage of waterbodies has decreased by 0.51%.

Table 12: Percentage land cover and land cover change

Land-use category	% Area			% Area change	
	1964	1990	2013	1964-1990	1990-2013
Natural	36.87	33.93	34.44	-2.94	0.51
Waterbodies	0.07	1.62	1.10	1.55	-0.51
Cultivated	61.89	34.82	43.03	-27.07	8.22
Bare ground/ Degraded	0.16	0.08	0.05	-0.07	-0.03
Built-up	n.a.	20.27	16.30	n.a.	-3.97
Plantations	1.02	9.28	5.07	8.26	-4.21

Although a useful parameter, the percentage change in land use only in part describes the change the catchment has undergone during this period. To understand the dynamic processes in the catchment further, it is necessary to look at what the land has changed to. In addition to showing what the land cover has changed to, it is equally important to know what it has changed from. Therefore, a detailed analysis of the types of changes between 1990 and 2013 was done (Appendix A). Only the largest forms of changes have been summarised below (Table 13) As seen from the table, a total of almost 72% of the catchment has not undergone any change. Of the remaining 28% that has undergone change, the largest change (7.27%) has been from grassland/ bush to cultivated land.

Table 13: Type and amount of land-use change in the Amitukulu-Nyoni catchment for the period between 1990-2013

Land-use Change	% Change
Farmland/ Cultivated to Grassland/ Bush	4.42
Farmland/ Cultivated to Urban/ Built-up	0.58
Forest/ Plantations to Farmland/ Cultivated	1.63
Forest/ Plantations to Grassland/ Bush	3.09
Forest/ Plantations to Urban/ Built-up	0.89
Grassland/ Bush to Farmland/ Cultivated	7.27
Grassland/ Bush to Urban/ Built-up	0.86
No change	71.66
Urban/ Built-up to Farmland/ Cultivated	4.16
Urban/ Built-up to Grassland/ Bush	2.09

When comparing the land-use maps as well as the percentage areas for these two periods, it is seen that there has been an increase in cultivated land 4.16% of previously built-up land has changed to cultivated land, and 1.63% of forests or plantations has changed to cultivated land. Mostly forests or plantations were converted to built-up land (0.89%) closely followed by grasslands or bush that have changed to built-up land (0.86%).

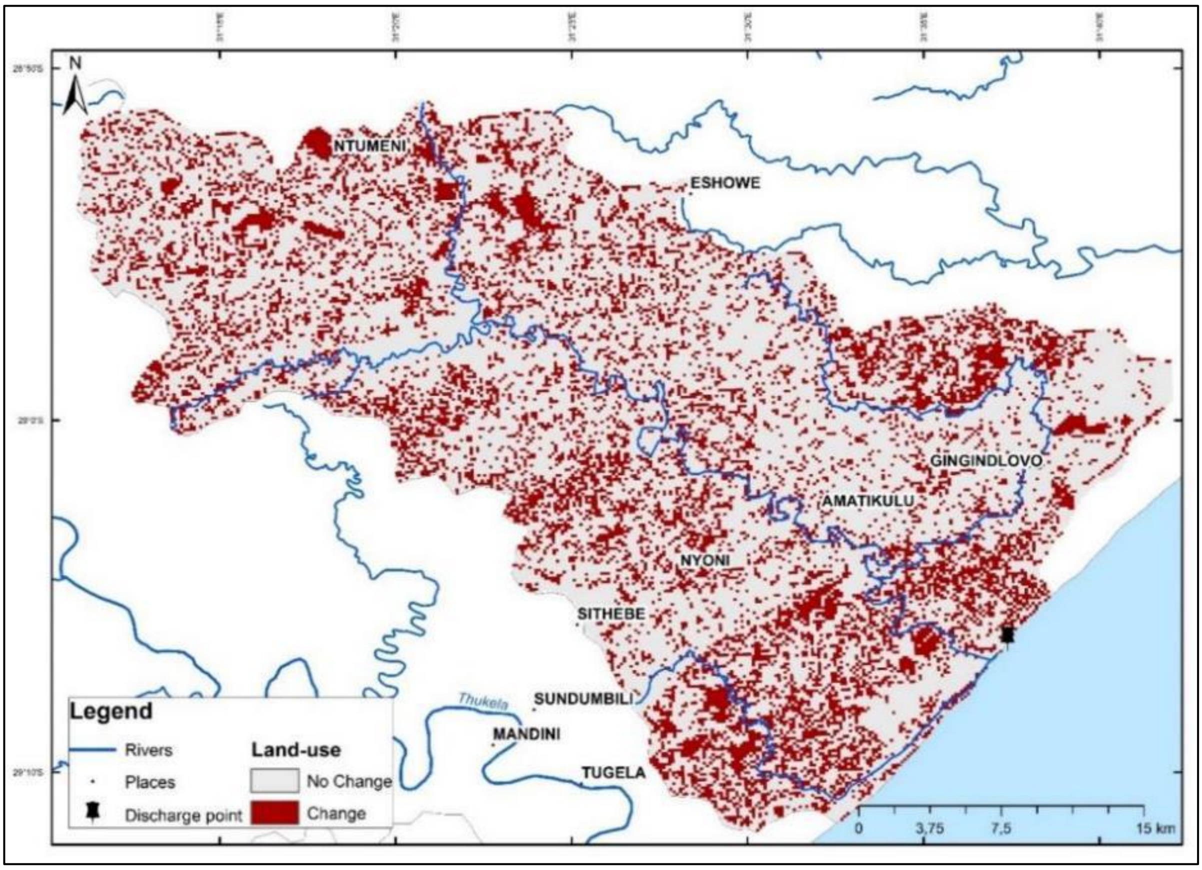

Figure 25: Distribution of Land-use change versus no land-use change for the period 1990-2013 in the Amatikulu-Nyoni catchment

A map illustrating areas of “Change” and areas of “No change” was created to illustrate the distribution of change (Figure 25). Changes in the land use are fairly well distributed within the catchment. However, most changes occurred along the southern coastal areas and the upper north-western catchment.

5.2. Climate

The influence that climate has on the catchment was evaluated through several means. The observed climate data of the past was summarised in graphs to establish trends in precipitation and temperature. In the following graph (Figure 26), the total monthly precipitation is shown for the period 1930-2015.

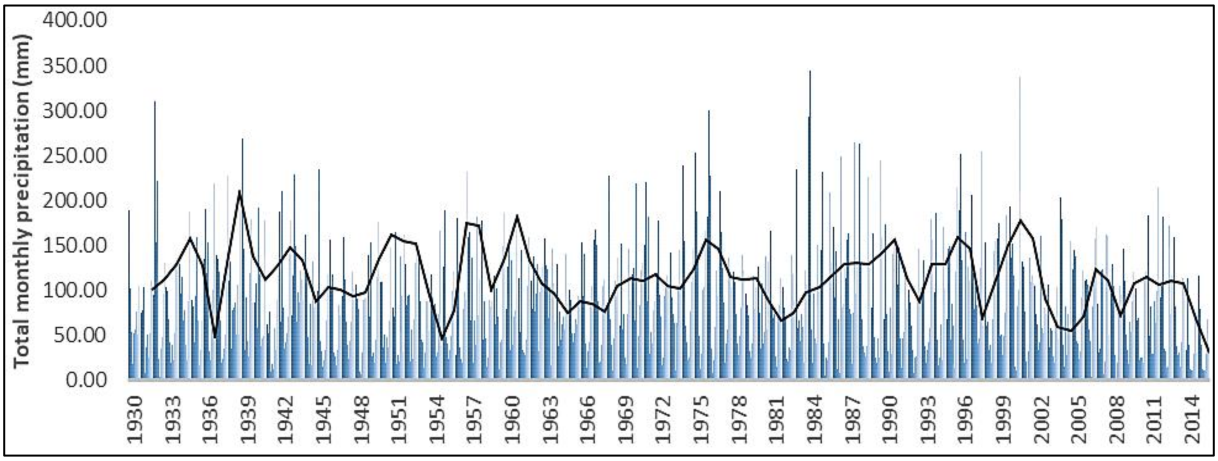

Figure 26: Total monthly precipitation from 1930-2015 for the Amatikulu-Nyoni catchment

The moving average trend line from 1933 to 2015 shows the general precipitation pattern as close to decadal wet-dry periods. This means that roughly every decade, starting in 1933, there would be periods of elevated precipitation followed by periods of lower precipitation. As calculated for the wet months, the average difference in observed rainfall is between 100mm and 120mm, which indicates that during a wet decade, there is on average 100mm to 120mm more monthly precipitation than during a dry decade.

Total monthly precipitation is shown in Figure 27 for each decade starting from 1965 to 2015. The Amatikulu-Nyoni catchment receives summer rainfall, with the most rain falling in January and February. The decadal pattern in this graph is much more obvious, where a wet decade is followed by a dry decade. Another observation is that the last decade (2005-2015) has been the driest in the study period, whereas the decade just before (1995-2004) has been the wettest decade.

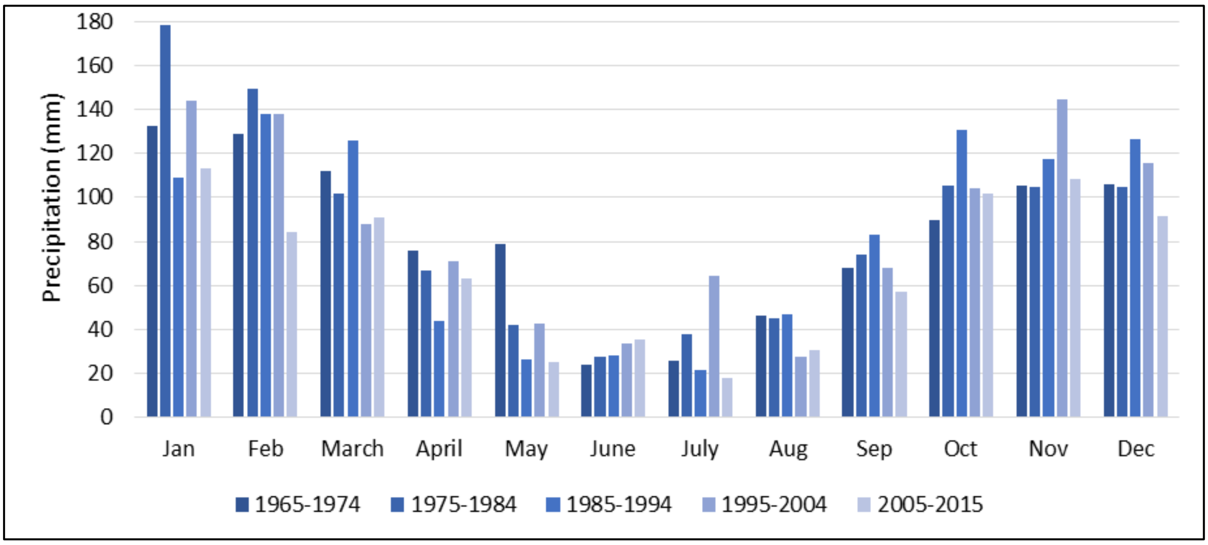

Figure 27: Total monthly precipitation for the study period (1965-2015) in the Amatikulu-Nyoni catchment

The observed average annual temperature records are depicted in Figure 28. The average annual temperature follows roughly a similar pattern to that of the total monthly precipitation pattern seen in Figure 26. For each warm period, a colder period would follow. It is interesting to note that the warm period somewhat coincides with the wetter period except for the period 1984-1996. A slight warming trend based on January temperatures is further identified in this graph.

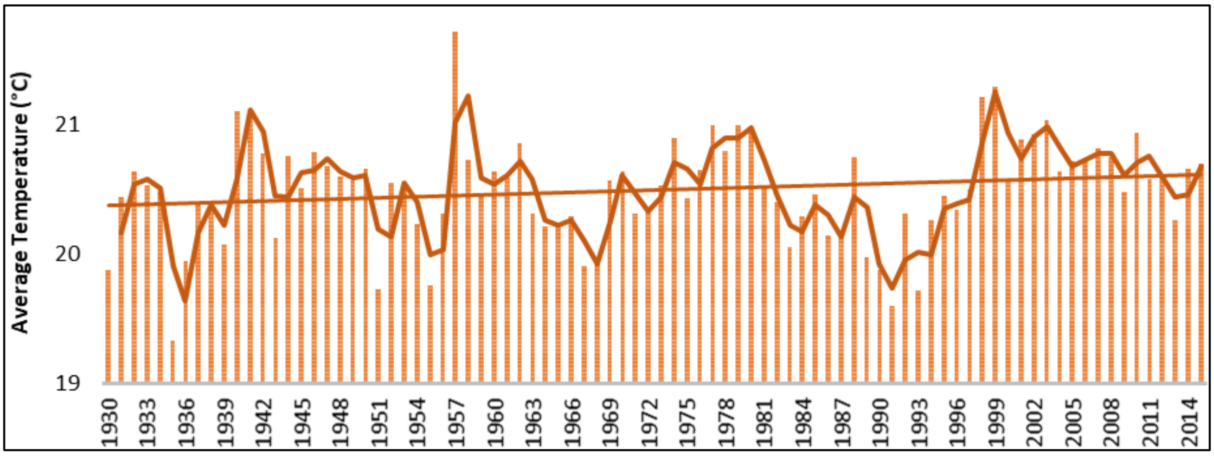

Figure 28: Average annual temperature from 1930-2015 for the Amatihulu-Nyoni catchment

Following the observations above, a graph combining average annual total precipitation and average annual temperature for each decade for the study period was created (Figure 29). This graph more clearly illustrates the relationship between temperature and precipitation. The higher the decade's average annual temperature, the higher the annual precipitation for that decade is shown.

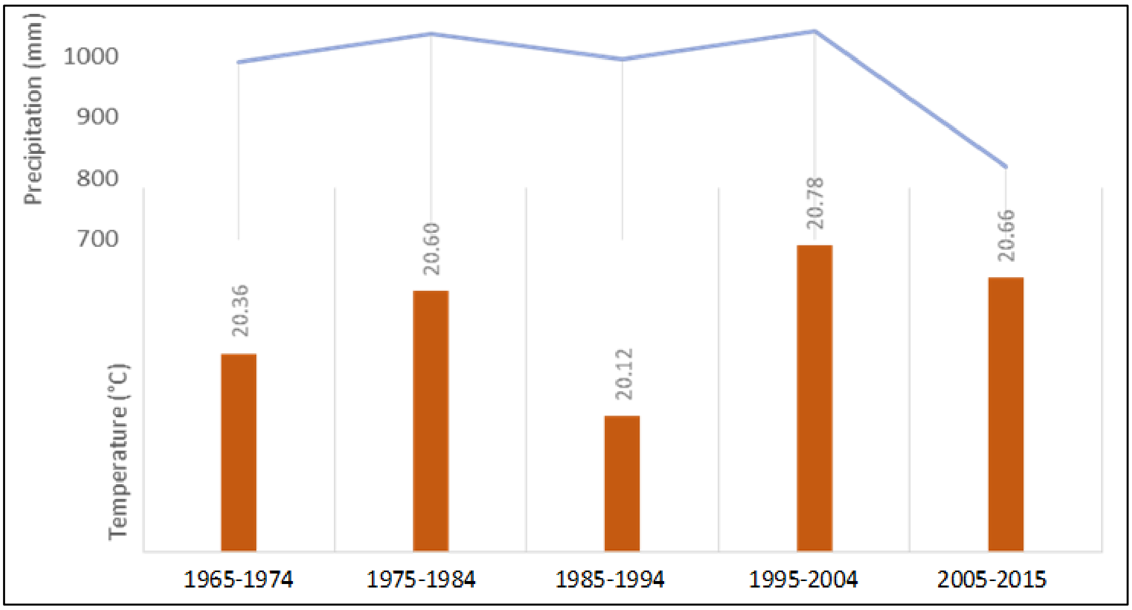

Figure 29: Average annual temperature and total annual rainfall for every decade in the study period (1965-2015) for the Amatikulu-Nyoni catchment

5.3. Model calibration

To calibrate the model, a graph with the measured discharge values for the period between 1965-1992 was used, as well as calculating the Pearson correlation coefficient (R) and the coefficient of determination (R^2) value. Figure 30 shows the distribution of measured discharge data and the STREAM simulated discharge where the first graph represents the complete set of measured discharge values (1964-1992) and the inserted graph represents the calibration period between 1988-1992.

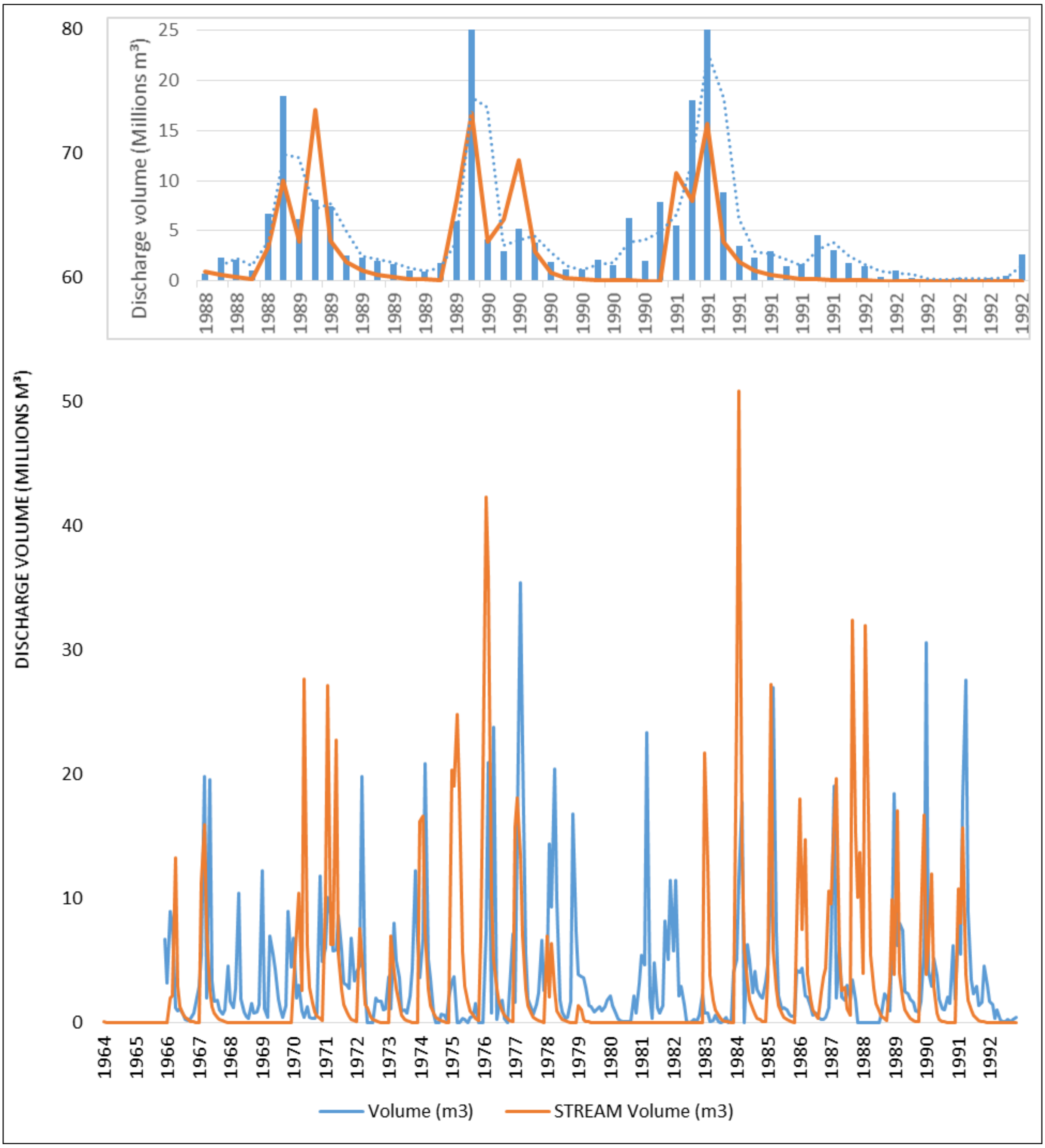

Figure 30: Actual discharge volumes versus STREAM simulated discharge volumes over the study period (1964-2015) for the Amatikulu-Nyoni catchment

The values for R and R^2 were calculated at R=0.8 and the R^2=0.63 which falls within the accepted values of R>0.8 and R^2>0.6. These values represent the model's forecasting ability and therefore the accepted values indicate that the model simulates reality to an acceptable standard.

5.4. Model simulations

The aim of the study was to establish the cause for the change in discharge volumes of the Amatikulu-Nyoni rivers. In order to determine the cause for the change in discharge volumes, past land-use and climate data were used for the first set of simulations. Once it was established which factor had the larger influence, several scenarios focusing on change in land use or change in climate were also tested. The following section will first look at land use and land-use change scenarios on discharge volumes and then at climate and potential future climate scenarios.

5.4.1. The relationship between discharge and land-use change

To test the impact that previous land uses had on the catchments discharge volumes, the STREAM model was set up to simulate discharge volumes with 1964 LUM and 2013 LUM over the complete study period. By simulating the two different LUMs over the same period, comparisons in discharge volumes can be made, as shown in Figure 31.

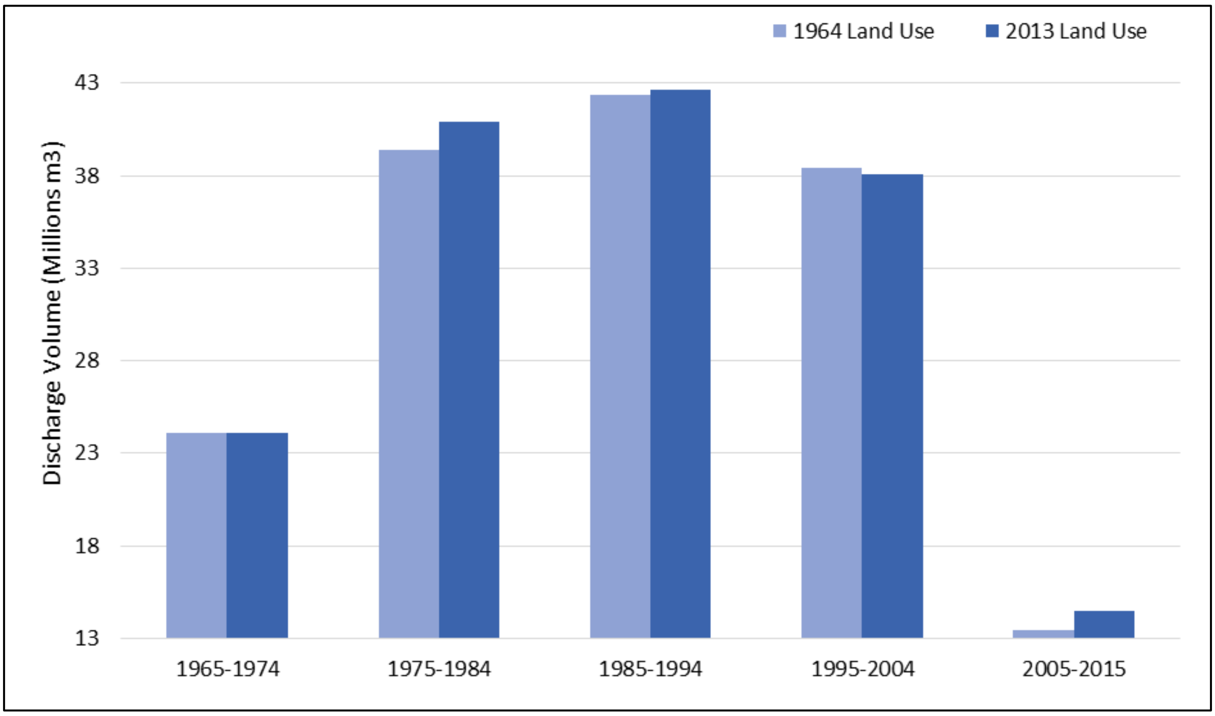

Figure 31: Simulated discharge volumes for the different land-use map years

From Figure 31, minor differences are observed between the discharge volume distributions when using the 1964 LUM compared to the distribution when using the 2013 LUM. Table 14 shows a summary of the calculated values as well as the critical t-values and P values.

Table 14: Summary of land-use scenario statistical analysis

Period	**Average Annual Discharge Volume (1964 LU)**	**Average Annual Discharge Volume (2013 LU)**	**t Critical two-tail**	**P (T<=t) two-tail**
	(millions m^3)	(millions m^3)		
1964-2015	31.56	32.06	1.96	1
1964-1974	24.10	24.10	1.97	1
1975-1984	39.41	40.94	1.97	1
1985-1994	42.38	42.67	1.97	1
1995-2004	38.45	38.05	1.97	1
2005-2015	13.44	14.51	1.97	1

5.4.2. Land-use scenarios on discharge

Since there is no significant difference found in the simulated discharge volumes for 1964 LUM and 2013 LUM, the STREAM model was set up to simulate single crop factor scenarios to determine whether a difference in discharge volumes could be detected (Figure 32). A value of 0.7 is calculated as the mean crop factor value for the values between 0.3-1.1. The scenario that most closely follows the same discharge volume distribution to the distributed crop factor scenario (reality) is where the whole catchment consists of a 0.8 crop factor. Total coverage of 0.8 crop factor values would include grassland, urban or built-up areas as well as bush and shrubbery, and represents the least impact scenario. When the catchment is completely covered by 1.1 and 1.0 crop factor values, the discharge volumes are expected to be critically low. These crop factor values include land uses such as forests, plantations, wetlands and cultivated areas. High discharge volumes can be expected when the catchment is covered by 0.5 and 0.3 crop factor values. Thus, high discharge volumes are expected for changes in land use to barren land or water bodies.

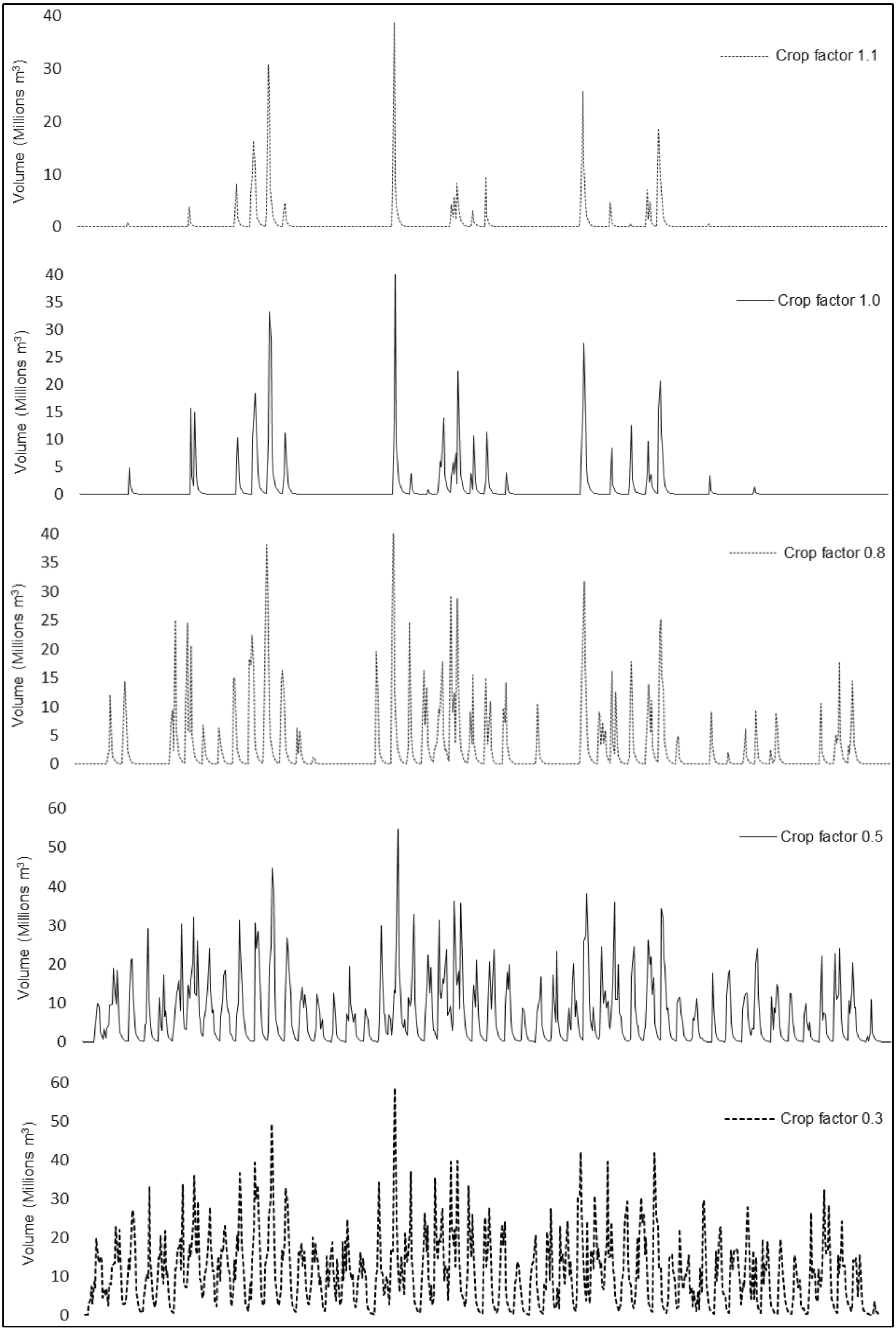

Figure 32: Simulated discharge volumes per crop factor scenario

5.4.3. The effect of past climate on discharge

To evaluate the impact of climate on the catchment's discharge volumes, the STREAM model was set up using observed climatic data. A strong correlation is observed between the discharge volume and the climate indicators (i.e. precipitation and temperature). Figure 33 illustrates the relationship between discharge volume, precipitation and temperature.

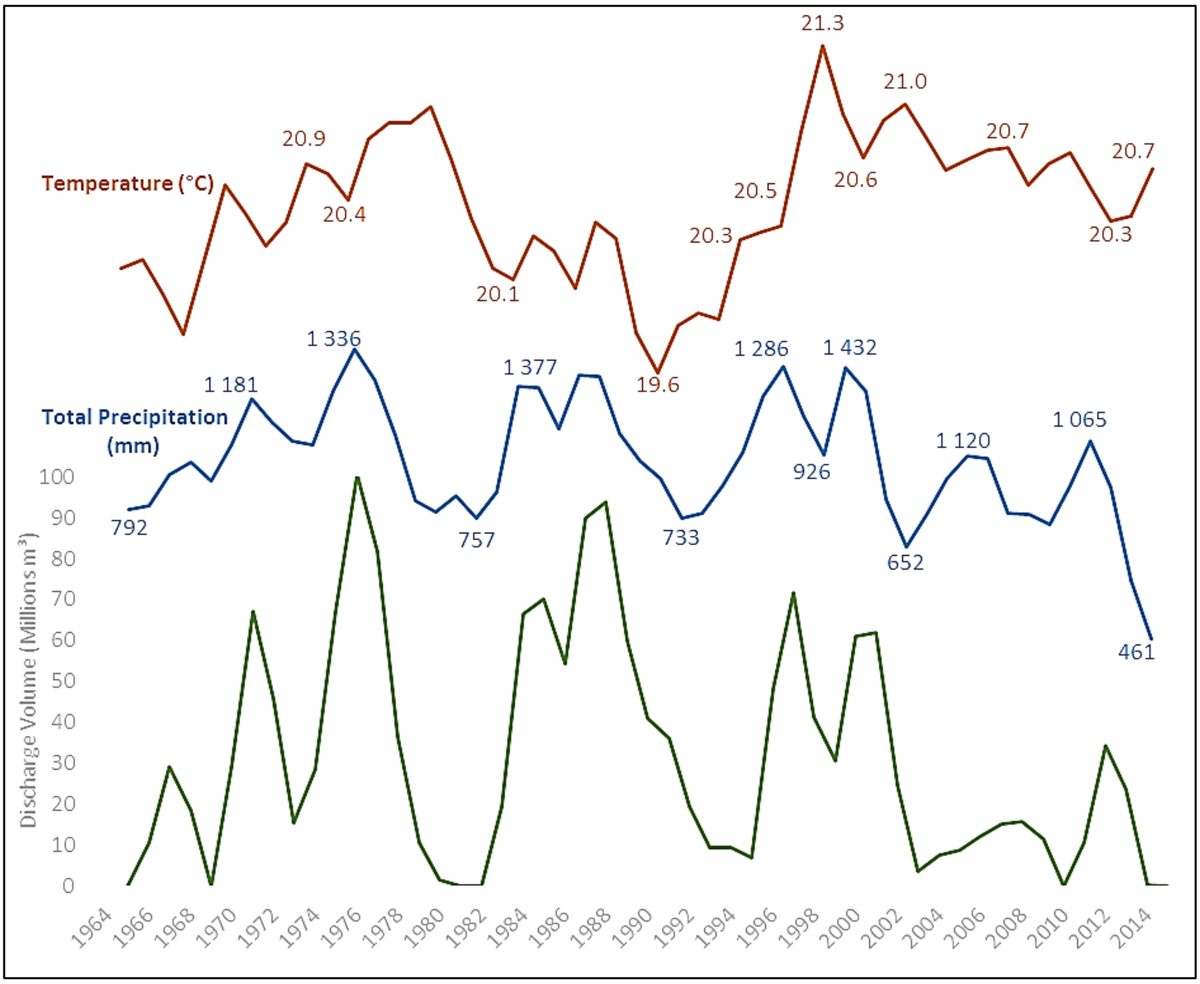

Figure 33: Correlation between discharge volumes, precipitation and temperature for the period between 1964-2015

There appears to be a delayed response of precipitation to temperature (visually observed). To explain this more clearly, from Figure 33 it is seen that approximately one or two years after a warm year (peak in temperature values) a wet year follows (peak in precipitation values). Further visual observations showed that for the period from 1964 until 2010, as the temperature increased, precipitation and discharge increased. However, a change was observed in the period from 2010 to 2015, where there was still an increase in temperature, but also a decrease in precipitation, resulting in a decrease in discharge. In the table below (Table 15), the highest discharge volume is measured for the period with the coolest temperatures (20.1°C) and average precipitation of almost 1000mm. However, the second highest discharge volumes (≈41 million m^3) were calculated for the period with an average annual temperature of 20.6°C and approximately 1040mm average annual precipitation.

Table 15: Summary of climatic factors compared to discharge volumes

	Average Annual			Minimum Annual Discharge Volume (millions m³)	Maximum Annual Discharge Volume (millions m³)
Period	**Precipitation (mm)**	**Temperature (°C)**	**Discharge Volume (millions m³)**		
1965-1974	991.5	20.4	24.10	2.79E-04	76.13
1975-1984	1037.8	20.6	40.94	3.17E-08	108.40
1985-1994	996.8	20.1	43.61	4.66E-02	117.07
1995-2004	1041.4	20.8	36.52	9.75E-03	82.75
2005-2015	818.2	20.7	11.40	9.11E-07	47.42

A simple Pearson correlation test was carried out to test the statistical correlation between precipitation, temperature and discharge volumes over the study period. It was found that there was a strong correlation (r=0.86) between precipitation and discharge volumes but poor negative correlations between temperature and discharge volumes (r=-0.38), and precipitation and temperature (r=-0.15).

5.4.4. The effect of climate change scenarios on discharge

The model was used to simulate scenarios for discharge volumes based on the IPCC's Representative Concentration Pathways or rather, the RCP2.6 and RCP8.5 projections (Appendix B). Table 16 summarizes the calculated results for percentage reduction in annual discharge volumes.

Table 16: Percentage reduction in annual average discharge volumes as calculated for climate scenarios compared to the measured historical values

	% Reduction in Discharge Volume			
Period	**2°C Temperature Increase**	**5°C Temperature Increase**	**10% Precipitation Decrease**	**20% Precipitation Decrease**
1965-1974	22.7	71.3	36.1	51.8
1975-1984	11.8	37.4	16.4	30.1
1985-1994	28.2	48.9	27.4	43.7
1995-2004	20.1	46.3	23.8	42.3
2005-2015	31.6	96.6	35.9	75.1

Across all the scenarios, there is a difference of more than 15%, meaning that for all scenarios the discharge volumes will reduce by 15%, or more, from the discharge volume calculated with measured precipitation and temperature values. It is seen across all periods that the scenario with a temperature increase of 5°C would result in the largest reductions in discharge volumes. The second largest impact will be seen when precipitation decreases by 20%. Discharge volumes calculated for a precipitation decrease of 10%, or an increase in temperature of 2°C, are closest to discharge volumes calculated for measured temperature and precipitation values. Figure 34 depicts how the discharge values for each period compares.

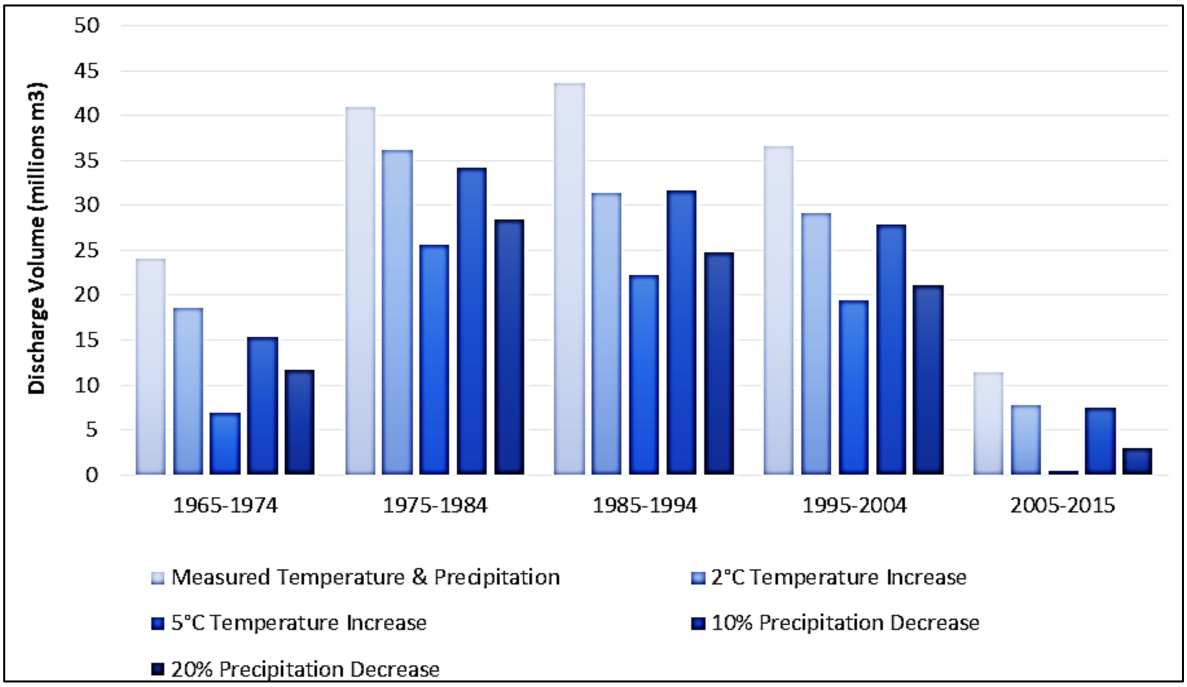

Figure 34: Simulated discharge volumes based on climate scenarios

A test for significant difference as determined using a student two-tailed t-test for a confidence level of 95% was further carried out between the measured temperature and precipitation discharge simulations and the IPCC scenario discharge simulations. For a t-critical value of 1.98 and a DF value of 100, the t-stat was calculated and summarized in Table 17.

Table 17: Summary of t-stat values for each climate scenario

Scenario	**t-stat**	
2°C Temperature Increase	1.213	-1.98<1.21<1.98
5°C Temperature Increase	3.211	-1.98<3.211>1.98
10% Precipitation Decrease	1.495	-1.98<1.49<1.98
20% Precipitation Decrease	2.643	-1.98<2.643>1.98

These values indicate that there is no significant difference for the 2°C temperature increase scenario, or the 10% decrease in precipitation scenario. However, there is a significant difference for the scenario with a 5°C temperature increase as well as for the scenario with 20% decrease in precipitation.

Chapter 6: Discussion

The results indicate that climate has had the largest effect on the discharge volumes and will continue to do so. Land-use change in this particular catchment has not influenced the discharge significantly for various reasons, which will be discussed in this chapter.

6.1. STREAM model performance

Previous studies that have used the STREAM (Spatial Tools for River Basins and Environment and Analysis of Management options) model, regard it as a capable method for investigating the hydrological response to either or both climate factors and land-use change (e.g. Aerts & Bouwer, 2002; Aerts *et al.,* 2011; Aerts *et al.*, 2005; Maina *et al.,* 2013). STREAM is a spatially distributed model, making it a complex model because, instead of looking at linear relationships, it evaluates the flow to streams by considering different parameters at different levels of influence (e.g. Aerts & Bouwer, 2002; Aerts *et al.,* 2011; Aerts *et al.*, 2005). This characteristic of the model made it well-suited for this study.

Apart from the capabilities of the model, researchers in the field are questioning whether using complex models such as STREAM is a viable method (Hughes, 2004; Cooper & Pilkey, 2008; Mileham *et al.*, 2009; Breuer *et al.,* 2009). However, based on the complex nature of the model, the information gathered from it is largely used for a holistic but descriptive view of the catchment's response to different environmental changes (Cooper & Pilkey, 2008). This does not diminish the value of the model, since the aim of the study was to gather information and test whether land-use and climate changes have affected the discharge volumes in the river, which was achieved. Several studies highlight the value of descriptive models, where the intrinsic nature of environmental processes are so complex that it is difficult to define the exact contribution of each individual factor (Hughes, 2004; Phillips, 2007; Cooper & Pilkey, 2008; Hughes, 2015). Models similar to STREAM are used in a more descriptive manner in order to understand the complex dynamics of the catchment system and how the fluvial dynamics are affected as a result of human-induced changes and climate change (Coulthard *et al.,* 2007 & Bracken *et al.*, 2013).

This study found the STREAM model's simulating performance to be satisfactory after calculating the coefficient of determination at a value of 0.63 and a Pearson correlation coefficient of 0.8. For a model's performance to be regarded as acceptable, a determination coefficient value and a correlation coefficient of more than 0.6 and more than 0.8 respectively are needed (Alansi *et al.,* 2009). Therefore, it was determined that the model has adequately simulated discharge volumes and could be used to determine the effects of changes in climate and land use. STREAM is used in this study to determine a more comprehensive view of the Amatigulu-Nyoni catchment processes and, as such, this model is considered to have performed well in establishing a descriptive and holistic view of the changes within the catchment's discharge volumes. This method is ideally suited as an initial investigation into catchment processes. Coulthard *et al.* (2007) and Bracken *et al.* (2013) agree that complex modelling studies should be the first step in improving management strategies.

What sets this model apart from others is its ability to model spatially distributed input layers, whilst considering several parameters and not only precipitation and land use. Spatially distributed models account for terrain data, making it more complex; however, it is also considered to be more accurate (Hughes 2015). Since the model is a complex model, it is also extremely useful in simulating different scenarios in land use and in climate conditions (Maina *et al.,* 2013). More complex models can include more parameters, enabling the model to determine which land uses might affect the catchment the most and in what degree it would do so. The model is an instrument that facilitates scenario analysis, therefore it is also able to determine the effect of higher temperatures as well as less rainfall, which represents a realistic prediction for parts of southern Africa (Aerts *et al.*, 1999; Pachauri *et al.*, 2014).

STREAM has been successfully applied to several European catchments as well as catchments in Asia, Africa and Madagascar (see: Aerts & Bouwer, 2002; Aerts *et al.,* 2011 Notebaert *et al.*, 2011a; 2011b; Maina *et al.,* 2013; Kiptala *et al.*, 2014). This study adds to the range of environments in which STREAM has been applied, to include the humid subtropical east coast of South Africa. One of the considerations of hydrological models such as STREAM was that it is was not known how these models would perform outside of northern and central Europe (van Rompaey *et al.,* 2005). This is therefore an important application of the model to see how the model would perform in different climate zones, especially since it was originally developed to model European catchments that would receive snow during winter.

However, some limitations were identified causing the model to perform marginally within the acceptable range in this case, such as poor data quality causing low-resolution calculations. Data availability is frequently considered as the largest constraint in hydrological studies (Nijssen *et al.,* 2001; Thomas *et al.,* 2010; Kiptala *et al.*, 2014). Difficulties in obtaining data are particularly evident in Africa and South Africa (Kiptala, *et al.*, 2014) which highlights the necessity for similar studies (Hughes, 2015). Since it is impractical and, in some cases improbable, to carry out studies that require extensive field observations, it is necessary to develop advanced methods to generate the information required to carry out similar studies (Kiptala *et al.,* 2014).

The data available for this study was limited and, in some cases, difficult to obtain. In order to complete this study, it was necessary to find aerial photographs dating back as far as possible, which was difficult, because even though some photographs date back as far as 1933, complete sequences for the catchment only started in 1964. Discharge data for the Amatikulu River may date back as far as 1965, but the data is fragmented, and to be able to use this data for model calibration, it was limited to measurements for the period between 1988-1992. Climatic data was gathered from several stations around the catchment area, where some of the stations have closed and opened at different periods, making it difficult to import into the model as is. Climate data should be imported into the model as a temporal and spatial entity as a series of matrices (Aerts *et al.*, 2005). However, all the necessary data was obtained and the model was adapted to be applied in the study area to perform the simulations needed to carry out this investigation.

The model simulation resolution is dependent on the lowest input parameter resolution (Aerts *et al.*, 1999). In this study, and most other similar studies, the model simulation capability is limited by climatic input parameters (as stated in: Aerts *et al.,* 1999; 2005; de Vente *et al.*, 2008, Notebaert *et al.*, 2011a; 2011b; Maina *et al.,* 2013). The climatic input parameters for this study were determined through interpolating weather data from stations near the catchment. Through using interpolated climate data, the accuracy and resolution of the findings are affected. The accuracy of interpolation is also dependent on how far apart weather stations are, influencing the resolution of weather data. When interpolating data over the surface, the topography of the area was not considered. In catchments, the topography can play a large role in certain weather phenomena, such as mountain winds, mist or precipitation and temperature. The reason that climate could not be imported as a spatially distributed parameter like all the other input parameters was because of the temporal nature of climate as well. The model calculates discharge volumes through using matrices with three dimensions, whereas climate as a spatially and temporally distributed entity has four dimensions. To account for this difficulty, the spatial character of climate was kept constant for the catchment. Considering that the catchment is relatively small (900km^2) and the alternative source of climate data is the CRU database which will give interpolated climate data on a 0.5° x 0.5° grid which covers an area of 2500km^2 (Aerts & Bouwer, 2002), the procedure followed gave a higher resolution of climate data.

As mentioned previously, data quality only partly explains model performance. Another factor to consider is the model setup and the format in which it requires the data. Different input parameter matrices are imported into the model and, together with the internally-generated parameters, the discharge volume is generated (refer to Figure 17: pg 40). The model calculates for each cell the runoff towards the river, where the volume is given at a single discharge point (Aerts *et al.*, 1999; 2002; Aerts *et al.,* 2011). Within this single statement, three extremely important factors need attention. When the model calculates the discharge volume, it calculates several other values first, which are then used to calculate discharge at a single point. It is for this reason that a warm-up period of five years is suggested (Aerts *et al.,* 2005). Runoff or flow direction is determined by the topography and slope, and the total volume of water routed is determined by precipitation, surface temperature and crop factor values (Aerts *et al.*, 1999; Aerts *et al.,* 2005).

The model further requires calibration parameters to be defined (see Table 9, pg 44), which will route fractions of the total volume of water available to certain allocated areas (runoff, groundwater or evapotranspiration). Thus, the calibration parameters are tweaked to simulate discharge volumes similar to actual measured discharge volumes. For example, the calibration parameter for the fraction of the total water in the system that is routed to groundwater (TOGWcal), is set manually between the values 0 and 1 (Aerts *et al.,* 2011). Since it is based on simulating the model as close to the actual values for discharge volumes as possible, this does not make the model inaccurate; however, this does mean that the actual fractions of these parameters might be different from reality. This could possibly create an uncertainty in the model output accuracy, because this fraction is not based on a predefined calculation using measured information or actual measured and tested data. However, since the calibration of the model was tested against actual measured discharge volumes, the accuracy of the calibration parameters was also tested, and it was able to simulate discharge volumes similar to those measured.

Crop factor values are used to determine the volume of water that will eventually run off into the river. Considering that the crop factor value is an index of how much water will run off and the amount of soil lost, it is acceptable to use crop factor values (Renard *et al.,* 1991). This indicates how susceptible the soil is to erosion, as the crop factor value represents the effectiveness of the land cover to let water infiltrate, or whether it will runoff with detached soil particles (Renard *et al.,* 1991). However, it should be noted that according to the crop factor values there is no distinction between urban/built-up land and bush/ shrubbery (Van Deursen & Kwadijk, 1994). Therefore, when determining the effect of land-use changes on the discharge volume of the catchment, the actual influence of urbanisation cannot be determined with STREAM, but an idea of the influence of such a land-use type can be gained. It is seen that there are differences in different crop factors, regardless of what that crop factor represents, which indicates that STREAM can be used in gaining a general understanding of the catchment processes, but more detailed investigations are still needed in determining the detailed influence of land use and land-use changes on catchment processes.

The internally generated parameters are part of the calibration process, calculated based on the previous simulations. Once again it is for this reason that it is necessary to use a calibration period that will simulate at least five years before the actual calibration period (Aerts *et al.,* 2005). The unfortunate reality of the study area was that the measured discharge data available (1965-1992) was fragmented. Once again, data availability influences the capability of the model to perform better. This problem has occurred in a previous study using the STREAM model in assessing the Perfume River, where it was recommended to have reliable and long-term discharge data (Aerts & Bouwer, 2002). To overcome this problem, the calibration period chosen to test model performance was determined by access to sufficient hydrological years of measured data were available (from 1988-1992).

Discharge volume for the catchment is calculated at a single point, or rather a single cell. The cell is referenced by the x;y cell co-ordinates. Although the discharge point also has x;y co-ordinates determined by the position of the discharge gauge, the position used in the model is a whole cell rather than a single point. The modelled discharge point for this study was set to include discharge from both the Nyoni and Amatigulu rivers, where the discharge gauge only measured the Amatigulu River discharge. This positioning of the discharge point in the model was deemed necessary since the aim of the study is to look at the discharge dynamics of both the Nyoni and Amatigulu rivers. Although the investigation seemed successful, it was noted in the Perfume River study that the exact position of the discharge gauge is necessary (Aerts & Bouwer, 2002). Considering that the calibration values were already within the accepted range, it validates the positioning of the discharge point for this study. However, positioning a gauge at the Amatigulu and Nyoni confluence, to be able to get exact measurements for the combined river flow, will improve the accuracy of the calibration.

When considering all of the above, it is still considered that STREAM has performed acceptably for the purpose of the study. The number of limitations mentioned were not necessarily based on poor model design, but more on limitations due to data availability. Once again, this was also found in another study done in Africa, where STREAM was modified to accommodate these limitations (Kiptala *et al.*, 2014). When Maina *et al.* (2013) applied the model, it was found that it was an easy-to-use model and that it could evaluate the processes affecting the catchment and determined that the largest influence in the catchment would be deforestation. Hydrological models are considered useful in investigating the complex nature of catchments, and this model performed well within the context of gaining a holistic understanding of the processes involved in the Amatigulu-Nyoni catchment.

6.2. The effect of changing land use on discharge

Several studies had contradictory results when considering the impact of anthropogenic influences, such as land use, on catchments (for example: Longhitano & Colella, 2007; Ma *et al.,* 2008; Park *et.al.,* 2011; Liu *et al.,* 2014; Kong *et al.,* 2016). Kong *et al.* (2016) found that human activities had the largest influence in the decreased runoff rate. In another study, the combination of land-use changes were found to have resulted in changes in river morphology, which have altered the hydrological process (Liu *et al.,* 2014).

One of the focus areas in this study was the influence of land use and land-use change on the Amatigulu-Nyoni catchment. It was therefore necessary to determine the land use for the specified periods. Although the model includes the land-use parameter in the calculations by means of crop factor values, land-use categories were used to describe the change between land uses and the distribution thereof. A study into the world's major river catchment processes used this particular method to determine the effect of land use and climate change; however, this study focused more on the effects of climate change (Aerts *et al.,* 2006). Another investigation using the STREAM model (Aerts & Bouwer, 2002) considered the soil water holding capacity, crop factors and climate (present and future), and found that all these factors increased the soil aridity whilst decreasing the discharge volumes of the catchment. In both studies it is evident that land use is not the major driver behind the changes noted in the discharge dynamics, although it is noted to affect the amount of runoff a catchment will experience (Aerts & Bouwer, 2002). Maina *et al.* (2013) also successfully applied this method of investigating the influence of climate and land use and found that land use had a significant impact on catchment discharge dynamics.

One of the largest changes observed in the Amatikulu-Nyoni catchment is that of conversion of grassland to cultivated land. Since it is assumed that land use would change to suit a growing population, this change is not that surprising. Deforestation for agricultural and urban land is one of the largest noted changes in land use and will have different scales of impact within the catchment (Syvitski *et al.,* 2005; Syvitski & Milliman, 2007, Nejadhashemi *et al.,* 2011). However, what is more surprising is that measured urban areas have decreased between 1990 and 2013. A reason for this might be the method of land-use classification. Since the study focuses on land-use change between the periods of 1990 and 2013 because of the similar method of land-use classification, this explanation seems unlikely. It is, however, worth mentioning that the 2013 land-use classification was done before the 1990 classification using satellite imagery available for those periods. The method of classification could have been refined by the time 1990 land use has been classified in 2015.

Almost two thirds of the catchment has stayed unchanged, with the largest changes seen where grasslands have changed to cultivated land. Seeing that a large part of the catchment contributes to the sugarcane industry, this change seems understandable. Grasslands are much easier to transform into sugarcane fields than bush or forests. The opposite seems to be true as well, where previous croplands have changed to grasslands. This is could be an indication of abandoned land or croplands now serving as grazing land for cattle. In addition, some of the previously built-up land seems to have been transformed into cultivated land. This can be explained by the refinement of land-use classification techniques, where the small patches of farmland in between houses were previously considered built-up and now it can actually be classified as cultivated. On the other hand, previously built-up land could have been transformed into cultivated land; however, this seems unlikely. All these changes contribute to cultivated land being the largest growth in land use.

Even with a third of the catchment having undergone changes in land use, it was determined that there was no significant difference in the discharge volumes calculated based on land-use maps for 1964, 1990 or 2013. This thus means that the differences in land use established between these years do not significantly influence discharge volumes in the catchment, which correlates with the previous studies conducted by Aerts and Bouwer (2002) and Aerts *et al.* (2006). However, this finding contradicts a number of studies that have used the STREAM and ACRU models which found that land use would have the greater effect on the river (Maina *et al.*, 2013; Rebelo *et al.*, 2015). It is clear that rivers can react differently as a result of the different characteristics within the catchment (Notebaert *et al.,* 2018).

Several explanations consider the insignificant impact of land use on discharge volumes. The first is that slight land-use changes, such as that experienced within these decades, do not impact the catchment runoff and eventual discharge to the extent that it could be observed. Another explanation could be that using crop factor values hides the actual change in land use to a large extent. Crop factor values might include two or three extremely different land uses; however, it actually considers the soil's susceptibility to erosion (Renard *et al.,* 1991). What this implies is that although two extreme land-use types could fall within the same crop factor value, the model calculates how much water and sediments will be routed to the river as influenced by the crop factors.

To test how the model output will change from the distributed land use changed to single crop factors, single crop factor layers were used in the model simulation. Changes were seen between the simulations. The changing of crop factor values between simulations resulted in differences in peak flow and low flow frequencies. The simulation closest to reality is seen when the land use is completely covered by land-use types falling within a crop factor value of 0.8, although the volumes might be slightly less in this scenario. Considering that the mean crop factor value for the values between 0.3-1.1 is 0.7, the model simulation for the 0.8 crop factor would result in discharge values similar to a distributed crop factor simulation. Since this scenario follows the distributed crop factor scenario most closely, and the types of land uses affect the actual water runoff to the river the least, it is important to consider which land-use types these crop factors refer to for possible catchment management scenarios. Land uses classified in the 0.8 crop factor value include shrubland (bush), urban or built-up, grasslands and mixed grassland and shrubland, which is an interesting finding, since deforestation and urbanisation have been found to increase surface runoff (Ward *et al.*, 2009; Germer *et al.,* 2010; Notebaert, 2011b).

More frequent and higher peak flow conditions in the discharge volumes of the Amatikulu-Nyoni catchment are observed for crop factor values of 0.5 and 0.3. Crop factor values of 0.5 and 0.3 indicate barren land or land covered by water. Considering that barren land would most likely be compacted land with little infiltration capacity or impermeable rock preventing any form of vegetation to grow, and that land covered by water is already saturated, runoff to the river would be higher. Thomas *et al.* (2010) also found that the runoff discharge loads would increase with increases in compacted, channelized or impervious land surfaces. Converting land to barren land might result in more intense erosional events, causing more sediments to enter the river. Downstream effects would be felt in the estuary, where increased sediment deposition downstream might cause a permanent closure of the mouth (Cooper, 1993; 2001; Green *et al.*, 2013; Jackson *et al.,* 2013).

Low flow and less frequent peak flow conditions will be experienced when the catchment is covered by land uses with crop factor values of 1.0 and 1.1. For this scenario to be likely, the catchment has to be completely covered by cultivated land, wetlands, forests or plantations. If crops, trees and wetlands cover the land, infiltration would be very high, therefore, little water would be available for runoff. Rebelo *et al.* (2015) found that with an overall decline in water and reduction in flood attenuation, the catchment degraded. Eventual effects of less water in the catchment would be felt largely in the estuary, especially since the Amatikulu estuary is a river-dominated estuary (Cooper 1993; 2001; Green *et al.*, 2013; Jackson *et al.,* 2013). The Amatikulu mouth would also become permanently closed to the sea since there would not be enough water to maintain the channel.

Whether there are high discharge volumes or low discharge volumes observed, it is seen that the estuary will become permanently closed to the sea. Permanent closure of the mouth has impacts on the salt-to-freshwater balance of the estuary, affecting the ecosystem health (Cooper, 1993; 2001; Grange *et al.,* 2000; Bond *et al.*, 2001; Green *et al.*, 2013). Not only will the change in discharge volumes influence the ecosystem health, the morphology of the river and river inlet will also be affected, as seen in other studies that have suggested that upland land uses will affect the morphology of related landscapes (Cooper, 1993; 2001; Grange *et al.,* 2000; Longhitano & Colella, 2007; Pelacani *et al.*, 2008). It is found that the largest effect of crop factors on the discharge in this study is seen in the land-use scenarios that will cause the most runoff into the river, or those scenarios that result in the most infiltration. Although land use does not seem to influence this catchment as yet, land-use change will likely result in the degradation of the catchment eventually, as was found in several other studies in a South African context (Thomas *et al.,* 2010; Kabanda & Palamuleni, 2013; Rebelo *et al.,* 2015).

6.3. The effect of climate on discharge

The role that climate plays in environmental or landscape change has been considered by numerous studies to be one of the most important drivers of environmental change (see for example: Middlekoop *et al.,* 2001; Vandenberghe, 2003; van Griensven *et al.*, 2006; Ma *et al.,* 2008; Ward, 2009; Zang & Lu, 2009; Notebaert & Verstraeten, 2010). In these studies, it was found that climate either had a major influence on environmental change (Coulthard & Macklin, 2001; Ma *et al.,* 2008; te Linde *et al.,* 2008; Kiss & Blanka, 2012; Cuo *et al.,* 2013) or had a minimal impact (Vandenberghe, 2003; Bouwer *et al.,* 2006; Maina *et al.*, 2013).

Considering that the aim of this study was to identify whether climate or land-use change had the largest impact on discharge volumes, it was deemed necessary to evaluate any significant changes in the climate of the area. An evaluation of temperatures and precipitation records from the earliest possible recorded dates, dating from 1930, was completed. The general assumption for climatic and climate change studies is a warming climate (Park *et al.,* 2011; Moser *et al.,* 2012) and, in this case study it seemed likely. Although one assumes a drying climate alongside this warming trend, the overall global precipitation has increased since the start of the 20th century (Cong *et al.,* 2010). However, this global trend is not spatially or temporally uniform (Cong *et al.,* 2010). Increasing temperatures will have an indirect effect on the catchment through affecting the evapotranspiration (Kiss & Blanka, 2012; Cuo *et al.,* 2013). Within the Amatigulu-Nyoni catchment, it was observed that there was an increase in precipitation, therefore it is assumed that the increased temperatures caused higher evaporation rates leading to increased precipitation (Kiss & Blanka, 2012; Cuo *et al.,* 2013).

A change was observed in the period between 2010-2015, during which the area seemed to experience extremely dry conditions together with increased temperatures. In a previous study, it was noted that increased temperatures would lead to reduced water resources although it still led to higher evaporation rates (Cuo *et al.,* 2013). There is an overall increasing trend in precipitation noted in line with the overall global trend (Cuo *et al.,* 2013). The catchment follows an almost decadal cycle of wet and dry periods, therefore the past few dry years could be part of the dry cycle. It is necessary to note that even though this has been the driest period since 1930, it has not been the warmest.

It is extremely important to investigate how different weather patterns affect water resources so as to be able to identify risk conditions. Changes in the volume and intensity of precipitation have a control on the hydrological characteristics such as river morphology in a catchment, since precipitation changes will control runoff or infiltration rates. Temperature changes also have an effect, although indirect (Kiss & Blanca, 2012). Three extremely high peak flows were recorded within the study period (1964-2015), all of which occurred after dry periods followed by higher rainfall events. It can therefore be assumed that after a dry period, high peak flows can be expected once the wet period starts. This is a likely case since dry conditions result in the compaction and cementation of soils, leading to less infiltration and higher runoff, which has a similar result when creating impermeable surfaces (Thomas *et al.,* 2010). Since runoff is considered to affect the discharge regime (Middelkoop *et al.,* 2001; Choi & Deal, 2008), increased runoff in the catchment would lead to higher discharge volumes in the river.

Further investigations focused on the climatic data from 1964 since this period coincides with the period for which there is discharge and land-use data, and aimed at establishing the relationships between climate and discharge. Based on the observations from the graphs, there seems to be a clear relationship between climatic parameters and discharge volumes, which strongly agrees with a number of studies that found that climate has the dominant impact on discharge volumes (for example see: Aerts *et al.,* 2006; Notebaert, *et al.,* 2011). It is clear from the literature that there is a definite relationship, and Nejadhashemi *et al.* (2011) recognise that climate change is the key driver for increased streamflow. It was observed that within decadal periods, a direct influence between temperature and precipitation was identified. On a finer scale, it was observed that the response to increased temperatures resulted in increased precipitation close to two years later. A more direct, however delayed, response to the increased precipitation was seen in the peak discharge volumes close to a year later. From Kong *et al*. (2016) it is established that the relationship between precipitation and runoff is asynchronous.

Since observations alone cannot completely describe the relationship between two entities, a simple correlation test between discharge volumes and individual climate parameters was performed. This test revealed that a strong correlation between precipitation and discharge volumes, similar to what Kong *et al.* (2016) found. A poor negative correlation was found between temperature and discharge volumes. This means that there is no reason to believe that the temperatures would influence the volume of discharges and, if any, it has a negative influence. Therefore, if in some cases the temperature would be the cause for the discharge volume observed, it would be that, as the temperatures increase, the discharge volumes would decrease, which is supported by the study of Cuo *et al.* (2013). However, a previous study mentioned that, as a result of increased global surface temperatures, anomalies on the precipitation and evaporation rates occurred, which in turn could affect river flow (Khaliq *et al.,* 2009). Kiss and Blanka (2012) mention that temperature has an indirect impact in a river, because temperature changes affect evapotranspiration. In this case, higher temperatures would lead to higher evaporation and therefore less water on the land surface. This is contradictory to the previous observation where higher temperatures caused higher precipitation following higher discharge, indicating that there are more processes involved that have not been considered in this study.

A poor negative correlation was found between precipitation and temperatures; however, a positive relationship between the temperature and precipitation were observed visually in the graphs. An explanation for this discontinuity in observations can be that the graph established a trend line based on summer precipitation and summer temperatures (January measurements), whereas the Pearson correlation test was performed on the complete distribution, which includes every season’s precipitation and temperature values. Temperature affects the amount of precipitation through the rate of evapotranspiration, which would be highest in the summer months (Kiss & Blanka, 2012; Cuo *et al.,* 2013).

Several studies have found that the anticipated changes in climate and land use will intensify the effects on the environment, and will affect the resilience of these environments to human or climatic stressors (Schulze, 2000; Scavia *et al.,* 2002; Dymond *et al.,* 2010; Ma *et al.,* 2010; Notebaert *et al.*, 2011a, 2011b). The effect on the coastal environment in this case could have similar consequences (Klein *et al.,* 2001). From the observations in this study, it is assumed that an increased temperature, such as those experienced, might result in higher precipitation in the study area, which will eventually cause higher water volumes in the river (Kong *et al.,* 2016). However, from the correlation tests, it is unclear what the result in precipitation on this catchment would be if the temperatures were to change. Although it is unknown what increasing temperatures might result in, another study did find that water availability would be affected, as climate systems are interactive with the hydrological cycle (Jiang *et al.,* 2007).

The change in discharge volumes could either force the river mouth to be permanently open or closed to the sea (Cooper 1993; 2001). The possible increase in precipitation could result in higher volumes of water routed to the mouth, resulting in an open mouth. However, when higher volumes of water are routed towards the river, more erosion could take place, since climate is one of the major factors controlling erosion rates (Jansson, 1988). The river would have more energy and would be able to take a greater load downstream. The effect of this would be visible in the estuary, where the increased sediments carried downstream will be deposited at the river mouth. Together with the increased longshore drift forcing coastal sediments onto the beach, the river mouth could be pushed further north.

Future climate predictions were included in this study to evaluate the impact of climate further. To identify individual implications, the precipitation was kept constant when the increased temperature scenarios were simulated, and vice versa. The observed trend shows an increase in temperature and precipitation; however, the IPCC's climate scenarios considered a decrease in precipitation with increasing temperatures (Pachauri *et al.*, 2014). These are important scenarios to test, since it was found that in the last 5 years, a decrease in precipitation was observed alongside an increasing temperature. Although it is only observed for the period from 2010-2015, this could be a permanent shift in the area's climate.

In the simulation of these scenarios, it was found that as precipitation decreased, the discharge volumes also decreased, highlighting the strong correlation between precipitation and discharge volumes. However, reducing the amount of precipitation by the worst-case scenario (20%) does not result in the lowest discharge volumes. The most extreme result is seen when temperature is increased 5°C; discharge volumes drastically decreased to lowest calculated volumes. Cuo *et al.* (2013) also found that temperature changes have impacted the water balance the most. Therefore, by only increasing the temperature, evapotranspiration increased, but precipitation did not increase as a result. With decreased precipitation associated with climate change, South Africa might be pushed into a more arid zone (Pachauri *et al.*, 2014). Thus, climate change directly influences the estuary, possibly forcing the river mouth to close permanently since less water will reach the mouth (Cooper, 1993; 2001; Green *et al.*, 2013).

Chapter 7: Conclusion

The basic aim of the research was to compare and evaluate whether climate or land use change would exert the largest influence on the discharge volumes of the Amatikulu-Nyoni catchment. This was achieved through studying the different aspects individually and evaluating each influence independently. Overall, it is clear that climate has had the largest impact on the Amatikulu-Nyoni catchment discharge volumes, which is likely to continue based on the IPCC's projections. Considering that other researchers have found that the impact of land use, and more specifically deforestation, will be larger than that of climate (Kabanda & Palamuleni, 2013; Maina *et al.*, 2013; Rebelo *et al.*, 2015), the need for similar detailed analysis of different catchments is highlighted.

Despite the limitations, it was possible to adapt the STREAM model to conduct this research. The model performed well and could be calibrated to simulate the discharge volumes for the catchment under different land-use and climate scenarios, which enabled the investigation into the effects of present-day climate and land use as well as the effect of climate change and different land-use covers. Although the model performed well, there were difficulties mainly caused as a result of data availability and model complexity. To be able to complete more accurate water modelling studies, it is continuously necessary to update and improve the data necessary to investigate hydrological processes (Thomas *et al.*, 2010).

Land-use changes observed for 1964 to 2013 had no significant impact on the discharge volumes of the catchment. Similar studies have found that land-use changes have resulted in the degradation of catchments (Maina *et al.*, 2013; Rebelo *et al.*, 2015). These results however, might reflect regional impacts for specific catchments, which proves that because of the heterogeneous impacts on different catchments, there is a need for regional as well as more local catchment scale investigations. Most researchers studying catchment processes (Schulze, 2000; Kiptala et al., 2014; Kling et al., 2014) support this suggestion.

For land use to have a remarkable effect on the discharge volumes, it is necessary to change completely, whereas with climate, even the small changes would influence the river discharge dynamics. These changes will significantly affect the river dynamics, which will affect the river morphology in the end. Currently the observed coastal changes are attributed to longshore drift and, since river-dominated estuaries define this part of the coastline, the alterations in river discharges will further change estuarine environments and coastal morphology (Cooper, 1993; Smith *et al.,* 2010; Bond *et al.,* 2013). Most of the crop factor scenarios, however different from one another, end up forcing the river mouth to be permanently closed. When land cover consists mainly of cultivated land or forests, more infiltration occurs, with less runoff. This results in lower discharge volume, which will eventually result in the permanent closure of the mouth. Alternatively, if land use is completely transformed into barren ground, or water bodies (saturated ground) it results in more runoff and higher discharge volumes in the river. Higher peak flows have higher erosional potential, thus more sediments can be carried towards the river mouth and these sediments can cause a permanent closure of the inlet when deposited, except if the discharge carries the sediments into the sea. Another aspect to investigate is whether the sediments will be deposited at the mouth be pushed into the sea.

Climate has a significant impact on the discharge volumes. It was found that as the temperature increases, a delayed response in precipitation would cause higher discharges. The higher temperatures cause higher evaporation and within two years increased precipitation was recorded. However, the increase in temperature alone will not result in increased discharge volume. It is seen from the scenarios that increasing temperature without altering amount of precipitation, will decrease discharge volumes significantly. An increase of 5°C will result in the lowest discharge volumes, therefore affecting the river most. The effect of decreased discharge volumes has been mentioned already, and therefore an increased temperature with no change in precipitation will likely cause the river mouth to close permanently as well.

Although this study has not investigated the combined effect of the crop factor scenarios and the IPCCs scenarios, the combination of climate and land-use changes could force hydrological changes. This assumption is based on the results found when either altering climate, or completely altering land use. When looking at the literature, several studies support this finding (Longhitano & Colella, 2007; Paris & Chérubin, 2008). Just from assuming the degree to which projected climate and land-use scenarios would influence the river discharge, it is suggested that investigations into the combined effect of land-use change and climate change should be undertaken.

When all of the above is considered, the STREAM model can be used for preliminary catchment investigations to determine simple correlations between land use and climate. It is, however, not detailed enough to consider using the STREAM model for detailed analysis of catchment changes. Adaptations to the model should be made to include a more refined method of including different land uses. As with many other studies, it is recommended that more hydrological studies should be done continuously to improve our understanding of hydrological systems.

Future studies could also focus on attaining better-quality data and more complete data for observed climate and measured discharge volumes. It is further recommended that studies determine whether another method of implementing land use as a parameter in the STREAM model, or the combination of two models would be more accurate. More research needs to be done on South African catchments, especially considering the interior and western parts of the country in the light of projected climate changes.

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Appendix A: Type and amount of land-use changes in the Amitukulu-Nyoni catchment for the period between 1990-2013

Land-use Change	**% Change**
Barren to Farmland/ Cultivated	0.01
Barren to Forest/ Plantations	0.00
Barren to Grassland/ Bush	0.05
Barren to Urban/ Built-up	0.00
Barren to Water/ Wetlands	0.00
Farmland/ Cultivated to Barren	0.01
Farmland/ Cultivated to Forest/ Plantations	0.31
Farmland/ Cultivated to Grassland/ Bush	4.42
Farmland/ Cultivated to Urban/ Built-up	0.58
Farmland/ Cultivated to Water/ Wetlands	0.12
Forest/ Plantations to Barren	0.01
Forest/ Plantations to Farmland/ Cultivated	1.63
Forest/ Plantations to Grassland/ Bush	3.09
Forest/ Plantations to Urban/ Built-up	0.89
Forest/ Plantations to Water/ Wetlands	0.07
Grassland/ Bush to Barren	0.02
Grassland/ Bush to Farmland/ Cultivated	7.27
Grassland/ Bush to Forest/ Plantations	0.83
Grassland/ Bush to Urban/ Built-up	0.86
Grassland/ Bush to Water/ Wetlands	0.32
No change	71.66
Urban/ Built-up to Barren	0.00
Urban/ Built-up to Farmland/ Cultivated	4.16
Urban/ Built-up to Forest/ Plantations	0.20
Urban/ Built-up to Grassland/ Bush	2.09
Urban/ Built-up to Water/ Wetlands	0.04
Water/ Wetlands to Barren	0.01
Water/ Wetlands to Farmland/ Cultivated	0.45
Water/ Wetlands to Forest/ Plantations	0.21
Water/ Wetlands to Grassland/ Bush	0.62
Water/ Wetlands to Urban/ Built-up	0.05

Appendix B: Discharge volumes based on the IPCC's RCP projections (Pachauri *et al.*, 2014)

1965-1974	**Measured Temperature & Precipitation**	**2°C Annual Temperature Increase**	**5°C Annual Temperature Increase**	**10% Annual Precipitation Decrease**	**20% Annual Precipitation Decrease**
Precipitation (mm)	991.51	991.51	991.51	892.36	793.21
Temperature (°C)	20.36	20.53	20.78	20.36	20.36
Average Annual Discharge Volume (millions m^3)	24.10	18.63	6.92	15.41	11.62
Minimum Discharge Volume (millions m^3)	2.79E-04	2.26E-04	2.46E-07	2.21E-04	1.06E-04
Maximum Discharge Volume (millions m^3)	76.13	65.80	44.49	50.13	51.36
P(T<=t) two-tail		0.61	0.07	0.37	0.21
t Critical two-tail		2.09	2.13	2.11	2.10
1975-1984	**Measured Temperature & Precipitation**	**2°C Annual Temperature Increase**	**5°C Annual Temperature Increase**	**10% Annual Precipitation Decrease**	**20% Annual Precipitation Decrease**
Precipitation (mm)	1037.77	1037.77	1037.77	933.99	830.21
Temperature (°C)	20.60	20.77	21.02	20.60	20.60
Average Annual Discharge Volume (millions m^3)	40.94	36.11	25.63	34.21	28.35
Minimum Discharge Volume (millions m^3)	3.17E-08	4.87E-10	1.22E-14	5.68E-10	5.16E-12
Maximum Discharge Volume (millions m^3)	108.40	103.61	89.72	99.17	88.80
P(T<=t) two-tail		0.80	0.41	0.72	0.49
t Critical two-tail		2.10	2.11	2.10	2.11
1985-1994	**Measured Temperature & Precipitation**	**2°C Annual Temperature Increase**	**5°C Annual Temperature Increase**	**10% Annual Precipitation Decrease**	**20% Annual Precipitation Decrease**
Precipitation (mm)	996.79	996.79	996.79	897.11	797.43
Temperature (°C)	20.12	20.29	20.54	20.12	20.12
Average Annual Discharge Volume (millions m^3)	43.61	31.33	22.30	31.65	24.72
Minimum Discharge Volume (millions m^3)	4.66E-02	3.25E-02	1.44E-07	3.13E-02	1.12E-02
Maximum Discharge Volume (millions m^3)	117.07	76.64	58.63	74.07	62.01
P(T<=t) two-tail		0.38	0.12	0.39	0.17
t Critical two-tail		2.12	2.13	2.12	2.13
1995-2004	**Measured Temperature & Precipitation**	**2°C Annual Temperature Increase**	**5°C Annual Temperature Increase**	**10% Annual Precipitation Decrease**	**20% Annual Precipitation Decrease**
Precipitation (mm)	1041.39	1041.39	1041.39	937.25	833.12
Temperature (°C)	20.78	20.95	21.20	20.78	20.78
Average Annual Discharge Volume (millions m^3)	36.52	29.18	19.38	27.84	21.09
Minimum Discharge Volume (millions m^3)	9.75E-03	4.80E-03	1.37E-04	5.12E-03	1.45E-04
Maximum Discharge Volume (millions $m^{3)}$	82.75	78.32	67.75	75.01	67.27
P(T<=t) two-tail		0.57	0.18	0.50	0.22
t Critical two-tail		2.10	2.11	2.10	2.11
2005-2015	**Measured Temperature & Precipitation**	**2°C Annual Temperature Increase**	**5°C Annual Temperature Increase**	**10% Annual Precipitation Decrease**	**20% Annual Precipitation Decrease**
Precipitation (mm)	818.23	818.23	818.23	736.41	654.58
Temperature (°C)	20.66	20.82	21.07	20.66	20.66
Average Annual Discharge Volume (millions m^3)	11.40	7.80	0.39	7.42	2.95
Minimum Discharge Volume (millions m^3)	9.11E-07	9.11E-07	9.11E-07	9.11E-07	9.11E-07
Maximum Discharge Volume (millions m^3)	47.42	38.75	1.95	37.45	24.21
P(T<=t) two-tail		0.55	0.04	0.50	0.12
t Critical two-tail		2.09	2.23	2.09	2.14