DEVELOPMENT OF A CONNECTIVITY INDEX TO ASSESS AQUATIC MACROINVERTEBRATE SPECIES VULNERABILITY TO THERMAL CHANGE: A CASE STUDY IN KWAZULU-NATAL PROVINCE

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ABSTRACT

Connectivity of river systems is a critical ecological component affecting not only the integrity of aquatic systems but also freshwater species' habitat, community structure, migration and other life activities such as feeding rate and reproduction. Connectivity is a product of longitudinal and lateral conditions of rivers that in turn impact on flow and water temperature time series patterns (temporal connectivity). No comprehensive connectivity index of rivers has previously been developed for South Africa's KwaZulu-Natal Province. The aims of this study were to develop a connectivity index for selected main rivers in KwaZulu-Natal, where free-flowing rivers represent full connectivity, and to assess quaternary catchments which would most be vulnerable to the impacts of increased water temperatures in response to climate change in terms of aquatic biota.

A connectivity index at quaternary catchment scale was developed for main rivers in KZN based on in-stream barriers, land cover fragmentation and small dams density. The temporal dimension of connectivity involved an examination of stream flow and water temperature changes at selected stations based on comparisons of data from before and after construction of in-stream barriers. Temporal connectivity was incorporated into the longitudinal connectivity index score using the concept of reset distance. Reset distance was calculated based on mean daily flow volumes and the distance between impoundments at each of the selected quaternary catchments. Based on these assessments, catchments likely to be most vulnerable to species community changes were detected as a function of connectivity of rivers and slope gradient of streams. The assumption was that aquatic macroinvertebrate species are likely to be most impacted by rapid thermal change (based on temperature lapse rates) in the high altitude catchments particularly where such rivers have reduced connectivity.

The uMngeni catchment emerged with the most disconnected river in the province due to its closely located in-stream barriers and long distance recovery potential of flow. The quaternary catchment with lowest lateral connectivity also occurred within the uMngeni catchment. It is concluded that catchment management authorities should consider both connectivity and vulnerability (climate change) assessments of river systems as a tool negotiating for sustainable conservation plan of aquatic species and ecological integrity of rivers.

PREFACE

The work described in this dissertation was carried out in the Centre for Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg from October 2012 to August 2014, under the supervision of Dr. NA. Rivers-Moore (Research Fellow – Centre for Water Resources Research, UKZN) and co-supervisor Dr. Helen Dallas (Freshwater Research Centre).

This study represents original work by the author and has not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others, it is duly acknowledged in the text.

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Mr. Ramulifho Pfananani Anania Date

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Dr. NA Rivers-Moore (Supervisor) Date

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Dr. H. Dallas (Co-Supervisor) Date

DECLARATION

I, ………..……………………………………………declare that:

1. The research reported in this dissertation, except where otherwise indicated, is my original research.
2. This dissertation has not been submitted for any degree or examination at any other university.
3. This dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
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Signature: …………………………… Date: ....
Dr. H. Dallas (Co-Supervisor)

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List of Acronyms

ACCESS	Applied Centre for Climate and Earth Systems Science
ARC	Agricultural Research Council
DLA-CDSM	Department of Land Affairs: Chief Directorate of Surveys and Mapping
DRD-LR	Department of Rural Development and Land Reform
DRIFT	Downstream Response to Imposed Flow Transformation
DWA	Department of Water Affairs
EKZNW	Ezemvelo KwaZulu-Natal Wildlife
ESRI	Environmental Systems Research Institute
FRC	Freshwater Research Centre
GIS	Geographic Information System
HIS	Hydrological Information System
ICF	Index of River Connectivity
IHA	Indicators of Hydrologic Alteration
ILF	Index of Land-use Fragmentation
IPCC	Intergovernmental Panel on Climate Change
ITA	Indicators of Thermal Alteration
KZN	KwaZulu-Natal Province
NFEPA	National Freshwater Ecosystem Priority Area
NLC	National Land Cover
PES	Present Ecological State
RCC	River Continuum Concept

RDI	River Disturbance Index
SAEON	South African Environmental Observation Network
SANBI	South African National Biodiversity Institute
SDD	Small Dam Density
TNC	The Nature Conservancy
WCD	World Commission on Dams
WMA	Water Management Areas
WRC	Water Research Commission
WWF	World Wild Fund for Nature

Glossary of Terms

Many definitions in the science world are not widely accepted, and are therefore used differently by different authors. In this current study, the following alphabetically listed terms and their definitions are used:

Ecological Integrity - the undiminished ability of an ecosystem to continue its natural path of evolution, its normal transition over time, and its successional recovery from perturbations (Nel *et al.*, 2009).

Environmental Flow - a set of operational rules for water resource schemes to limit adverse ecological impacts to acceptable levels which may be designed for a river subject to a new water resource development or more commonly, a historical development for which insufficient consideration has been given to the ecological impacts (Arthington and Zalucki, 1998).

Free-flowing river - any river that flows undisturbed from its source to its mouth, either at the coast, an inland sea or at the confluence with a larger river, without encountering any dams, weirs or barrages and without being hemmed in by dykes or levees (WWF, 2006).

Gauging Station - A gauging station is a site on a river which has been selected, equipped and operated to provide the basic data from which systematic records of water level (stage) and discharge may be derived (Wessels and Rooseboom, 2009).

Impoundments - Dams, weirs, lakes and other in-stream structural barriers break the natural continuum of a river, converting it into a sequence of isolated sections (Stein *et al.*, 2002).

Land Cover - the physical surface of the earth, including various combinations of vegetation types, soils, exposed rocks and water bodies as well as anthropogenic elements, such as agriculture and built environments (DRD-LR, 2009).

Land Use - the purpose to which the land cover is committed or rather man's activities on land which are directly related to the land (DRD-LR, 2009).

Recovery Distance - is the length of stream required for a particular parameter to recover to levels which prevailed in the unregulated system (Palmer and O'Keeffe, 1989).

River connectivity - the degree of hydrological-mediated transfer of mass, momentum, energy or organism within or between spatially connected upstream and downstream extent (Freeman *et al*., 2007). The connectivity of a river is facilitated the movement of water between the river channel and the floodplain, and between the surface and the subsurface compartments (Ward *et al*., 1999).

Resilience - a more traditional meaning, is as a measure of resistance to disturbance and the speed of return to the equilibrium state of an ecosystem (Rieman and Isaak 2010).

Vulnerability - is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes (Parry *et al.,* 2007).

Large dam - a large dam has a height of 15 metres or higher. Dams between 5 and 15 metres with a reservoir volume of more than 3 million cubic metres are also classified as large dams (Mantel *et al.*, 2010).

CHAPTER ONE

INTRODUCTION

1.1 Background

Connectivity of rivers is the sum of the degree in which channels or streams are connected and the degree of free species movement throughout a river system (Fryirs *et al.,* 2006). Connectivity of a river system is essential for maintaining ecological integrity of river ecosystems. Ecological integrity defines the undiminished ability of an ecosystem to continue with its natural path of evolution, its normal transition overtime, and its successional recovery from disturbances (Driver *et al.,* 2011; WWF, 2006). Relative to terrestrial integrity, the physical variables within a connected river system, from source to sea extent, should present a continuous gradient of conditions including width, depth, velocity, flow volume, temperature and entropy gain (Vannote *et al*., 1980). However, stream alteration appears as one of the most critical challenges facing aquatic ecosystems. Stream alteration has the potential to reduce the natural connectivity of rivers hence the ecological integrity of these aquatic systems. In this way, severe aquatic impacts occur where river systems are affected by flow regulations and landscape changes as a result of land use and other modification such as dams, and levees (Freeman *et al*., 2007).

South African river systems are no exception from these modifications such as building of dams, regulations and contaminations by pollutants relative to global trends, due to the strong influence of human civilization and development factors including interbasin transfers and land-use changes which alter flow and sediment regimes (Driver *et al.,* 2011; Rivers-Moore *et al*., 2007). These factors break the hydrological connectivity between river channels and floodplain environment, and between surface and subsurface compartments (Ward *et al*., 1999). Furthermore, these factors act as barriers to the migration of aquatic and semi-aquatic species, which affect the population biology of migrating species, by causing local extinctions due to the lack of dispersion and recolonisation, genetic isolation, impediments to reproduction and non-accessibility of feeding resources and shelter areas (Sola *et al*., 2011).

Climatic changes have been linked to decreasing connectivity of rivers globally. According to Lawler (2009) rising air temperatures and changing patterns of precipitation have altered temporal connectivity of rivers, due to the resultant impacts on stream flow and water temperature patterns over a specified period of time (Caissie, 2006; Richter *et al.,* 1997). Several long term studies have documented changes in the trends of climatic warming and increased frequencies of droughts and floods which threaten freshwater systems' integrity and connectivity (Bush *et al.,* 2012; Domisch, *at el.,* 2012; Landis *et al.,* 2013). In this way, water temperature and stream flow patterns not only affect the temporal connectivity of rivers, but also potentially impact on the distribution patterns of aquatic and semi-aquatic species, through their effects on reproduction, growth, and metabolic rates (Dallas and Rivers-Moore, 2012a). Various studies such as by Chessman, 2012; Dallas 2008; Dallas and Rivers-Moore, 2012b; Durance and Ormerod, 2007; McCarty, 2001, have reviewed this issue and found that effects are typically species-specific, where cold-water organisms are generally negatively affected and warm-water organisms positively affected.

Lack of connectivity between catchments could severely hinder the adaptation response of affected species (Bush *et al.,* 2012) and assuming that species' capacity for dispersal is the most critical determinant of vulnerability (Chessman, 2012). An assessment of connectivity of rivers, i.e. both river flows and water temperature patterns, and availability of barriers is therefore important for effective protection and management of freshwater ecosystems (Dallas and Rivers-Moore, 2012b; Januchowski-Hartley *et al.,* 2013; Sola *et al.,* 2011). According to Fryirs *et al*. (2006) connectivity assessments is best presented by the degree in which channels or streams are connected and degree of free species movement throughout a river system. This enables prediction of the future trajectory of species for adaptation to both thermal and ecological changes.

This study seeks to develop a connectivity index at a quaternary catchment scale for selected rivers in the KwaZulu-Natal (KZN) province of South Africa, where free-flowing rivers represent a yardstick of full connectivity of rivers. A free-flowing river is any river that flows undisturbed from its source to its mouth, either at the coast, inland, sea or at the confluence with a larger river without encountering any dams, weirs, or barrages and without being hemmed in by dykes or levees (WWF, 2006; Driver et *al.,* 2011). These rivers should be in a good ecological condition; have natural flow patterns, i.e. flowing permanently or seasonally; and with length of not less than 50 km for inland rivers, with no length threshold for coastal rivers (Driver *et al.,* 2011). KZN is the only province in South Africa which is not water scarce (Rivers Moore *et al*., 2007), and together with the Eastern Cape forms the two provinces with the highest number of flowing rivers in the country (Driver *et al.,* 2011).`

1.2 Research Rationale and Research Gaps

Globally, freshwater resources play a major role in not only sustaining aquatic biota but also human life through contribution in sectors such as agriculture, power generation, and industrial processes (Arnell and Liu, 2001). Rivers in KZN are of great importance as most still retain their free-flowing character (Driver *et al.,* 2011), providing a substantial environment for studying their natural health and also offering opportunity for sustainable management practise (Nilsson and Renöfält, 2008; Richter *et al.,* 1997). Rivers in KZN also provide habitat to freshwater species, and also serving source of water for use agricultural and industrial sectors (Rivers-Moore *et al.,* 2007; Wilson *et al.,* 2004). However, with the growing concerns over anthropogenic and climate related issues on water resources (Driver *et al.,* 2011; King *et al.,* 2003; WWF, 2006), thus understanding the implications of anthropogenic influence and climate change on rivers and other aquatic resources through research is currently relevant.

There is a growing body of literature relating to river connectivity. However, no comprehensive connectivity index of rivers has previously been developed for South Africa's KZN Province. In a South African context, longitudinal connectivity of rivers has been researched based on ecological category and existence of dams (Driver *et al.,* 2011; Rivers-Moore *et al.,* 2007). Generally, longitudinal and lateral connectivity of rivers have been studied using different observations (Allan, 2004; Poff and Zimmerman, 2010; Richter *et al.,* 1997). The different methods of scaling connectivity of rivers include a traditional fish pass assessment at a particular impoundment along river channel, land-use assessments, number of barriers and also recently defined through flow regime analyses (Cote *et al.,* 2009; Driver *et al.,* 2011; Januchowski-Hartley *et al.,* 2013; Rivers-Moore *et al.,* 2007; Sola *et al.,* 2011).

Despite this effort to understand connectivity, longitudinal and lateral connections of rivers have not been considered together. A study on spatial analysis of anthropogenic river disturbance by Stein *et al.* (2002), indicated a need for a holistic connectivity measuring methodology incorporating the scoring system of in stream barriers which includes, amongst other, waterfalls and natural lakes. A comprehensive assessment of river connectivity has also not been undertaken either regionally or nationally in South Africa (Driver *et al.,* 2011). Furthermore, such an assessment needs to be scale-specific, since there is a growing realization that any effective connectivity assessment be adopted at the quaternary catchment scale as the unit for measurement (Cote *et al.,* 2012; Januchowski-Hartley *et al.,* 2013). Within this context, such quaternary catchment units are largely used as tools for best management of freshwater resources and aquatic species vulnerability. The current study provides an opportunity to develop these management tools.

This study was undertaken as part of a larger research project through the Freshwater Research Centre (FRC) (K5/2182 – "Adaptability and vulnerability to climate change – developing tools for assessing biological effects") funded by Water Research Commission. The main objective of the project was to understand the biological consequences of thermal stress, and to incorporate this stress in the development of biological temperature thresholds for selected aquatic species. This approach is crucial in assessing the condition of ecological reserves, and will provide a valuable tool for managing aquatic resources. Such knowledge could provide insight into the adaptability and vulnerability of biota to climate change and allow for the generation of recommendations linking biota and climate change.

For the current study, river disruptions as a function of both physical barriers (impoundments and natural waterfalls) and abiotic factors (abstractions, changes in flow and temperature patterns) were assessed with an aim of developing an index of river connectivity. As opposed to other river connectivity assessments (Sola *et al.,* 2011), the current study evaluated hydrological conditions based on the prevailing patterns during the time of inspection and historical data (pre- or natural impact data) for connectivity assessments. A weighted index for all identified river barriers was developed based on connectivity metrics linked to both longitudinal and lateral condition along a river axis. The level of vulnerability of aquatic biota to changes in connectivity was then estimated, since breaks in the natural river continuum differentially affect system resilience depending on where they occur along the longitudinal axis (Rivers-Moore *et al.,* 2012). Resilience and vulnerability of biota were tested against various conditions of the river system, e.g. stenothermic cold water species versus eurythermic warm water species, migratory versus non-migratory species. This is because resilience and vulnerability are functions of both sensitivity and connectivity (Gitay *et al.,* 2011).

1.3 Aims and Objectives

The aims of this study were first to develop a connectivity index for rivers in KwaZulu-Natal, where free-flowing rivers represent full connectivity (Keruzoré *et al.* 2013; Nel *et al*. 2009), and second to assess which river systems, and which particular zones, would be most vulnerable to climate change based on temperature change and connectivity along river profiles. The output of this study include, amongst others, a longitudinal index map showing free-flowing rivers and spatial distribution of barriers, a lateral index map and description of aquatic biota vulnerability in the province. Such products are useful to ecologists, river managers and policy-makers who prioritize and promote effective protection and sustainable management of freshwater assets (Driver *et al.,* 2011; Landis *et al.,* 2013).

Specific objectives of this study were to:

a) Develop a connectivity index for main rivers in KwaZulu-Natal based on a process of identifying and weighting parameters effecting river connectivity.
b) Measure a recovery distance of stream flow alteration at all selected quaternary catchments.
c) Analyse temporal (flow and thermal) changes using the pre-impact versus post-impact regime methodology.
d) Assess the quaternary catchments that are vulnerable to thermal and stream flow changes relating to aquatic species survival.
e) Describe the likely ecological effects of disconnected index of rivers in the study area.

1.4 Study Outline

This study is summarized using the schematic framework that outlines the three components of river connectivity assessed in this study (longitudinal, lateral and temporal) and examples of each component provided as part of the final assessment of overall river connectivity (Figure 1.1). Connected river systems are attributed to the undisturbed nature of both longitudinal and lateral components which in turn yields the undisturbed temporal connectivity over a specified period. Species vulnerability and survival are as a result of a connected river system (Figure 1.1). This framework was used to guide the assessments and the development of the index of river connectivity throughout this study.

Chapter one provides the background information on the importance of river connectivity, its implications to aquatic species, the rationale and the overall objectives of this study. Chapter two is a literature review on the various aspects of connectivity. It provides a review of social aspects of disconnected river systems and the vulnerability of aquatic species to changes in flow and water temperature. Chapter three provides a description of the study area, including physical and climatic characteristic, and types of datasets used in the assessment of both longitudinal and lateral connectivity of rivers.

Temporal connectivity (flow and water temperature changes) and spatial connectivity of rivers in KZN are assessed in chapter four and five respectively. The outputs of this chapter included maps illustrating the level of disturbance in rivers. Chapter six presents the vulnerability assessment of selected aquatic species based on the developed connectivity index of rivers in the previous chapters. Chapter seven synthesizes the outcomes of the project and provides a discussion of the results and conclusions.

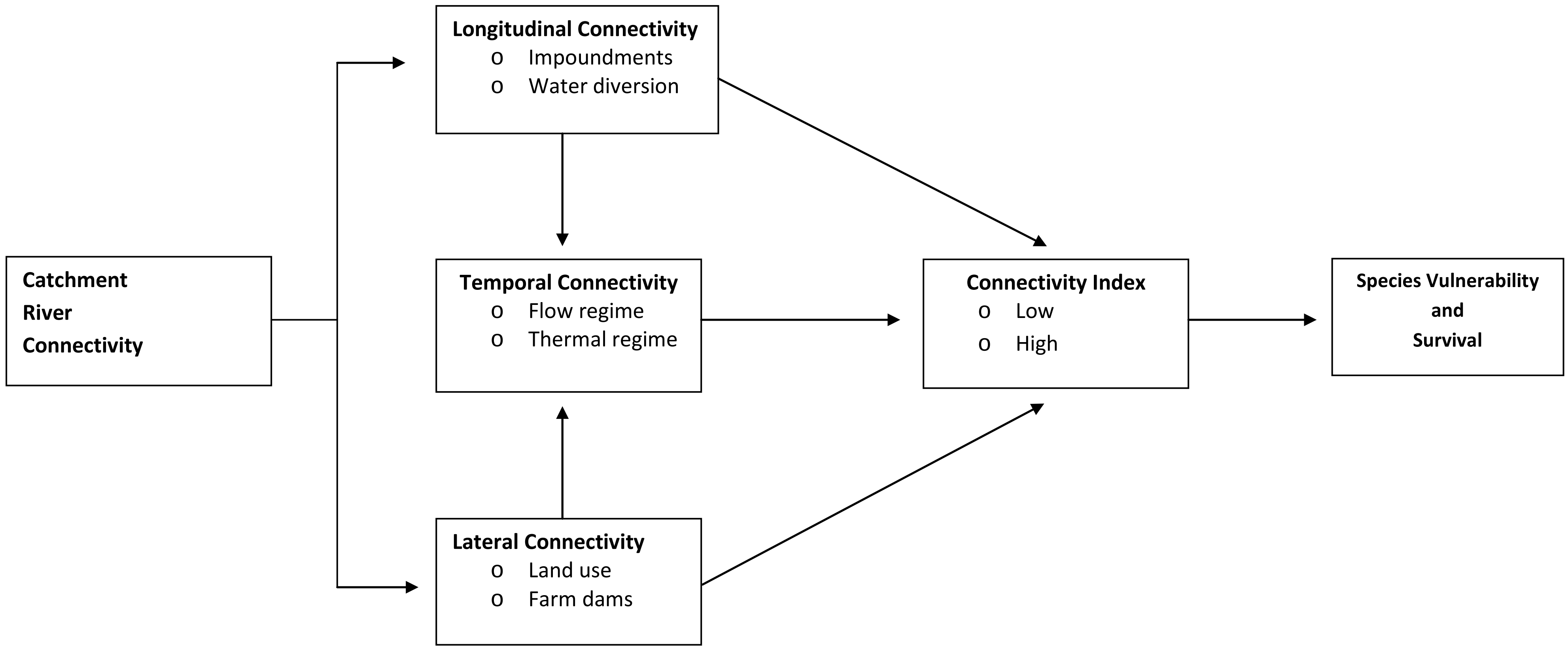


Figure 1.1: Schematic framework for assessing river connectivity and vulnerability of aquatic species.

1.5 Limitations of the Research

The following study limitations are acknowledged. First, the assessment of flow alteration required data that has been recorded prior to and after the installation of any river barrier factor. In this way, the pre- and post-impact analyses were limited to a small number of 7 sites on rivers of KwaZulu-Natal as large proportion of rivers had only recorded the post-impact flow patterns. However, these sites were used as representatives of sites with similar climatic (rainfall), land cover and hydrologic features such as runoff.

Second, this study has relied on simulated values rather than site recorded water temperature data as this phenomenon has not been largely studied in rivers of the KZN province. However, the statistical simulated data which was used does not necessarily represent natural or true experience of rivers conditions as they are generated from surrogates (Rivers-Moore *et al.*, 2005). Only three sites in the uMngeni River had water temperature records covering few months between 2003 and 2004. This data was used for ascertaining simulation confidence by comparing by means of percentage between observed values and simulated figures of the same site in the uMngeni River.

Third, this current study could not undertake field works to attain aquatic macroinvertebrate species and records on their livelihood environments such thermal, water quality, location in relation to stream length and altitude and flow records. Data from the RHP sites which contained amongst others information on type of species occurring, temperature, and date sampled was used to predict the survival probability of specific taxa in climate change vulnerable catchments.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Connectivity of rivers is a reflection of ecological integrity and plays an influential role in structuring aquatic community composition (Walther, 2010). There is a general consensus amongst aquatic researchers that the connectivity of rivers is maintained by interactions between river channels and surrounding landscapes (Allan, 2004; Bunn and Arthington, 2002; Freeman *et al*., 2007). Four dimensions of river connectivity are recognized, namely longitudinal, lateral, vertical, and temporal, and each reflects the operation of different processes at different positions in a river (Fryirs *et al*., 2006). Longitudinal connection demonstrates the upstream-downstream linkage of ecological processes and is facilitated by movement of water (Amoros and Bonertte, 2002), while lateral connection includes both active and passive movements of organisms, and exchanges of both nutrients and organic matter between the channel and the adjacent floodplain system (Ward, 1989). Both longitudinal and lateral connections are influential drivers of ecological processes of a river through exchange of energy, mass, momentum and organisms (Nadeau and Rains, 2007; Nel *et al.,* 2009). Vertical connection of rivers refers to the surface–subsurface interactions of water, sediment and nutrients (Fryirs *et al.*, 2006). According to Kondolf *et al.* (2006) vertical connectivity is less readily visible in rivers yet significant interactions may occur between surface running water and ground waters. Temporal connection refers to changes occurring on both annual and historical (long term) variability of both flow and water temperature in a river system (Amoros and Bonertte, 2002). Changes in hydrologic conditions are essential to successful life-cycle completion and play a major role in population dynamics (Chessman, 2012).

In this chapter, the importance of longitudinal and lateral connectivity as major drivers of aquatic life (Januchowski-Hartley *et al.,* 2013) is discussed. In Addition, temporal connectivity provides insights into the understanding of natural river temperature and flow variability, and the extent to which changes have historically occurred (Richter *et al.,* 1997). This study will not consider vertical connection of rivers since this dimension deals with surface-subsurface interactions which are beyond the objectives this project, and which is best represented using small scale site-specific studies (Fryirs *et al.*, 2006).

2.2 What is River Connectivity?

River connectivity refers to the degree of hydrologically-mediated transfer of mass, momentum, energy or organisms within or between spatially connected upstream and downstream river segments (Freeman *et al*., 2007). The connectivity of a river facilitates the movement of water between the river channel and the floodplain, and between the surface and the subsurface compartments (Ward *et al*., 1999). Studies have shown that the connectivity of rivers is an essential element of ecological integrity of the landscape (Nadeau and Rains, 2007; Pringle, 2003; WWF, 2006) and the disturbance of this ecological component by various agents including most notably human intervention, can have major negative environmental consequences (Pringle and Jackson, 2010). Under natural conditions, connected river systems should be able to support and maintain a balanced, integrated and adaptive community of organisms having a composition, diversity and functional organisation (Amis *et al.,* 2007). These systems form a physical gradient of consistent community structures and functional patterns along the length of a riverscape (Vannote *et al*., 1980). In this manner, ecosystems within connected river systems are able to adapt to changes, recover from disturbances, and continue its natural path of evolution (Amis *et al.*, 2007; Driver *et al.*, 2011; Nel *et al*., 2009).

Human activities and climate change have had a considerable impact on the connectivity of river systems in much of the world (Rieman and Isaak, 2010; Poff and Zimmerman, 2010). These impacts have had consequences for aquatic fauna, including the loss of habitat, fragmentation and isolation of populations, and direct mortality (Chessman, 2012; Stein *et al*., 2002). Disconnected river systems as a result of either or both human intervention and climatic change prevent the exchange of matter, energy and organisms between patches, reducing biodiversity through habitat fragmentation (Ward *et al.,* 1999), while with connected river systems, a smooth transition of sediments and organisms occurs throughout the system (Hooke, 2003). This smooth transition of sediments and organisms is likely to result in a high level of species diversity (Bunn and Arthington, 2002). However, with climatic changes and human alterations continuing (Rieman and Isaak, 2010), hydrologic alteration will continue to affect ecological functions through the loss of operating continuum of river systems (Keruzoré *et al.*, 2013). Effects will vary in relation to the amount of alteration of natural river connectivity, with some organisms likely to suffer and others benefiting from disconnected systems (Bush *et al.*, 2012).

2.3 Types of River Connectivity

The four dimensions of river connectivity are responsible for the exchange of mass momentum, energy and organism flowing in four pathways namely; longitudinal (channel to channel), lateral (channel to floodplain), vertical (channel to aquifer),and temporal (temporary to evolutionary change) connectivity (Figure 2.1) (Amoros and Bonertte, 2002; Nadeau and Rains, 2007; O'Keeffe *et al.*, 2002; Ward, 1989). These dimensions of river connectivity are detailed below.

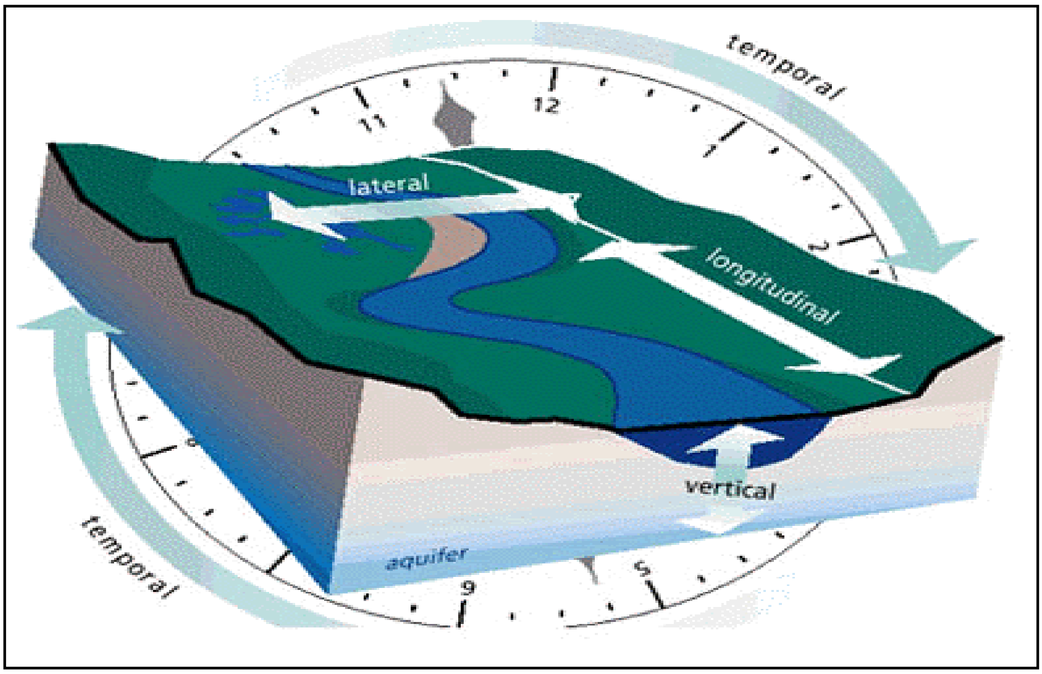


Figure 2.1: A four-dimensional model of river connectivity (after O'Keeffe *et al.*, 2002).

2.3.1 Longitudinal connectivity

Longitudinal connectivity refers to the upstream-downstream and tributary-main stem relationships that drive the transfer of flow through a system (Amoros and Bonertte, 2002). The upstream-downstream linkage of a river system represents a corridor of linear feature of the landscape, structured along narrow strip of alluvium extending from the headwaters to the sea (Ward *et al.,* 2002). Longitudinal connectivity is attributed to the ability of river channels to transfer or accumulate sediments of variable calibre on the floor (Fryirs *et al.,* 2006). Longitudinal connectivity is therefore comprised of stream channels which carry uniform discharge and sediment load along their upstream-downstream length (Rowntree and Wadeson, 1999). According to the River Continuum Concept (RCC), the upstream-downstream length of a river system assumes three rough classifications of river streams (Vannote *et al.,* 1980). Even though river channels go through structural changes, these classifications apply to all rivers. Classifications of river streams include headwater, transfer zone and lastly depositional zone (O'Keeffe *et al.*, 2002; Vannote *et al*., 1980).

Cumulative human alterations of longitudinal connectivity have increasingly become well understood (Pringle, 2003), and result in emergent ecological patterns of great concern (Poff and Zimmerman, 2010). These alterations, as a result of anthropogenic innovations, occur in different forms such as dams, weirs, crossings, gauging stations, and flow regulation (Bunn and Arthington, 2002; Freeman *et al*., 2007; Sola *et al*., 2011; WWF, 2006). The connectivity of streams and rivers is altered proportionally to the growing need for the use of water for hydropower generation, supplying reliable and affordable water to growing human populations and industrial uses (Driver *et al.,* 2011; Poff *et al.,* 1997). Consequently, the hydro-geomorphological and biological conditions of the river systems are directly or indirectly affected by this breakdown of longitudinal connectivity (Sola *et al.,* 2011). Transverse obstacles in a river prevent the exchange of sediments and fauna from flowing and this has important ecological consequences (Freeman *et al*., 2007).

After extended periods of little-to-no flow and denied migration routes, sensitive species are likely to fail to adapt to habitat changes and rising water temperature (Chessman, 2012) and may become locally extinct (Poff and Zimmerman, 2010). Habitat degradation through impoundments has been a central problem in conservation and management of native fishes and other aquatic species (Rieman and Isaak, 2010).However, despite exacerbating survival probability for many aquatic species, in-stream impoundments have few ecological merits. One potential benefit of in-stream impoundments is their use as a tool for preventing upstream invasions by alien fish species and for protection of endangered species (Pringle, 2003). Recent river management and restoration efforts have focused on enhancing connectivity through a variety of mechanisms which include, amongst others, removing dams, altering reservoir management to provide more natural flow regimes, restoring natural morphology to streams disturbed by channelization, removing tide gates, and eliminating inter-basin transfers (Pringle and Jackson, 2010; Sola *et al.*, 2011, WWF, 2006).

2.3.2 Lateral connectivity

Lateral connectivity refers to slope-channel and channel-floodplain relationships that drive the supply of water and material to a network (Ickes *et al*., 2005; Fryirs *et al.*, 2006). Lateral connectivity accounts for the creation of new side-arms (of river) and cut-off active meanders which may become highly connected patches (Amoros and Bonertte, 2002). Like longitudinal connectivity, lateral is sensitive to human activities (Keruzoré, 2013). Thus, the transition from undisturbed to human-dominated landscapes impacts aquatic ecosystems. The quantification of land-use a valuable indicator of the state of hydrological conditions (Allan, 2004).

There is a need amongst scientists to develop a reliable method for assessing the dynamic nature of lateral connectivity of river systems (Januchowski-Hartley *et al.*, 2013; Ickes *et al*., 2005). However, it is widely recognized that any means of measurement of lateral river connectivity should be based on a mechanistic understanding of how physical and biological systems interact and how human activities influence these interactions (Allan, 2004; Stein *et al.*, 2002). According to Stein *et al*. (2002) quantification of the extent of land-uses that alter the flow regime within the catchment provides a surrogate indicator of the extent of disturbance of natural river processes.

The development of effective conservation and restoration strategies is critical, given the magnitude of land-use change and alterations of lateral connection of rivers systems (Allan, 2004). Confronting these global environmental challenges of land use will require assessing, managing, and meeting immediate human needs and maintaining the capacity of ecosystems to provide goods and services in the future (Foley *et al.*, 2005; WWF, 2006). This will ensure that land use provides crucial social and economic benefits, while maintaining the social, economic and conservation value of freshwater ecosystem supporting the livelihoods of people in the catchment (Driver *et al*., 2011).

2.3.3 Vertical connectivity

This type of connectivity refers to the vertical exchange of water, chemicals and organisms between the surface and the groundwater through infiltration and exfiltration (Amoros and Bonertte, 2002). Vertical connectivity involves downwelling and upwelling of materials through permeable streambeds (Kondolf *et al.,* 2006). According to O'Keeffe *et al.* (2002), it is always important to recognize that water bodies are not purely surface features, rather rivers and streams constantly interact with groundwater aquifers and exchange water, chemicals, and even organisms. These fluxes are clearly observed between thermally stratified bodies of water in lakes or between hyporheic zones and flowing surface waters in rivers (Ickes *et al*., 2005). All of these vertical ecotones are characterized by relatively steep gradients, thereby collectively forming a high level of environmental heterogeneity across the riverine landscape (Amoros and Bonertte, 2002). According to Ward *et al*. (1999), this environmental heterogeneity across the riverine landscape can be thermal, chemical or organic.

The breakdown of natural vertical connectivity of water is attributed to impediment factors referred to as blankets. Blankets include features such as floodplain sediment sheets that smother other landforms, and protecting them from reworking (Fryirs *et al.*, 2006). Physical barriers reduce vertical connectivity by reducing permeability such by siltation and the clogging of pore spaces of streambed gravels (Hancock, 2002). Moreover, silt input and deposition may alter the vertical movement of water by the terrestrialisation of the water bodies and construction of the alluvial bars at their connecting ends (Amoros and Bonertte, 2002). According to Kondolf *et al.* (2006) these organic and fine materials gradually decrease the porosity of riverscapes making it difficult for aquifers to receive water from the surface. Like other types of river connectivity, vertical interaction of water affects the local ecology by acting as source of water to plants. Given the fine-scale patchiness and functionality of natural vertical connectivity zones, different aquatic species carry out different functions across a range of habitats (Boulton, 2007).

2.3.4 Temporal Connectivity

There are two main types of temporal connectivity of river systems, namely flow and thermal regimes. These two factors are explained in Section 2.3.4.1-2 below.

2.3.4.1 Flow regime

The range and variation of flows over historical specific time are referred to as the flow regime (Poff *et al.,* 1997). River flow regime is of great concern amongst aquatic scientists and river managers as it drivers both the distribution of aquatic species (Dallas *et al.,* 2012; Heino *et al.,* 2009). Flow regime is referred to as a 'master variable' because it arranges and resets river populations throughout the extent of the river (Power *et al.,* 1995). It also sets a template for contemporary ecological processes, evolutionary adaptations and native biodiversity maintenance (Bunn and Arthington, 2002; Poff and Zimmerman, 2010). As noted by Bunn and Arthington (2002), the effects of river flow regime are spread throughout the physical and biological environments, determining the form of the channel and the nature of the sediments, affecting the physiology, distribution and abundance of organisms. Flow regime varies geographically in response to climatic factors such as precipitation and temperature, and catchment controls of flow that drivers stream flow characteristics including topography, geology, land cover, runoff, and relative position of a site within a stream network (Poff and Zimmerman, 2010).

There is a growing consensus amongst scientists and river managers that a naturally variable regime of flow rather than just an inadequate minimum or low flow, is required to sustain freshwater ecosystems (Poff *et al.,* 1997). This is referred to as the natural flow regime (Arthington *et al.*, 2006) or as environmental flow (Gippel and Stewardson, 1998; Poff *et al.* 2009). The acceptance of a natural flow regime concept takes into consideration the sustainability of ecosystem integrity by protecting aquatic life and ecological processes that creates and maintain biodiversity (Arthington *et al.*, 2006; Richter *et al.*, 1996).The natural flow-regime concept should support the quantity, quality and timing of water required to sustain freshwater and maintain the essential goods and services provided by rivers (Poff and Zimmerman, 2010; Richter *et al.,* 1997). According to Poff *et al.* (1997), there are five critical components of the flow regime that regulates ecological functions or processes in river ecosystems, namely;

- Magnitude of flow conditions

Magnitude refers to the amount of water moving (discharge) past a fixed location per unit time (Poff *et al.*, 1997). According to Arthington and Zalucki (1998) there is no single widely accepted methodology for determining the magnitude of river flow and the existing techniques falls within the following; field observations or controlled release, sediment entrainment calculations, hydraulic geometry, hydrological methods, and professional judgement.

- The frequency of occurrence (of a flow event)

The frequency of occurrence refers to the interval of occurrence of specific river flow conditions such as floods or droughts (Taylor, 2001), typically assessed based on a defendable threshold. This drives the reproduction and mortality events for many aquatic species and influences population dynamics (Richter *et al.*, 1996).

- Duration of flow conditions

The duration of flow condition is the period of time associated with a specific flow condition (Poff *et al.*, 1997). According to Poff and Zimmerman (2010) alterations in flow duration of specific water events are primarily associated with the decrease in both in-stream and riparian ecological variables.

- The timing or predictability of flows

The timing or predictability refers to the time of year at which particular flow events such as floods or low flow extremes occur (Taylor, 2001). The timing can determine whether certain life-cycle requirements for aquatic species are met or not (Richter *et al.*, 1996).

- The rate of change

The rate of change refers to how quick a specific flow event changes from one magnitude to another or from one flow condition to another (Arthington *et al.*, 2006; Poff *et al.*, 1997). These five components of flow regime are considered to be sensitive to a wide variety of changes from anthropogenic activities to climatic change (Heino *et al.*, 2009; Poff and Zimmerman, 2010). Global climate change will primarily affect freshwater ecosystems through changes in the quantity and quality and through changes in the timing and duration of stream flows (Combes, 2003). This will modify aquatic habitats for many species whose life is only supported by a specific range of flow conditions. Extreme flow levels are necessary for maintaining populations of a number of species whose feeding and migration are dependent on predictable seasonal flooding (Combes, 2003). On the other hand, modification of short-term flow clearly leads to a reduction in both the natural diversity and abundance of many native fish and invertebrates (Poff *et al.,* 1997).

2.3.4.2 Thermal regime

The thermal regime of rivers plays an important role in the overall health of aquatic ecosystems (Morrill *et al.,* 2004; Caissie, 2006), and is recognised as one of the most influential abiotic drivers of aquatic ecosystems (Dallas and Rivers-Moore, 2012a; Li *et al.,* 2013). The thermal regime of rivers regulates issues of water quality (Morrill *et al.,* 2004), and the distribution of aquatic species within the river environment (Dallas, 2008). Aquatic species' growth, metabolism, food availability, migration and reproduction are all influenced by water temperature (Caissie, 2006; Dallas and Ketley, 2011; Dallas and Rivers-Moore, 2012a; Morrill *et al.,* 2004). According to Li *et al.* (2013), it is the sensitivity of aquatic species to environmental conditions such as thermal regime that determines their geographical distribution and abundance in particular habitats. However, several factors influence the variability of the thermal regime of river systems. Among other factors, climate change is considered to be a major driver of changes in water temperature and several authors have reviewed the subject (Combes, 2003; Dallas, 2008; Heino *et al*., 2009; Rieman and Isaak, 2010). Some examples of natural drivers, buffers and insulators of water temperature are listed in Table 2.1. From the natural drivers it is clear that water temperatures are affected by a large number of variables interacting at a range of spatial and temporal scales.

Water temperature in rivers can also fluctuate as a result of anthropogenic perturbations such as thermal pollution and land use activity (Caissie, 2006). With projected global climate change, water temperature due to warming air will impose severe challenges to aquatic biodiversity, although projections of the directions, magnitude, and confidence surrounding changes in both air temperature and precipitation vary by regions and seasons (Landis *et al.,* 2013; Lawler, 2009). Warming air temperature and changing precipitation patterns are some of the effects of climatic change and these have a relationship to surface water temperature (Hari *et al.,* 2006; Morrill *et al.,* 2004; Rieman and Isaak, 2010). Water temperature regimes of rivers experience changes in the magnitude, frequency, timing and duration of thermal events and this affects aquatic biota by impacting on their life history cues and fecundity (Dallas and Rivers-Moore, 2012a; River-Moore *et al.,* 2012). According to Olden and Naiman (2010) the thermal regime of rivers describes the distribution of the magnitude of water temperatures, the frequency with which a given temperature occurs, the time of the day or year when a certain temperature occurs, and the duration of time.

Table 2.1: Examples of natural drivers, insulators and buffers of water temperature in rivers (after Dallas, 2008; Poole and Berman, 2001; Rivers-Moore *et al.*, 2011).

Drivers	Insulators	Buffers
• Solar radiation#	• River width *	• Geology$
• Air temperature#	• River depth *	• Aquifer depth#
• Tributary temperature and flow#	• Topographic shade *	• Water travel time#
• Precipitation#	• Upland vegetation *	• Pool or riffle sequence#
• Velocity#		
• Phreatic groundwater temperature and discharge#		
• Relative humidity#		
• Cloud cover#		

The spatio-temporal scale at which these operate is indicated accordingly: * represents a **micro-scale** (spatial = site or reach/ areas < $10m^2$; temporal = daily); # represents a **meso-scale** (spatial = longitudinal/ area $10m^2$ to $10km^2$; temporal = daily to monthly); and lastly $ represents **macro-scale** (spatial = regional/ areas > $10km^2$; temporal = years). Climate change will affect the assemblages of aquatic species with biological consequences acting at several levels, including that of an individual species to that of an entire community (Dallas and Rivers-Moore, 2012a). Warming streams as a result of rising air temperatures may make in-stream environments unsuitable for many species (Chessman, 2012; Bush *et al.,* 2012; Rivers-Moore *et al.,* 2007). This is likely to affect cold-water fish populations negatively at the warmer boundaries of their habitat, and positively at the cooler boundaries (Hari *et al.,* 2006). This will result in many cold-adapted species becoming increasingly vulnerable and their range of dispersal decreasing dramatically (Rivers-Moore *et al.*, 2007). In this way, higher water temperature threatens cold-water tolerant species as many areas may not possess refuges for these species (Heino *et al.,* 2009; Lawler, 2009), while warm water species may increase their relative abundance and expand into new up-stream habitats (Bush *et al.,* 2012).

2.4 Effects of Disconnectivity on River Functions

This section reviews the likely effects of loss in connectivity on aquatic communities, and how these are intensified by the impacts of climate change. Particular emphasis is placed on the health of rivers and this aspect involves an understanding of the ecological integrity of freshwater ecosystem and aquatic species response to disconnected river systems. Social and economic implications on the human communities making direct use of river system are also discussed in this section. It is relevant to discuss social and economic component of rivers as they provide an opportunity for development through infrastructure, and provide importance service to sectors such as agriculture and industries.

2.4.1 River health

River flow variability and water temperature regimes are important control factors of the health of freshwater ecosystem (Combes, 2003; Morrill *et al.,* 2004; Nilsson and Renöfält, 2008). According to Driver *et al*. (2011) freshwater ecosystem health should be measured with aims beyond the quantification of fundamental needs such as water for drinking and irrigation, but to include ecological processes, maintenance, persistence (i.e. how these ecosystems become capable of reducing the loss of aquatic life), and provision of important regulating ecosystem services, such as preventing floods and easing the impacts of droughts. The health of rivers supports and maintains ecological integrity of the ecosystem and ensures the survival of aquatic communities over time (WWF, 2006). Effects of both connected and disconnected river systems on ecological integrity and aquatic species response are discussed below.

2.4.1.1 Ecological integrity of freshwater ecosystems

Ecological integrity of river systems refer to the capacity of a rivers to support and maintain a balanced, integrated, and adaptive biological system having the full range of elements and processes expected in a region's natural habitat (WWF, 2006). This concept provides an effective tool for describing the extent to which ecosystems have been altered by anthropogenic activities from their original natural condition (Driver *et al.*, 2011). There are six factors that are considered in the assessment ecological integrity of freshwater ecosystems. These factors include; river flow, water quality, stream or bed condition, inundation, introduced in-stream biota, and river bank condition (Nel *et al.,* 2007). To describe the ecological conditions of river systems in relation to these factors, ecological categories referred to as 'Present Ecological State' are used (Table 2.2) (Driver *et al.,* 2011; Nel *et al.*, 2009).

Table 2.2: Present Ecological State (PES) categories used to describe the current and desire future condition of South African rivers (after Driver *et al.,* 2011).

Ecological category	**Description**
A	Unmodified, natural
B	Largely natural with few modifications
C	Moderately modified
D	Largely modified
E	Seriously modified
F	Critically/Extremely modified

The categories are arranged in a progressively decreasing ecological condition pattern in river systems from the unmodified natural river condition at category A. This first category has almost all river channel features retaining their natural characters (WWF, 2006). In category B and C, a small changes in the natural habitats in a descending manner have been observed respectively. However, the ecosystem functions are essentially unchanged for both category B and C (Driver *et al.*, 2011). From category D to F, the ecological condition of rivers ranges from loss of large natural habitat and basic ecosystem functions to completely destroyed and irreversible ecosystem functions respectively (Driver *et al.*, 2011; Nel *et al.*, 2009; WWF, 2006).

2.4.1.2 River channel response to altered flow

Channel structures and river flow regimes are being manipulated and redesigned by human societies and many of these impacts have led to changes in physical and chemical variables in rivers (Nilsson and Renöfält, 2008). According to Gendaszek *et al.* (2012), anthropogenic changes to fluvial systems, including flow regulation and floodplain alteration, establish new geomorphic conditions and this influences the structures of aquatic ecosystems. The likely geomorphic response by river channel after the flow alteration include *inter alia*; downstream channel erosion and tributary head-cutting, deposition of fines in gravel, channel bank erosion and widening, reduced channel migration and formation of secondary channels (Table 2.3) (Poff *et al.*,2009). These changes in the flow regimes of rivers are attributed to dams, diversion, land-use activities, channelization and ground water pumping. To minimize effects on river channels and aquatic ecosystems, two solutions are recommended namely; elimination of barriers and implementation of environmental flows (Nilsson and Renöfält, 2008, Sola *et al.*, 2011; Poff *et al.*, 2009).

2.4.1.3 Aquatic species response to disconnected rivers

The alteration of both flow and thermal regimes is often claimed to be the most serious and continuing threat to ecological sustainability of rivers (Bunn and Arthington, 2002, Dallas, 2008). Modification of the natural flow regime and water temperatures affects both aquatic and riparian species in streams and rivers worldwide (Poff *et al.*, 1997). This exerts selective pressure on aquatic populations and regulates the distribution, abundance and diversity of stream and river organisms (Bunn and Arthington, 2002; Poff and Zimmerman, 2010). According to Pringle (2003) the loss of aquatic and macroinvertebrate species in rivers is one of the legacies of reduced hydrologic connectivity. This is because many aquatic organisms are vulnerable to rapid diurnal changes in flow and thermal regimes (Bunn and Arthington, 2002).

Table 2.3: Physical responses of stream channel to altered flow regimes (after Poff *et al.*,2009).

Types of Barrier	Hydrologic change	Geomorphic response
a) Dam	• Capture sediment moving downstream.	• Downstream channel erosion and tributary head cutting. • Bed armouring (coarsening)
b) Dam, diversion	• Reduce magnitude and frequency of high flows.	• Deposition of fines in gravel. • Channel stabilization and narrowing. • Reduced formation of point bars, secondary channels, oxbows, and changes in channel platform.
c) Urbanization, tiling, drainage	• Increased magnitude and frequency of high flows. • Reduced infiltration into soil.	• Bank erosion and channel widening. • Downward incision and floodplain disconnection. • Reduced baseflows.
d) Levees and Channelization	• Reduce overbank flows.	• Channel restriction causing downcutting. • Floodplain deposition and erosion prevented. • Reduced channel migration and formation of secondary channels.
e) Groundwater Pumping	• Lowered water table levels.	• Stream bank erosion and channel downcutting after loss of vegetation stability.

Disconnected river systems negatively impact on upstream-downstream river migration which is important for diadromous fish species such as the salmon and eel, whose life cycles includes long distance migration between marine and freshwater habitats in the inland (Rivers-Moore *et al.,* 2011). Fortunately, connected rivers with natural high flows can help in minimizing the effects and the success of non-native species by removing species that are poorly adapted to dynamic river environments (WWF, 2006). Several studies confirm that macroinvertebrate communities and fish species along connected gradients in riverscapes show higher species diversity compared to highly disconnected river systems (Bunn and

Arthington, 2002; Gitay *et al.*, 2011; Januchowski-Hartley *et al.*, 2013; Poff and Zimmerman, 2010).

2.4.2 Socio-economic aspects

Although freshwater ecosystems occupy less than one per cent of the world's surface, they make some of the largest contributions of all ecosystems to human welfare (WWF, 2006). They offer considerable social, economic and conservation value, supporting the livelihoods of people in the catchment (Driver *et al.,* 2011). With pressure arising from social and economic needs, freshwater ecosystems are stressed and degraded. The wise use of freshwater resources is critical to the sustainable development of the economy and for meeting of social needs of people who depend directly on the health of natural resources for their livelihoods (Driver *et al.,* 2011, Poff *et al.,* 1997). Numerous methods are available for assessing the impacts of developing freshwater resources. One such model which has been widely applied in South Africa to predict the bio-physical and socio-economic impacts of proposed water-resource developments on rivers is the scenario-based Downstream Response to Imposed Flow Transformation (DRIFT) model (King *et al.,* 2004).

There is a range of economic and social benefits associated with freshwater resources and their developments. Rivers systems can create opportunities such as recreation and ecotourism, cultural heritage, educational, spiritual and religious, and fishery (Driver *et al.*, 2011; Nilsson and Renöfält, 2008; WWF, 2006). Communities can benefit from water resource developments through *inter alia*; hydroelectric power generation, water irrigation, and domestic and industrial water supplies (King *et al.,* 2004; Nilsson and Renöfält, 2008). In this way, economic value focuses on economic return linked to tourism and other income generation opportunities (Rieman and Isaak, 2010). However, according to WWF (2006) the benefits gained from water infrastructure are often at an environmental cost, the extent of which is difficult to quantify and subsequently difficult to restore. King *et al.* (2004) listed the following likely negative socio-economic impacts of freshwater resource development and emphasized that these impacts are by no means insignificant.

- loss of homes
- loss of ancestral grounds

- loss of resources such as fishing and hunting grounds
- loss of cropping lands
- loss of areas for eco-tourism
- health problems during and post water resource development
- far reaching lifestyle changes

Identifying priority actions to restore aquatic connectivity requires an understanding of ecological, socio-economic, and political constraints (Januchowski-Hartley *et al.,* 2013), and this should not be underrated as the loss of some species may have little impact ecologically, but larger impacts socially or economically (Lawler, 2009). However, a growing demand for reliable safe water supply and also the growing scarcity of safe water threatens the persistence of freshwater ecosystems and progress in poverty suppression, public health, and food supply (Nilsson and Renöfält, 2008). According to Rivers-Moore *et al.* (2011), it is not possible to allocate high levels of protection to water resources without prejudicing social and economic development, yet equally not sustainable for all resources to be classified at a uniformly low level of protection so as to permit maximum use from competing land users. River managers who are officials responsible for decision marking and scientists studying river systems and dynamics are faced with a challenge to ensure that freshwater ecosystems satisfy the needs of both humans and nature, without sacrificing one for another.

2.5 Vulnerability of Aquatic Macroinvertebrate Species to Thermal Change

There is no single widely-accepted definition of vulnerability (Gitay *et al.* 2011).Various studies define vulnerability as a product of exposure (Boardley and Schulze, 2005), sensitivity (Rieman and Isaak, 2010) and adaptive capacity of the system (Parry *et al*., 2007). This current study will adopt a definition by IPCC in Parry *et al*. (2007) which states that vulnerability is “the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes”. The level of vulnerability of freshwater organisms to climate or thermal change is determined based on their sensitivity and adaptive capacity (Gitay *et al.* 2011). As noted by Rieman and Isaak (2010) sensitivity reflects both the absolute value and the probability of change or departure in that value, given change in climate. Adaptation capacity is the ability of an ecosystem to adjust to climate change, to take advantage of opportunities, or to cope with or moderate the consequences of climate change (Gitay *et al.,* 2011). Highly sensitive aquatic systems with very low adaptive capacity are the most vulnerable to effects of changes in the ecosystem. On the contrary, aquatic systems with low sensitivity and very high adaptive capacity are likely to survive changing environmental conditions (Table 2.4).

Climate change has implications for aquatic organisms, particularly fish and macroinvertebrate species (Rieman and Isaak, 2010). Different aquatic macroinvertebrate and fish communities are affected by changes in both stream flow and water temperature (Table 2.5). These changes drive the distribution and survival of aquatic species (Buisson *et al.,* 2008; Dallas *et al.,* 2012; Poff and Zimmerman, 2010; Power *et al.,* 1995; Richter *et al.,* 1996; Rivers-Moore *et al.,* 2012). Thermally sensitive aquatic species may be useful as bio-indicators of thermal alteration and can be surrogates for rivers' vulnerability to thermal change (Dallas and Rivers-Moore, 2012a). Poff *et al.* (2009) developed an essential structure of ecological factors to consider when assessing the vulnerability of freshwater habitats and aquatic organism to changes including stream flow alteration. According to Poff *et al.* (2009) these factors including amongst others, mode and rate of response, habitat responses linked to biological changes, taxonomic groupings, functional attributes, biological level of response and social value (Table 2.6).

Table 2.4: Vulnerability assessment as a function of sensitivity and adaptive capacity (Gitay *et al.*, 2011).

Sensitivity	Adaptive Capacity		
	High	Medium	Low
High			Highly Vulnerable
Medium		Vulnerable	
Low	Not Vulnerable		

The vulnerability of freshwater species to thermal and climate change is expected to be exacerbated by habitat degradation, fragmentation, and regulation of stream flow that together reduce the connectivity required for species to adapt (Bush *et al.,* 2012). Vulnerability of freshwater species to climate change is therefore sensitive to human induced pressure or disturbance on aquatic ecosystems. According to Schneider *et al.* (2007) human developments substantially reduce the resilience of ecosystems and make many species more vulnerable to climate change through blocked migration routes, fragmented habitats, and reduced populations. In this way, aquatic species fails to cope and adapt to prevailing climatic changes, and they would fail attempting to move upstream or further downstream to find new habitats (Bush *et al.,* 2012). However, it is important to recognise that fish and aquatic macroinvertebrate respond differently to the same environmental gradients (Rivers-Moore *et al.,* 2012). One of the most specific elements of vulnerability to climate change for aquatic species is the reduction and loss of habitat for cold water fish (Gitay *et al.,* 2011). Cold water fish are those that are likely to favor cool water rather than either warm to suit their tolerance abilities and behavior (Chessman, 2012).

Table 2.5: Aquatic macroinvertebrate and fish communities' response to altered stream flow and water temperature regimes.

i.	**Changes in Flow regime**	**Fishes**	**Macroinvertebrate**
a)	Magnitude	• Alteration of flow result in loss of sensitive species (Poff and Zimmerman, 2010) • The magnitude of flood peaks can determine the degree of scouring mortality of fish egg (Poff *et al.*, 2009)	• Alteration of flow result in loss of sensitive species (Poff and Zimmerman, 2010) • Greater magnitude of extreme cause life cycle disruption (Poff and Zimmerman, 2010)
b)	Frequency	• High frequency of flow, non-native species of fish may fail to establish (Poff *et al.*, 2009) • Influences the reproduction and mortality events of various species (Richter *et al.*, 1996)	• Increasing frequency of high flow disturbances, macroinvertebrate communities shift toward species adapted to high mortality rates, such as those having short life cycles and high mobility (Poff *et al.*, 2009) • Increased variation results in life cycle disruption (Poff *et al.*, 1997)
c)	Duration	• Reducing the duration of low flows would not be expected to have a large effect on native fish (Poff*et al.*, 2009) • Increasing the duration of low flows could dewater habitat and damage native species (Poff et *al.*, 2009)	• Decreased duration of floodplain inundation causes loss of floodplain specialists in mollusc assemblage (Poff and Zimmerman, 2010) • Increasing the duration of low flows would limit habitat available for invertebrate assemblages
d)	Timing	• The natural timing can prevent the establishment of non-native fish (Poff *et al.*, 2009) • Loss of seasonal flow peaks disrupt cues for fish: spawning (Poff *et al.*, 1997)	• Reduced survivorship of larval atyid shrimps following early summer spates (Bunn and Arthington, 2002). • Human-induced changes in timing may cause productive failure, stress and mortality (Richter *et al.*, 1996)
e)	Rate of Change	• The loss of seasonal flooding can promote success of non-native fish species (Poff *et al.*, 2009)	• Accelerated flood recession results in failure of seedling establishment (Poff *et al.*, 1997)

ii.	Changes in Thermal Regime	Fishes	Macroinvertebrate
a)	Magnitude	• Modified temperature regimes eliminates temperature specific species of fish and increasing mortality (Bunn and Arthington, 2002; Caissie, 2006). • A reduction in thermal habitat result in population decline at low altitudes (Hari *et al.*, 2006).	• Influences the growth of aquatic insects (Caissie, 2006). • Temperature influences many aspects of an organism's existence including its growth rate, feeding rate, metabolic rate, fecundity emergence, behaviour and ultimately survival (Dallas and Rivers-Moore, 2012a).
b)	Duration	• The duration of thermal events drives the loss of brook trout (Wenger *et al.*, 2011).	• Modified temperature regimes also strongly influence invertebrate communities by eliminating key developmental cues and influencing the rate of egg development and juvenile growth (Olden and Naiman, 2010).
c)	Timing	• The timing of thermal events influences the migration of fish (Caissie, 2006) • Cooling and delayed timing of maximum temperatures has significant consequences for the spawning success of several native fish species (Olden and Naiman, 2010). • If water temperatures increase, especially at critical times of the year, shifts in aquatic biota could result (Morrill *et al.*, 2004)	• Under diel cycles of water temperature, eggs may hatch sooner than under constant thermal conditions (Ward and Stanford, 1982). • Year-to-year changes in temperature alter the emergence times, the order in which species emerge does not change (Ward and Stanford, 1982). • Increase temperatures may speed up life cycle responses with earlier emergence of invertebrates in rivers that are warmer and/or greater diurnal variability (Caissie, 2006)
d)	Frequency	• When frequency of thermal events exceeds species ability to deal with stress results in mortality (Dallas and Rivers-Moore, 2012a).	• The frequency and rate of change of temperature determines lethality of habitat and causing mortality (Dallas, 2008)

Table 2.6: Ecological factors to consider for the assessment of vulnerability of aquatic species to habitat change and their response (after Poff *et al.*,2009).

Mode of response
Direct response to flow, e.g. spawning or migration orIndirect response to flow, e.g. habitat-mediated

Habitat responses linked to biological changes
Changes in physical (hydraulic) habitat (width–depth ratio, wetted perimeter, pool volume, bed substrate)
Changes in flow-mediated water quality (sediment transport, dissolved oxygen, temperature)
Changes in in-stream cover (e.g. bank undercuts, root masses, woody debris, fallen timber, overhanging vegetation)

Rate of response
Fast versus slow
Fast: appropriate for small, rapidly reproducing, or highly mobile organisms
Slow: long-life span
Transient versus equilibrial
Transient: establishment of tree seedlings, return of long-lived adult fish to potential spawning habitat
Equilibrial: reflect and end-point of 'recovery' to some 'equilibrium' state

Taxonomic groupings
Aquatic vegetation,Riparian vegetation, Macroinvertebrates, Amphibians, Fishes,Terrestrial species (arthropods, birds, water-dependent mammals, etc.) or Composite measures, such as species diversity, Index of Biotic Integrity

Functional attributes
Production
Trophic guilds
Morphological, behavioural, life-history adaptations (e.g. short-lived versus long-lived, reproductive guilds)
Habitat requirements and guilds
Functional diversity and complementarity

Biological level of response (process)
Genetic
Individual (energy budget, growth rates, behaviour, traits)
Population (biomass, recruitment success, mortality rate, abundance, age-class distribution)
Community (composition; dominance; indicator species; species richness, assemblage structure)
Ecosystem function (production, respiration, trophic complexity)

Social value
Fisheries production, clean water and other ecosystem services or economic values
Endangered species
Availability of culturally valued plants and animals or habitats
Recreational opportunities (e.g. rafting, swimming, scenic amenity)
Indigenous cultural value

2.6 Sustainable Management of Vulnerable Freshwater Resources

There are a number of specific assessment mechanisms for species and freshwater resources vulnerability, which are aimed at conserving these resources by predicting and assessing change in their natural character. These measures do not provide specific protection against developments involving river modification, such as construction of dams (Margules and Pressey, 2000; WWF, 2006). The Ramsar Convention has developed a conceptual framework for wetland vulnerability assessment, including guidance on predicting and assessing change in the ecological character of wetlands (Gitay *et al.*, 2011). The definition of wetlands under the Ramsar convention incorporates rivers and streams. In this current study, rivers are used as a surrogatefor wetlands in the Ramsar framework definition. The vulnerability assessment of rivers under the Ramsar framework recognizes the usefulness of early warning systems against risk. Risk is defined in terms of the probability of the extent and effect of a hazard impacting or losing a value attached to a system (Gitay *et al.*, 2011; Rieman and Isaak, 2010). The Ramsar framework for assessing the vulnerability of freshwater assets embodies a series of steps which recognizes that aquatic ecosystems are extremely important not only for biodiversity conservation, but also for maintaining the ecological character of freshwater ecosystem and for the wellbeing of human communities (Gitay *et al.*, 2011; WWF, 2006). The Ramsar framework (Gitay *et al.*, 2011) enshrines four steps to follow in process of assessing the vulnerability of freshwater assets to climate change;

- 1. Risk Assessment

Analyze the probability of the risk event such as constructing reservoirs and other forms of impoundments along rivers and the likely impact of the event.

- 2. Risk Perception

This step involves a series of actions including *inter-alia* assessing the present condition and recent trends in the ecological character rivers and determining their sensitivity and resilience including adaptive capacity and the influence of surrounding social systems.

- 3. Risk Minimization or Management

This step involves developing a response option or coping strategy that could minimise abruption changes in the ecological integrity of rivers. These can include strategies that amongst others, change people's behaviour, improve community awareness and ensure integrated management plans are developed.

- 4. Monitoring and Adaptive Management

Monitoring and adaptive management involves using early warning systems, rapid assessment indicators, GIS-based approaches for detecting changes and the effect of the risk management options. Depending on the results from the monitoring studies, adaptive management actions could be taken to modify any of the above steps.

Vulnerability assessment presents an approach that can provide information and guidance for maintaining the ecological character of rivers subject to adverse change as a consequence of climate change (Gitay *et al.,* 2011). The Ramsar framework for vulnerability assessment is unlike other management plans which only present guidance for land patches identified as reserves in relation to physical and biological patterns (Margules and Pressey, 2000). The Ramsar vulnerability assessment framework incorporates maintaining ecological character of rivers as an obligation to governments to minimize impacts of river modification. Governments are legally obliged to make all feasible efforts to maintain the ecological character of the rivers (Gitay *et al.,* 2011).

2.7 Conclusions

Rivers are connected through several dimensions and these connections are necessary for maintaining the ecological integrity of the river. Disturbance to these dimensions occurs through temporal (thermal and flow) changes and spatial anthropogenic catchment and in-stream modifications. Channelization of rivers, flow regulation, and constructing of dams for hydropower generation, and supply to household and agriculture are some of the challenges affecting the natural continuum of rivers. Changes in water temperature and flow variability contribute to the overall breakdown of the connectivity of rivers thereby serving as a major driver of aquatic ecosystem condition and community distribution. Disturbing the natural continuum of freshwater ecosystems reduces the ability of species to adapt and cope with changes. Highly sensitive species loses habitat as water temperatures increase and distribution ranges are expected to shrink due to the degraded connectivity of rivers as a result of spatial and temporal barriers.

CHAPTER THREE

STUDY AREA AND DATASETS

3.1 Introduction

This chapter provides an overview of the study area and different datasets that were used in this study to assess spatial connectivity in rivers. This chapter describes the geographic location where the study was conducted and the physiographic conditions which include *inter alia*; climate, ecological and topographic characteristics of the province. This is followed by a description of the datasets, which originated from various sources and were used not beyond purpose of investigating connectivity of river systems in the study area. Figures and tables are used to illustrate the nature of data used for the assessment of both spatial (longitudinal and lateral) and temporal connectivity of rivers.

3.2 Characteristics of the Study Area

The province of KwaZulu-Natal (KZN) in South Africa was selected as the priority area for this study (Figure 3.1). KZN province covers an area of some 92,000 km² and lies between the 26°50' and 31°10' south of the equator line and 28°50' and 32°50' east of the prime meridian line, in the eastern side of South Africa (Eeley *et al.*, 1999). This province, situated on the eastern coastline along the India Ocean, shares boundaries with other provinces (Eastern Cape, Free State and Mpumalanga) and three neighbouring countries (Lesotho, Mozambique and Swaziland). KZN province experiences summer rainfall (Eeley *et al.,* 1999), with some areas (Drakensberg) receiving a mean annual precipitation of 2 000 mm while lower-lying valley regions receive annual precipitation as 550 mm in the drier seasons, (Lynch, 2004; cited by Schulze *et al.,* 2005). The mid-winter monthly mean temperature ranges from sub-zero along the Drakensberg mountains to values that generally range from about 26°C to 28°C in mid-summer months (Schulze *et al.*, 2005).

The province includes different ecological and topographic characteristics that range from grasslands to forest biome for the former and from relatively flat coastal plains to hilly and valley escarpment of the Drakensberg Mountains for the latter, forming the western boundary of the province (Eeley *et al.*, 1999). The selection of this province as the study area met the scientific requirements for achieving objectives of this current study on riverine connectivity and vulnerability of aquatic biota to climate change. This is because the province still preserves the second highest number of rivers with top priority for retaining their free-flowing character (Driver *et al.*, 2011) and is a home to many freshwater species (Rivers-Moore *et al.*, 2007). With changing climate, a sound knowledge of how rivers will respond to the growing water demand and varying uses is necessary for the KZN. It is also necessary to protect these free-flowing rivers for their ecosystem services.

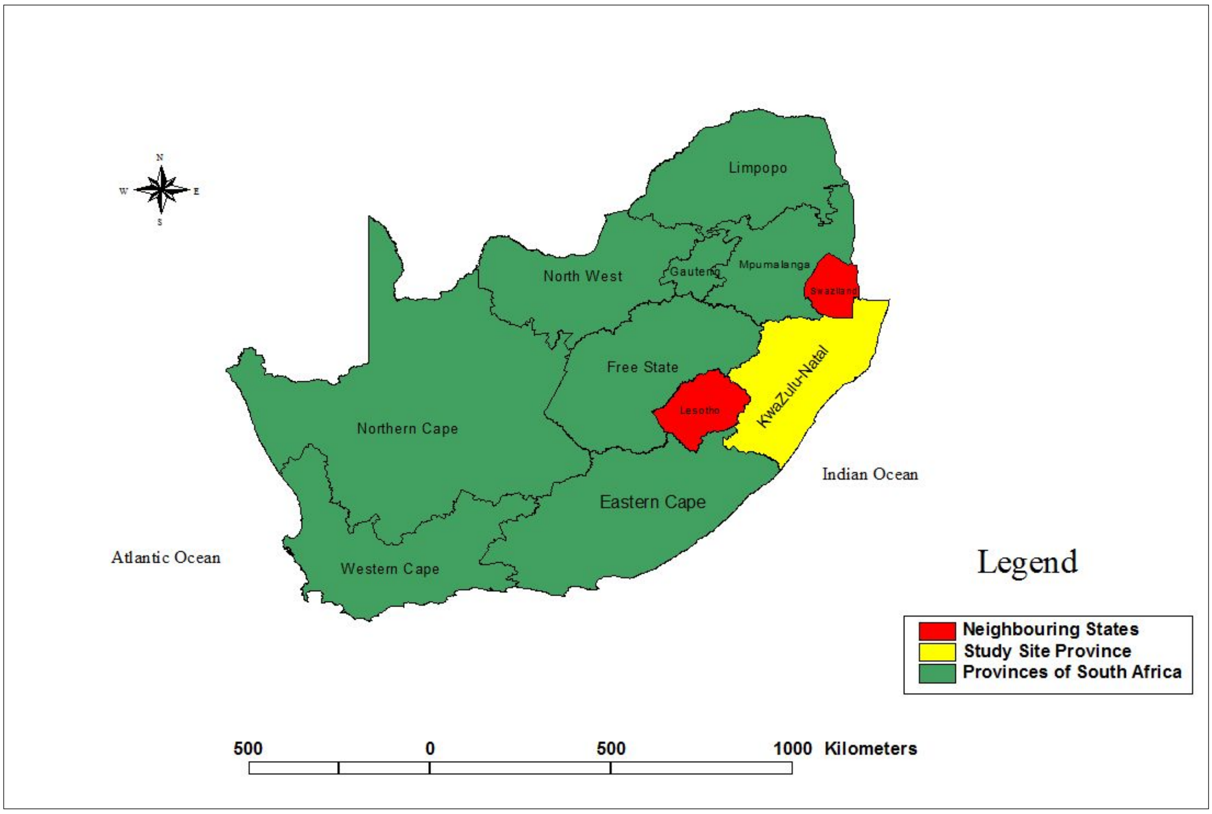


Figure 3.1: Map of the study-area (KZN) in relation to South Africa's other eight provinces.

3.3 Selected Datasets

This study involved the use of several Geographic Information System (GIS) data layers which were collected from numerous sources during the assessment of river connectivity. While datasets included a range of spatial scales and coverage, many were available at a national scale, and these were subsequently clipped to include only features of interest occurring within the boundaries of KZN (Table 3.1).

Table 3.1: KZN Spatial GIS coverage used in this study, their spatial resolution, source and rationale for their use.

Spatial Coverage	Resolution	Data Source	Rationale
Quaternary Catchment	1: 500 000	DWA (2004)	This is a suitable resolution for spatial level data and analyses (Driver *et al.*, 2011).
Rivers	1: 500 000	DWA (2005)	This layer includes various hydrological attributes, and is the most used rivers coverage in South Africa (Driver *et al.*, 2011).
Large Dams	1: 50 000	DLA-CDSM (2005)	Dams affect both the flow and thermal regimes of stream (Caissie, 2006; Poff and Zimmerman, 2010)
Farm Dams	1: 50 000	DWA (1999)	Small (farm) dams have cumulative impacts on the ecological conditions of rivers (Mantel *et al.*, 2010)
Land-Cover	30m	Van den Berg *et al.* (2008)	Land cover can be used to infer information about factors that impact ecological integrity of freshwaters (Allan, 2004).
Waterfalls	Point Data	EKZNW (2006)	Waterfalls acts as natural barriers and eliminate fish species from upstream catchments (Rivers-Moore. 2013 *personal communication*)
Flow Gauging Stations	Point Data	HIS (2006)	Stream flow rates used for Hydrological alteration analyses (Richter *et al.*, 1996)
Air Temperature Stations	Point Data	Schulze and Maharaj (2004)	Used when simulating water temperature (Rivers-Moore, 2013)

3.3.1 Rivers dataset

This study used the 1:500 000 rivers GIS layer that was developed by DWA (2005). Spatial attributes of this dataset includes amongst others; the length of the river, stream order and river class (perennial or non–perennial). Majority of rivers in KZN province are perennial (Figure 3.2), while non-perennial rivers are mostly found in the north-east and -west of KZN. Since total length of rivers decreases exponentially with increasing stream order (Table 3.2), the study made a trade-off between total stream lengths versus practicality at a quaternary-scale study. According to Nel *et al.* (2009) small rivers and tributaries can only extent within a single quaternary catchment whilst some main rivers stretching in more than just one quaternary catchment. For this reason, this study has only made use of rivers with stream order of not less than two (discussed in further details in Section 5.2.1 of Chapter 5).

Table 3.2: Number of river segments, average length and total river length per stream order from DWAF (2005) 1:500 000 river coverage (Rivers-Moore *et al.*, 2007).

Order	**Count**	**Avg. length (km)**	**Total length (km)**
1	340	31	10 500
2	89	47	4 100
3	25	92	2 300
4	8	154	1 200
5	1	316	300
Total	463	N/A	18 400

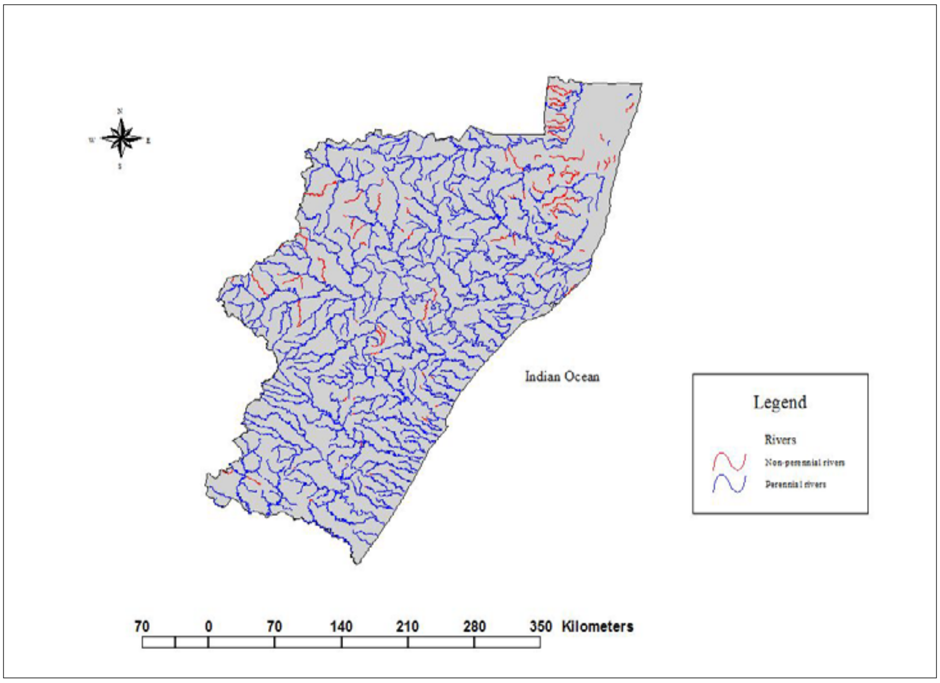


Figure 3.2: Map of KwaZulu-Natal Province showing perennial or non–perennial rivers at a 1:500 000 scale.

3.3.2 Quaternary catchments

The quaternary catchments dataset has been developed by the Department of Water Affair (DWA. 2004; Figure 3.3). Quaternary catchments are drainage areas that are marked by watershed lines, dividing them into smaller hydrological units from a primary catchment level to secondary catchments, tertiary catchments and then quaternary catchments (Nel *et al.*, 2009). They represent zones of homogeneous hydrological response, and are the smallest broadly accepted level in the order of catchment types used for water planning in South Africa (Schulze *et al.*, 2005). There are 305 quaternary catchments in KZN province (Figure 3.2) ranging from 71.02 to 3209.55 km^2 in area, with an average area of 441 km^2. However, only 214 quaternary catchments were relevant to this study as these catchments carry rivers that are selected for spatial connectivity representation. (See section 3.4.1 for selected rivers).

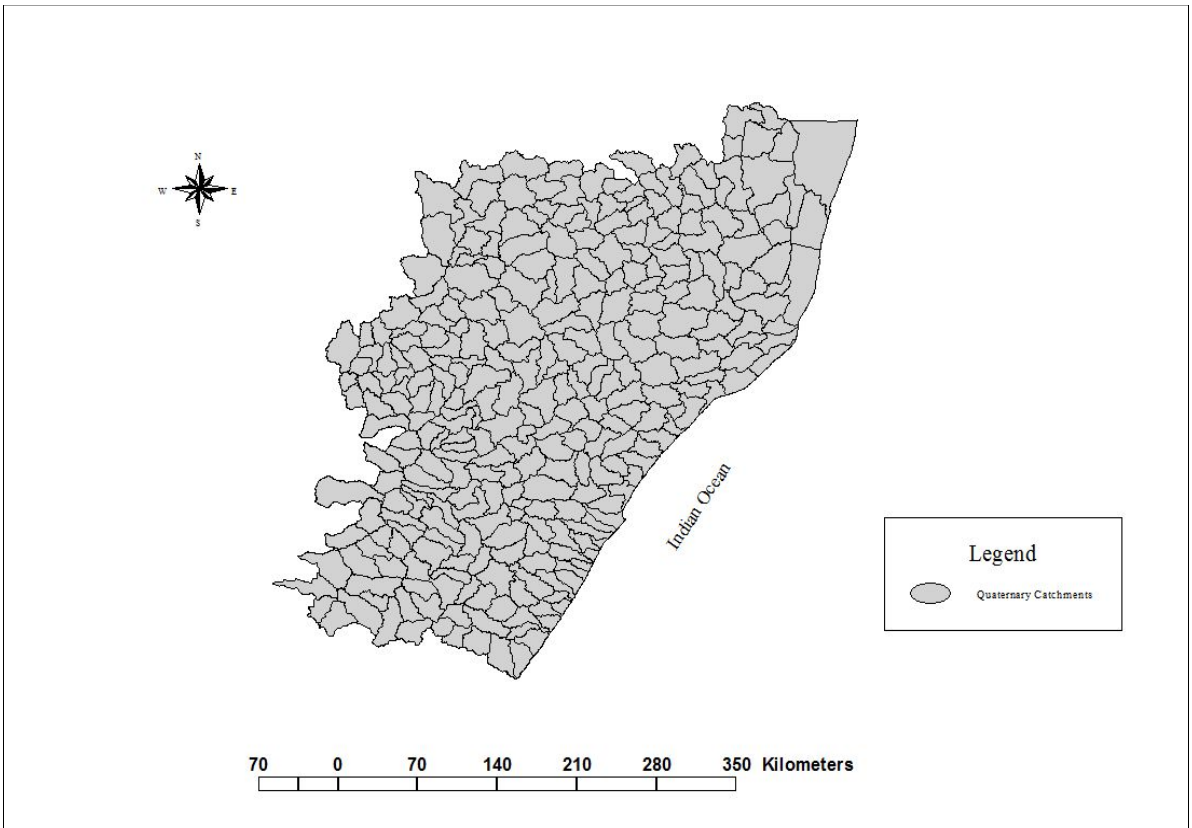


Figure 3.3: Quaternary catchments of KZN province developed by DWA (2004).

3.3.3 Land-cover dataset

The National Land-Cover (NLC) 2000 dataset developed by the Agricultural Research Commission (ARC) was used in this study (Van den Berg *et al.*, 2008). The NLC 2000 was used because newer products have NLC 2000 as their base layer and if this study were to be applied outside of KZN it would need to be based on a national accepted data set and the 2000 NLC is the best for this. The NLC 2000 dataset was generated from high resolution digital Landsat imagery acquired primarily from 2000 to 2001 (Schoeman *et al.*, 2013) and is composed of 49 different land cover types as described in Appendix B. The mapping accuracy for NLC 2000 is at 65.8% (Schoeman *et al.*, 2013) and this provided sufficient information to determine whether the land cover exists in a natural condition or whether it is degraded (Van Dam, 2011).

3.3.4 Dams dataset

This study used the national GIS dataset layers of large dams and small (farm) dams that were developed at the scale of 1:50 000 by Department Land Affairs - Chief Directorate: Surveys and Mapping (2005) and DWA (1999) respectively. These datasets were used to determine locations of in-stream barriers (large dams) and to quantify the number of farm dams occurring within each quaternary catchment. These datasets were complemented by the use of the Google ™ Earth application which was used to verify and trace dams that were either excluded or built after the development of the national GIS dataset layer for dams.

3.3.5 Flow gauging stations

This study extracted Mean daily stream flow data from gauging stations that are installed and monitored by the Department of Water Affairs (DWA) of South Africa. A flow gauging station is a site along a river extent which has been selected, equipped and operated to provide the basic data from which systematic records of water level and discharge may be derived (Wessels and Rooseboom, 2009). There are 391 flow gauging stations in the network of rivers in KZN province. These stations record a time series data for average daily and monthly flow volume, and this data was accessed from the DWA website (http://www.dwaf.gov.za/hydrology). It is known that a large proportion of gauging weirs in many of the rivers in KZN province have only been installed after completion of impoundments and this create a challenge for analysis of the natural and post-impact stream flow conditions (Rivers-Moore *et al.,* 2007).

3.3.6 Air temperature stations

Considerably more air temperature data exist for southern Africa than water temperature data (Rivers-Moore and Lorentz, 2004; Rivers-Moore *et al.*, 2008; Schulze and Maharaj, 2004). As a result, water temperature is yet to be widely recorded in most of the rivers across the province of KwaZulu-Natal. Therefore, this study examined thermal changes at selected sites using simulated water temperature, and based on the correlation between air and water temperatures. Daily minimum and maximum air temperatures from 1950 to 2000 (Schulze and Maharaj, 2004) were available for temperature stations closest to the flow gauging weirs used in this study.

3.3.7 Conclusion

The province of KZN still preserves a number of free-flowing rivers and provides habitation for a diversity of aquatic macroinvertebrate species. This makes this province a perfect environment for undertaking a study of this nature. This province is also characterized by a distinct climate and landscapes features which tell of the unique conditions this study will explore. This study intended to employ GIS techniques to analyses different landscape process of this province. River coverage layer enlighten this study with information on the length of the river, stream order and river class. Quaternary catchments, which are zones of homogeneous hydrological response, were unit of measurement for all the landscape assessments of this study. Other datasets that were used include the land cover and spatial coverage of dams. These datasets were the basis in the process of analysing spatial human activities in the province at each quaternary catchment. Temperature and flow data were also sourced from Schulze and Maharaj (2004) and DWA respectively. All these datasets contributed to the achievement of the main study aims and objectives.

CHAPTER FOUR

ASSESSMENT OF TEMPORAL CONNECTIVITY OF SELECTED RIVERS IN KWAZULU-NATAL

4.1 Introduction

Stream flow and water temperature are important regulators of distribution and survival of aquatic macroinvertebrate species (Dallas and Ketley, 2011; Sheldon, 2012; Richter *et al.,* 1996). It is relevant for regional freshwater ecological studies to assess the magnitude of changes in both stream flow and temperature to understand how species respond to such changes (Richter *et al.,* 1996). In this chapter, changes in pattern and magnitude of both flow and water temperature time series data as a result of impoundments were assessed in selected rivers. This study's assessment quantified alteration of these two variables (flow regime and water temperature) based on two periods component, namely the natural conditions before a river was altered and the modified conditions post river alteration.

A number of quantitative approaches exist for the description of both flow and water temperature alterations. This study used the 'Indicators of Hydrological Alteration' (IHA) method (See methodology) as it provides a credible approach to study and estimate changes in flow patterns relative to natural variability. IHA method assesses the magnitude, frequency, duration, timing and rate of change of flow, which are all metrics of biological importance. River flow plays an important role in sustaining biodiversity and ecological integrity, and organizes essential ecological characteristics of a river ecosystem (Poff and Zimmerman, 2010; Power *et al.,* 1995). Relative to IHA, water temperature was assessed using a similar statistical approach called Indicator of Thermal Alteration (ITA). This model assesses changes in long-term temperature records based on the magnitude, timing, frequency and duration of events (Rivers-Moore, 2013) of pre-and post-impoundment periods (See methodology). This is important as water temperature is a primary factor influencing aquatic ecosystems and drives many aspects of an organism's existence such as metabolic, growth, feeding, etc (Dallas and Ketley, 2011; Poole and Berman, 2001).

4.2 Methodology

Temporal connectivity assessment was limited to rivers with flow data recorded pre- and post-impact events downstream of the in-stream impoundments. This came as a result of comparing the date at which each of the in-stream impoundments occurring within selected rivers was built and the first date in which flow was recorded (see Table 4.3).

4.2.1 Flow regime

Changes in flow regime of selected rivers were assessed using daily mean flow values ` recorded before and after construction of large dams. These time series flow data were extracted from gauging stations situated downstream of large dams. Gauging stations located upstream of impoundment are not ideal as they receive undisturbed or unregulated flow of a river. Changes in stream flow regime were analysed using the Indicator of Hydrological Alteration (IHA) method by Richter *et al*. (1996) which assesses both natural and human induced hydrological modification of aquatic systems. The IHA regime metrics consider the magnitude, timing, frequency, duration and rate of change of stream flow as factors determining stream flow alterations for aquatic ecosystems (Richter *et al.,* 1996). These five factors of stream flow characteristics consist of 33 hydrological parameters which can be attributed to determining the nature of aquatic and riparian ecosystems regime (Taylor *et al.,* 2003). The IHA method analysed the two distinct time periods (natural and modified) of flow records of river systems that has experienced changes attributed to construction of a dam. This was to determine the degree of alteration between pre-impact and post-impact flow of rivers. The method ideally required a minimum of 20 years of flow records to minimise the effects of inter-annual climatic variation on the IHA parameter statistics (Taylor *et al.,* 2003) and to observe meaningful trends in the data (Rivers-Moore *et al.,* 2007).

This flow data containing flow figures of each single day was collected from seven stations with pre- and post-impoundment flow regime, and was run through the IHA software (TNC, 2009) separately using non-parametric statistics because of the skewed (non-normal) nature of many hydrologic datasets (TNC, 2009) and which is more suitable for South African conditions (Taylor *et al.,* 2003). The outcomes of these analyses were presented in a scorecard spreadsheet consisting of values for IHA regime metrics. A summary of the statistical parameters, and their characteristics used in the Indicators of Hydrologic Alteration

(IHA) analyses is provided in Table 4.1. After running this analysis for all the stations, the data or values were then structured into a single scorecard spreadsheet for easy comparison of flow changes between stations. This structured data in a Microsoft Office Excel contained a yearlong monthly average of pre-and post-impoundment flow and ran using PCA approach to compare changes between sites and periods (pre-and post-impoundment).

Table 4.1: A summary of the hydrological parameters applied in the Indicators of Hydrologic Alteration (IHA), with associated characteristics (after Richter *et al.*, 1996).

IHA statistics group		**Regime characteristics**	**Hydrologic parameters**
Group 1	Magnitude of monthly water conditions	Magnitude Timing	Mean value for each calendar month
Group 2	Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means
Group 3	Timing of annual extreme water conditions	Timing	Julian date of each annual 1 day maximum Julian date of each annual 1 day minimum
Group 4	Frequency and duration of high and low pulses	Magnitude Frequency Duration	Number of high pulses each year Number of low pulses each year Mean duration of high pulses within each year Mean duration of low pulses within each year
Group 5	Rate and frequency of water condition changes	Frequency Rate of change	Means of all positive differences between consecutive daily means Means of all negative difference between consecutive daily means Number of rises Number of fall

4.2.2 Water temperature simulation and verification

Time series values for water temperature were not available as this phenomenon is not largely measured in many rivers as opposed to air temperature (Rivers-Moore *et al.,* 2005). However, it was possible to simulate water temperature based on the statistical relationship between stream thermal variation and both flow rates and air temperatures; as recognised by a number of studies (Jeppesen and Iversen, 1987; Morrill *et al.*, 2004; Rivers-Moore *et al.,* 2005; Rivers-Moore *et al*., 2012; Webb and Nobilis, 1997). Time series values for stream flow were readily available for all selected sites and were downloaded from the DWA database (http://www.dwaf.gov.za/hydrology). The validity or accuracy of simulated water temperature was verified using observed daily water temperatures recorded between the period of 23rd of November 2003 to 7th of July 2004 in the uMngeni River at gauging station U2H014 which is located downstream of the Albert Falls Dam. Water temperature and verification analyses were run to establish the correctness or validity of simulated data as compared to observed natural figures.

However, it is important to note that simulated water temperatures do not necessarily reflect real ground conditions as they are based on surrogates (Rivers-Moore, 2013). Daily maximum and minimum air temperature data for selected sites were extracted from a database of daily air temperatures for southern Africa from Schulze and Maharaj (2004). Daily maximum and mean water temperature of selected sites were simulated using multiple linear regression models (Equations 4.1-2) developed by Rivers-Moore and Lorentz (2004) and Rivers-Moore *et al.* (2008) respectively. These equations were used as they incorporated a flow term. Equation for simulating maximum water temperature is;

$$WT_{max} = \beta + A_1 AT_{mean} - A_2 (1/\ Flow) + A_3 AT_{min} \qquad (4.1)$$

Where WT_{max} represents maximum water temperature, β is the regression constant (4.004), 1/Flow is the inverse of mean daily flow rate ($m^3.s^{-1}$), AT_{mean} and AT_{min} is mean and minimum daily air temperature (°C) respectively, and A_1 (0.8995), A_2 (0.4827) and A_3 (N/A) are coefficients values for generic multiple regression models that include flow rate,

For daily mean water temperature (WT_{mean}), the following multiple linear regression model equation was used:

$$WT_{mean} = \beta - A_1 \log(flow + 1.0) + A_2 AT_{mean-1} \qquad (4.2)$$

Where β is the regression constant (8.593), flow is mean daily flow value, with 1.0 added to allow for zero flows in the log conversion, AT_{mean-1} is mean daily air temperature (24 hours behind), A_1 (2.667) and A_2 (0.477) are both the coefficients values for generic multiple regression.

4.2.3 Water temperature analysis

Simulated daily mean, minimum and maximum water temperatures for the selected stations were used for water temperature analyses. The Indicators of Thermal Alteration (ITA) method by Rivers-Moore *et al.* (2012) was used for assessing changes in water temperature regime analyses. The ITA method enables quantification of the extent of alteration of water temperature metrics in response to an impact such as an impoundment, based on changes in magnitude, frequency, timing and duration of thermal events (Rivers-Moore *et al.*, 2012; see Table 4.2). For this study, the water temperature data (mean, minimum and maximum) was averaged to cover a one year period before and a one year after in-stream for each separate impoundment. This is because the ITA system has only been designed to analyse a single year of water temperature data (Rivers-Moore, 2013; Personal communication). The calculations of ITA parameter groups and annual descriptive statistics (Table 4.2) for a period before and after impoundment effects were calculated using a Microsoft Office Excel for each period (before and after) for all selected stations. The outcomes for all sites were assembled into a single spreadsheet for PCA analysis.

4.2.4 Principal component analysis

Principal Component Analysis (PCA) is a powerful tool for identifying patterns in data, and it expresses the patterns in such a way as to highlight their similarities and differences (Smith, 2002). Data suffers the least possible distortion as its graphical presentation preserves the spacing of the points through PCA analyses (Pielou, 1977). In this study, PCA analyses were undertaken to project and ordain correlation matrix for both flow and water temperature models before and after impoundments effect at each of the selected stations. These analyses (PCA) were undertaken using the statistical software MVSP (Multi-Variate Statistical Package) (Kovach Computing Service, 2008). Analyses were undertaken for both water temperature and flow data metrics to assess changes in time series before and after impoundment.

Flow data included a spreadsheet that resulted from IHA analyses containing the 33 hydrological flow parameters for pre and post impoundment effect for all selected stations. Temperature spreadsheet data included the monthly and annual values for both mean water temperature and coefficient of variability. The data contained in the spreadsheets were systematically transposed and standardized or transformed to a default value of one. The PCA outcomes were based on eigenvalues and correlation percentage between variables. PCA was used as is one of the common and simple methods that best explains the variance in the data or provides an understanding of how sites compare with each other. Canonical Correlation Analysis (CCA) could not be used as it describes the cross-covariance between two dataset (Smith, 2002).

Table 4.2: Indicators of Thermal Alteration parameters for water temperature analyses (after Rivers-Moore *et al.*, 2012).

Annual descriptive statistics		Mean annual temperature SD of mean annual temperature Annual coefficient of variability Predictability (Colwell 1974) Annual range (mean) SD of annual range Annual coefficient of variability of range Summer range Winter range
Group 1	Monthly **Magnitudes** (measure of central tendency)	Oct – Sept mean temperatures
Group 2	Magnitude and **Duration** of annual extreme water temperature conditions(Based on moving averages of different durations)	1, 3, 7, 30 & 90-day minim 1, 3, 7, 30 & 90-day maxima Degree days (annual/ monthly/ seasonal) Mean daily minimum Maximum diel range
Group 3	**Timing** - Julian date of maximum and minimum metrics (thermal triggers)	Date of minimum Date of maximum
Group 4	**Frequency** and duration (successive days of event above or below a threshold)	Min. temp threshold count & duration Max. temp threshold count & duration Duration between two temperatures

4.3 Results

Flow data that met the minimum requirements (covering of years before and after a large dam was built) for temporal connectivity assessments were only available for seven flow gauging station out of maximum possible nineteen sites downstream of large dams combined. It was also found that most of the flows gauging stations have only been installed after the construction of most large dams in the province. The names of rivers in which these stations are found together with the name of a large dam, year built, flow station downstream, nearest air temperature station and the length of stream flow data recorded are provided in Table 4.3. The simulation distance confidence was high as all the air temperature stations selected for this study were close to the location of the flow gauging station in question. The assumption is that air temperature stations located in the periphery of the river would experience similar climatic condition to that experienced in the river in areas of the same landscape gradient.

Table 4.3: Selected stations and the length of flow data for temporal connectivity assessment.

Station Number (site)	Name of River	River Disturbance	Year Built	Flow Station	Air Temp Station	Data Period (Years)
Station 1	Lovu/ Illovo	Beaulieu Dam	1986	U7H007	0239566_A	Pre (22) And Post (26) impact
Station 2	Mdloti	Hazelmere Dam	1977	U3R001	0241214_S	Pre (2) And Post (36) impact
Station 3	Boesman	Wagendrift Dam	1963	V7H020	0268631_W	Pre (1)And Post (49) impact
Station 4	Mgeni	Midmar Dam	1965	U2H001	0269477_A	Pre (17) And Post (28) impact
Station 5	Mgeni	Albertfalls Dam	1976	U2H014	0269744_S	Pre (12) And Post (37) impact
Station 6	Mhlatuze	Goedertrouw Dam	1982	W1H028	0304043_A	Pre (3) And Post (31) impact
Station 7	Hluhluwe	Hluhluwe Dam	1965	W3H022	0339488_A	Pre (1) And Post (48) impact

4.3.1 Stream flow analysis

IHA analyses were undertaken for all seven stations with pre- and post-impoundment flow data. However, stations two and three (Table 4.3) could not be assessed because of very short data periods (1-2 years) for pre-impoundment periods. The results for the remaining five stations are presented in the scorecard format in Table 4.4. The first row of the scorecard compares the annual descriptive statistics between pre and post-impact. Amongst others, the values of the following parameters were given; median annual flow, flow constancy, annual coefficient of variation and length of flood free season. The five hydrological parameter groups (row 2 to 6) compared between the pre and post impoundment impact at each of the five stations (columns) in Table 4.4.

Except for December and January, the monthly medians (Parameter Group 1) for pre impoundment flow conditions were higher at station one compared to the post dam construction flow (Table 4.4; Figure 4.1a). Similarly, flows were high at station two during the pre-impact period with only three month recording high median during the post impact era. The same cannot be said for station five, six and seven as they all showed high flow conditions for majority of months during the post dam era than during the natural flow regime period (Table 4.4). Parameter Group 2 shows the minimum and maximum of extreme annual flow conditions following a moving average of 1, 3, 7 (weekly), 30 (monthly) and 90 (seasonal) days. The minimum extremes mean were high during the pre-flow era than after dam conditions for almost all stations with an exception of station five. The maximum extremes mean flow also showed high pre-conditions flows for all stations (e.g. Figure 4.1b) with exception counted for only the 90-days maximum in station six. This means that higher flow conditions were experienced during the pre-dam construction era at all stations.

Parameter Group 3 showed the number of days in which both 1-day minimum and maximum flow conditions were experience before and after impoundment constructions. Most 1-day minimum flows were experienced after dams were installed in four stations (exception is station one), while 1-day maximum were high during the pre-dam flow era in three of the five stations (station one, four and seven) (Table 4.4). The 1-day maximum flow conditions for station five are shown in Figure 4.1c, where the mean is at the low of 44.00m^3s^{-1} during the pre-impact era and high at 62.50m^3s^{-1} post dam impacts.

Group 4 parameters include the duration (days) and the number of both low and high pulse of flow conditions before and after the construction of in-steam dams at the five stations. An equal low pulse of 3 for both pre and post dam flow was recorded for station one, while station six has recorded the mean low pulse flow of 9 and 0 during pre and post dam construction respectively (Figure 4.1d). The longest duration for high pulse flow was 43 days during the 2.50 high pulse events recorded for pre-impact flow at station seven (Table 4.4).

Group 5 parameters measured the mean rate of change (positive and negative) in flow conditions between each of the two data periods (pre and post impact). The most positive changes were at the mean of 0.22 and 0.19 experienced at station 5 and 4 respectively during the natural flow era, while the most negative mean change of minus 0.23 experienced at station 5 during the same era. This gives evidence to the high degree of variability of flow during the pre-impact period at station 5. However, the mean reversal counts for station seven during the pre-impact were 33.50 and increased post dam construction to 108.50 (Figure 4.2).

Table 4.4: IHA median score for the five stations that have responded to the analysis.

PARAMETERS	STATION ONE		STATION FOUR		STATION FIVE		STATION SIX		STATION SEVEN	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Annual Descriptive										
Normalization Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mean annual flow	0.45	0.35	6.30	5.39	8.92	6.99	1.29	3.40	0.51	1.29
Non-Normalized Mean Flow	0.45	0.35	6.30	5.39	8.92	6.99	1.29	3.40	0.51	1.29
Annual C. V.	2.76	2.23	1.22	2.56	1.36	1.62	3.44	2.20	12.39	8.03
Flow predictability	0.31	0.36	0.52	0.39	0.58	0.53	0.66	0.35	0.74	0.30
Constancy/predictability	0.60	0.61	0.62	0.78	0.76	0.87	0.31	0.79	0.45	0.80
% of floods in 60d period	0.32	0.33	0.37	0.37	0.40	0.31	0.37	0.26	0.50	0.26
Flood-free season	15.00	1.00	58.00	52.00	46.00	2.00	50.00	0.00	119.00	0.00
Parameter Group 1										
October	0.13	0.11	1.43	2.10	4.55	4.96	0.04	1.93	0.11	0.38
November	0.24	0.14	2.71	1.63	4.35	5.08	0.02	1.62	0.48	0.39
December	0.23	0.39	7.48	2.46	5.70	4.29	0.93	2.08	0.37	0.43
January	0.39	0.48	10.57	3.18	7.34	4.64	0.67	2.60	0.16	0.49
February	0.57	0.33	7.78	5.25	11.60	5.72	1.54	3.55	0.08	0.57
March	0.57	0.34	7.04	6.61	8.41	6.41	0.49	3.39	0.08	0.52
April	0.29	0.20	6.30	3.76	9.35	6.18	0.02	2.80	0.15	0.47
May	0.15	0.13	4.04	2.13	4.79	4.82	0.33	2.76	0.13	0.40
June	0.15	0.12	2.43	1.66	4.43	5.12	0.13	2.24	0.07	0.32
July	0.12	0.09	1.91	1.58	4.23	4.94	0.01	2.00	0.06	0.29
August	0.13	0.10	1.72	2.03	4.26	4.35	0.01	2.27	0.06	0.31
September	0.14	0.13	1.61	1.73	4.45	4.65	0.29	2.63	0.03	0.35

Parameter Group 2										
1-day minimum	0.00	0.02	0.74	1.07	2.27	1.55	0.00	0.02	0.01	0.02
3-day minimum	0.00	0.02	0.76	1.17	2.32	1.71	0.00	0.04	0.02	0.03
7-day minimum	0.00	0.03	0.84	1.22	2.40	2.24	0.00	0.06	0.02	0.04
30-day minimum	0.03	0.06	1.08	1.37	2.98	2.69	0.00	0.36	0.03	0.15
90-day minimum	0.09	0.10	1.73	1.52	4.04	3.62	0.17	1.34	0.05	0.23
1-day maximum	4.40	2.09	41.27	26.05	42.65	14.84	45.99	6.33	84.10	28.81
3-day maximum	2.69	1.78	36.64	24.46	37.44	14.65	26.58	6.20	35.94	17.31
7-day maximum	1.91	1.40	30.33	21.55	33.91	12.45	14.25	5.68	16.98	8.32
30-day maximum	1.14	0.83	19.29	15.08	23.21	10.11	5.22	5.03	4.47	2.91
90-day maximum	0.77	0.60	12.15	10.52	15.81	6.96	2.28	3.87	1.83	1.54
Number of zero days	4.00	0.00	0.00	0.00	0.00	0.00	2.00	0.00	108.50	0.00
Base flow index	0.01	0.14	0.13	0.26	0.28	0.32	0.00	0.02	0.13	0.07
Parameter Group 3										
Date of minimum	265.50	224.50	280.00	325.50	189.50	247.50	226.00	307.00	157.50	278.00
Date of maximum	45.00	31.00	48.00	31.50	44.00	62.50	16.00	44.00	203.50	42.00
Parameter Group 4										
Low pulse count	3.00	3.00	4.00	5.50	8.00	6.00	9.00	0.00	0.00	0.00
Low pulse duration	8.00	8.50	9.00	10.00	7.25	8.50	3.00	4.25	0.00	0.00
High pulse count	8.50	4.00	4.00	2.00	6.50	3.50	11.00	5.00	2.50	5.00
High pulse duration	4.00	5.75	5.00	9.00	3.75	5.00	3.00	23.00	43.00	21.50
Low Pulse Threshold	0.08	0.00	1.76	0.00	3.81	0.00	0.02	0.00	0.00	0.00
High Pulse Threshold	0.48	0.00	7.28	0.00	7.60	0.00	0.86	0.00	0.18	0.00
Parameter Group 5										
Rise rate	0.02	0.01	0.19	0.07	0.22	0.05	0.01	0.07	0.02	0.01
Fall rate	-0.01	-0.00	-0.16	-0.08	-0.23	-0.06	-0.05	-0.04	-0.02	-0.01
Number of reversals	93.50	71.00	80.00	97.00	121.50	93.00	104.00	114.00	33.50	108.50

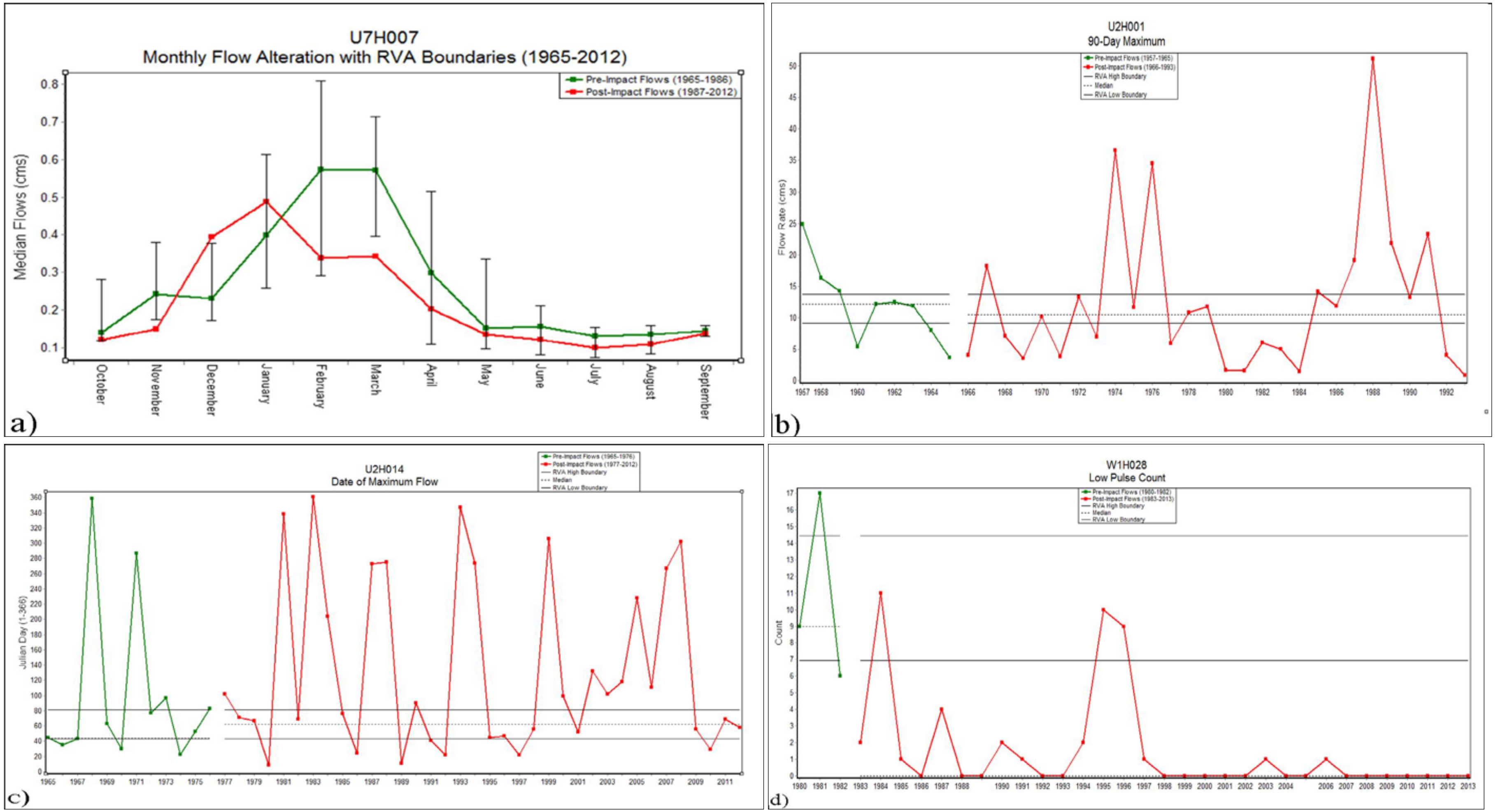


Figure 4.1: Examples of changes in the hydrological regime, a) Changes in monthly magnitude of mean daily flows from station one (Group 1), b) Magnitude and duration of extreme water conditions in station four (Group 2), c) Timing of annual extreme flow condition in station five (Group 3), and d) Frequency and duration of high or low pulse threshold of flow events in station six (Group 4).

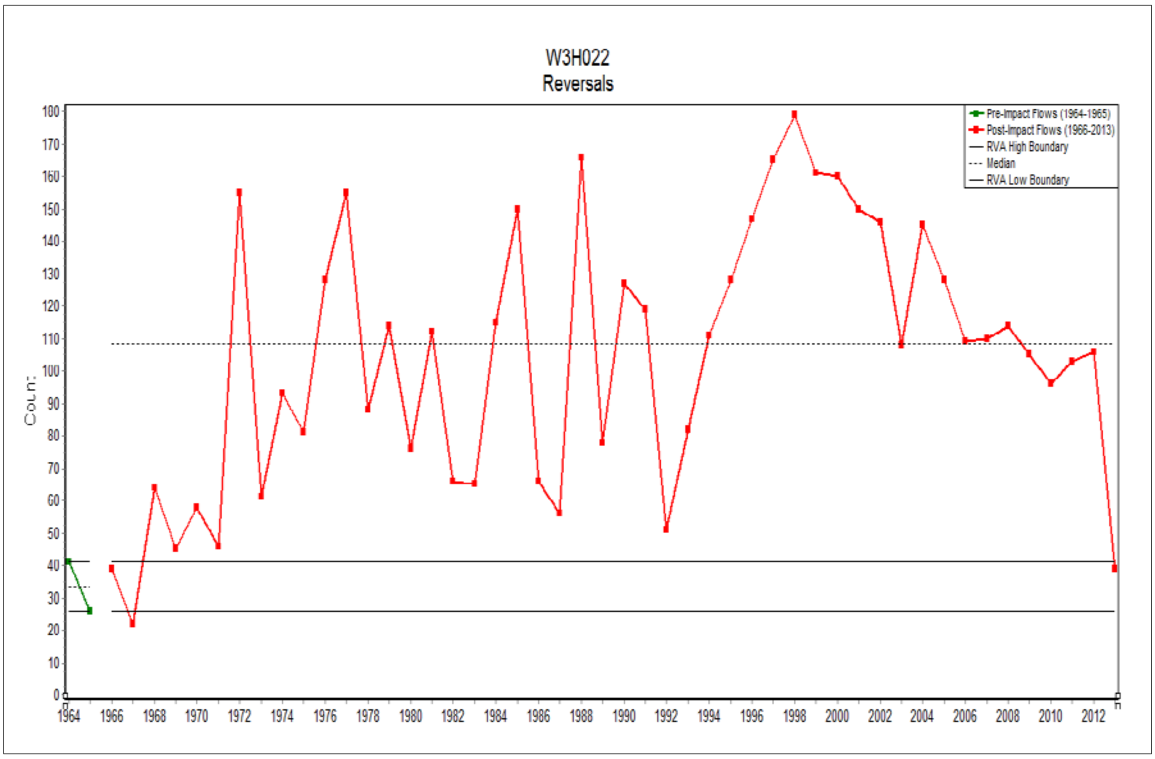


Figure 4.2: The number (counts) of reversals of flow conditions for station seven. The number of reversals is the number of times that flow switches from one period type to another.

4.3.2 Water temperature verification

This assessment used available water temperature data and air temperature values recorded for 198 days between 2003 and 2004 downstream of Albert Falls Dam in the uMngeni River. Simulation models used in these assessments were point based methods, predicting water temperature at the station of interest (U2H014) over time. It should also be noted that the air temperature station was 1.3 km from the river thus showing high confidence of simulation distance. The correlation between maximum values of both observed and simulated temperature had the R^2 value of 0.73 (Figure 4.3), while the R^2 value was at 0.70 for correlation between mean observed and simulated temperature values (Figure 4.4). However, the R^2 value was relatively poor (0.41) for the correlation between the minimum observed and simulated water temperature as shown in Figure 4.5. Given these correlations verification assessment, the level of confidence for two components of water temperature (mean and maximum) was high and values can therefore be used as surrogates for the unavailable observed water temperature values. Simulated minimum water temperature values was poor compared to the mean and maximum at 0.41 and were not used as substitutes for observed water temperature.

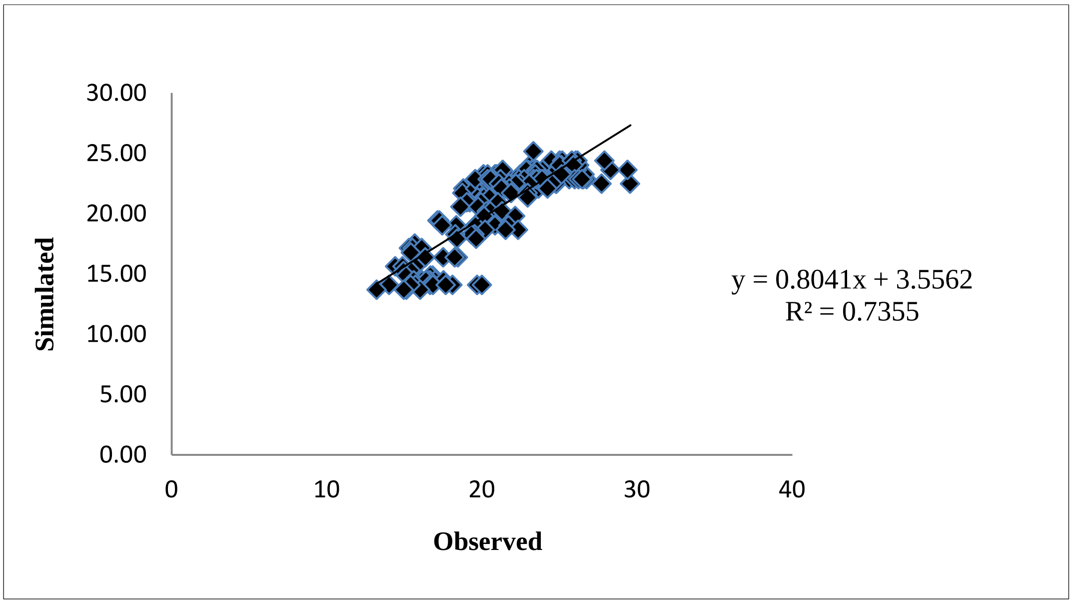


Figure 4.3: Simulated versus observed maximum water temperature studied at flow station U2H014 situated below Albert Falls dam in the uMngeni River.

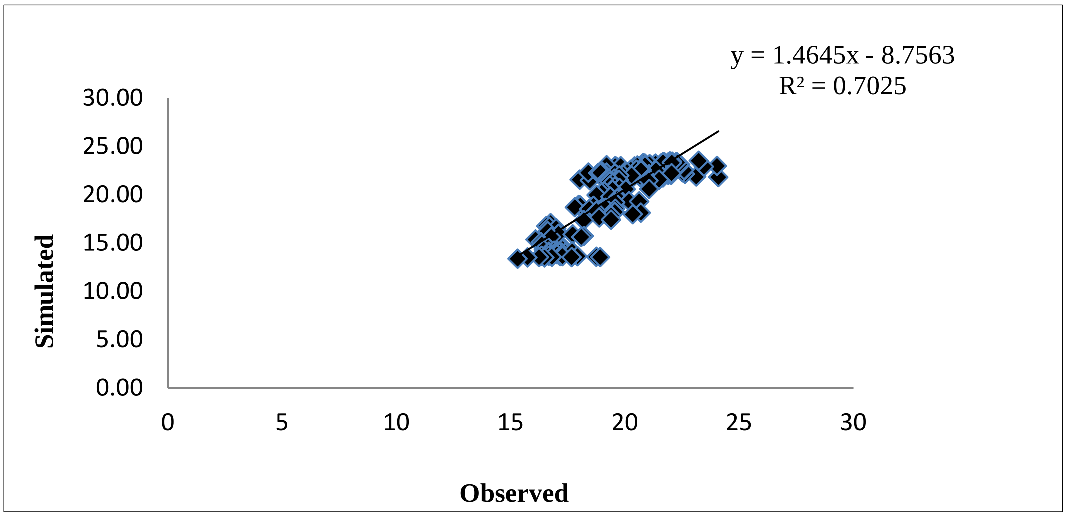


Figure 4.4: Simulated versus observed mean water temperature studied at flow station U2H014 situated below Albert Falls dam in the uMngeni River.

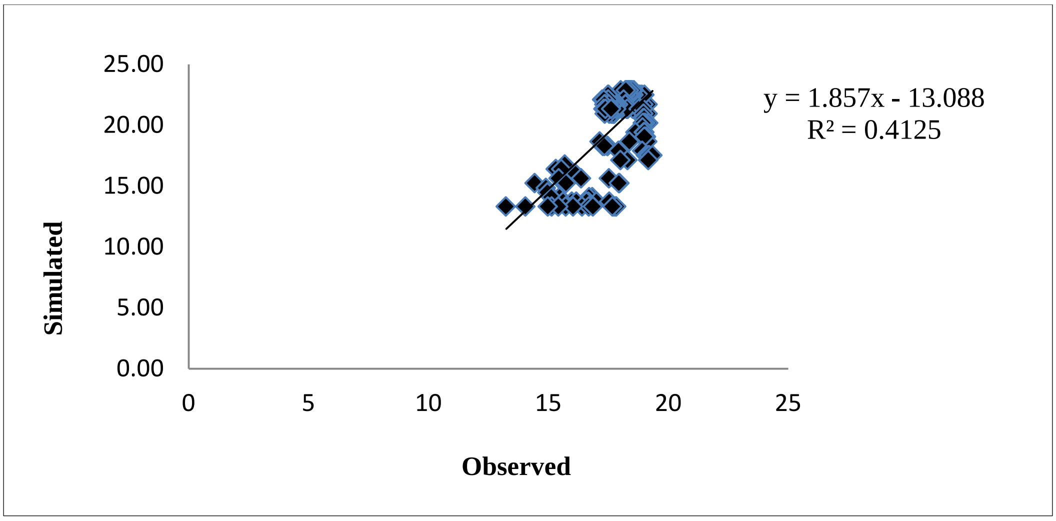


Figure 4.5: Simulated versus observed minimum water temperature studied at flow station U2H014 situated below Albert Falls dam in the uMngeni River.

4.3.3 Water temperature analyses

This study only considered the mean simulated water temperature for analyses thermal changes. Simulated minimum and maximum water temperature values from the used model produced extreme values (for example, 106°C minimum and -141°C maximum during the pre-impact era at station 6) and this could not be used. This was largely as a result of simulation models' inability to generate both minimum and maximum water temperature values from low flow values, since the models had been calibrated for higher flow values. For this reason, it was not possible to examine water temperature changes using the ITA methodology as it requires realistic and undistorted temperature values. Analyses were thus based only on a summarized or a yearlong monthly mean water temperature values for period of pre- and post-impact at all five stations examined (Figures 4.6a-d, 4.7). Data from all five stations showed similar trends, i.e. that water temperatures were less variable after a dam was built than before.

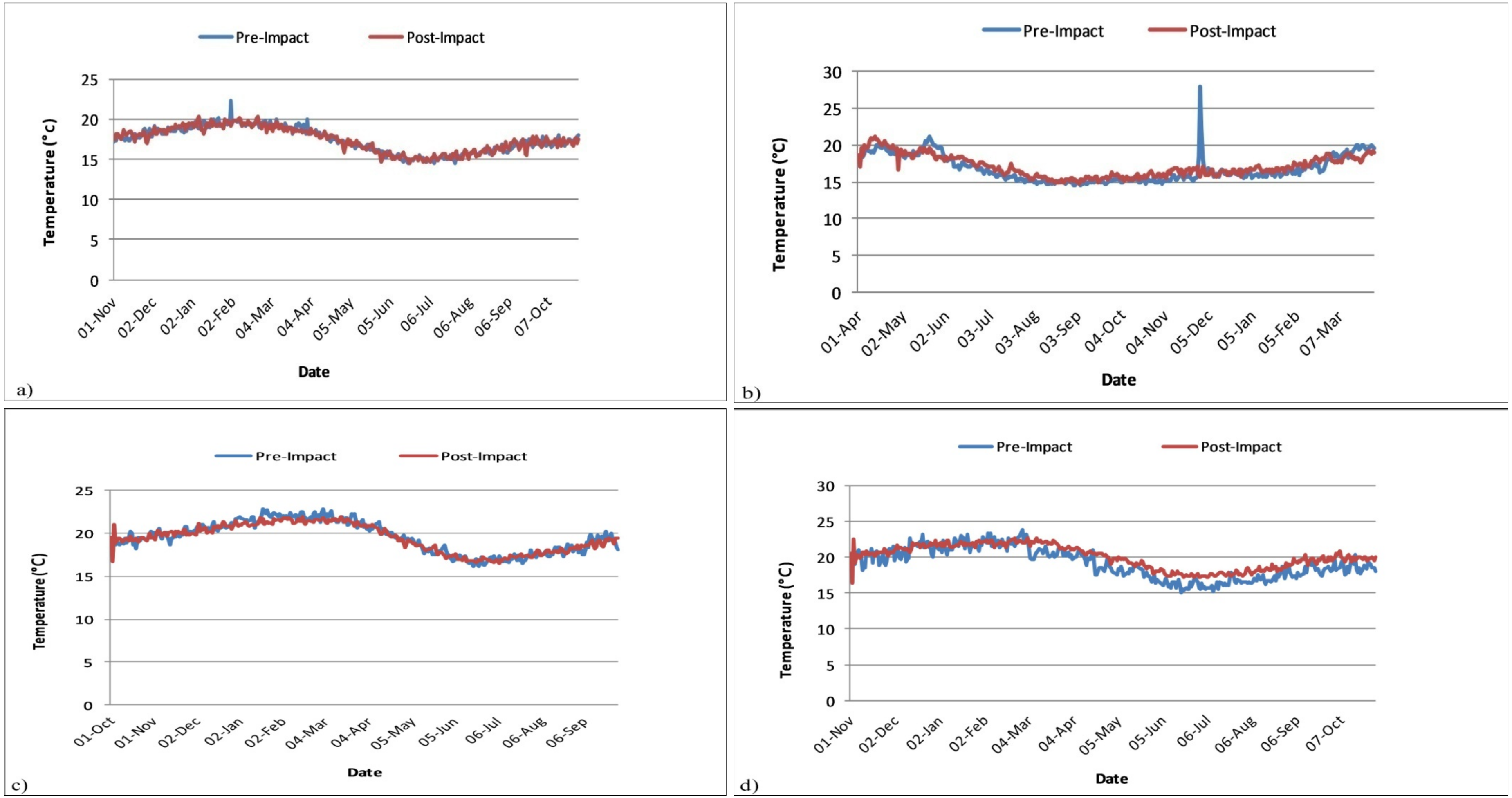


Figure 4.6: Linear graphs of monthly mean figures of pre- and post-impoundment water temperatures in; a) Station 1, b) Station 4, c) Station 5, and d) Station 6.

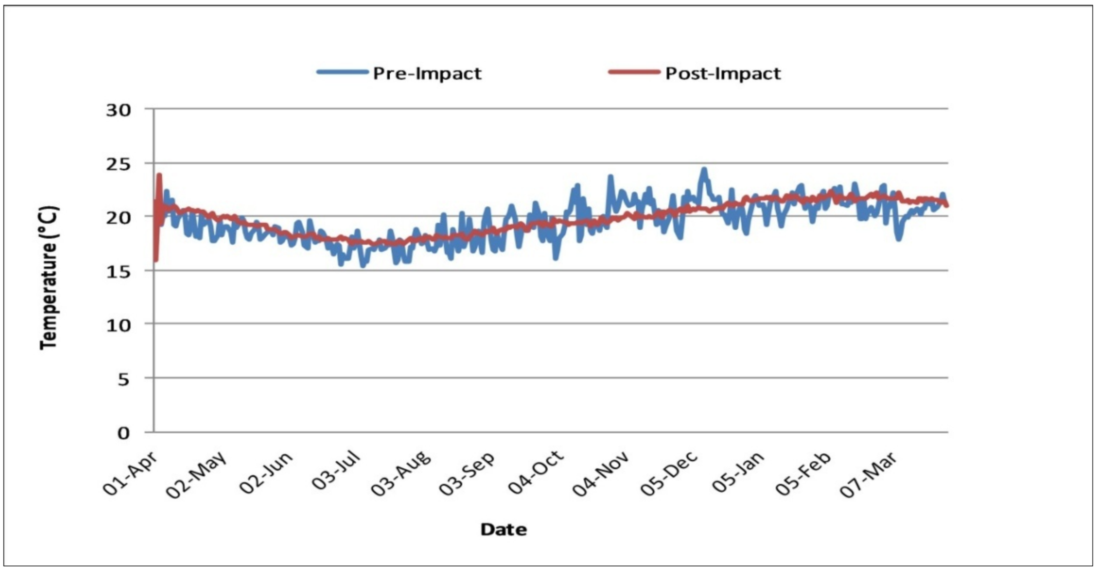


Figure 4.7: A linear graph showing monthly mean figures of water temperature for pre- and post-impoundment at station number 7.

4.3.4 PCA analyses

4.3.4.1 Stream flow changes

The PCA correlation matrix for stream flow pre and post impoundment effect included the hydrological parameters as defined by IHA methodology (Table 4.1 and 4.4). However, not all the 33 IHA parameters were used in this regard as can be seen in Figure 4.8 and Table 4.5 found in the next pages. Highly correlated variables were withheld from the graphic representation matrix as they all showed great correlation of value. Most of these variables were from the group 1 parameters that contains magnitude of monthly water conditions. Therefore, by deciding to leave out some variables of lesser significance (though of high correlation), no data lose was encountered because the eigenvalues were small and therefore the final PCA graphic set had less dimensions than the original (Figure 4.8). Conversely, the stream flow PCA matrix figure featured the variables with the large eigenvalue and most significant relationship between the data dimensions (Table 4.5).

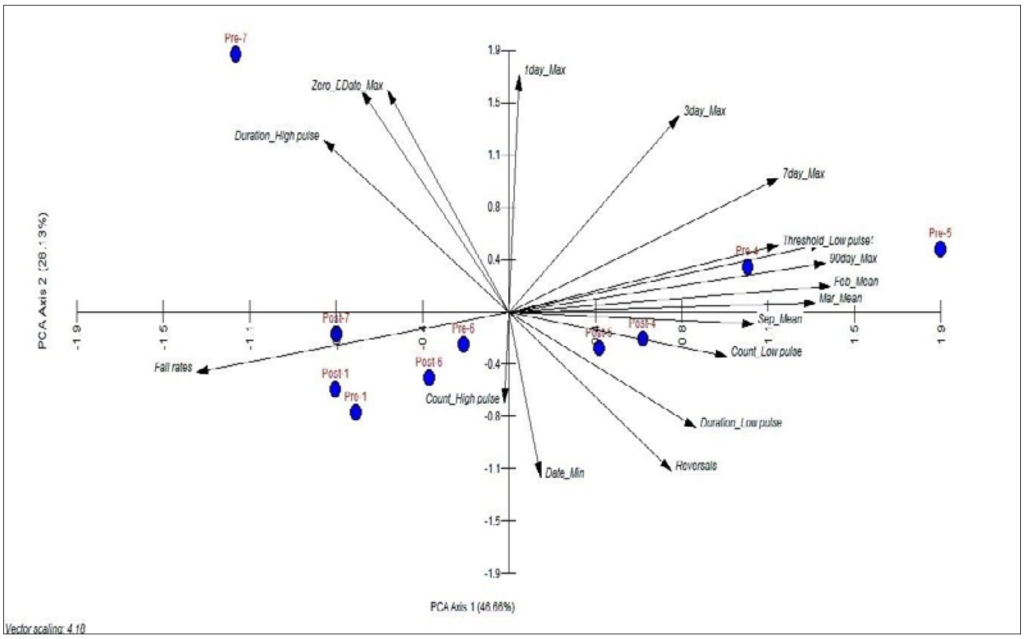


Figure 4.8: Principal components analysis of IHA variables for five flow stations showing how flow differs between pre- and post-impoundment conditions.

The variables in PCA axes one and two explained 46.66% and 28.13% respectively of the relationship between IHA variables and two separate regimes of each station (pre- and post-impoundment) (Figure 4.8). The relationship between pre- and post-regimes of each station in axis one was largely controlled by Feb_Mean, 30day_Max, 90day_Max and Fall rates of flow events. Axis two was largely explained by changes in 1day_Max, 3day_Max, Date_Max and Date_Min of flow events (Table 4.5). Changes in flow conditions were observed in all the five stations that were evaluated. Major changes were recorded between pre and post-impact flow regimes at station seven, four and five respectively in the manner of a decreasing scope of change. Mean flow was high during post-impact era at station seven and high during pre-impact era for both station four and five. Station one and six have recorded minor changes as the former experienced high mean flow during the pre-impact era and the latter undergoing high flow during post-impact flow era (Table 4.4 and Figure 4.8).

Table 4.5: IHA variables and eigenvalues of axis one and two that contributed the most significant relationship towards the PCA (Figure 4.8). The variables with the highest eigenvalue (bolded) are the principle components of the data set.

	Axis 1	Axis 2
Eigenvalues	8.400	5.063
Cum. Percentage	46.668	74.797
February_Mean	**0.337**	0.044
March_Mean	0.321	0.015
September_Mean	0.257	-0.021
1day_Max	0.011	**0.411**
3day_Max	0.179	**0.340**
7day_Max	0.283	0.232
30day_Max	**0.329**	0.116
90day_Max	**0.333**	0.085
Zero_Days	-0.155	0.384
Date_Min	0.033	**-0.288**
Date_Max	-0.128	**0.385**
Count_Low pulse	0.229	-0.076
Duration_Low pulse	0.196	-0.201
Count_High pulse	-0.005	-0.16
Duration_High pulse	-0.194	0.298
Threshold_Low pulse	0.283	0.116
Fall rates	**-0.328**	-0.104
Reversals	0.171	-0.275

4.3.4.2 Water temperature changes

The water temperature PCA correlation matrix is composed of both monthly and annual values of mean and coefficient of variability of water temperature. Similar to flow PCA, not all of these variables (monthly and annual values of mean and coefficient of variability of water temperature) were used to show how water temperature varied between pre- and post-impoundment conditions through PCA at the five evaluated stations. Highly correlated variables that showed similar results were reduced from the PCA matrix, leaving behind highly significant variables in terms of PCA graphic presentation perspective (Table 4.6). This PCA analyses had a finer cumulative percentage of 82.89%, as axis one represent a total of 49.19% and axis two accounting for 33.70% of correlation between variables and two separate regimes of each station (pre- and post) (Figure 4.9).

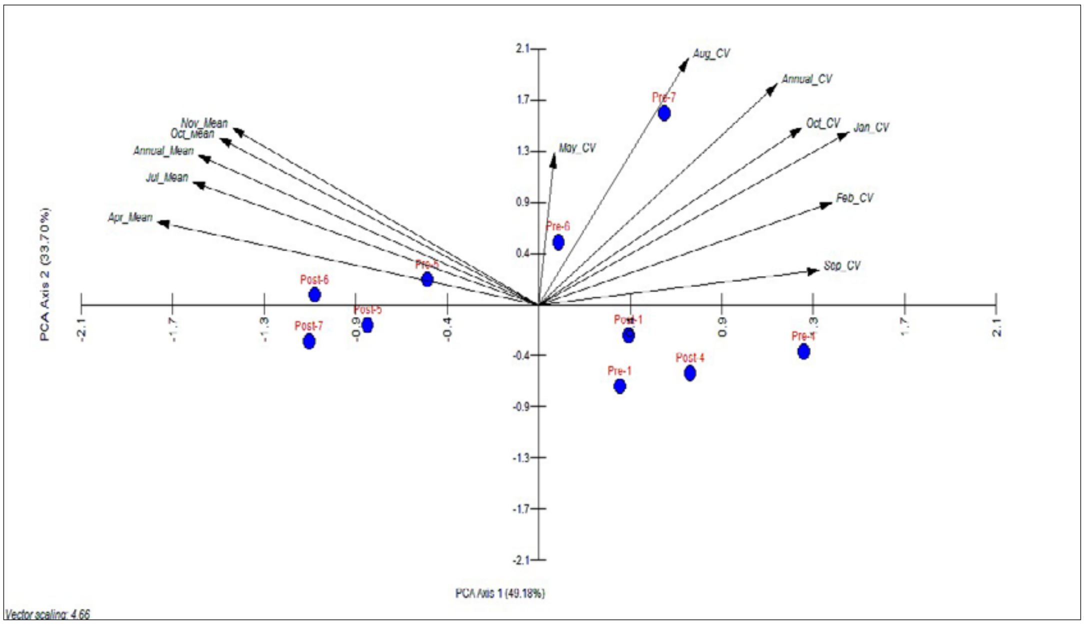


Figure 4.9: Principal components analysis of mean temperature variables for the five stations showing how temperature differs between pre- and post-impoundment conditions.

Table 4.6: Temperature variables and eigenvalues of Axes one and two that contributed the most significant relationship towards the PCA (Figure 4.9). The variables with the highest eigenvalues are indicated in bold.

	Axis 1	Axis 2
Eigenvalues	5.902	4.045
Cum. Percentage	49.187	82.896
January CV	**0.313**	0.311
February CV	**0.295**	0.184
April Mean	**-0.384**	0.149
May CV	0.016	0.274
July Mean	-0.348	0.220
August CV	0.151	**0.444**
September CV	0.282	0.062
October Mean	-0.322	0.300
October CV	0.265	**0.319**
November Mean	-0.308	0.318
Annual Mean	-0.342	0.269
Annual CV	0.240	**0.397**

The component that accounted for most of the variation in Axis 1 were Jan_CV, Feb_CV and April_Mean values of water temperature (Table 4.6). Variability in Axis two was predominately explained by changes in Aug_CV, Annual_CV and Oct_CV respectively in the order of their influence. Similar to flow PCA, all five stations evaluated showed measurable change between pre- and post-impact water temperature conditions (Figure 4.9). Station seven has experienced the greatest water temperature changes after impoundment effect as compared to other stations (see Figure 4.6 and 4.7).

4.4 Discussion

4.4.1 Modelling of spatio - temporal connectivity of selected rivers

One of the goals of this study was to assess the changes in flow and water temperature regime in response to the introduction of selected impoundments across selected rivers in KZN. The IHA and ITA methods used in this study are well established in the literature (for example, King *et al.,* 2004; Rivers-Moore *et al.,* 2011; Tharme, 2003), and a fair application for the latter given that it is recently developed and adapted from the IHA methodology (Dallas and Rivers-Moore, 2012b; Eady *et al.,* 2013; Rivers-Moore *et al.,* 2012; Rivers-Moore *et al.,* 2013). However, the long term nature of data required to run both of these methodologies has restrained their potential broad application in this study to only five stations. Two of the five stations are located in the uMngeni River, while Hluhluwe, Lovu and Mhlatuze Rivers each had one station.

The results of two methodologies (IHA and ITA) have shown that both flow and water temperature time series (and patterns) of KZN rivers were sensitive to the introduction of impoundments, particularly with respect to the frequency, duration, timing and rate of change of flow. The changes in frequency, duration, time and rate of change pre- and post-impoundment could have resulted from the unspecified flow release system and variability in regulation after the introduction of the dams. This study has also identified that a lack of water release guideline for post-impoundment flow at all station poses the danger of greater temporal change which will affect ecological integrity. As also noted by Poff and Zimmerman (2010), guidelines to support regional environmental flow standards should include threshold of the relationship between flow magnitude alteration and ecological responses for effective conservation. This guideline will also serve a power tool towards the management and conservation of aquatic systems of the KZN province.

4.4.2 Ecological effects of impoundments on stream flow and water temperature.

This study has recorded changes in both stream flow and water temperature regimes at all stations evaluated as a result of impoundments. It is important to note that the same impoundment type in different rivers may cause different degrees of changes due to different modes of operation and specific methods of water release, and therefore have different ecological consequences. It is acknowledged that any long term change in components of either or both flow and thermal regime (magnitude, frequency, duration, timing and rate-of-change) will have profound consequence on the biology of aquatic ecosystem (Rivers-Moore *et al.*, 2013; Olden and Naiman, 2010; Poff and Zimmerman, 2010; Caissie, 2006). The magnitude (consequence) of which depends on size of change, position of impoundment installed and on the sensitivity of the component or element of aquatic ecosystem involved.

As a result flow alteration; the anticipated ecological impacts to rivers in KZN by impoundments vary amongst individual species and community level (aquatic macro invertebrates). The anticipation is based upon the observed flow changes after impoundment introduction and known ecological response of species to such observed flow changes. Station one, four and five experienced the decrease in magnitude of monthly mean water flow conditions, while station six and seven increased in monthly mean flow during the post-dam era. Species which depends on the magnitude of flow regime not only for migratory survival but also for other life activities such as feeding and spawning will be affected by these flow changes. As indicated in literature (Chessman, 2012; Dickens *et al*., 2008; Poff and Zimmerman, 2010), high magnitude water flow is likely to favour species such as amongst others beetles, stoneflies and mayflies, while low magnitude water flow would favour species such as beetles, true bugs and damselflies. This will results in the loss of sensitive species and reduced diversity for species which might not tolerate certain magnitude and patterns of flow downstream of impoundments.

Alteration of frequency and timing of flow events is more likely to reduce reproduction of species (Richter *et al.*, 1996). These two statistical components of the flow regime have changed at all stations, with the greatest changes observed at the uMngeni River sites. Rate of change and duration of flow events are expected to have implications for species in rivers of KZN. Having changed after the introduction of impoundments, these two components (rate of change and duration) of flow will influence the abundance or replacement of young aquatic species as a result of increasing or decreasing flow respectively (Poff and Zimmerman, 2010). The predictions of this study are consistent to those highlighted by Rivers-Moore *et al.* (2007), who noticed that stream flow changes in KZN rivers essentially degrades the natural temporal habitat template and this is more likely to result in reduced species diversity and migratory signatures of species. Bunn and Arthington (2002) have reported that in-stream barriers contribute to the decline of populations of migratory species in the upstream streams.

Regarding water temperature, the introduction of impoundments has seen changes in water temperature signatures in relation to the ‘prior natural thermal conditions’ of rivers in KZN. Besides the introduction of impoundments, temperature changes in these stations could have been influenced by amongst others; type of water release, position of the dam along the river, topography and streambed. These long term changes in water temperature poses significant implication for biotic response of species and this plays a crucial role in structuring aquatic communities (Caissie, 2006).

The post-impoundment changes in water temperature regime are expected to restructure the distribution of aquatic species communities in KZN rivers. This is because most aquatic macroinvertebrate species only tolerate a specific range of water temperature (Caissie, 2006; Dallas and Ketley, 2011). Taking into account the observed mean water temperature increase after the introduction of impoundments, the projected increase in global mean air temperature of 1.1°C to 6.4°C by 2100 (Parry, 2007) as a result of climate change and general temperature lapse rate of 0.7°C for every 100m (Rivers-Moore *et al.*, 2013), cold water adapted species are likely to lose most of their habitat space in all impounded and mountainous rivers of KZN. However, it is appropriate to make known that not all aquatic invertebrates respond to environmental temperature gradients (Heino, 2009; Rivers-Moore *et al.,* 2007; Sheldon, 2012).

Although this study has not sampled aquatic species in relation to their habitat preference, both local and international literature does show that cold adapted family species such as amphipods and stoneflies will be the most likely to be affected (Burgmer *et al.,* 2007; Chessman, 2012; Dickens *et al*., 2008; Li *et al.*, 2013; Rivers-Moore *et al.*, 2012). Similarly, Rivers-Moore *et al.* (2007) identified the same problem for aquatic species if waters of the Great Fish River were to warm. More interestingly, Dickens *et al*. (2008) also speculated that the flow regulation below the Albert Falls dam may in part account for the absence of stonefly (*Neoperla spio*) downstream of the wall of the dam as this flow type is opposed to stonefly’s preference for cool water and fast-flowing. The prediction from this research is identical to that made by Hari *et al.* (2006) who studied rivers at high altitudes and concluded that the presence of impediments to longitudinal migration prevents species from taking advantage of new potential thermal habitat that would otherwise become available upstream.

4.4.3 Relationship between recovery distance and temporal connectivity

In this study, the departure from natural river signatures was demonstrated and quantified in terms of flow and water temperatures, in response to impoundment. The challenge in this study was to spatially model changes in temporal connectivity. One suitable approach to incorporate was the concept of 'recovery distance', which defines the length the stream requires for a particular parameter (flow and temperature) to recover to levels which prevailed in the unregulated system (Palmer and O'Keeffe, 1989). In a longitudinal river system, the recovery of both flow magnitude and water temperature from impoundment disturbance is largely dependent on downstream distance and the volume of flowing water. Several scholars share the same opinion and have in one way or another recorded the recovery of rivers from disturbance with downstream distance and flow magnitude (Dickens *et al.*, 2008; Olden and Naiman, 2010; Palmer and O'Keeffe, 1989; Sedell *et al.*, 1990; Stein *et al.*, 2002). For example, higher flow volumes have greater recovery distance (Palmer and O'Keeffe, 1989). Dickens *et al*. (2008) has recorded an early recovery distance of 4 km of aquatic macroinvertebrate downstream of the Albert Falls dam. Since aquatic insects' composition is driven mainly by flow and thermal conditions (Chessman, 2012; Dallas and Rivers-Moore. 2010; Filipe *et al.,* 2012), a recovery of 4 km can be translated as an indicator of recovered favourable flow and thermal conditions. Therefore, the assessment of temporal connectivity (flow and water temperature) of selected river in KZN justified the inclusion of recovery distance as a crucial component regulating both the hydrological and ecological connectivity score of streams downstream of impoundments. The recovery distance component of rivers has been discussed in greater detail in the next chapter.

4.5 Conclusion

This study made use of temporal change assessment methodologies called IHA and ITA to determine the size of change in flow and thermal regime prior and after the introduction of in-stream impoundments in KZN. The results of two methodologies (IHA and ITA) have shown that both flow and water temperature time series (or patterns) of KZN rivers were sensitive to the introduction of impoundments, particularly with respect to the frequency, duration, timing and rate of change of flow. This study has recorded changes in mean flow volume and thermal conditions at five sites that were assessed in KZN. These changes are driven by the introduction of in-stream impoundments and the amount of water release downstream of the dam. This study provides a potentially valuable tool to river managers and guide towards adaptation mechanism for aquatic species in the changing aquatic environment of the province. This study has also identified that a lack of water release guideline for post-impoundment flow at all station poses the danger of greater temporal change which will affect ecological integrity. It is further concluded that the water release approach downstream of the dam should embrace natural variation of a hydrological regime to sustain biodiversity and connectivity of aquatic.

CHAPTER FIVE

ASSESSMENT OF SPATIAL CONNECTIVITY OF RIVERS

5.1 Introduction

As emphasised in Chapter 2, connectivity of river systems plays a critical role in the integrity of aquatic systems, by enabling upstream-downstream and channel-floodplain ecological processes in river systems. Reduced connectivity in turn has considerable implications for aquatic communities because of the resulting impacts on migration and species behaviour. To assess the level of connectivity for the selected rivers in the study area, both longitudinal and lateral dimensions of rivers were examined using different methods (see methodology). For lateral connectivity, small dams (farm) density and the degree of land cover fragmentation were examined in all selected quaternary catchments, while longitudinal connectivity was quantified on the basis of in-stream barriers.

The results of both longitudinal and lateral connectivity were combined to obtain an index of spatial connectivity of all selected river systems in the province. The degree of connectivity was compared between rivers with the final product being a map showing level of connectivity across the province at a quaternary catchment scale.

5.2 Methodology

5.2.1 Longitudinal connectivity assessment

Longitudinal connectivity assessment considered only permanent rivers that flow during years of normal rainfall, which is the quantity of rainfall well above or well below the seasonal average (Warburton and Schulze. 2005). According to Driver *et al.* (2011), permanent rivers include both perennial and seasonal flowing rivers as opposed to ‘not permanent or ephemeral’ rivers that go dry for many years without flowing. Ephemeral rivers are naturally dry and sustain life adapted to short, unpredictable and intermittent periods of flow. However, not all permanent rivers in the province have formed part of this study. The stream order classification method by Strahler (1952) was used to select suitable rivers in relation to aquatic diversity and survival. Rivers with stream order of two and above in KZN province were selected at a mapping of 1: 500 000 (Figure 5.1). Stream order classes are important because ecological functions of a stream system intensify as the order increases (Vannote *et al.*, 1980). In this way, this study has eliminated all areas of river's origin by excluding all independent and isolated small tributaries that sources the second and other stream order classes.

5.2.1.1 Identification of in-stream barriers

The process of identifying in-stream barriers took into consideration both man-made impoundments and natural barriers (waterfalls) that occurred along the length of all selected rivers. Man-made impoundments range from large dams and weirs to flow regulation, while natural barriers include waterfall and lakes. Weirs are structures in a river constructed to measure water level and discharge rate (Wessels and Rooseboom, 2009). It is necessary to distinguish between large and small dams. According to the Mantel *et al*. (2010), the World Commission on Dams (WCD) defines a large dam has either a height of 15 metres or higher, or a height of between 5 and 15 metres with a storage capacity volume of more than 3 million cubic metres. The process of identifying both man-made impoundments and natural barriers from headwater to downstream extent of selected rivers included determining their geographic positions within each catchment. This process was achieved through the use of two computer-based methods, rather than through ground-truthing which is time-consuming and costly (Heywood *et al.*, 2006).

First, the identification process of impoundments included overlaying the provincial coverage of man-made impoundments (large dams, weir, and canals) and natural barriers (waterfalls and lakes) upon the selected rivers using GIS. This ensured the elimination of impoundments and barriers positioned outside the rivers of interest, while ascertaining the availability and latitudinal position of those occurring along source to sea extent of selected rivers. The second task involved the use of the Google ^{TM} Earth application to verify the correctness or accuracy of the outcome of the initial GIS exercise. This involved the visual identification of physical structures and cross-checking the geographic position of all dams and waterfalls of interest occurring within selected rivers. Other information collected during this assignment included *inter alia*, type of impoundment, the date on which the barrier was introduced, and downstream flow gauging station number and historic flow data.

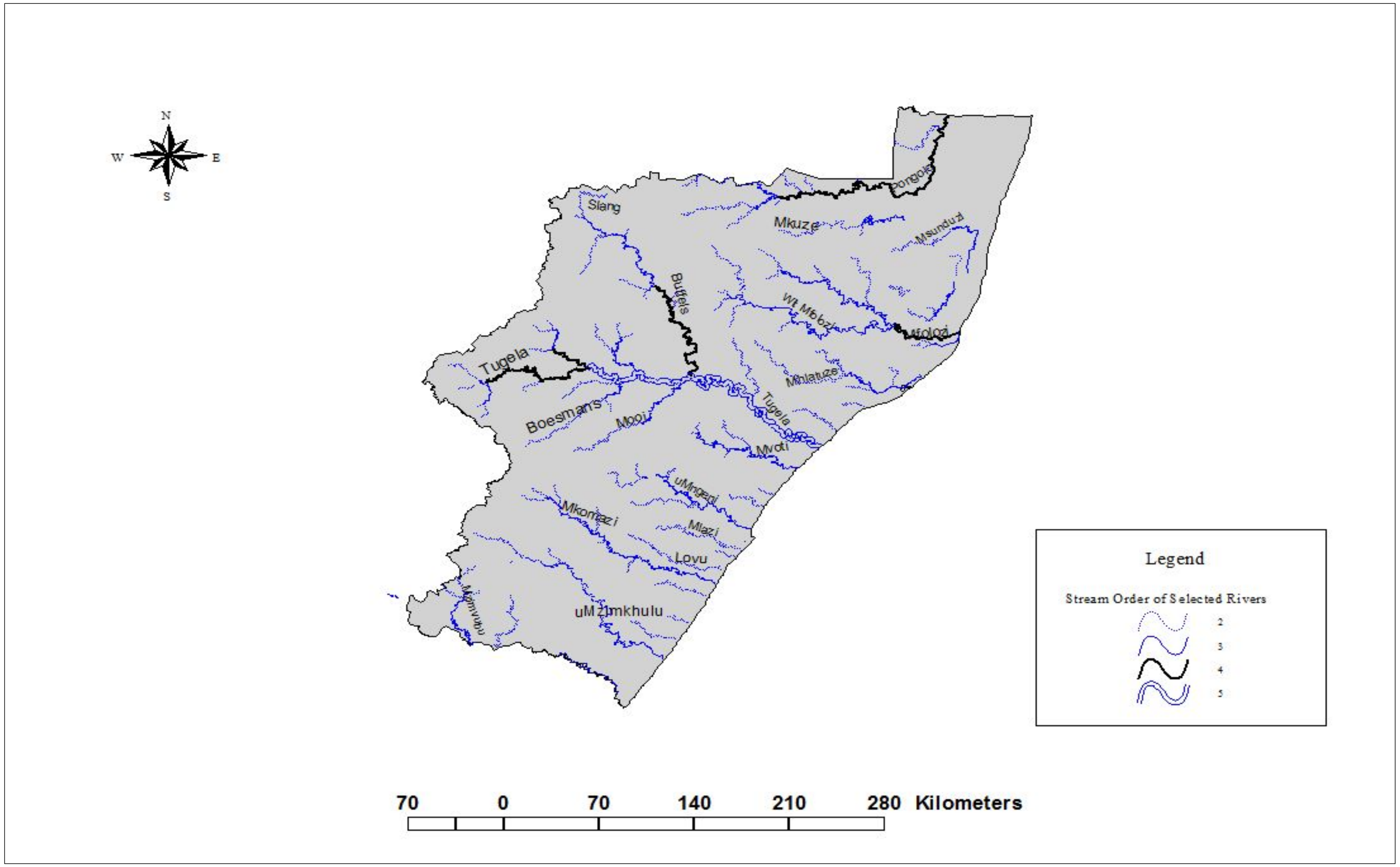


Figure 5.1: A map of KwaZulu-Natal province showing selected rivers with different order classes of not less than two.

5.2.1.2 Profile of selected rivers

Modelling of river profiles assists with understanding river behaviour and morphology, and provides opportunity for levels delimiting river segments and demarcation of reach breaks (Rowntree and Wadeson, 1999; Rivers-Moore *et al.,* 2007). Google ^{TM} Earth application was instrumental in the process of developing the graphic profile of selected rivers. This process involved flying or navigating over each and every segment of the selected rivers while measuring distance away from the sea (upstream) and recording height above the sea level (altitude) at a constant upstream interval distance of 20 km. Rivers that joined others were measured starting from the area of confluence as part of the main river. However, the distance measured away from the sea for selected rivers cannot be treated as the complete upstream to downstream length as it only covered channels with stream order of not less than two. An excel software was then used to produce a linear profile graph of rivers of interest using the recorded data.

5.2.1.3 Disturbance value for in-stream impoundments

The River Disturbance Index (RDI) model by Stein *et al*. (2002) which provides weights to river disturbance parameters with potential to alter river natural processes and conditions was used as the basis for assigning weights to in-stream barriers. This model was adopted to develop longitudinal connectivity level index of rivers at quaternary catchments scale. The model is based upon the notion that there should be an absence of impoundments and land-use activities within rivers' periphery as it alters the health, ecological integrity and connectivity of rivers (Allan, 2004; Stein *et al.*, 2002; Teixido *et al*., 2010). In this study, longitudinal connectivity index was developed based on the cumulative score of each river segment taking into consideration the recovery distance within each quaternary catchment. The RDI model offers to undisturbed catchments the score value of or near zero (0), while catchments at or near one (1) have very low longitudinal connectivity. Disturbance score for each impoundment parameter was determined according to the RDI model structure for different impoundments and their weights (Table 5.1).

Table 5.1: Categories of river impoundments and weights (*afte*r Stein *et al.*, 2002)

Category number	**Description**	**Weight**
1	Un-impounded river	0.0
2	Rapids	0.05
3	Minor dam structure	0.1
4	Water Falls	0.1
5	Pipelines	0.1
6	Lake	0.1
7	Weir	0.3
8	Canals	0.6
9	Major dam structure	1.0

First, a basic cumulative score for each river was assigned based on the weights of disturbance parameters (Table 5.1). Next, a refined cumulative score for each river was calculated based on the concept of a reset distance linked to flow volumes and downstream distance (Palmer and O'Keeffe 1989), as a tool for incorporating temporal connectivity into the longitudinal connectivity index (See Chapter 4). The following series of steps were followed to measure this revised longitudinal connectivity based the weights of impoundments using an excel software;

a) Downstream distance between disturbance parameters along each river extent was measured using both GIS and Google ™ Earth application.
b) Recovery distance was measured based on the Mean Annual Runoff (MAR) of each catchment (Middleton and Bailey, 2008). Recovery distance is critical as modelling longitudinal changes requires knowledge of flow recovery potential. Recovery distance was calculated from each catchment's MAR using Equation 5.1 from Palmer and O'Keeffe (1989).

$$\text{Recovery distance} = 35.5*\text{LN}\ (x+1)-11.1 \qquad (5.1)$$

c) Where LN (Natural Logarithm) is a constant value of 2.7182818 and x is daily mean flow in cubic metres per second.

d) Based on whether the river has recovered or not, revised cumulative score was determined using a Microsoft Office Excel software, based on the following logic equations;

- Single impoundment river

Revised Score = [A1>B1, 0, (C1)] (5.2)

- Multiple impoundments river

Revised Score = [A1>B1, 0, (C1+D1)] (5.3)

Where A1 is the distance between disturbance parameters (Table 5.1), B1 is the recovery distance of the river, C1 is the score of the impoundment and D1 is the revised score of the previous impoundment account.

e) The revised score was converted into percentage for each quaternary catchment using the following equation;

Revised score (%) = Score ⁄ Maximum score x 100 (5.4)

f) Finally, the percentage score for each quaternary catchment was standardized into 0-1 score range to correspond with the Stein *et al*. (2002) disturbance scale. The following equation was used;

Disturbance scale = % QC / $ Maximum score (5.5)

Where A1 is the percentage score of each quaternary catchment and $ Maximum score is the absolute reference of the maximum score.

The undisturbed catchments with free-flowing rivers were labelled with a score value of zero (0) whereas the value of one (1) represents extremely disturbed catchments. Unlike other models such as the Index of River Connectivity (ICF) model which assesses longitudinal connectivity index based on the number of fish pass per impoundment (Sola *et al.,* 2011), the RDI model was ideal and relevant to the modern developing society as it assesses human activities and their influence to the degree of connectivity of rivers (Stein *et al*., 2002).

5.2.2 Lateral connectivity of rivers

Lateral connectivity of rivers of selected rivers was based on two assessment components, namely, land cover fragmentation and density of small dams. Land cover fragmentation is a product of landscape changes, and it creates important threats to stream habitat pattern and biodiversity (Teixido *et al.,* 2010). Small dams (floodplain occurring) have known effects on habitat structure through capturing sediment and reducing the density of cold-water fishes, such as trout, and shifts macroinvertebrate community composition due to increases in mean summer temperatures below dams (Mantel *et al*., 2010).

5.2.2.1 Land cover fragmentation assessment

The National Land Cover (NLC) 2000 dataset coverage for KZN province was used in the land use fragmentation index assessment. The NLC 2000 dataset coverage contains 45 different land cover type (Schoeman *et al.*, 2013). The Index of Land-use Fragmentation (ILF) method by Liu *et al*. (2011) was used to quantify the degree of land-use fragmentation within each quaternary catchment for this study. This involved overlaying and merging together of NLC 2000 dataset coverage with each absolutely corresponding quaternary catchment area through GIS application. The ILF method is a product of the sum of land-use parcels divided by total area of each catchment quantified through the use GIS analyses. The following steps were undertaken in the assessment of land use fragmentation index;

a) The total surface area covered by each quaternary catchment was extracted from quaternary catchment dataset using GIS area size quantification.
b) The sum of land use parcel occurring within each quaternary catchment was calculated using GIS application statistics.
c) The following equation was applied when determining the degree of fragmentation for each catchment.

$$C = N / A \tag{5.6}$$

Where C is the degree of land-use fragmentation while N and A are the number of land-use parcels and the total area of each studied catchment respectively.

d) The degree of land-use fragmentation was then calculated and expressed as a percentage by dividing each catchment's score of C by the maximum land-use fragmentation score, multiply by 100. The following equation was used;

$$C\ (\%) = C\ \text{Score} \,/\, \text{Maximum score} \times 100 \qquad (5.7)$$

This assessment was taken with an understanding that entirely fragmented catchments (agriculture, residential areas, etc.) negatively influence ecological integrity, connectivity and health of rivers (Teixido *et al.*, 2010; Allan, 2004; Stein *et al.*, 2002). This approach allowed for the evaluation of river flow and ecological implications of land-use practices that occur across the catchment floodplain areas (Sponseller, 2001; Stein *et al*., 2002).

5.2.2.2 Density of farm dams per catchment

Farm dams were extracted from GIS coverage produced by the Chief Directorate of Surveys and Land Information (1999). The quantity of farm dams per each quaternary catchment was measured using the method developed by Mantel *et al.* (2010). The method is referred to as small dam density (SDD). In this study, farm dams were treated as small dams as is easy to differentiate the latter from large dams (Mantel *et al.*, 2000). The SDD method involved quantifying the sum of small dams occurring within each quaternary catchment and the catchment area using GIS area size quantification (Equation 3.9).

a) Small Dam Density (SDD) for each single quaternary catchment.

$$\text{SDD (catchment)} = \sum \text{dams} \,/\, \sqrt{\text{area}} \qquad (5.9)$$

Where SDD in a catchment is the product of the sum of dams divided by the square root of the catchment surface area in km^2. This small dam measure was standardised to the square root of the catchment area in km^2 to reduce catchment size bias (Mantel *et al.*, 2010).

b) SDD was expressed as percentage by dividing the density score for each quaternary catchment by the density score using the equation below;

$$\text{SDD \% (catchment)} = \text{SDD Score} / \text{Maximum score} \times 100 \qquad (5.10)$$

5.2.2.3 Lateral connectivity index

Lateral connectivity index for each selected quaternary catchment in KZN was developed using the score results from the ILF and SDD method (Equation 3.11).

$$\text{Lateral Connectivity Index} = \text{ILF Score} + \text{SDD Score} \qquad (5.11)$$

The two methods that were combined together (ILF and SDD) to yield lateral connectivity index were measured in the same level and were easily added together because their equivalent score range and both their results were expressed as a percentage.

5.2.3 Developing an integrated spatial connectivity index of rivers

Developing the overall spatial connectivity index for all selected rivers at their corresponding quaternary catchment involved the use of catchment scores of both longitudinal and lateral indices. The catchments score values from both longitudinal and lateral connectivity indexes were added together to determine the value of the total catchment connectivity index. The score values for the two independent connectivity indexes (longitudinal and longitudinal) were at the same score range (0-1). The overall spatial connectivity index was developed using Equation 5.12.

$$CI = \sum (longitudinal + lateral)\ index \qquad (5.12)$$

Where *CI* is the Connectivity Index, the sum between longitudinal and lateral connectivity indexes.

The development of the overall connectivity index of rivers at quaternary catchments exclude temporal assessment as is itself the product of both longitudinal and lateral connectivity. This is evident in that temporal connectivity is sensitive to anthropogenic influences of land use changes and stream flow modifications such as abstraction for irrigation and impoundment (Richter *et al.*, 1996).

5.3 Results

5.3.1 Profiles of selected rivers

Rivers in the study area generally showed similar profile trends, with a gradually increasing slope gradient stretching from the east coast through the mid or inland transition zones to the western elevated upper sections of the KZN province (Figure 5.2). Some of the rivers showed a common trend of steeper upstream points reflecting the influence which the Drakensburg escarpment has in their points of origin. These rivers included the Tugela, Mkomazi and uMzimkhulu, as they all have an upstream altitude of not less than 1500m. Amongst these three elevated rivers, Mkomazi River has a steepest slope with altitude increasing exponentially at the upper reaches, while uMzimkhulu River is the highest river with altitude of not less than 2250m above the sea level. The Pongola River which is situated in the north-eastern direction of the province has a relatively flat profile as a result of limited presence of mountain ranges within its horizons. The shortest major river (Mdloti) amongst the selected is the fastest raising river with its profile reaching 600m altitude at 70km upstream distance (Figure 5.2). The Tugela came to be the longest river covering the length of about 510km.

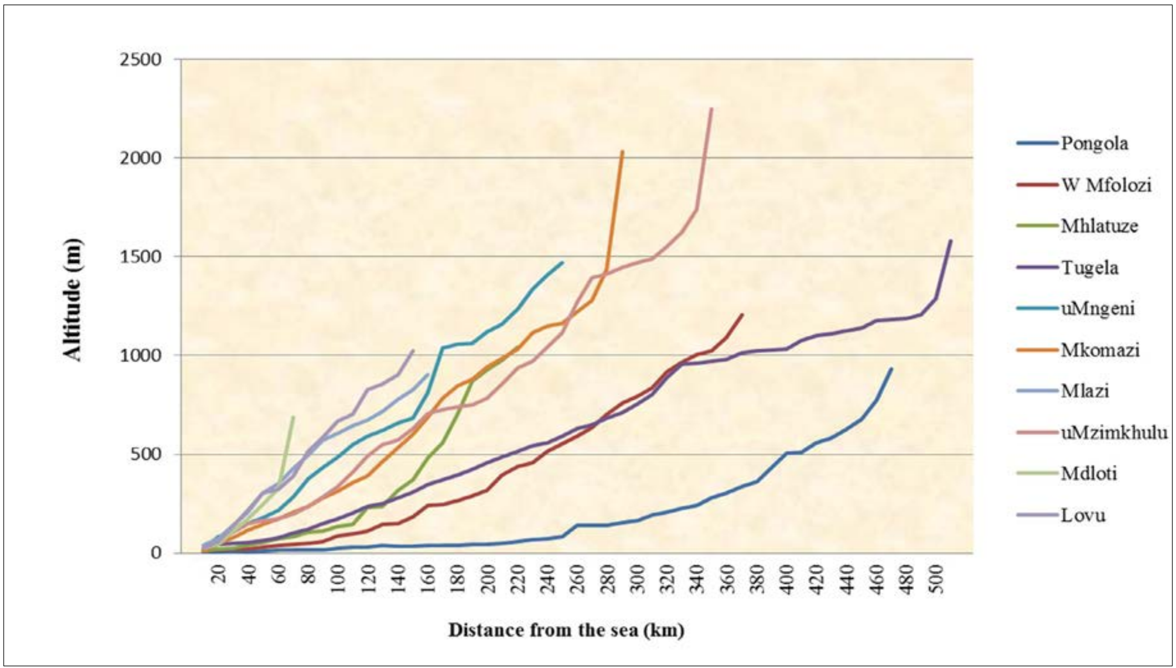


Figure 5.2: The longitudinal profile of selected rivers in KZN province.

5.3.2 In-stream barriers

A total of 275 in-stream barriers were found along a total river length of 7900 km of rivers (stream order 2 and above; 1:500 000 scale) in KZN, extending over four primary catchments and 215 quaternary catchments. After both assessments (GIS and Google ™ Earth application) it was found that out of the 95 selected river segments, 56 percent (54 river segments) were disturbed by one or more barriers. These in-stream barriers included 194 flow gauging weirs, 19 large dams, 29 waterfalls, 17 pipelines, 12 canals, and 4 natural lakes (Figure 5.3). A detailed description on the names and geographic positions of the different in-stream barriers are provided Appendices B1-6.

River disruption factors (Table 5.1) were assembled and arranged systematically using the GIS datasets described in chapter 3. However, the existing list of barriers from the GIS coverage was improved through the additional of one major impoundment (Bivane or Paris Dam on the Bivane River, a tributary of the Pongola River and completed in 2000), and two waterfalls (30˚9′56″ E - 29˚6′48″ S and 30˚16′41″ E - 29˚4′24″ S) on the middle reaches of the Mooi River. This was achieved through the use of Google ™ Earth application. More than half of the weirs and waterfalls in the GIS datasets were not visible in the images from Google ™ Earth. This might be due to very low visibility as a result of cloud conditions in some areas, weirs obtrusive because of high stream flows and geographic positions not coded for some waterfalls.

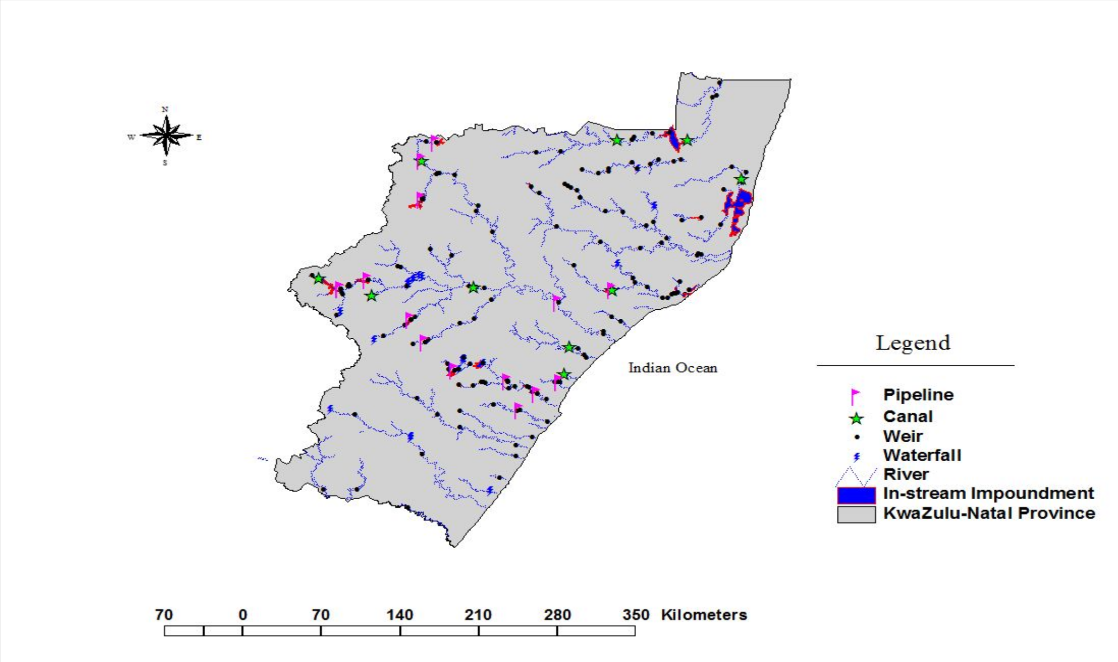


Figure 5.3: A map of KZN province showing in-stream barriers along selected perennial rivers and seasonal flowing rivers.

The Tugela and uMngeni Rivers were the most impounded of all selected rivers, particularly in their upper reaches. They respectively have three and four large dams, fifteen weirs and three pipelines (Figure 5.4).

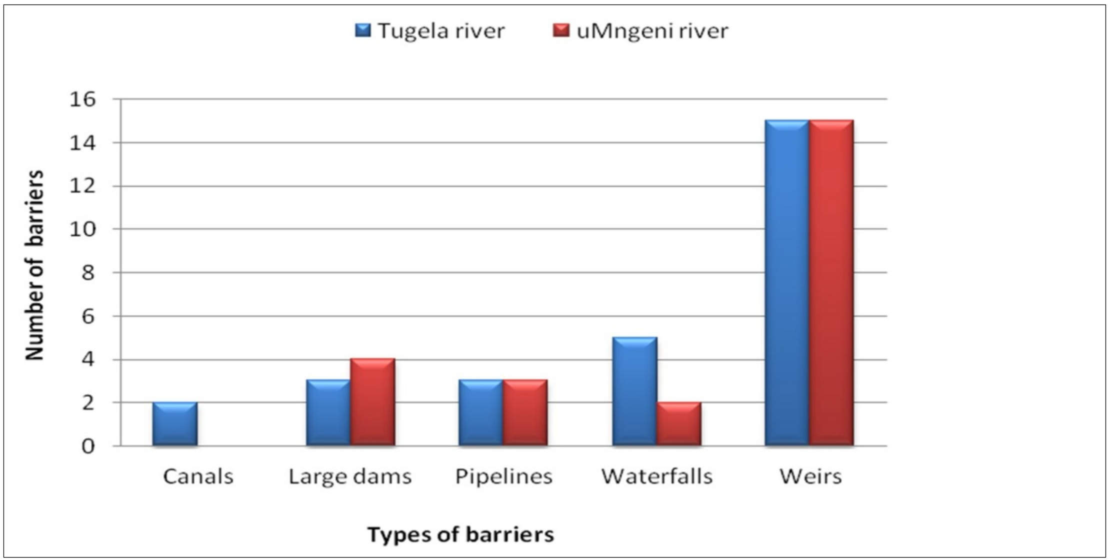


Figure 5.4: Number of different in-stream barriers found in the Tugela and uMngeni Rivers.

All the dams built in these two rivers are for the purpose of municipal, industrial and irrigation water supply. Apart from its waterfalls, the Tugela River has two canals as opposed to uMngeni River which has none. Besides the impounded streams, the province still has 47 river segments with an average length of 45 km which show undisturbed free-flowing conditions with most of them being small tributaries. Amongst these, this study found that the Bloukrans, Mzumbe, Nsuze, Nwavuma, and Sundays Rivers are the only undisturbed rivers longitudinally whose length is greater than 50 km. Conditional free flowing rivers include *inter alia* the uMzimkhulu River have slightly been disturbed by waterfalls and flow gauging weirs. A detailed description of more free-flowing rivers can be found later in the discussion section of this chapter after assessing both lateral and longitudinal connectivity and consideration of recovery distance potential.

5.3.3 Longitudinal connectivity index of rivers

The longitudinal connectivity index of rivers was assessed at a quaternary catchment scale (Figure 5.5) and the results of are presented statistically in Figure 5.6. Class intervals were based on natural breaks, with the highest class (0.76 to 1) representing the highest disturbance. According to this index, more than two third (79.06%) of all selected quaternary catchments in KZN province still exist in a relatively pristine condition in class 1 of between 0 to 0.04 disturbance. Most of the natural catchments are found in the lower regions along the Mvoti to uMzimkhulu Water Management Area (WMA) and also from mid-lands regions of the province extending towards upper regions of KZN (Figure 5.5). Many of these regions have few flow gauging weirs and large dams. In addition, nearly 6% of all selected catchments are moderately disturbed by in-stream barriers (Figure 5.6). The moderately modified catchments have a score level from 0.17 to 0.40 and are randomly scattered along the eastern and western parts of the province (Figure 5.5).

The highest class of disturbance (severely transformed by in-stream barriers) contains only 0.93 percent of all selected catchments (Figure 5.6). Some of these catchments (e.g. U20G and U20M) are degraded as a result of short distance between flow gauging weirs resulting in low flow magnitude and low recovery potential.

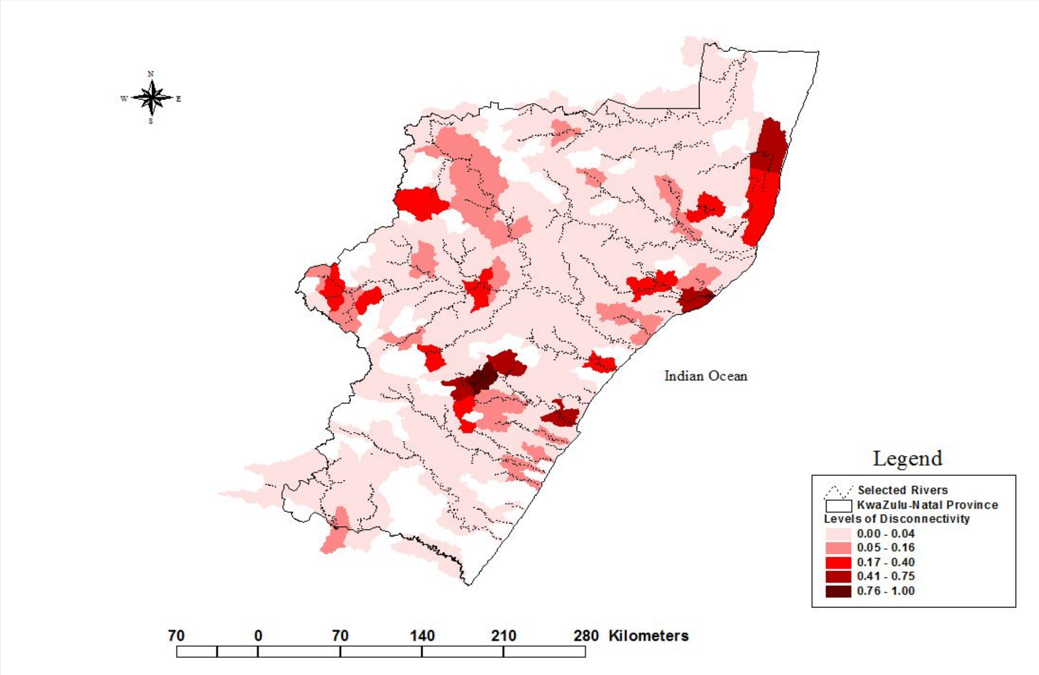


Figure 5.5: Longitudinal connectivity index based on cumulative scores of weighted in-stream barriers for selected quaternary catchments in KZN province without the recovery distance potential.

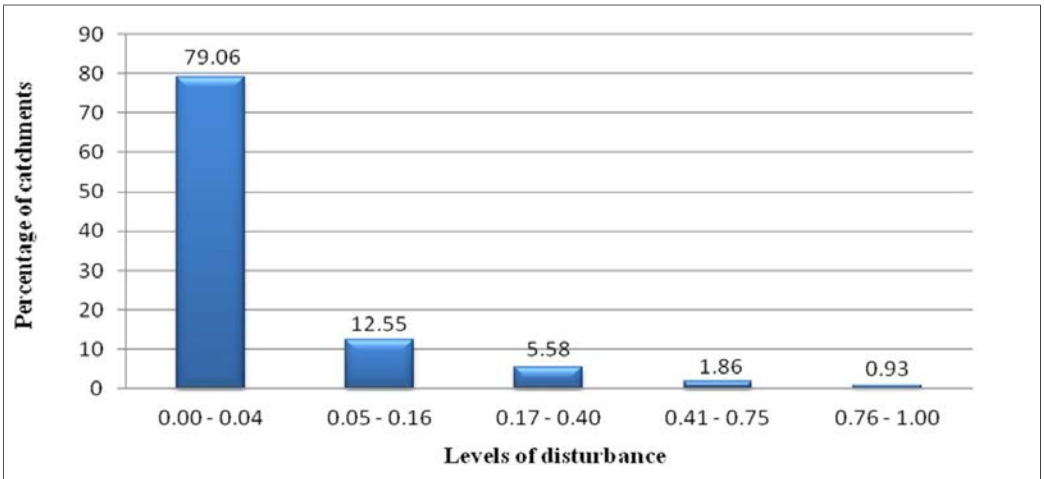


Figure 5.6: Percentage of various categories of catchment disturbance for longitudinal connectivity index of rivers per quaternary.

The uMngeni River is a good example of this rivers with impoundments are closely located. The uMngeni River was the most impounded in the province, with impoundments built during the second half of the 20th Century. The first impoundment of this river was Nagle

Dam of which construction was completed in 1950 and has a carrying capacity of 24 million m^3 (Figure 5.7). The second and third impoundments to be constructed were Midmar and Albert falls dams. These two dams are situated in the upper and middle reaches of the river and were constructed in 1965 and 1976 respectively. The storage capacity of Midmar Dam is 235 million m^3, while that of Albert Falls 287 million m^3 (Vuuren, 2012). Inanda Dam was the last to be completed in 1989, with the capacity of 251 million m^3. All these dams are very closely situated and calculations revealed that there is an average distance of 50 km between these impoundments. According to the impact score (Table 5.1), these dams and other barriers have progressively impacted the river to the longitudinal connectivity cumulative score of 7.5 (see Appendix C).

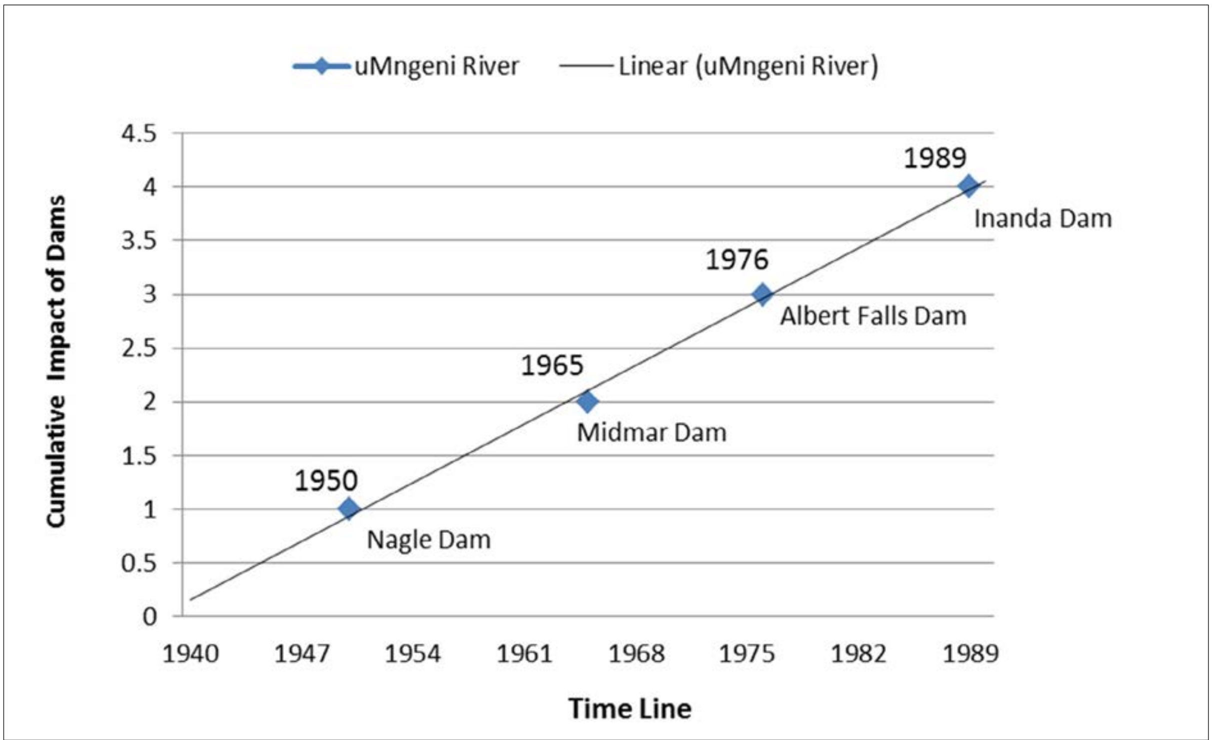


Figure 5.7: Timeline of construction of impoundments on the uMngeni River, showing that a cumulative longitudinal dis-connectivity score is a function of time.

5.3.4 Recovery distance of flow

Recovery distance plays an important role in the downstream cumulative impoundment scores. An example of how reset distance affects cumulative downstream connectivity scores is shown using the unrecovered and the recovered Tugela River (Figure 5.8). At a downstream distance of 31 km, the Tugela River recovered from the impoundment effects of weir, canal and dam (Woodstock). During this period, the required distance for recovery was 8.55km. Apart from recovery distance consideration, the river would have stayed at a cumulative impact score of 1.9. The recovery was possible because the distance between the dam (Woodstock) and following barrier (Spioenkop dam) was 10km. Furthermore, between 260 and 400 km in a downstream direction of the Tugela river, conditions have recovered to pristine condition while from the cumulative score perspective the river disturbance score reaching the high of not less than 7 during the same period (Figure 5.7).

This study records that Tugela River is natural from the recovery score perspective as a result of its favourable recovery distance. Another good example of recovery distance can be seen between uMngeni and uMzimkhulu River (Figure 5.9). The uMngeni River could not recovery from its congested impoundments yet the uMzimkhulu River has recovered due to the long downstream distance between the weir and the coast line.

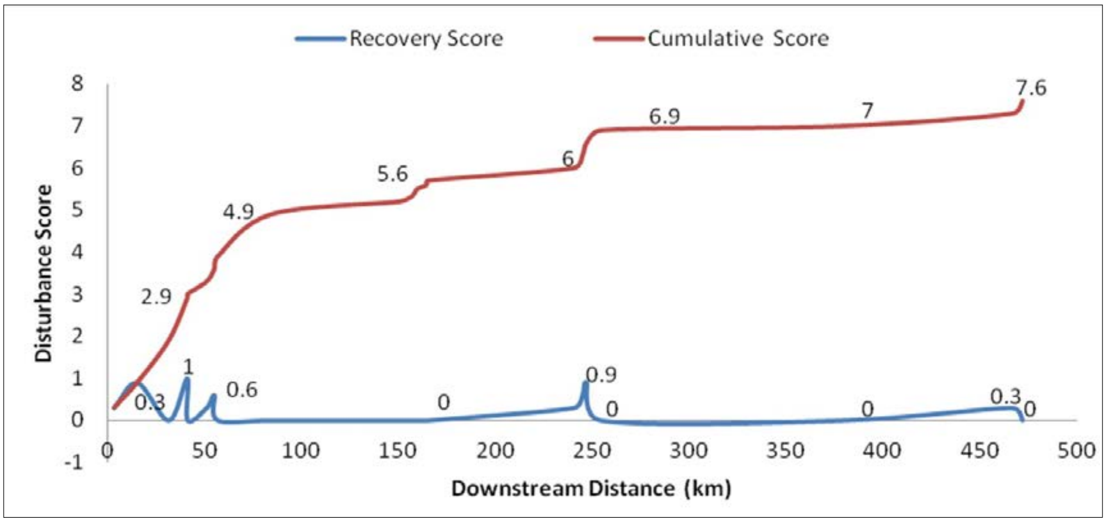


Figure 5.8: Line graph showing cumulative of barriers versus recovery score of the Tugela River.

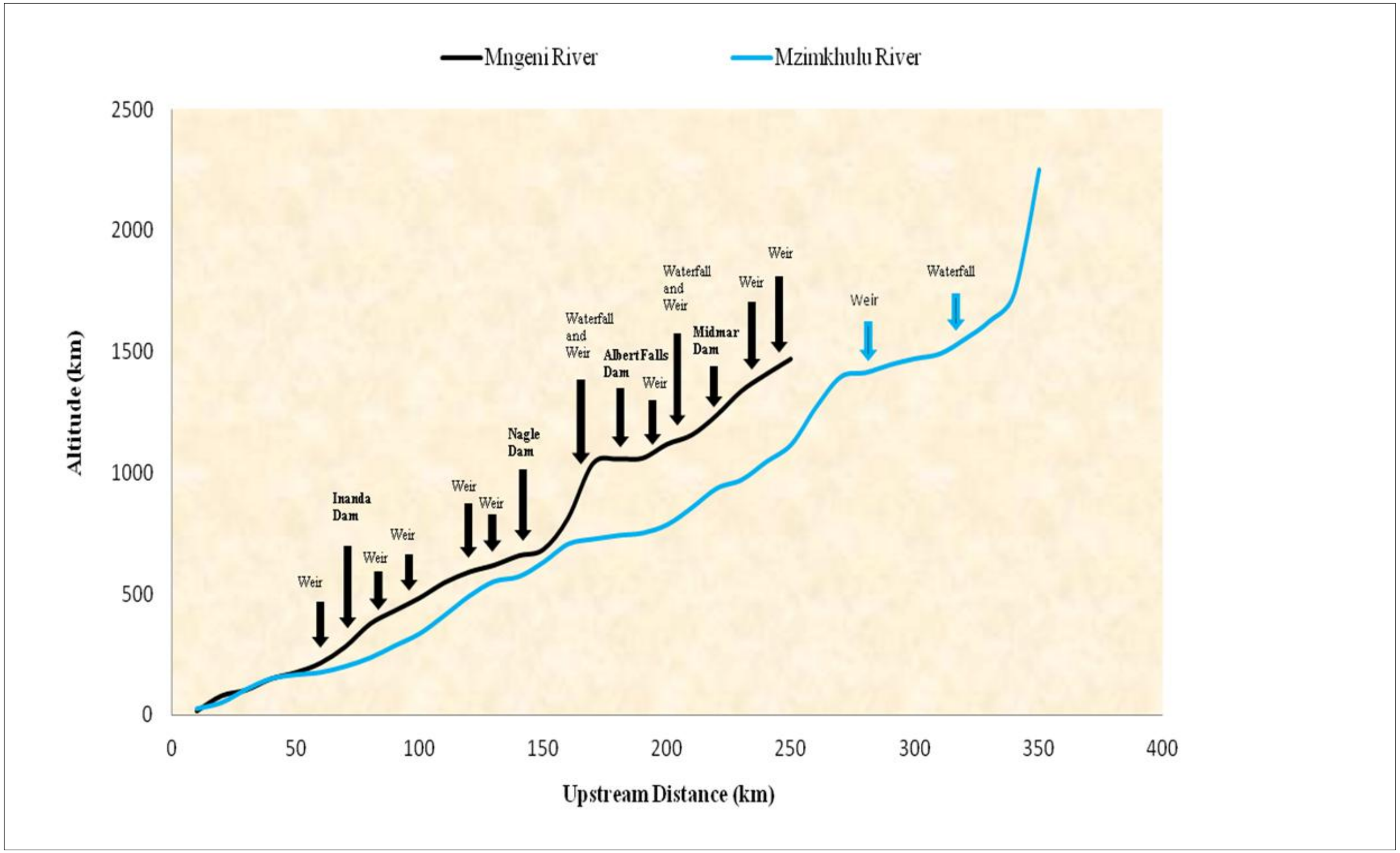


Figure 5.9: The longitudinal profile showing in-stream barriers of the uMngeni and uMzimkhulu Rivers of KZN province.

Based on this logic presented in the method (5.2.1.3) of this study, reset distances were calculated for all quaternary catchments selected. The length of stream required for a particular parameter to recover to levels which prevailed in the unregulated system (natural flow) was measured at a quaternary scale. The lowest level of distance required for rivers to recover from in-stream barrier parameters was 6 km (Figure 5.10). This lowest extreme distance required for recovery was due to relatively low average daily flow which is found in catchment number W31 and W44 which accommodate Mkuze and Pongolo Rivers respectively. Based on the relationship between flow volumes and recovery distance, the majority of catchments' recovery distance (35.34%) ranged from 6.01-15.34 km. This included most quaternary catchments embedded in some of tertiary catchments such as T32, T40, U60, U70, V32 and W21. Some rivers of these catchments include amongst others the Lovu and Mlazi Rivers, lower and upper sections of the Buffels River, sections of the Mfolozi River (Figure 5.10).

The longest distances measured for flow recovery potential of rivers was between 36.53 and 59.67 km. Of great interest, the high average of daily flows that resulted in long distance recovery potential in quaternary catchments U10A, U10B and U10D. This occurrence affected flow recovery distance in the upper sections of the Mkomazi River. However, not only the Mkomazi River but also small sections of other isolated rivers show this level of flow recovery (dark red catchments, Figure 5.10).

From all 215 selected quaternary catchments, only 63 have rivers that have recovered from in-stream barrier parameters mentioned in Table 5.1. Assessments were based on the distance between barriers, cumulative score and stream flow. Where distance between barriers was greater than the recovery distance, the cumulative score resets to zero. Recovered catchments shown in Figure 5.11 include the following rivers; the calculated length of Mkuze and Mooi, large section of the Boesman and Msunduze, middle reaches of Mkomazi, Mfolozi and Pongolo. Catchments that have not recovered include the entire length of the Buffels River, large sections of Tugela and Mvoti catchments, and isolated patches of uMngeni, uMzimkhulu, and Mkomazi catchments (Figure 5.11).

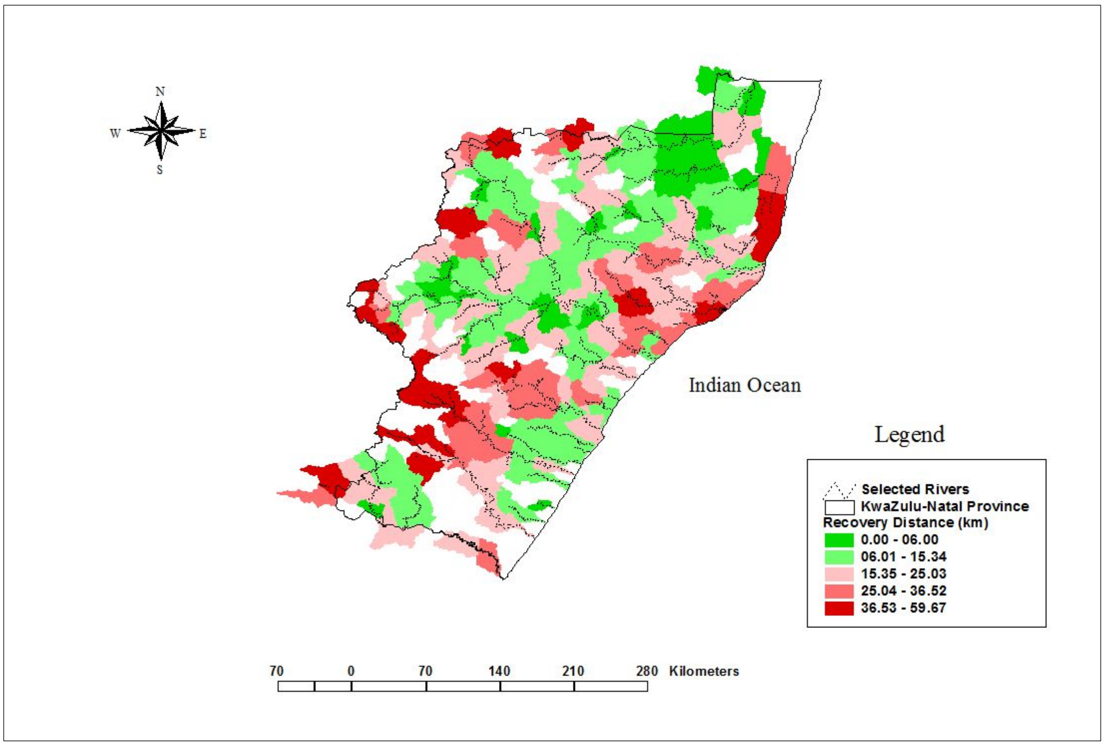


Figure 5.10: A map showing the recovery distance of rivers for selected quaternary catchments in KZN province.

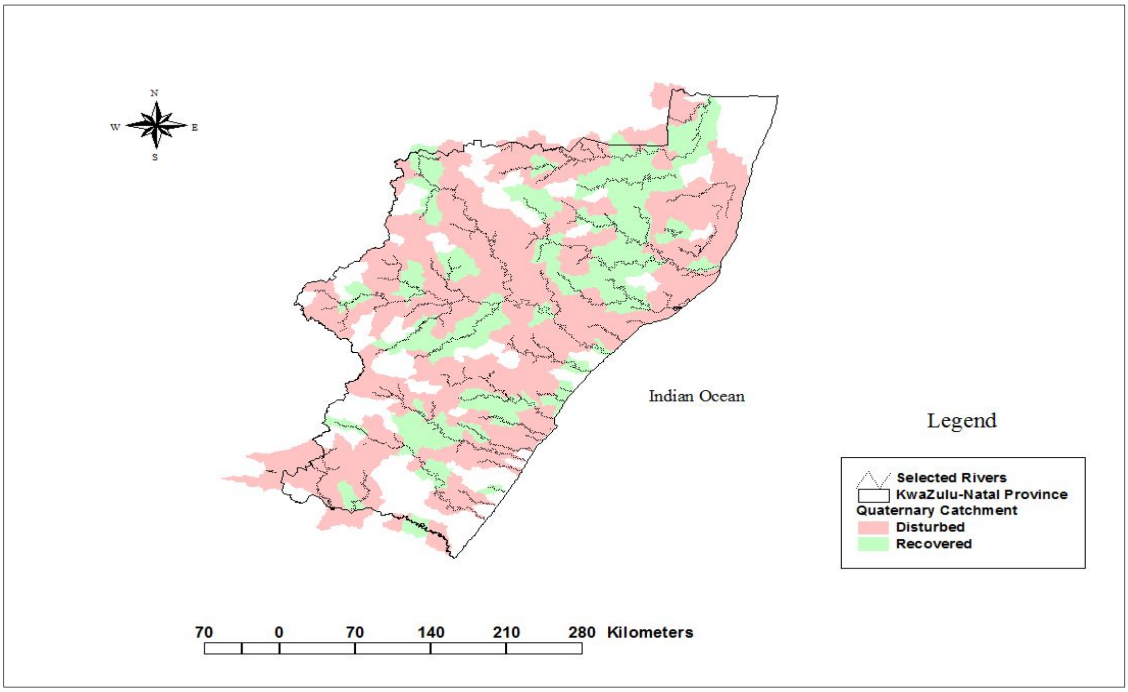


Figure 5.11: Quaternary catchments within KwaZulu-Natal that have recovered from in-stream barriers.

5.3.5 Lateral connectivity of rivers

As mentioned in the Methods (Section 5.2.2), two assessments were done under lateral connectivity of rivers. These included the land cover fragmentation based on the National Land Cover (NLC) 2000 dataset coverage, and the small dams density based on GIS coverage of farm dams for KZN province.

5.3.5.1 Land cover fragmentation

The outcomes of this assessment are systematically classified based on the natural breaks in the data rather than the regular equal interval classification. The first class category of land-use fragmentation represented catchments with least fragmentation of land use parcel ranging between 0 and 17.57 (Figure 5.12, left). This class includes just over 23% of the catchments assessed (50 of 215 catchments assessed) within the province. These least fragmented quaternary catchments were located along the most of the west boundary of the province and very few at the north-east coast (Figure 5.13, left). The former area is mountains covered while the latter has large areas of wetlands and lakes. Rivers that are found along these mountainous areas include the upper Tugela, Mzintlala, Klip, Ngwangwane, and Mzimvubu located in the outer-most western parts of the province as part of the Mvoti to uMzimkhulu WMA, while the Pongolo and Mkuze Rivers are found in the north-east parts of the province. The class category with the second highest number of catchments (21.86 percent) is between the fragmentation range of between 33.83 and 50.77 percent. These catchments are largely found in the northern and southern parts of the province (Figure 5.13, left), hosting rivers such as Pongola, Bivane and Mkomazi respectively.

The last category reflects catchments with the highest fragmentation of land use ranging between 66.78 and 100 percent. About 16.27 percent of selected quaternary catchments (35 of 215 catchments) are highly fragmented (Figure 5.12, left). A large group of high fragmented catchments are found in the central regions, while few are scattered towards the central coastal sections of the province. These catchments cover rivers such as the Sundays and its tributaries, Buffels, Nsuze, and White Mfolozi in the central regions, while Mdloti and lower section of uMngeni River are found towards the central coastal sections catchments (Figure 5.13, left).

5.3.5.2 Small dams density

There are many quaternary catchments with less density of small dams than with high density of small dams. A high number of catchments recorded a lower density while high density accounting for a very small number of catchments. Therefore, the number of selected quaternary catchments with the least density (0.00-7.10 percent) of small dams in the province was at 40.47 percent (Figure 5.12, right). Most of these catchments were located in the central and isolated areas of the north east region of the province (Figure 5.13 – right). Most affected rivers within these catchments in the central regions are Mhlatuze, Black Mfolozi and large central sections of the Tugela River. The second class of density is between 7.11 and 18.61 of small dams in a quaternary. About 65 out of the 215 total catchments (30.23%) reflect this level of density. These catchments are scattered in different regions as seen in Figure 5.13 (right) and have therefore affected small sections of several rivers of the province. The densest catchments in terms of small dams contains from about 59.97 to 100 percent of small dams. However, only about 5.11% (11 of the 215 selected quaternary catchments) contains this highest density of small dams in the province (Figure 5.13, right).

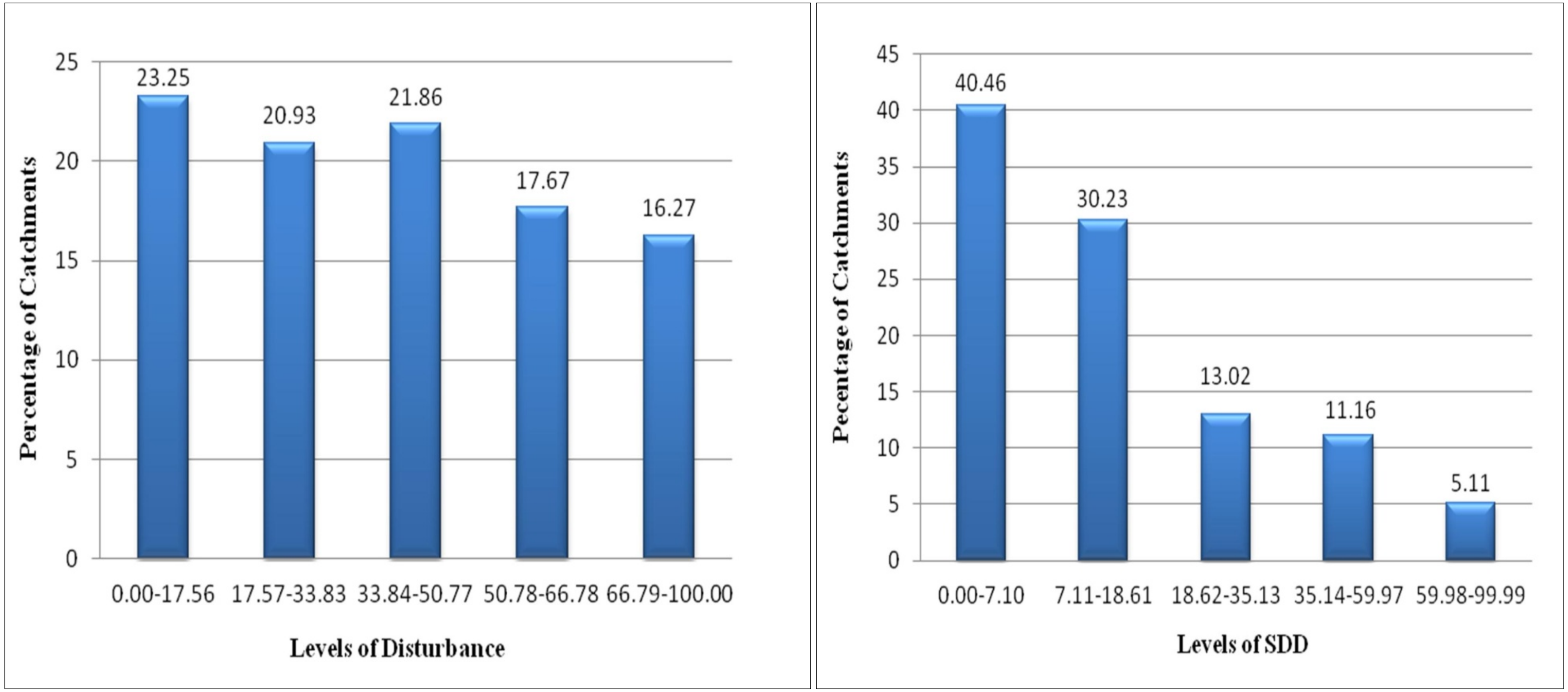
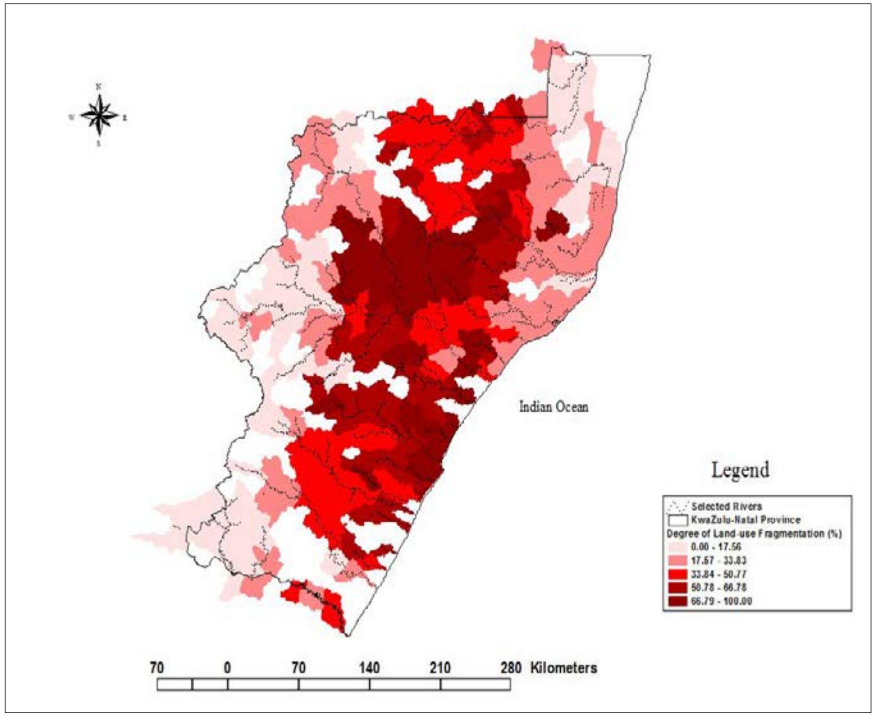


Figure 5.12: Bar-graphs showing the percentage of quaternary catchments disturbance for categories of fragmentation of land-use (left) and categories of SDD or small dams density (right).



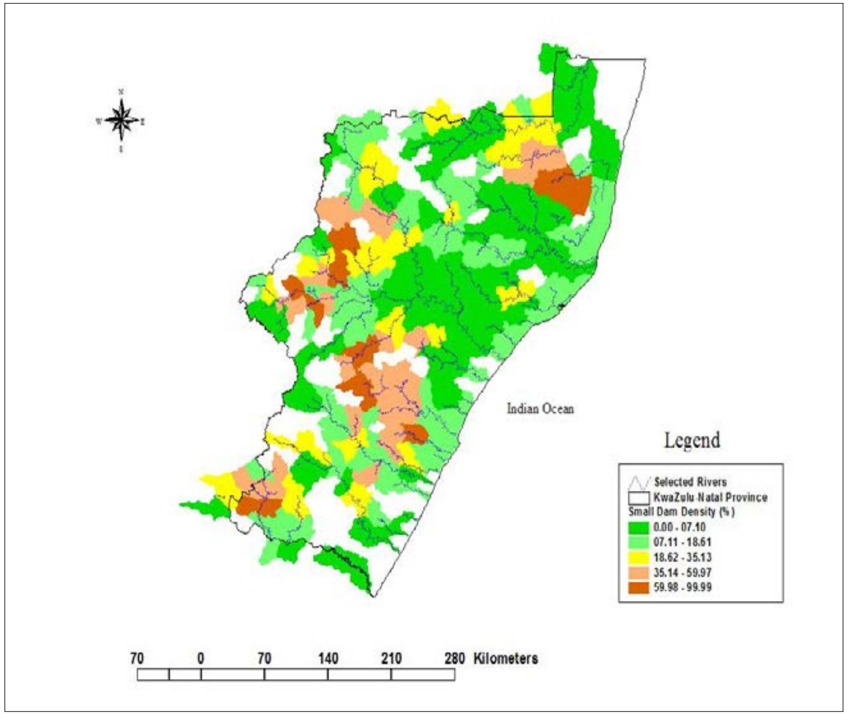


Figure 5.13: Land-use Fragmentation index (left) and Small Dams Density index (right) for selected quaternary catchments in KZN province.

5.3.5.3 Lateral connectivity index

The lateral connectivity index of rivers in selected quaternary catchments was the sum of land-use fragmentation and density of small dams in each catchment, which was standardized to a disturbance score of 0-1. The results were grouped into five classes representing major breaks with the highest reflecting extreme disturbance. The first disturbance group ranged from 0.04 to 0.20 and had 23.72 percent of all selected catchments (Figure 5.14). The catchments of this group are dominant along the north east sections of the province. The highest numbers of catchments at nearly 27 percent contained a lateral disturbance range 0.21 to 0.34 and have dispersed across all directions of the province. Not only the second group, however in the similar manner the third group (0.35 to 0.47) which has 24.65 percent of all selected catchments have disseminated into almost all directions of the province. These two groups of catchments disturbance covers or affects one or more sections of almost all selected rivers in the province as can be interpreted from Figure 5.15.

Catchments (17%) with the second highest lateral connectivity disturbance range from the score of 0.48 to 0.63. These catchments were grouped together in the central western to eastern interior of the province (pink region - Figure 5.15). Only 7.9 percent of all selected quaternary (17 of 215) have seen the most catchments lateral connectivity disturbance ranging from 0.64 to 1.00 in the province. Of all the 17 catchments, only one catchment (U20B) showed a 100 percent lateral connectivity disturbance score. Rivers of this catchment include the upstream zone of Lions and other small tributaries which sources the uMngeni River. Twelve of these 17 catchments occurs within the Mvoti to uMzimkhulu WMA and they provide a flowing environment for the following rivers; Mzimvubu, Msunduzi, Lovu, Mlazi, uMngeni and Mvoti. The remaining five catchments occurred within the Tugela WMA and include the Mooi, Tugela, Buffels and Mzinyashana Rivers.

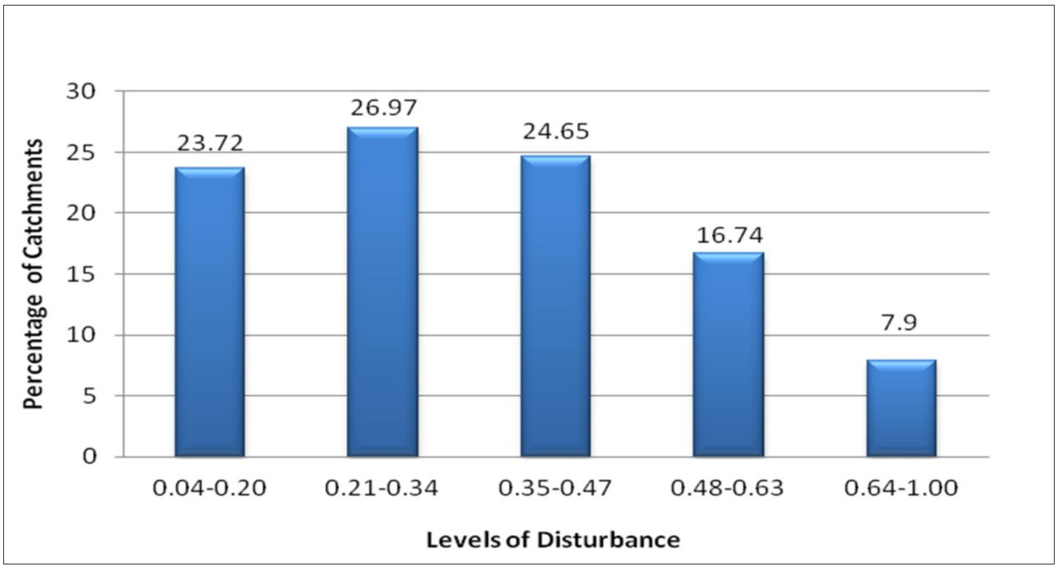


Figure 5.14: Bar-graph showing the percentage of catchment for various levels of disturbance for lateral connectivity index of rivers per quaternary.

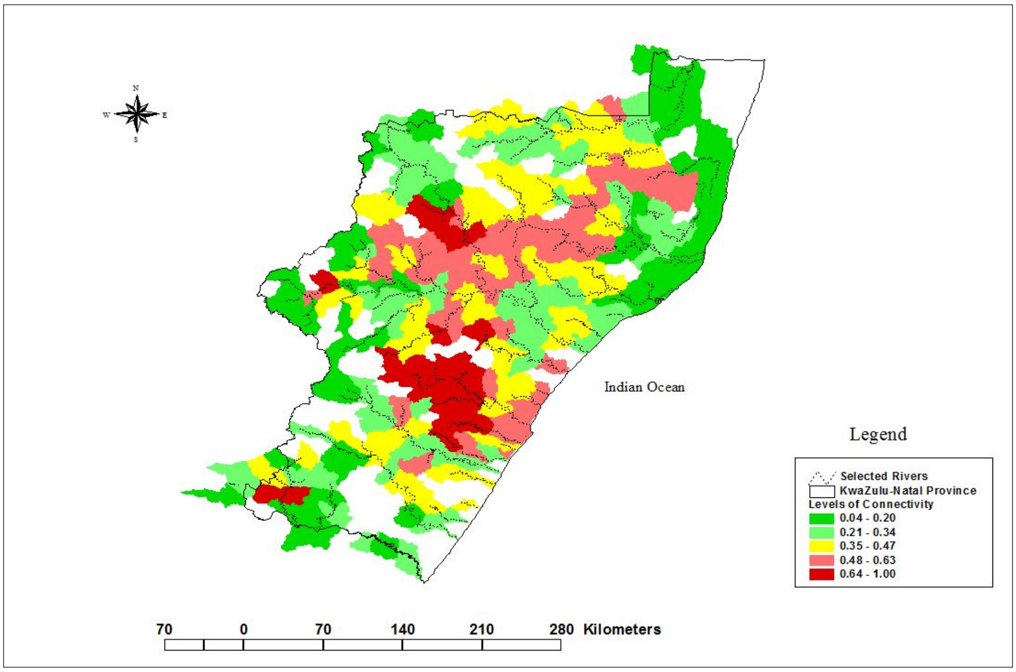


Figure 5.15: Lateral connectivity index for selected quaternary catchments in KZN province, based on the combined land use fragmentation and small dams' density index scores.

5.3.6 Integrated spatial connectivity index of rivers

The integrated spatial connectivity index was derived from the combination of the longitudinal and lateral connectivity indexes (see Appendix D for catchments scores). The lowest class of catchments disturbance ranged from 0.00 to 0.22 (Figure 5.16). Catchments of this class were 43 from a total of 215 selected catchments (20 percent) and occurred at the outskirts of the province (Figure 5.17). Some of the rivers of this class are Sundays, Mlalazi, downstream of the Tugela and uMzimkhulu Rivers. The second river disturbance class ranging from 0.23 to 0.40 disturbance rates included the highest number of catchments (34.88 percent, 75 catchments). The third river disturbance class ranging from 0.41 to 0.64 disturbance rates had 32.09 percent (69 catchments). This third disturbance class represented the average disturbance rate at of both lateral and longitudinal environments ranging at between 0.41 and 0.64 respectively. These catchments are dominant in both the Tugela and Usutu to Mhlatuze WMA, with large areas of Buffels, Pongola and White Mfolozi Rivers respectively affected.

The number of catchments in the fourth disturbance class of between the ranges of 0.65 to 1.07 decreased to 10 percent (21 catchments). The fifth and last class ranges at disturbance scale from 1.08 to 1.69, and contains a very small number of three out of the total 215 quaternary catchments. This figure can be translated as only 1.39 percent of all assessed catchments. Thus, these areas are hotspots of river disturbance and require a rehabilitation intervention. The assessment of this study showed that the whole upstream to downstream extent of the uMngeni River has severely been impacted by land use activities and in-stream impoundments (see both Figure 5.9 and 5.17). Few other isolated catchments that have severely been impacted by in-stream barriers and land-use activities include those that accommodate the following rivers; the small areas of upper and middle reaches of Tugela, whole of Mzinyashana and mid–sections of the Buffels River.

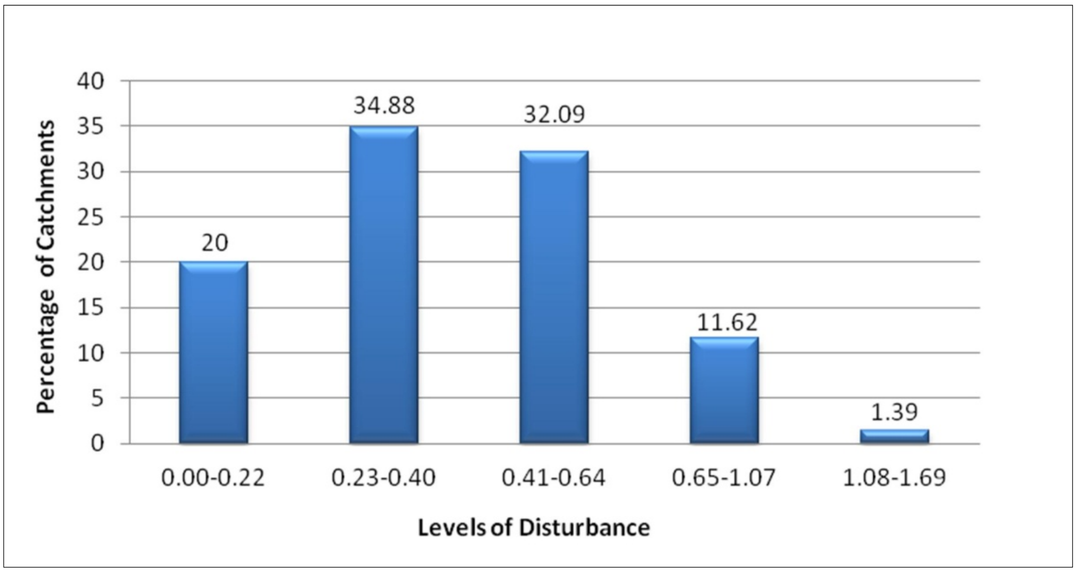


Figure 5.16: Bar-graph showing the percentage of catchment for various levels of disturbance for integrated spatial connectivity index of rivers per quaternary.

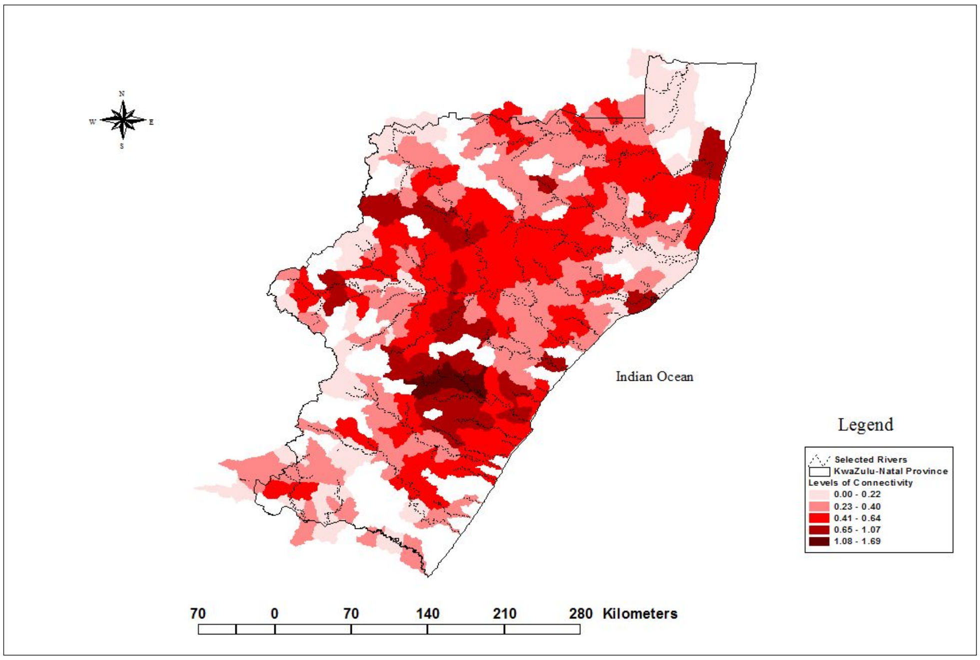


Figure 5.17: Spatial connectivity index for selected quaternary catchments in KZN province.

5.3.7 Stream order and connectivity of rivers

Rivers have responded differently to connectivity at different stream order classes in the province. This assessment examined the relationship between stream order of selected rivers and their connectivity using the overall cumulative longitudinal connectivity of all rivers that were studied. A high score represented high in-stream disconnectivity while a low or zero score represented natural undisturbed connectivity. The general linear trend shows that rivers are well connected (natural) at lower stream order classes as compared to high stream order classes (Figure 5.18). The current conditions shows that a river with stream order of five (Tugela) has the connectivity of 0.6, while the average connectivity of rivers of stream order four was 1.6.

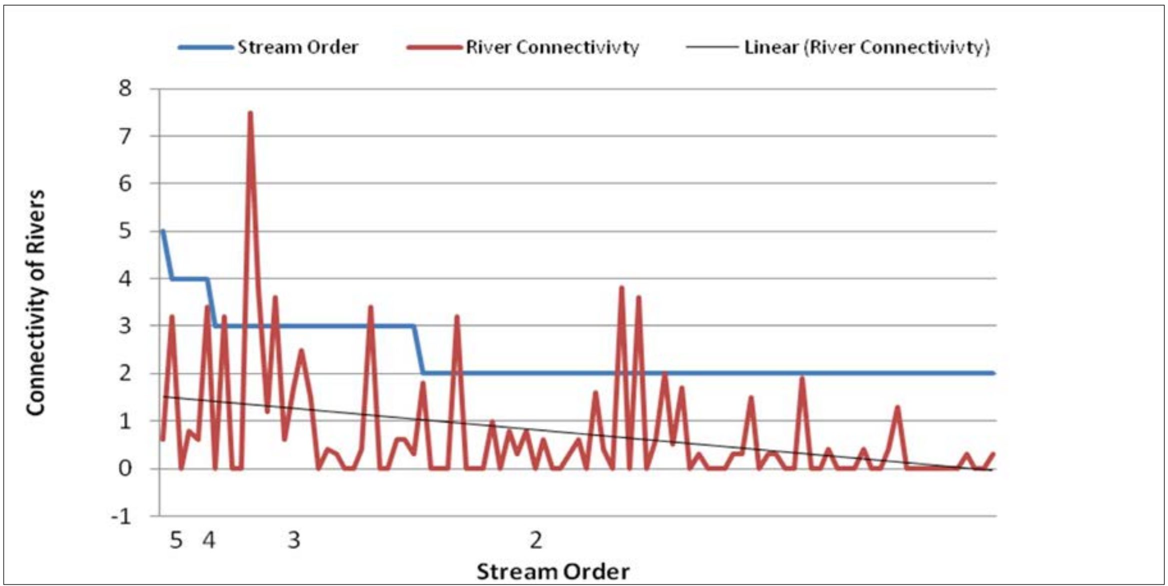


Figure 5.18: Graph showing relationship between stream order classes and longitudinal connectivity of rivers in KZN province.

About 25 rivers formed part of the stream order class number 3. The most impounded river (uMngeni) (see Figure 5.9) is found in this class with a disturbance score of 7.5. The average connectivity of stream order class number 3 is 1.26. Some of the rivers in this class include the Mkomazi, Mkuze and uMzimkhulu Rivers. Stream order class 2 included approximately 66 different rivers. The highly disturbed river (Mhlatuze) of this class had a connectivity score of 3.8 (Figure 5.18). The average connectivity of this class order is low 0.47. During this assessment, it was clear that the level of disturbance decreased with decreasing stream order classes of KZN rivers, i.e. lower order streams had lower disturbance and vice versa. Therefore, in general, most of rivers in this province are relatively natural and preserves the ecological integrity of the ecosystem.

5.4 Discussion

5.4.1 Factors driving connectivity of rivers

The data from this study suggest that connectivity of river systems decreases with increasing stream order, and it is likely that this is driven by social evolution and development. For example, the Tugela river catchment has undergone considerable modification in relation to anthropogenic development and high population density moving towards the coast (Schulze, 2000; Schulze *et al.*, 2005). Alterations to natural connectivity of river systems resulted from impoundments such as large dam structures and large number of flow gauging weirs in the province. Land use also influenced alteration of natural river connectivity in catchments where fragmentation was high, and this trend is not unique to KZN (Januchowski-Hartley *et al.*, 2013; Sola *et al.*, 2011; Stein *et al.*, 2002).

The combined connectivity index suggested that the most disturbed river system includes the uMngeni River as a result of its four large dams and highly fragmented floodplains. The four large dams in this river system were built to provide irrigation, industrial and municipal services to local people (Vuuren, 2012). In this regard, Dickens *et al.* (2008) recorded changes in the quality of water along banks of the uMngeni River next to Albert Falls Dam as a result of on-going agricultural activities. The lateral connectivity along the uMngeni River accounted for 66-100% fragmentation of land use activities (Figure 5.13). There were only 16% of catchments of this fragmentation extent and the increasing conceptual undertaking is that rivers of this environment are spatially and temporally complex to understand and highly vulnerable to change.

Rivers that have a moderate scale of disturbance were largely as a product of either a combination of weirs and dams, weirs and waterfalls, or weirs and canals. Weirs are sites with a structure on a river which has been selected, equipped and operated to provide the flow data from which systematic records of water level discharge or flow are extracted (Wessels and Rooseboom, 2009). These structures are installed by DWA to monitor the level of water flow at specific sites along rivers. In certain situations, these structures are used as storage areas for irrigation water (Wessels and Rooseboom, 2009). For example, the Mkuze, uMngeni and Mfolozi River each have eight flow gauging weirs along their length. It is arguable that the presence of gauging weirs in some of the rivers has been influenced by farming and subsequent urban land. The presence of waterfalls and pipelines as independent factors had a little influence (see Table 5.1) on the connectivity of rivers and has occurred in a limited scale (Figure 5.3). Though waterfalls are natural, they prevent upstream migrations of aquatic species in response to increasing water temperatures as a result of changing thermal conditions (Rivers-Moore *et al.*, 2008). The occurrence of pipelines is most likely to be driven by the need for irrigation water, waste treatment, industrial and other municipality services. These influential factors have also been recorded as the major water infrastructure and transfer schemes in the Tugela River (Wilson *et al.*, 2004).

5.4.2 Connectivity of rivers in KZN

The methods used to generate both longitudinal and lateral indexes of rivers were transparent, repeatable and, while developed at a quaternary catchment scale, could just as easily be applied to other scales. It was found that there is a good correlation between the longitudinal and lateral index metrics, and as such the confidence of true reflection of connectivity index of rivers is credible. It is recommended that for future analyses the usage of more recent datasets is advisable for more accurate results. This would improve the reliability of outcomes.

Based on the assessment of this study, 47 river segments are without any form of barrier within their longitudinal length, with 5 rivers (Bloukrans, Mzumbe, Nsuze, Nwavuma, and Sundays) longer than 50km. The 47 river segments are listed alphabetically in appendix E. These are rivers that are found to be natural and have sustained the free flowing condition. A large number of these rivers are small streams of the second order class. An additional 15 rivers have recovered from impoundments to conditionally become free flowing downstream of impoundments. This happened in situations where the downstream distance is greater than the recovery distance before the next impoundment occurs (See Appendix E for a list of names of these rivers). In comparison, a study by Rivers-Moore *et al.* (2008) recorded 24 rivers within KwaZulu-Natal province that are free flowing. This study by Rivers-Moore *et al.* (2008) did not take into consideration other disturbance factors such as weirs, canals and waterfalls. However, free-flowing rivers common to both these studies include uMzimkhulu, Mkuze and Mzumbe Rivers.

Another study was conducted by Driver *et al.* (2011) to develop a basis for enabling effective implementation of measures to protect freshwater ecosystem priority areas, including free flowing rivers. Several factors were used in the study by Driver *et al.* (2011) to define free flowing rivers as opposed to the study by Rivers-Moore *et al.* (2008). According to Driver *et al.* (2011), a free flowing river had to be permanent or seasonally flowing rivers, good ecological category (A or B), not impounded, and longer than 50km. Thus, 15 rivers in KZN were defined as free flowing and eight had length greater than 100km. Free-flowing rivers that are common to those of this current study include Mzumbe, Nsuze, Nondweni, Ngogo and uMzimkhulu. The current study differed to the study by Driver *et al.* (2011) in that free flowing rivers assessment was not assessed in terms of ecological categories.

This study highlights that the uMngeni River is the most disturbed river in the province. As shown by the evidence in Figure 5.7, the disturbance of this river is attributed to its four dams. This study agrees with the findings of a study by Dickens *et al.* (2008) that the uMngeni River has been impounded in a manner that is consistent to the development of the catchments in which it flows. Other studies such as by Rivers-Moore *et al.* (2008) and Driver *et al.* (2011) have evaluated free flowing rivers using different methodologies and find that the uMngeni river is the most disturbed. The former study has however showed the discontinuity of rivers based on the length of rivers and number of dams at a primary catchment scale.

No study considered the influence of land use on the connectivity of rivers in KZN province. To gain this knowledge in future assessments, it will be equally important to include land use assessment when determining the ecological integrity of rivers. Several studies have found these relationships (land use and river health) to be stronger although the methods of assessment vary greatly. Stein *et al*. (2002) has used the land use transformation score to predict the effects of land use to freshwater resources, while others have used fragmentation and multi site comparisons (Keruzoré *et al.,* 2013; Liu *et al*., 2011; Allan, 2004; Sponseller, 2001).

5.4.3 Ecological implications

The outcome of the connectivity of rivers in KZN comes with a number of ecological implications. The results in this study have shown that there are 47 out of 95 river segments with average length of 45km in KZN that are undisturbed and free flowing. First and foremost, free-flowing rivers allow aquatic species to disperse and adapt to the effects of climate change (Sola *et al.*, 2011; Sheldon, 2012). This is because free flowing rivers flow from source to sea without encountering any barrier (Rivers-Moore *et al.*, 2008; WWF, 2006; Driver *et al.*, 2011), allowing species to move from one area to another in response to changing habitat conditions (Walther, 2010; Sola *et al.*, 2011; Rivers-Moore, 2012). Secondly, these free flowing rivers provide critical services for aquatic biota of the KZN province. Free-flowing rivers are also seen as channels in which the invasion of aquatic ecosystems by non-native species occurs and now is rapidly becoming one of the most serious threats to local aquatic life (Combes, 2003).

Based on the approach of this study, the uMngeni River is likely to have the most threatened aquatic ecosystem within the province, based on the critically broken connectivity in the catchment in which it flows. Elsewhere, this fate of disconnected river system has been largely studied and documented by several scholars (Bunn and Arthington, 2002; Dallas, 2008; Poff *et al*., 1997; Poff and Zimmerman, 2010; Rivers-Moore *et al.*, 2012). If the current connectivity conditions of the uMngeni and other rivers of related disturbance are not changed, these rivers are faced by an inevitable fatal response of aquatic species. These will include *inter* alia the loss of sensitive aquatic species, reduced migration and recruitment, local extinction, and disrupted spawning activities (Bunn and Arthington, 2002; Poff *et al*., 1997). Furthermore, studies show that these effects are mostly predetermined in rivers impounded by large dams (Freeman *et al*., 2007; Poff and Zimmerman, 2010).

In contrast, there are valuable and extensive ecological benefits of enhanced or reduced (not natural) connectivity of river systems wherein impoundments have been installed and landscape environment has been intensively modified by human activities. With reference to a study by Pringle and Jackson (2010), rivers in KZN that are disturbed including the uMngeni, Lovu and Mhlatuze will have their endangered species protected by dams and other of forms of created barriers. Elsewhere, these findings are supported by Combes (2003) who noted that well-protected areas by either thermal or physical barriers eliminate stresses from non-native species that can cause disturbance to native communities. Other benefits include protection of biotic integrity of the catchment, protecting stream against sediments by reducing peak flow, and in the same time improving the quality of water (Pringle and Jackson, 2010).

5.5 Conclusion

The methodologies used in the assessment of longitudinal connectivity were all useful and provided the anticipated outcomes. A continuous assessment of both longitudinal and lateral connectivity of rivers in KZN over time as a monitoring strategy for effective management is advisable. The use of connectivity indices as a tool in prioritizing river systems most vulnerable to climate change is in this way important. Based on the assessment of this study, 47 river segments are without any form of barrier within their longitudinal length, with 5 rivers longer than 50km. These are rivers that are found to be natural and have sustained the free flowing condition. A large number of these rivers are small streams of the second order class. An additional 15 rivers have recovered from impoundments to essentially become free flowing downstream of impoundments. Based on the approach of this study, the uMngeni River is likely to have the most threatened aquatic ecosystem within the province, based on the critically broken connectivity in the catchment in which it flows. If the current connectivity conditions of the uMngeni and other rivers of related disturbance are not changed, these rivers are faced by an inevitable fatal response of aquatic species.

CHAPTER SIX

ASSESSMENT OF MACROINVERTEBRATE SPECIES VULNERABILITY TO THERMAL CHANGES

6.1 Introduction

Change of thermal conditions in aquatic systems is attributed to the on-going human-induced climate change and has considerable potential as a major threat to global freshwater biodiversity, although the projection of the size, direction and confidence of effects vary by region and season (Bush *et al.,* 2012; Filipa *et al.,* 2012; Lawler, 2009; Parry *et al.,* 2007). The effects of climate change (thermal condition) to aquatic biota are determined by species vulnerability, adaptive capacity and resilience (Gitay *et al.,* 2011). Vulnerability is the degree to which a system is susceptible to and unable to cope with, injury, damage or harm of climate change and other (anthropocentric) pressures on its ecological character (Parry *et al.,* 2007; Gitay *et al.,* 2011). Adaptive capacity (also termed recovery potential or adaptation) is the degree to which an ecosystem is able or unable to adapt to changes (De Lange *et al.,* 2010). Resilience in this study was viewed not only as the measure of the amount of disturbance that can be absorbed before the ecosystem changes its natural structure, but also as the speed of return to the equilibrium state of an ecosystem (De Lange *et al.,* 2010; Rieman and Isaak, 2010).

These changes (climate and habitat) have profound implications for aquatic biota in an ecosystem and these effects are well documented in literature. Effects of climate change on aquatic invertebrates species include changes in the phenology, physiology and the distribution and range shifts of species (Filipa *et al.,* 2012; Lawler, 2009; Dallas and Rivers-Moore, 2014; Walther, 2010). Phenological changes of species related to climate change include altered feeding, behaviour, growth, emergence and mating patterns (Dallas and Ketley, 2011; Durance and Ormerod, 2007; Walther, 2010). Although every species is not equally responsive to climate change, the change in the physiology of species include amongst other; thermal tolerance, and productivity (Olden and Naiman, 2010; Rieman and Isaak, 2010). A small change in temperature and thermal habitat condition has the potential to affect population dynamics and habitat use by many aquatic species (Lawler, 2009). Thermally-induced species' range shifts and distribution change have been reported along altitudinal and latitudinal gradients as temperature rises and aquatic species can only tolerate a specific range of thermal condition (Bush *et al.,* 2012; Chessman, 2012; Filipa *et al.,* 2012; Walther, 2010).

The relationship between aquatic system dynamics and connectivity (spatially and temporally) is important for aquatic diversity conservation. This relationship informs measures to be taken for aquatic systems management (Lawler, 2009). The lack of connectivity between catchments could hinder the adaptive response of species to climate change henceforth enhancing and lowering both their vulnerability and resilience (Burgmer *et al.,* 2007; Bush *et al.,* 2012; Chessman, 2012). According to Cote *et al.* (2009) species are increasingly vulnerable to climate change because of limited adaptive movement as a result of barriers such as dams and culverts that alter velocity, water depth and create vertical drops of downstream water that change the hydrology and thermal regimes of aquatic systems. Thus, identifying vulnerable species and understanding why they are vulnerable is seen as an important measure towards developing climate change adaptation strategies and reducing aquatic species diversity loss (Dallas and Rivers-Moore, 2014).

Aquatic macroinvertebrate species often show shifts for habitat preferences along latitudinal and altitudinal gradients at a family level (Lessard and Hayes, 2003). Rising air temperatures are expected to warm streams to the detriment of cold-adapted species with narrow thermal tolerances (Chessman, 2012). Furthermore, family level assessments act as an indicator for types of habitats as each macroinvertebrate community has a habitat-specific characteristic (Smith *et al.,* 1999). Therefore, families of species of cold water at high altitude areas are more vulnerable to warming temperature and climate than species of warm water found along the mid- and lower-reaches of the river's upstream to downstream extent (Chessman, 2012; Dallas and Rivers-Moore, 2014; Domisch *et al.*, 2012). Chessman (2012) demonstrated that a simple family-level calculation of thermal ratio, whereby aquatic macroinvertebrate families may be classified as either thermophilic or thermophobic. It is likely that thermophobic families will be more negatively impacted by climate change by losing their thermal refuges as temperature rises in high-altitude streams (Domisch *et al.,* 2012; Olden and Naiman, 2010; Dallas and Rivers-Moore. 2014; Rivers-Moore, 2013; Sheldon, 2012).

To lessen the impending loss of biodiversity as a result of climate change, there is a need to identify the ecosystems that are most vulnerable and formulate actions to protect them where feasible (Chessman, 2012; Linke *et al.*, 2007). Spatial connectivity, catchment condition and species tolerance are major considerations in the identification of ecosystems for systematic conservation action and management of aquatic systems (Li *et al.*, 2013: Rivers-Moore *et al.*, 2011). This study assumes that using a connectivity index in a holistic manner, it provides a tool to prioritise catchments for conservation action on the basis that catchments at high altitude with poor resilience are of higher conservation priority than lower catchments.

6.2 Methodology

6.2.1 Relationship between temperature change and gradient

To justify that freshwater ecosystems are likely to be negatively affected by global warming caused by climate change (Domisch *et al.*, 2011), this study used the relationship between temperature and stream gradient change to show that upper mountainous areas are likely to be more vulnerable to warming temperatures. A demonstration of how thermal conditions change with changing stream gradient was undertaken at two rivers as they are characterised by a sharp gradient in their profiles, namely; Tugela and uMzimkhulu Rivers. The rate at which water temperature changes per upstream gradient in each of the two rivers, based on the assumptions that mean annual water temperatures were assumed to be same at an equivalent altitude point of 5m above sea level in all the two rivers, and a lapse rate of 0.7°C per 100m upstream (Rivers-Moore *et al.*, 2013). Temperature change in two rivers was test as one moves upstream under a given temperature lapse rate.

6.2.2 Vulnerability and resilience of catchments to climate change

To assess the utility value of connectivity index to species response (Burgmer *et al.*, 2007; Cote *et al.*, 2009) and conservation planning (Rivers-Moore *et al.*, 2011), the next step was to identify vulnerable catchments. Vulnerability of catchments to thermal change as a function of change in the gradient of 13 selected streams (based on slope gradient and connectivity score) in the study area was assessed based on the logic of expression of equation 6.1.

$$\text{Vulnerability} = f\ (\text{gradient}) \qquad (6.1)$$

The value above average gradient calculated for all assessed rivers in the study area was assumed to be the point of reference for increased vulnerability of aquatic macroinvertebrates to warm water temperatures. A number of studies have indicated that highlands streams and associated biota are the most vulnerable to warming temperature and climate change (Domisch *et al.,* 2011; Rivers-Moore *et al.,* 2012; Sheldon, 2012). The upper sections of rivers with the gradient greater than the average gradient change were assumed to be vulnerable to thermal climate, while lower reaches of less than average stream gradient were regarded as less vulnerable. Vulnerability and the level of dis-connectivity of a river system are both crucial when assessing the resilience of catchment and biota. Thus, the next step was to determine resilience of catchments using the product of their disconnectivity and vulnerability indices index (Equation 6.2).

$$\text{Resilience} = \text{Vulnerability} \times \text{dis-connectivity} \quad (6.2)$$

Three levels of resilience (low, medium and high) were used to distinguish between the speeds of recovery each catchment requires to return to the natural equilibrium state of an ecosystem. Low resilient zones defined areas of catchment that are vulnerable and highly disconnected; medium resilient zones are catchments areas of either connected rivers or vulnerable inflected (steep) reaches with medium rate of recovery. Highly resilient catchments indicated rivers that are not vulnerable (low gradient) and well connected (natural) and recover from disturbance faster than other levels.

6.2.3 Species sensitivity and prioritizing catchments for conservation action

The thermal sensitivity of aquatic macroinvertebrate families and catchment conservation priority were assessed using selected common family groups that are contained in the River Health Programme (RHP) database by Dallas (2005) and also were used to test climate change species distribution shift by Chessman (2012). Selection of these families was based on their thermal sensitivity (thermophobic and thermophilic), availability within the study area and the ease at which they are distinguished, collectively making them good indicators of thermal stress (Chessman, 2012; Dallas, 2005; Dallas and Rivers-Moore, 2011). This includes the following families; Amphipoda, Blephariceridae, Gyrinidae, Heptageniidae, Notonemouridae, Philopotamidae, and Simulidae. The thermal sensitivity of each family using mean instantaneous temperature associated with sites in which that family was divided by the mean water temperature of all samples in the RHP (Equation 6.3) (Chessman, 2012; Dallas, 2005).

$$\text{Thermophily} = \text{mean instantaneous temperature} / \text{mean water temperature} \quad (6.3)$$

The thermophily estimate for each family is the mean instantaneous temperature associated with sample in which that family was detected, divided by mean water temperature of all samples, ignoring samples which temperature was not recorded.

Families with greater value of estimate are thermorphilic in nature, while a low estimate value defines the nature of thermophobic families. Finally, ratio of sensitive to non-sensitive families for selected catchment was then determined by family occurrence for upstream sites where RHP data were available. These different sites were selected based on their proximity to a river and availability of family occurrence data (Appendix F). The latest records of most family occurrence at each selected site were used. Quaternary catchments with high proportion of sensitive species and low thermal resilience capacity were assumed to be high conservation priority.

6.3 Results

6.3.1 Relationship between thermal change and gradient

Thermal conditions in the two experimental rivers changed with changing upstream gradient (Figure 6.1). The greatest thermal change was recorded along the uMzimkhulu River from -0.085 °C/km at 340km upstream to -0.357 °C/km at 350 km upstream. This was because of the very sharp vertical (upright) steep surface that resulted in gradient change of almost 40 m/km within a distance of 10 km upstream of the river. The Tugela River has also experienced a negative change in thermal condition of flow. At 20km upstream, thermal conditions changed at -0.018 °C/km relative to 3 m/km gradient change. At the measured peak of the studied escarpment (510 km), the Tugela River had a negative thermal change of -0.20°C/km with a gradient of 30 m/km. This might be as result of the Tugela River having a medium strength gradient and a longer longitudinal profile than all major rivers of KZN. This study assumes that as Tugela River is characterised by a sharp inflection, water temperatures change rapidly over a small upstream distance.

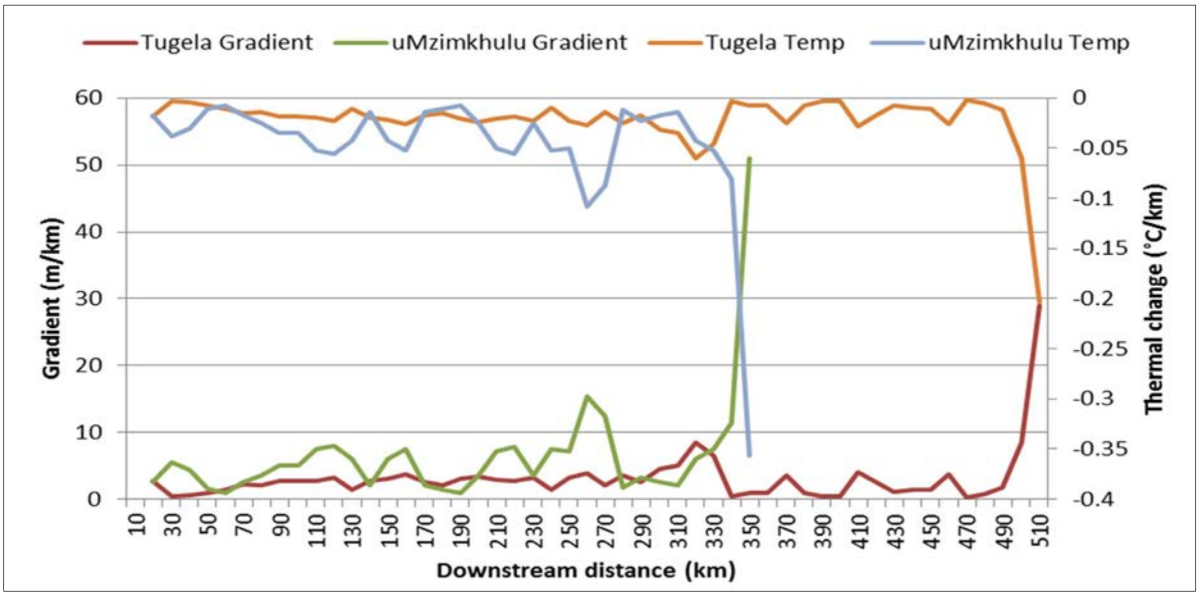


Figure 6.1: Hypothetical change of thermal condition as a function of stream gradient for the Tugela and uMzimkhulu Rivers based on an assumed lapse rate using 0.05°C/km per 10m/km upstream gradient.

6.3.2 Vulnerability and resilience of catchments to climate change

More than half (7 of 13) of the rivers which were assessed were identified as being vulnerable to the effects of thermal change based on their slope gradient that exceeded an average of 5.29 degree (Table 6.1). Amongst the seven vulnerable rivers, the Mdloti River recorded the steepest gradient at 11.05 degrees. All the 7 vulnerable rivers are found within the southern-most provincial WMA (Mvoti and uMzimkhulu) in KZN, which is the most elevated basin. Rivers that have shown to be ‘not vulnerable’ to thermal habitat change had their longitudinal profile comprising of slope gradient less than the measured overall average gradient. Six rivers existed in a relatively flat condition and are found within both the Tugela and uSuthu to Mhlatuze WMAs. Pongolo and Mooi rivers have the least slope gradient of 2.02 and 2.21 respectively and their ecosystems have the greatest ability to modulate to stress over time as compared the rest of the rivers that were assessed.

Resilience of rivers was divided into three levels namely; low, medium and high (Table 6.1). The three levels defined the scale of resistance and the speed of return of a river from thermal change to the natural conditions. The uMngeni and Msunduzi are the two rivers with low resilience capacity and are thus more vulnerable to thermal changes. As shown in Figure 6.2, catchments where these two rivers occur have emerged as the most vulnerable catchments to water temperature changes. Because both these two rivers are located in highlands areas and have each recorded a low longitudinal connectivity, aquatic life is threatened. However, amongst the 13 rivers assessed, only 8 were subjected to medium resilience to thermal change. These rivers have either suffered from low connectivity or are vulnerable to thermal habitat change due to their high elevation areas. It is further concluded that the Mooi, Pongolo and Tugela River are high resilient rivers. These rivers have recorded relatively low dis-connectivity due to the effects of recovery distance potential and also showed to be resistant to thermal change as a result of their favourable stream gradient.

Table 6.1: An assessment of river' vulnerability and resilient to thermal change based on slope gradient and connectivity.

River	Highest - Lowest Altitude Measure (m)	Longest - Shortest Distance Measure (km)	Change in Gradient	Vulnerability Based on average gradient change (5.29)	Longitudinal Disconnectivity Score	Resilience (Low, Medium and High)
Mooi	1381-585	370-10	2.21	No	0.04	High
Pongolo	932-2	470-10	2.02	No	0.06	High
Tugela	1580-16	510-10	3.12	No	0.23	High
Msunduzi	1124-345	110-10	7.79	Yes	1.01	Low
uMngeni	1469-18	250-10	6.04	Yes	1.22	Low
Buffels	1649-517	360-10	3.23	No	1.58	Medium
Lovu	1000-25	150-10	6.96	Yes	0.43	Medium
Mdloti	687-24	70-10	11.05	Yes	0.03	Medium
Mhlatuze	1042-9	220-10	4.91	No	0.79	Medium
Mkomazi	2030-12	290-10	7.20	Yes	0.07	Medium
Mlazi	905-41	160-10	5.76	Yes	0.15	Medium
uMzimkulu	2250-25	350-10	6.54	Yes	0.00	Medium
W. Mfolozi	1205-9	370-10	3.32	No	1.07	Medium

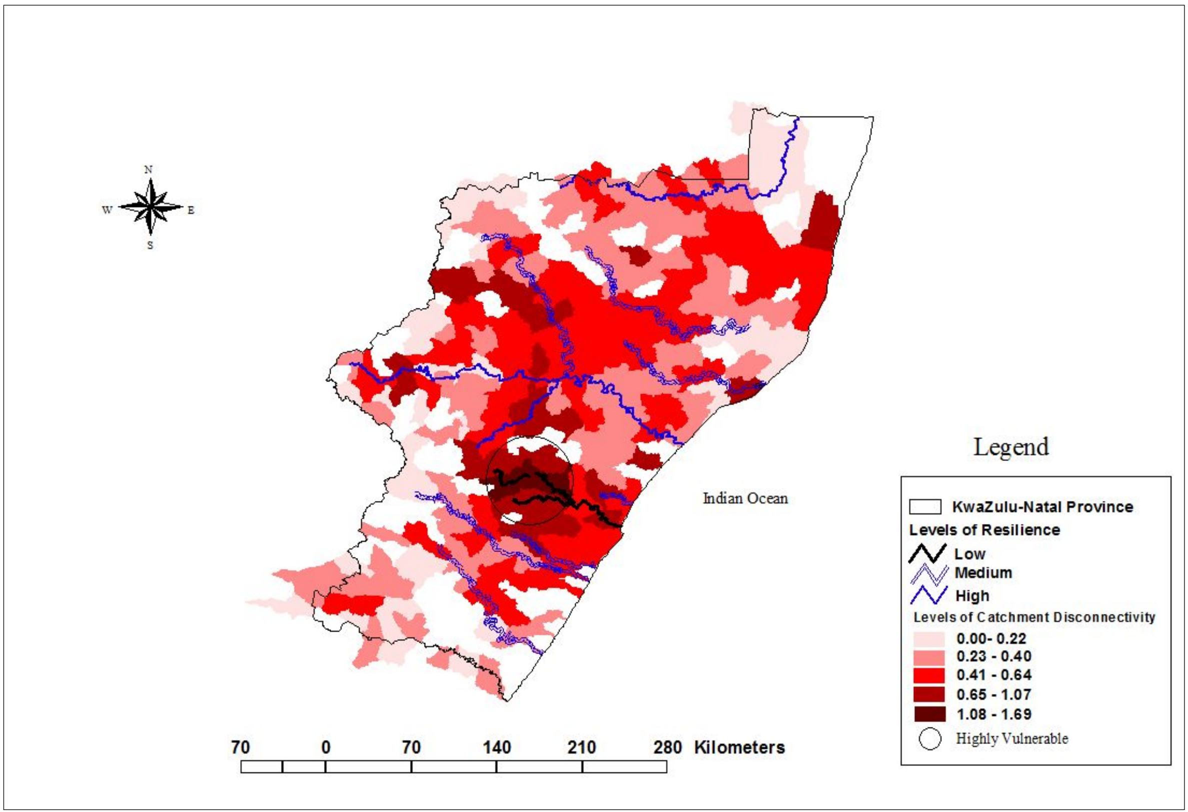


Figure 6.2: Level of resilience for different rivers, disconnectivity at quaternary catchment and area of high family vulnerability.

6.3.3 Family sensitivity and prioritizing catchments for conservation action

The family thermal sensitivity results are summarized in Table 6.2, while Table 6.3 shows the ratio of thermophobic against thermophilic families at each of the nine selected sites that represented different catchments. Collectively, selected families occurred in 8694 data records collected under the RHP across South Africa (Table 6.2). Amongst the selected families, Blephariceridae and Notonemouridae showed a greater preference for cooler water respectively occurring at a mean temperature of 14.35°C and 14.81°C, while Gyrinidae and Simulidae have showed the direct opposite at a mean water temperature of 17.96°C and 17.54°C respectively. The mean water temperature of 17.95°C was calculated by adding temperature values from all sites (5302) sampled under RHP and then dividing by the count of those numbers.

Table 6.2: Estimates of thermophily for aquatic macroinvertebrate families (Dallas, 2005).

Families	**Number of Sites**	**Mean Instantaneous Temperature**	**Mean Water Temperature**	**Estimate of Thermophily**
Notonemouridae	395	14.81	17.95	0.82
Heptageniidae	1295	17.33	17.95	0.96
Philopotamidae	634	16.81	17.95	0.93
Amphipoda	167	16.44	17.95	0.91
Blephariceridae	110	14.35	17.95	0.79
Simulidae	3596	17.54	17.95	0.97
Gyrinidae	2497	17.96	17.95	1.00

There was variation in the thermal sensitivity or thermal ecology preference of biota occurring at the selected sites. Four families namely, Notonemouridae, Philopotamidae, Amphipoda, and Blephariceridae were found to be thermophobic, while Heptageniidae, Simulidae, and Gyrinidae families are thermophilic. Comparably, this is because the former families showed lower estimate values than the latter (Table 6.2). For example, Notonemouridae holds a thermophily estimate of 0.82 as a product of its mean instantaneous temperature 14.81°C divided by mean water temperature of 17.95°C, and Gyrinidae is warm adapted at an estimate of 1.00 as a result of 17.96°C mean instantaneous temperature divided by mean water temperature of 17.95°C.

Therefore, the next assignment was to assess which upper catchments had a greater ratio of thermophobic families using surrogates sites, acknowledging that family sensitivity varies spatially and this has potential to inform conservation priority. The hypothesis was that catchment with high ratio of sensitive families compared to non-sensitive families, and either low or medium resilience to thermal change would be prioritized for management intervention. Selected sites had at least one of the selected family observed. The upper catchment of Mkomazi River had a greater ratio of 3 sensitive families to 2 non-sensitive families, and was of medium resilience, therefore it was declared a high priority catchment (Table 6.3 and Figure 6.3).

Other catchments of high conservation priority included the upper reaches of the Mlazi and uMngeni River, both with their ratio high in sensitive families and thermal resilience being medium and low respectively (Table 6.3). No sensitive species was observed for the catchments of uMzimkhulu, Tugela, Mooi, Buffels, Mfolozi, and Pongolo River, and as a result these catchments are likely to have low conservation priority.

Table 6.3: The ratio of sensitive to non-sensitive familiesat different RHP sites and catchment conservation priority.

RHP Site Code	River Catchment	Sensitive Species	Non Sensitive Species	Thermal sensitivity Ratio	Catchment Resilience	Conservation Priority
U1QUNU-NGB06	Mkomazi	3	2	3:2	Medium	High
U6MHLA-BOOTC	Mlazi	2	1	2:1	Medium	High
U2KARK-DMB02	uMngeni	2	2	2:2	Low	High
T3MZVB-JNSBR	uMzimkhulu	0	3	0:3	Medium	Low
V1SITU-WTN02	Tugela	0	1	0:1	High	Low
V2LITT-DSHLA	Mooi	0	1	0:1	High	Low
V3SAND-CTSWL	Buffels	0	1	0:1	Medium	Low
W1LENJ-NAT29	Mfolozi	0	1	0:1	Medium	Low
W4TSAK-NAT25	Pongolo	0	1	0:1	High	Low

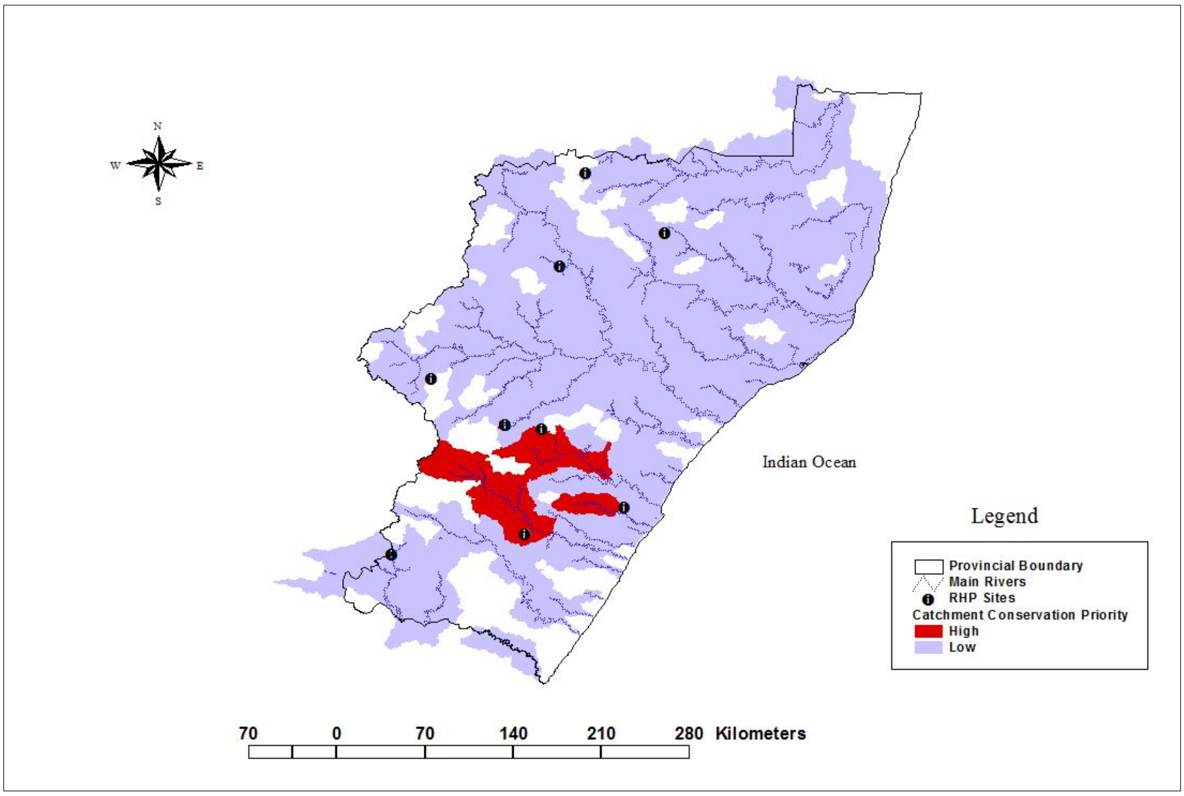


Figure 6.3: A map showing selected RHP sites and the levels of catchment conservation priority.

6.4 Discussion

6.4.1 Connectivity and vulnerability index as tools for conservation planning and prioritization of aquatic systems

An understanding on how climate change and other drivers (ecosystem health, flow regulation, etc) associated with trends in community assemblage of aquatic ecosystems helps in improving the management strategies of freshwater resources (Bush *et al.,* 2012). Vulnerability assessment provides such a tool to guide the prediction and analysis of climate change impact in the ecological character of rivers and also act as a method to estimate the conservation value of river systems (Linke *et al.,* 2008). Thus, both connectivity and resilience as indicators of vulnerability are central to systematic or integrated conservation planning and prioritization of aquatic system for sustainable management (Margules and Pressey, 2000; Rivers-Moore *et al.,* 2007; Rivers-Moore *et al.,*2011). However, as shown in this study, determining the vulnerability of ecological system is a complex process and different studies (Bush *et al.,* 2012; Gitay *et al.,* 2011; Ippolito *et al.,* 2010; Sheldon, 2012) have considered different methods. Using both vulnerability and connectivity as a tool for conservation and prioritization, vulnerability of rivers to thermal stress was assessed in this study based on the products of stream gradient, rate of thermal change, and level of dis-connectivity of rivers.

The approach to vulnerability in this study was appropriate as it relates connectivity to the potential impacts on thermal habitat for macroinvertebrate families. This type of approach allowed has a potential to be studied further than this on climate-induced range shifts of aquatic taxa (Sheldon, 2012) and vulnerability assessment of stream communities to climate change based on landscape scale (Bush *et al.,* 2012). This study showed that some rivers in KZN are vulnerable to thermal changes. These rivers are those that extend from low-lying coastal areas to the high altitude areas of the Drakensberg escarpment with impoundments acting as exacerbating factors to susceptible aquatic biota. Here, elevated upstream areas are relatively cooler compared to lower-lying areas, and based on their steeper gradients, are likely to be more greatly impacted by warming of water temperatures in response to climate change.

The results of this study are similar to those of a number of scientific studies. For example, Bush *et al.* (2012) found that climate change was the only possible explanation of increasing proportion of species turnover in upper stream zones, thus indicating greater potential for vulnerability to climate change in high-elevation streams. Similarly, Filipe *et al.,* (2012) indicated that cold-water aquatic species at high grounds regions will probably face habitat losses and extinction leading from strong reductions in their range because of increase rate of thermal change. For this reason, this study argues that high altitude zones which are prone to warm temperature should be prioritized as more urgent conservation zones. Management options should include maintaining or increasing connectivity in upper reaches to improve resilience to warm temperature.

Rivers of medium resilience to climate change were more compared to highly resilient streams. Medium resilience rivers were as a result of both high stream dis-connectivity and stream with gradient greater than average. Taking species preference into consideration, warm-adapted and generalist species are likely to be favoured by medium resilient rivers. Supporting this, Domisch *et al.* (2011) argued that generalist species are best buffered against climate change impacts by their ability to colonize and they can tolerate a broad range of climatic conditions, enabling them to potentially take advantage of suitable climates along a wider range of latitudes. The prediction of this study is supported by a study by Chessman *et al.* (2012) where warm adapted species are more likely to expand their ranges while cool-adapted species habitat contract.

Highly resilient rivers are however not necessarily natural in conditions but these rivers have high climate change effect resistance capacity. For example, the Tugela River is a highly resilient river yet this river is impounded at the upstream sections. However, given lower altitudinal gradients and relatively low dis-connectivity of high resilient rivers, aquatic species are more likely to be able to adapt to the effects of climate change at suitable stream condition which supports completion of their life cycle. Heino (2009) has recorded the ease of many species expanding their ranges to higher latitudes and altitudes in response to climate change within well connected river systems. Highly resilient rivers can theoretically be considered as of lower conservation and priority concern. More species-specific research is crucial at different altitudinal zones of KZN province to ascertain the effects of climate change at species level and therefore prioritize catchments based on the ecological stress level.

6.5 Conclusion

As discussed in this study, aquatic ecosystems and biota are increasingly becoming vulnerable to climate change. To maintain river systems that are able to support both natural ecosystems and human societies, competent and innovative management is required (Nilsson and Renöfält, 2008). Besides the controversy of scale for catchment management units between biophysical, social, legal, and economic defined spatial units, the best and effective catchment management policies and socio-economic acceptability for sustainability occurs in hotspots catchments (Newson, 2009). Therefore, connectivity of river systems play a central role in survey, data collection and monitoring of catchment conditions, and thus paying attention to hotspot catchments reduces uncertainty in the evidence based catchment prioritization process and empowers stakeholders for conservation (Newson, 2009). This study provided some evidence that cold waters of highlands escarpment of the Drakensberg Mountains will be the worst hit by the changing climate. This finding lays the foundation that promotes aquatic ecosystem integrity and formulation of management actions (policy) by developing an effective method that estimates both the level of aquatic system vulnerability and the amount of conservation priority. This study has demonstrated that vulnerability and connectivity assessment are useful tools in freshwater conservation planning, because they show rivers of conservation priority.

CHAPTER SEVEN

KEY FINDINGS AND CONCLUSION

7.1 Introduction

This study had two broad aims which were to develop a connectivity index of rivers in KwaZulu-Natal, where free-flowing rivers represented full connectivity, and to appraise zones of river systems which are most vulnerable to climate change based on temperature change and connectivity of river profiles. The literature review, methodology, results and where appropriate, discussions relative to results were discussed separately in their respective chapters and all these components collectively contributed to the integration of this study. Therefore, the purpose of this chapter is to:

- Assess whether the objectives of this study as stated in chapter One have been met or not.
- Summarize the main findings and implications of this study, and
- Recommend necessary measures and or future research areas for the benefit of aquatic systems conservation in the study area.

These factors will be addressed in their respective order under each intended objective in the next subheading of this chapter.

7.2 Key Research Findings

a) Connectivity index for main rivers in KwaZulu-Natal

The first objective was to generate a connectivity index based on in-stream parameters and land use fragmentation affecting river connectivity. This study successfully developed an index by measuring the connectivity of rivers in KZN. Key findings regarding connectivity included the following; from a longitudinal dimension, the province still holds 49 free-flowing river segments with an average length of 45 km, while the Tugela and uMngeni Rivers were the most impounded of all selected rivers, particularly in their upper reaches or catchments. These findings were not unique from the lateral assessment perspective, where the whole upstream to downstream extent of the uMngeni River has been severely impacted by land use fragmentation. Thus, these areas are hotspot regions of river disturbance and require a rehabilitation intervention and sustainable management actions. However, it is advisable that any management plan should also include strategies not compromising the daily basic survival needs of people from river resources.

b) Recovery distance of stream flow alteration at all selected quaternary catchments

Recovery distance was calculated based on the natural logarithm of flow volume and downstream distance. Here, the higher the flow volumes, the longer the downstream distance below an impoundment for recovery. Based on this, 63 quaternary catchments were likely to have recovered based on the distance between barriers, cumulative score of barrier and stream flow (Section 5.3.4). Recovery distance has the potential to inform the suitable distance between new barriers, aquatic species livelihood, and offers opportunity for conservation of freshwater assets (Dickens *et al.*, 2008; Palmer and O'Keeffe 1989; Poff and Zimmerman, 2010; Sheldon, 2012).

c) Temporal connectivity changes using the pre-impact versus post-impact regime methodology

The temporal connectivity assessment consisted of two parts; namely stream flow and water temperature analyses. Of the seven flow gauging stations in the province for which pre-and post-impoundment flow data were available, two stations had insufficient flow data for pre-impact periods and were excluded from further analyses. This left five sites for which comparisons could be made. Through the use of Principal Components Analysis, this study found that both river flow and water temperature time series, including their variability, had changed after the introduction of impoundments (Figures 4.8 - 9). Ecological implications of flow and temperature changes in rivers are expected to include loss of specialist species, affected migration cycles, disturbed spawning and feeding signatures, and reduced diversity. Thus, a well-accepted solution to impoundment based flow and temperature changes is centred on implementation of environmental flows as central to maintaining connectivity and ecosystem integrity of river systems (Dallas and Rivers-Moore, 2014).

d) **Vulnerable quaternary catchments to thermal changes relating to aquatic species survival**

This objective was successfully completed using 13 rivers based on their slope gradient and connectivity score. The 13 rivers were selected because of their upstream inflection point which exceeded 0.6 km above sea level. The uMngeni and Msunduzi were found to be the two rivers with lowest resilience capacity within the province, based on the criteria used in this study, and are thus more vulnerable to thermal changes. River systems with the highest resilience were the Mooi, Pongolo and Tugela Rivers, all as a result of their greater resistance to thermal change as a result of their favourable stream gradient. The remaining eight river systems showed intermediate resilience (Figure 6.1). Thus, vulnerability and resilient assessment were effective tools for prioritizing rivers for sustainable management action on water resources against climate change. Therefore, more researches are needed at different altitudinal zones to ascertain the vulnerability and effects of climate change on aquatic biota and to guide management strategies.

e) **Ecological effects of disconnected index of rivers in the study area**

This study used the River Health Programme (Dallas, 2005) database of aquatic macroinvertebrate families from rivers in KZN to measure their vulnerability to thermal change. Ecological effects of connectivity and climate change to aquatic families (macroinvertebrates) described in this study was supported by other studies of similar interests (Chessman, 2012; Dallas and Rivers-Moore, 2014). Disconnected rivers will have profound impacts to taxa whose life involved migration cycles. Thermal change is more likely to affect higher altitude sections than lower areas of river. Studies show that cold adapted aquatic macroinvertebrate families such as Notonemouridae, Blephariceridae and amphipods will be the most affected by increasing water temperature at high altitude, while this will favour and increase the habitat range for warm adapted family species such as Simulidae, and Gyrinidae (Burgmer *et al.,* 2007; Chessman, 2012; Dickens *et al*., 2008; Li *et al.,* 2013; Rivers-Moore *et al.,* 2012). From this study, it was evident that there is a need studies that will not only build the database of biota but also help in developing an understanding of how specific biota responds to effects of impoundments and thermal changes in rivers of KZN.

7.3 Conclusion

Each chapter of this study included a narrated conclusion relating to the context of that chapter. Therefore, the current conclusion addresses and uses literature to justify findings of the whole study. The aims of this study were to develop an index of connectivity of rivers in KZN province and to model river reaches that are most vulnerable to temperature changes. This study was successful in developing and modelling an index of river connectivity and catchments which are thermal change prone respectively. The index of connectivity of rivers in KZN produced by this study has potential to assist in managing these freshwater resources. This index can be used to identify the most disconnected rivers as priority areas for managerial intervention. However, non-regulated (free flowing) rivers should also receive the top management priority as compared to disturbed rivers. A study by Dallas and Rivers-Moore (2014), showed that rivers impacted by neither dams and human development will require more management interventions to protect ecosystems and people than will catchments with free-flowing rivers.

Restoration efforts on regulated rivers are not discouraged in literature, yet the benefits put forward by free flowing rivers are arguably greater than those from regulated rivers (Combes, 2003; Poff and Zimmerman, 2010; WWF, 2006). The study by Rivers-Moore *et al.* (2012) has supported prioritizing free flowing rivers to protect their natural flowing condition as it increases capacity to resist climate change impacts and maximize the capacity for adaptation. If restoration path is taken, regulated rivers can be restored by eliminating impoundments (Sola *et al.,* 2011) or construct passages for fish to by-pass the dam wall (Driver *et al.,* 2011).

Furthermore, the index produced by this study can be extended not only to prioritize areas for protection, but also to guide river managers regarding development of river infrastructure on non-priority rivers. This can be done as long as measures to mitigate the worst effects of impoundments are put in place (Driver *et al.,* 2011). The implementation of environmental flow regime can be one of the management solutions to impounded rivers of KZN. A vast body of scientific papers agree to the implementation of environmental flow paradigm as central to maintain connectivity and ecosystem integrity (King *et al.,* 2004; Poff *et al.,* 1997; Richter *et al.,* 1997; Sola *et al.,* 2011; Tharme, 2003), hence reducing ecological consequences of global climate change (Dallas and Rivers-Moore, 2014). This study has failed to find a trace of environmental flow release practiced at all the impounded rivers that formed part of this assessment. Therefore, the river connectivity index of this study and the scientific knowledge pertaining flow alteration and ecological response will provide the bench mark in which river managers will effectively monitor the health and guide the implementation of environmental flow regime across these freshwater assets in the KZN province.

The connectivity index of river systems developed has the potential to assist future conservation plans. It can be used to identify conservation priority areas where intervention may be required based on the extent of disturbance ranging from free flowing rivers (with high connectivity) to most disturbed rivers (with low connectivity). However, there is a need to develop conservation strategy that takes connectivity and upstream threats of thermal change into account as priority tool for more effective and sustainable freshwater management practices. A need exists for freshwater studies that will seek to understand the response of different biota to both spatial and temporal connectivity change not only within the study area but also elsewhere in the world.

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APPENDICES

Appendix A: Description of the 49 Land Cover Types

(Schoeman *et al.*, 2013; Van Dam, 2011; Van den Berg *et al.*, 2008)

Number	Land Cover type	Description
1	Forest (indigenous)	All wooded areas with tree canopy > 70%. A multi-strata community, with interlocking canopies, composed of canopy, sub-canopy, shrub and herb layers. The canopy is composed mainly of self-supporting, single stemmed, woody plants > 5 metres in height. Essentially indigenous species, growing under natural or semi-natural conditions (although it may include some areas of self-seeded exotic species). Excludes planted forest (and woodlots).
2	Woodland	All wooden areas with a tree canopy between 10 – 70%. A broad sparse – open – close canopycommunity, typically consisting of a single tree canopy layer and a herb (grass) layer. The canopy is composed mainly of self-supporting, single stemmed, woody plants > 5 metres in height. Essentially indigenous species, growing under natural or semi-natural conditions(although it may include some areas of self-seeded exotic species). Excludes planted forests(and woodlots).Canopy cover density classes may be mapped if desired, based on sparse (< 40%), open (40 –70), and closed (>70 %).
3	Thicket, Bushland, Bush Clumps, High Fynbos	Communities typically composed of tall, woody, self-supporting, single or multi-stemmed plants (branching at or near the ground), with in most cases no clearly definable structure. Total canopy cover is greater than 10%, with canopy heights between 2 – 5 metres. Essentially indigenous species, growing under natural or semi-natural conditions (although it may includesome areas of self-seeded exotic species, especially along riparian zones). Presence of alien exotic species can be modelled spatially using broad principles or unlikely structural / temporal occurrences within a given vegetation biome or region. Dense bush encroachment would be included in this category.Canopy cover density classes may be mapped if desired, based on sparse (, 40%), open (40 –70 %), and closed (>70%).
4	Shrubland and Low Fynbos	Communities dominated by low, woody, self-supporting, multi-5stemmed plants, branching at or near the ground, Between 0.2 and 2 m in height. Total tree cover < 0.1 Typical examples are low Fynbos, Karoo and alpine communities.
5	Herbland	Communities dominated by low, non-woody, self-

		supporting, multi-5stemmed plants, branching at or near the ground, between 0.2 and 2 m in height. Total tree cover < 0.1 Typical examples are found in Namaqualand or “weed” dominated degraded areas.
6	Natural Grassland	All areas of grassland with 10% tree and/or shrub canopy cover, and >0.1% total vegetation cover. Dominated by grass-like, non-woody, rooted herbaceous plants. *Essentially indigenous growing under natural or semi-natural conditions.*
7	Planted Grassland	As above, except planted grassland, containing either indigenous or exotic species, growing under man-managed (including irrigated) conditions for grazing, hay or turf production, recreation (i.e. golf) etc.
8	Forest Plantations (Eucalyptus spp)	All areas of systematically planted, man-managed tree resources composed of primarily exotic species (including hybrids). Category includes both young and mature plantations that have been established for commercial timber production, seedling trials and woodlot / windbreaks of sufficient size to be identifiable on satellite imagery. Excludes all non-timber based plantations such as, sisal, citrus, nut crops etc.
9	Forest Plantations (Pine spp)	
10	Forest Plantations (Acacia spp)	
11	Forest Plantations (Other / mixed spp)	
12	Forest Plantations (clear felled)	
13	Water bodies	Areas of (generally permanent) open water. The canopy includes both natural and man-made water bodies, which are either static or flowing, and fresh, brackish and salt-water conditions.
14	Wetlands	Natural or artificial areas where the water level is permanently or temporarily at (or very near) the land surface, typically covered in either herbaceous or woody vegetation cover. The category includes fresh, brackish and salt-water conditions. Examples include pans (with non-permanent water cover), and reed-marsh or papyrus-swamp. Dry pans are included in this category unless they are *permanently dry.*
15	Bare Rock and Soil (natural)	Natural areas of exposed sand, soil or rock with no, or very little vegetation cover during any time of the year, (excluding agricultural fields with no crop cover, and open cast mines and quarries). Examples would include rock outcrops, beach sand, and dry riverbed material.
16	Bare Rock and Soil (erosion : dongas / gullies)	Non-vegetated areas (or areas of very little vegetation cover *in comparison to the surrounding natural vegetation*), that are primarily the result of active gully erosion processes. Typically located in association with areas of poor grassland cover along existing streamlines and / or on slightly steeper slopes than sheet erosion areas (i.e. greater than 6 degree slope). In some areas the full extent of donga activity may be obscured by either overhanging adjacent bushes, encroaching thorn bush, or,

		in the case of more stable dongas, by bush or grass cover along the actual streamline.
17	Bare Rock and Soil (erosion : sheet)	Non-vegetated areas (or areas of very little vegetation cover *in comparison to the surroundingnatural vegetation*), that are primarily the result of active sheet erosion processes. Typically located in association with areas of severe donga erosion and / or poor grassland cover (i.e. low image NDVI rating). In some areas the full extent of this process may be obscured by encroaching bush. Typically located on slopes less than or equal to 6 degrees
18	Degraded Forest & Woodland	Permanent or near-permanent, man-induced areas of very low vegetation cover (i.e. removal of tree, bush, or herbaceous cover) *in comparison to the surrounding natural vegetation cover*.
19	Degraded thicket, Bushland, etc	Level agriculture and rural population centres, where overgrazing or livestock and /or woodresource removal has been locally excessive. Often associated with severe soil erosion problems.
20	Degraded Shrubland and Low Fynbos	
21	Degraded Herbland	
22	Degraded Unimproved (natural) Grassland	
23	Cultivated, permanent, commercial, irrigated	Land which has been ploughed and / or prepared for the raising of crops (excluding timberproduction). Unless otherwise stated, includes areas currently under crop, fallow land, and landbeing prepared for planting. Class boundaries are broadly defined to encompass the main areasof agricultural activity, and are not defined on exact field boundaries. As such all sub-classesmay include small inter-field cover types (e.g. hedges, grass strips, small windbreaks), as well as farm infrastructure. Several sub-classes are defined, based on the following parameters: <u>Commercial</u>: characterised by large, uniform, well managed field units (i.e. + 50 ha), with the aim of supplying both regional, national and export markets. Often highly mechanised . <u>Semi-Commercial:</u> characterised by small – medium sized field units (i.e. + 10 ha), within an intensively cultivated site, often in close proximity to rural population centres. Typically based on multi-cropping activities where annual (i.e. temporary crops) are produced for local markets. Can be irrigated by either mechanical means or gravity-fed channels and furrows.
24	Cultivated, permanent, commercial, dry Land	
25	Cultivated, permanent, commercial, sugarcane	
26	Cultivated, temporary, commercial, irrigated	
27	Cultivated, temporary, commercial, dry land	
28	Cultivated, temporary, subsistence, dry Land	

		Medium – low levels of mechanisation. <u>Subsistence</u>: characterised by numerous small fields units (less than + 10 ha) in close proximityto rural population centres. Field units can either be grouped either intensively or widely spaced, depending on the extent of the area under cultivation and the proximity to rural dwellings and grazing areas. Includes both rainfed and irrigated (i.e. mechanical or gravity-fed), multi-cropping of annuals, for either individual or local (i.e. village) markets. May include fallow and 'old fields', and some inter-field grazing areas (which are often classified as degraded).
29	Cultivated, temporary, subsistence, irrigated	<u>Permanent Crops</u>: lands cultivated with crops that occupy the area for long periods and are not re-planted after harvest. Examples would include sugar cane and citrus orchards. Note in the case of sugar cane, the growing season is typically 15 – 18 months per ratoon (i.e. harvest), with 2 – 3 ratoons possible before re-planting. Sugar cane is mapped as a separate crop type, and includes both large and small- scale commercial activities, as well as fallow (i.e. burnt / cleared) areas. <u>Temporary Crops</u>: land under temporary crops (i.e. annuals) that are harvested at thecompletion of the growing season, and that will remain idle until re-planted. In general this refers to maize and soya bean cultivation within the Pongola catchment, although cotton is locally dominant amongst the larger commercial sugar cane plantation areas. <u>Irrigated / Non-irrigated:</u> major irrigation schemes (i.e. areas supplied with water for agricultural purposes by means of pipes, overhead sprinklers, ditches or streams), and are often characterised.
30	Urban /Build-up	A generic urban class, essentially comprising all formal built-up areas, in which people reside on a permanent or near- permanent basis, identifiable by the high density of residential and associated infrastructure. Includes both towns, villages, and where applicable, the central nucleus of more open, rural clusters. This class should be used if it is not possible to identify more industrial and transportation land-uses. Low-density smallholdings frequently located on the urban / peri-urban fringe should be mapped as separate

		smallholding sub-classes, subdivided by the appropriate (level 1) background vegetation type. If visible, individual farm units are to be mapped as isolated urban /built-up units (if no other class is applicable). Specific urban /built-up sub-classes as listed below – in such cases it could include residential, commercial.
31	Urban / Built-up (rural cluster)	Areas of clustered a rural dwelling (i.e. kraals) whose structural density is too low to beclassified as a formal village, but are of sufficient level to be easily identifiable as such onsatellite imagery. Small scale cultivation /garden plots often form a major spatial component, and are located amongst the residential structures.
32	Urban / Built-up (residential, formal suburbs)	Permanent residential structures, either single or multi-level, located within new or well-established residential areas, i.e. '*garden-suburbs'*, (often refers to 'middle-class' and 'Upper-class' residential areas). Includes both low and high building densities.
33	Urban / Built-up (residential, flatland)	Permanent residential structures, consisting mainly of 3 or more levels (often up to 10), resulting in a concentration of mid-to-high rise buildings.
34	Urban / Built-up (residential, mixed)	Mixture
35	Urban / Built-up (residential, hostels)	Permanent residential structures, typically located in formal township districts, consisting mainly of 1 or 2 levels in concentrated block- like structures.
36	Urban / Built-up (residential, formal township)	Permanent (i.e. brick etc) structures (predominately single level), usually located on servicedsites within formal black residential areas, laid out in an organised, pre-planned manner. Includes both low and high building densities.
37	Urban / Built-up (residential, informal township)	Permanent / semi-permanent shack type dwellings (i.e. corrugated tin structures) laid out and established in an organised, pre-planned manner on both serviced and non-serviced sites. Includes both low and high building densities.
38	Urban / Built-up (residential, informal squatter camp)	Non-permanent shack type dwellings (i.e. tin, cardboard, wood etc) typically established on an informal, ad hoc basis, on non-serviced sites. Typically high building densities.
39	Urban / Built-up (smallholdings, forest &woodland ...)	See "residential" definition above ...
40	Urban /Built-up (smallholdings, thicket, bushland ...)	See "residential" definition above ...
41	Urban / Built-up (smallholdings, shrubland...)	See "residential" definition above

42	Urban / Built-up (smallholdings, grassland...)	See “residential” definition above
43	Urban / Built-up (commercial, mercantile)	Non-residential areas used primarily for the conduct of commercial and other mercantileBusiness, typically located in the central business district (CBD). Often consisting of a concentration of multi-level buildings, but also includes small commercial zones (i.e. spazashops) within former black townships.
44	Urban / Built-up (commercial, education, health, IT)	Non-residential, non-industrial sites or complexes associated with education (i.e. schools, universities), business development centres such as industrial ‘techno-parks’, and / or socialservices (i.e. hospitals), often consisting of a concentration of multi-level buildings (Note: onlymapped if clearly identifiable, otherwise included within ‘commercial / mercantile’ or ‘suburban’ categories.
45	Urban /Built-up (industrial / transport :heavy)	Non-residential areas with major industrial (i.e. manufacture and / or processing of goods andproducts) or transport related infrastructure. Examples would include power stations, steel mills, dockyards, train stations and airports.
46	Urban/Built-up (industrial / transport :light)	Non-residential areas with major technology, manufacturing or transport related infrastructure.Examples would include light manufacturing units, warehouse dominated business development centres, and small airports. Also includes similar structures such as farm-based pig and battery hen breeding units.
47	Mines and Quarries (underground / subsurface mining)	Active or non-active underground or sub-surface based mining activities. Category includes all associated surface infrastructure etc.
48	Mines and Quarries (surface-based mining)	Active or non-active surface-based mining activities. Includes both hardrock or sand quarryextraction sites, and opencast mining sites i.e. coal. Category includes all associated surface infrastructure.
49	Mines and Quarries (mine tailings, waste dumps)	Primarily non-vegetated, exposed mining (and heavy industry) extraction or waste material.Major areas of managed vegetation re-habilitation on these sites can be mapped according tothe appropriate vegetation category.

Appendix B1

Names and Geographic Location of Large Dams

Name of Impoundment	Date Built	Latitude °S	Longitude °E	Type of Impoundment
Albert Falls	1976	-29.4424	30.4053	Large Dam
Beaulieu	1986	-29.8633	30.2371	Large Dam
Bivane	2000	-27.3110	31.3160	Large Dam
Driel Barrage	1973	-28.7718	29.2984	Large Dam
Goedertrou	1982	-28.7682	31.4379	Large Dam
Hazelmere	1977	-29.5823	31.0343	Large Dam
Henley	1942	-29.6303	30.2442	Large Dam
Hluhluwe	1965	-28.1103	32.1576	Large Dam
Inanda	1989	-29.7041	30.8705	Large Dam
Klipfontein	1983	-27.8217	30.8093	Large Dam
Midmar	1965	-29.5079	30.1941	Large Dam
Nagle	1950	-29.5939	30.6427	Large Dam
Ntshingwayo	1961	-27.9936	29.9133	Large Dam
Pongolapoort	1973	-27.3702	31.9496	Large Dam
Shongweni	1927	-29.8563	30.7208	Large Dam
Spioenkop	1973	-28.6896	29.4940	Large Dam
Wagendrift	1963	-29.0544	29.8328	Large Dam
Woodstock	1982	-28.7218	29.2082	Large Dam
Zaaihoek	1988	-27.4270	30.0854	Large Dam

Appendix B2

Station Number, Location and Period of Recorded Data for Each Gauging Weir. Weirs with useable pre-and post-impoundment data are shown in bold

Station Number	Location	Latitude °S	Longitude °E	Data Period
T3H004	Mzintlava River	-30.56833	29.42277	1947-09-01 2005-08-01
T3H008	Mzimvubu River	-30.57083	29.15055	1962-09-11 2005-08-01
T4H001	Mtamvuna River	-30.73389	29.82833	1951-09-05 2005-07-10
T5H001	uMzimkhulu River	-30.25500	29.94361	1931-07-19 1979-05-01
T5H009	Ngwangwane River	-29.89583	29.40666	No Data
U1H001	Mkomazi River	-30.00806	30.24500	1931-07-18 1936-02-18
U1H002	Mkomazi River	-29.89278	30.07055	1933-09-01 1935-03-01
U1H005	Mkomazi River	-29.74417	29.90583	1960-08-14 2005-08-01
U1H006	Mkomazi River	-30.16833	30.69777	1962-10-24 2005-07-01
U2H001	**uMngeni River**	**-29.48694**	**30.23777**	**1948-12-01 1993-01-01**
U2H002	uMngeniRiver	-29.65000	30.80000	1928-03-04 1975-05-21
U2H003	uMngeni River	-29.75889	30.93527	1931-05-22 1978-12-22
U2H006	Karkloof River	-29.38056	30.27750	1954-01-04 2005-08-04
U2H007	Lions River River	-29.43972	30.15000	1954-07-16 2005-08-16
U2H009	Henley Dam	-29.62306	30.24000	No Data
U2H014	**uMngeni River**	**-29.43278**	**30.43222**	**1964-09-28 2005-07-21**
U2H015	uMngeni River	-29.69111	30.82222	1971-11-18 1987-09-12
U2H022	Msunduze River	-29.66083	30.63694	1983-09-07 2005-09-17
U2H037	uMngeni River	-29.48694	30.15638	No Data
U2H040	uMngeni River	-29.44056	30.33027	No Data
U2H041	Msunduze River	-29.60750	30.45000	1996-01-31 2005-08-01
U2H043	uMngeni River	-29.59778	30.62777	No Data
U2H047	uMngeni River	-29.60222	30.41361	No Data
U2H048	uMngeni River	-29.49500	30.20444	1968-03-11 2005-09-24
U2H052	uMngeni River	-29.59194	30.62805	1993-07-06 2005-06-24
U2H054	uMngeni River	-29.70806	30.86777	1989-04-25 2005-09-12
U2H055	uMngeni River.	-29.64194	30.68750	1989-10-26 2005-10-12
U2H056	uMngeni River	-29.64556	30.78583	No Data
U2H058	Msunduze River	-29.63083	30.35333	1995-04-25 2005-08-02
U2H059	uMngeni River	-29.58583	30.62138	1995-04-25 2005-09-10
U3H001	Tongati River	-29.53333	31.08944	1966-10-07 1992-11-30
U3H002	Mdloti River	-29.60278	31.01666	1950-08-23 1977-01-20
U3H003	Mdloti River	-29.60056	31.00666	No Data
U3R001	**Mdloti River**	**-29.60000**	**31.04361**	**1975-11-01 2013-08-01**
U4H001	Mvoti River	-29.35361	31.24388	1928-04-01 1946-11-30
U4H005	Mvoti River	-29.28556	31.12972	1958-06-28 1961-03-21

U4H006	Mvoti River	-29.29556	31.18777	1962-07-27	1974-02-20
U4H007	Mvoti River	-29.28750	31.13138	1978-11-16	1980-10-02
U4H009	Mvoti River	-29.38333	31.25416	1992-02-27	1997-06-20
U6H001	Mlazi River	-29.96028	30.95000	1953-07-13	1955-08-03
U6H003	Mlazi River	-29.80361	30.51611	1981-11-13	2005-07-13
U6H004	Mlazi River	-29.85861	30.70194	No Data	
U7H002	Lovu River	-30.09639	30.82333	1957-08-01	1966-01-01
U7H007	**Lovu River**	**-29.86167**	**30.24416**	**1964-10-13**	**2005-08-13**
U8H002	Mtwalume River	-30.46222	30.56138	1987-01-15	1992-12-12
U8H003	Mpambanyoni River	-30.27167	30.69527	1987-05-27	2005-08-21
V1H001	Tugela River	-28.73556	29.82055	1924-11-04	2005-09-02
V1H002	Tugela River	-28.73750	29.35250	1931-11-01	1970-04-01
V1H004	Mlambonja River	-28.79583	29.30305	1962-04-08	1975-12-10
V1H010	Little Tugela River	-28.81806	29.54500	1964-11-26	2005-08-10
V1H024	Mhlwazini	-28.99778	29.26361	No Data	
V1H026	Tugela River	-28.72083	29.35916	1967-07-31	2005-07-31
V1H038	Klip River	-28.56167	29.75250	1971-10-19	2005-08-20
V1H041	Mlambonja River	-28.81167	29.31194	1976-12-10	2005-07-10
V1H048	Tugela River	-28.63972	29.06722	No Data	
V1H049	Tugela River	-28.73694	29.36250	No Data	
V1H051	Klip River	-28.56972	29.77666	1987-09-23	1993-11-10
V1H057	Tugela River	-28.68111	29.51666	1981-01-09	2005-08-10
V1H058	Tugela River	-28.76222	29.29250	1985-05-30	2005-07-10
V1H059	River Outlet (Sluice)	-28.68111	29.51666	No Data	
V2H001	Mooi River	-29.03278	30.36027	1931-09-14	1976-02-10
V2H002	Mooi River	-29.21944	29.99361	1950-06-12	2005-09-10
V2H004	Mooi River	-29.07083	30.24583	1960-05-01	2005-06-03
V2H006	Little Mooi River	-29.25806	29.86916	1972-08-24	2005-09-10
V2H008	Mooi River	-28.85944	30.50000	1981-12-17	1983-09-20
V2H009	Mooi River	-29.24583	29.97055	1990-06-25	2002-04-20
V2H014	Mooi River	-29.24583	29.97055	1990-06-27	2005-08-01
V3H001	Buffels River	-28.24556	30.50944	1928-03-17	1944-09-03
V3H002	Buffels River	-27.60222	29.94277	1929-07-01	2005-08-02
V3H003	Ngagane River	-27.92278	29.94944	1929-07-01	1961-10-01
V3H005	Slang River	-27.43556	29.97611	1947-08-06	1993-03-03
V3H006	Buffels River	-28.01000	30.39444	1947-08-01	1963-06-03
V3H010	Buffels River	-28.05889	30.37361	1960-04-27	2005-07-01
V3H015	Buffels River	-27.73750	30.20388	No Data	
V3H018	Ngagane River	-27.93833	29.94333	No Data	
V3H022	Buffels River	-27.71944	30.07777	No Data	
V3H023	Ngagane River	-27.72194	30.08027	No Data	
V3H024	Ngagane River	-27.72667	30.05500	No Data	
V3H027	Ngagane River	-27.95361	29.94888	1961-08-01	2005-08-02
V3H028	Slang River	-27.43750	30.06111	1988-09-14	2005-08-02

V3H030	Buffels River	-27.60222	29.94277	1929-07-01 1933-03-01
V3H033	Buffels River	-27.60222	29.94277	1993-12-03 2005-09-02
V5H001	Tugela River	-29.16972	31.39388	No Data
V5H002	Tugela River	-29.14056	31.39194	1956-08-01 2005-06-01
V6H001	Tugela River	-28.74861	30.36055	No Data
V6H002	Tugela River	-28.75000	30.44277	1927-01-01 2005-07-02
V6H004	Sondags River	-28.40444	30.01305	1954-01-01 2005-07-01
V6H005	Tugela River	-28.73722	30.32027	No Data
V6H007	Tugela River	-28.74583	30.37888	1982-11-19 1987-09-02
V6H019	Wasbank River	-28.45861	30.17916	No Data
V7H001	Boesmans River	-29.01583	29.88472	1928-09-01 1965-03-03
V7H017	Boesmans River	-29.18750	29.63694	1972-10-23 2005-09-02
V7H019	Boesmans River	-29.09111	29.80305	No Data
V7H020	**Boesmans River**	**-29.04222**	**29.85138**	**1962-11-16 2005-09-02**
W1H001	Mhlatuze River	-28.66028	31.62888	1921-08-09 1940-05-01
W1H002	Mfule River	-28.77083	31.48000	1928-04-01 1931-09-03
W1H006	Mhlatuze River	-28.77250	31.46666	1956-09-01 1979-11-01
W1H007	Matigulu River	-29.05667	31.52972	1956-09-01 1968-10-03
W1H009	Mhlatuze River	-28.74778	31.74583	1960-11-02 2005-08-01
W1H010	Matigulu River	-29.01000	31.45944	1965-10-14 1992-12-01
W1H011	Msingazi River	-28.76778	32.07916	1968-04-12 2005-06-01
W1H020	Mfule River	-28.70167	31.65138	No Data
W1H021	Mhlatuze River	-28.84500	31.86666	No Data
W1H023	Nseleni River	-28.69500	32.00666	No Data
W1H024	Mhlatuze River	-28.55222	31.15833	No Data
W1H028	**Mhlatuze River**	**-28.77250**	**31.46666**	**1979-10-30 2005-10-01**
W1H032	Mhlatuze River	-28.80083	31.95666	1993-02-02 2005-08-01
W1H033	Mhlatuze River	-28.81083	31.94388	No Data
W1H034	Mhlatuze River	-28.79861	31.97416	No Data
W1H035	Mhlatuze River	-28.79806	31.99138	No Data
W1H036	Mhlatuze River	-28.84194	31.91055	No Data
W2H001	Mfolozi River	-28.44556	32.15666	No Data
W2H002	Black Mfolozi River	-28.30889	31.90250	1947-09-06 1964-04-02
W2H003	White Mfolozi River	-28.34444	31.86361	1947-09-06 1960-11-02
W2H004	Mfolozi River	-28.45278	32.18083	No Data
W2H005	White Mfolozi River	-28.33833	31.37361	1960-10-19 2005-07-02
W2H006	Black Mfolozi River	-28.06833	31.55000	1963-08-20 2005-10-02
W2H008	Black Mfolozi River	-27.93500	31.20500	1965-08-03 1980-03-01
W2H009	White Mfolozi River	-27.89722	30.88388	1971-09-21 2005-08-01
W2H010	Mfolozi River	-28.45639	32.14694	1972-11-02 1984-01-02
W2H011	White Mfolozi River	-27.83750	30.81333	No Data
W2H015	Black Mfolozi River	-27.81667	31.08583	No Data
W2H016	Black Mfolozi River	-27.82972	31.10805	No Data
W2H017	Black Mfolozi River	-27.85167	31.13527	No Data

W2H018	Black Mfolozi River	-27.87611	31.18444	No Data
W2H022	White Mfolozi River	-28.20000	31.02361	No Data
W2H024	Black Mfolozi River	-28.06083	31.41250	No Data
W2H025	Black Mfolozi River	-28.19167	31.73472	No Data
W2H026	Mona River	-28.15833	31.79555	No Data
W2H027	White Mfolozi River	-28.39528	31.69027	No Data
W2H028	Black Mfolozi River	-27.93778	31.20944	1987-09-17 2005-09-01
W3H001	Mkuze River	-27.67833	31.66666	1928-09-08 1992-03-03
W3H002	Mkuze River	-27.59278	32.01055	1928-01-19 1961-03-03
W3H008	Mkuze River	-27.60917	31.95750	1965-07-29 2005-07-02
W3H011	Mkuze River	-27.66000	32.42277	1969-10-08 1990-05-03
W3H012	Mzinene River	-27.86500	32.35750	1969-10-06 1987-09-02
W3H013	Nyalazi River	-28.18194	32.33416	1969-10-14 1974-09-01
W3H016	Mkuze Marsh	-27.71083	32.53472	No Data
W3H017	Mkuze Marsh	-27.76667	32.50916	No Data
W3H018	Mkuze Marsh	-27.80000	32.50444	No Data
W3H020	Mkuze River	-27.67500	31.43944	No Data
W3H021	Hluhluwe River	-28.14000	32.02027	No Data
W3H022	**Hluhluwe River**	**-28.12111**	**32.17972**	**1964-04-01 2005-08-01**
W3H024	Mkuze River	-27.68194	31.22222	No Data
W3H026	Mkuze River	-27.71611	31.35500	No Data
W3H027	Mkuze River	-27.70500	31.43972	No Data
W3H028	Mkuze River	-27.62250	31.62472	No Data
W3H030	Mkuze River	-27.64056	31.77333	No Data
W3H031	Mkuze River	-27.59639	31.83638	No Data
W4H001	Phongolo River	-27.41972	31.62611	No Data
W4H002	Phongolo River	-27.35528	31.92416	1929-09-05 1968-10-02
W4H003	Phongolo River	-27.41972	31.51000	1950-06-02 1995-08-01
W4H004	Bivane River	-27.52750	30.85805	1950-08-02 2005-07-02
W4H006	Phongolo River	-27.36361	31.78333	1968-10-25 2005-09-02
W4H007	Phongolo River	-27.01972	32.30277	No Data
W4H008	Phongolo River	-27.39444	31.64277	1972-11-22 1984-01-01
W4H009	Phongolo River	-26.90500	32.32472	1975-07-01 2005-07-02
W4H010	Phongolo River	-27.03639	32.26666	2003-09-17 2005-09-01
W4H011	Phongolo River	-27.41667	31.62500	No Data
W4H013	Phongolo River	-27.41667	32.07166	1983-09-06 2005-09-02
W4H016	Bivane River	-27.51944	31.05166	1999-05-05 2005-07-01

Appendix B3

Names of River and Waterfalls That Were Assessed

River	Type of Barrier	Label
Karkloof River	Waterfall	Karkloof Falls
Karkloof River	Waterfall	Woodhouse Falls
Karkloof River	Waterfall	*Not Named*
Klip River	Waterfall	Little Niagara
Klip River	Waterfall	Klip River Falls
Kwa Cota	Waterfall	Kwa Cota Falls
Mkuze	Waterfall	Mkuze Falls
Tugela	Waterfall	*Not Named*
Tugela	Waterfall	*Not Named*
Tugela	Waterfall	Hart's Hill Falls
Tugela	Waterfall	*Not Named*
Tugela	Waterfall	*Not Named*
Umngeni River	Waterfall	Albert Falls
Umngeni River	Waterfall	Howick Waterfall
uMzimkhulu	Waterfall	Pitout or Cooper Falls

Appendix B4

Pipeline Stations and Geo- Location used in Longitudinal Assessment

Station Number	Location of Pipeline	Latitude °S	Longitude °E
U2H049	Pipeline From Midmar Dam	-29.49500	30.20444
U2H050	Pipeline From Inanda Dam	-29.70805	30.86777
U2H053	Pipeline From Nagle Dam	-29.59194	30.62805
U3H006	Left Pipeline From Hazelmere Dam	-29.60000	31.04361
U3H007	Right Pipeline From Hazelmere Dam	-29.60000	31.04361
U6H007	Pipeline From Shongweni Dam	-29.84972	30.72333
V1H060	Pipeline To Ladysmith	-28.68111	29.51666
V1H061	Pipeline To Jagersrust	-28.76222	29.29250
V1H062	Pipeline To Jagersrust	-28.76222	29.29250
V1H063	Pipeline From Dam To River	-28.76222	29.29250
V2H015	Pipeline To Lions River	-29.24583	29.97055
V3H026	Pipeline From Chelmsford Dam	-27.95305	29.94805
V3H029	Pipeline From Zaaihoek Dam	-27.43833	30.05888
V3H031	Pipeline From Buffels River	-27.60222	29.94277
V4H002	Pipeline From Tugela river	-28.88194	31.03916
V7H021	Pipeline from Wagendrift Dam	-29.04222	29.85138
W1H037	Pipeline From Goedertrow Dam	-28.77250	31.46666

Appendix B5

Station Number and Geo-Location of Canals used in Longitudinal Assessment

Station	Description Of Location	Latitude °S	Longitude °E
U3H004	Left Canal From Tongati River at Riet Kuil	-29.53333	31.08944
U4H008	Left Canal From Mvoti River at Hlanzane	-29.28750	31.13138
V1H035	Tugela Canal at Second	-28.66666	29.12527
V1H054	Right Canal From Little Tugela Riv. at Wintert	-28.81805	29.54500
V3H032	Left Canal From Dorps River at Weltevreden	-27.60222	29.94277
V6H008	Right Canal From Tugela River at Impafana Loc.	-28.74861	30.36055
W1H027	Right Canal From Mhlatuze River at Normanhurst	-28.77250	31.46666
W1H029	Left Canal From Dam at Mhlatuze	-28.77250	31.46666
W1H030	Right Canal From Dam at Mhlatuze	-28.77250	31.46666
W3H017	Mkuze Marsh at Demezane Canal	-27.76666	32.50916
W4H012	Right Canal From Phongolo River at The Bokfont	-27.41972	31.51000
W4H014	Right Canal From Dam at Jozini	-27.41666	32.07166

Appendix B6

Names of natural lakes and Geo-location used in Longitudinal Assessment

Name of Impoundment	**Latitude °S**	**Longitude °E**	**Type of Impoundment**
Lake Msingazi	-28.75852	32.09890	Natural Lake
Lake St. Lucia	-28.05970	32.47819	Natural Lake
Nsezi	-28.74723	31.97411	Natural Lake
Richards Bay	-28.79684	32.06570	Natural Lake

Appendix C

Example of Calculation of Longitudinal Connectivity using the uMngeni River

Downstream Distance (Kilometre)	Distance Between Structures	Type of Barrier	Score	Cumulative Score	Quaternary Catchment	Recovery Distance	Revised Scored
14.144	7.84	Weir	0.3	0.3	U20C	25.03	0.3
21.984	8.176	Weir	0.3	0.6	U20C	25.03	0.6
30.16	5.44	Dam	1	1.6	U20C	25.03	1.6
35.6	0.176	Weir	0.3	1.9	U20E	27.79	1.9
35.776	13.44	Waterfall	0.1	2	U20E	27.79	2
49.216	10.88	Weir	0.3	2.3	U20E	27.79	2.3
60.096	0.944	Dam	1	3.3	U20E	27.79	3.3
61.04	0.752	Waterfall	0.1	3.4	U20G	26.31	3.4
61.792	55.536	Weir	0.3	3.7	U20G	26.31	0
117.328	1.712	Dam	1	4.7	U20G	26.31	1
119.04	10.976	Weir	0.3	5	U20G	26.31	1.3
130.016	18.4	Weir	0.3	5.3	U20L	12.05	0
148.416	0.656	Weir	0.3	5.6	U20L	12.05	0.3
149.072	6.48	Weir	0.3	5.9	U20L	12.05	0.6
155.552	12.8	Weir	0.3	6.2	U20L	12.05	0
168.352	16.192	Dam	1	7.2	U20M	22.28	1
184.544	15.68	Weir	0.3	7.5	U20M	22.28	1.3
200.224		Ocean					1.3

Appendix D

Longitudinal and Lateral Scores That Contributed to the Overall Spatial Connectivity of Rivers in Each Quaternary Catchment

QUATERNARY NAME	Longitudinal Connectivity (0-1)	Lateral connectivity (0-1)	Overall Spatial Connectivity (0-2)
T31B	0.00	0.38	0.38
T31C	0.00	0.12	0.12
T31D	0.00	0.27	0.27
T31E	0.00	0.37	0.37
T31F	0.00	0.65	0.65
T31G	0.00	0.12	0.12
T31J	0.04	0.17	0.21
T32A	0.00	0.29	0.29
T32B	0.00	0.19	0.19
T32C	0.00	0.25	0.25
T32D	0.04	0.20	0.24
T32E	0.00	0.13	0.13
T33A	0.00	0.24	0.24
T33D	0.00	0.06	0.06
T40C	0.00	0.26	0.26
T40D	0.04	0.17	0.21
T40E	0.00	0.28	0.28
T51C	0.00	0.41	0.41
T51F	0.05	0.29	0.34
T51H	0.00	0.16	0.16
T51J	0.00	0.19	0.19
T52A	0.01	0.39	0.41
T52C	0.00	0.26	0.26
T52D	0.05	0.45	0.51
T52J	0.00	0.10	0.10
T52M	0.00	0.24	0.24
U10A	0.00	0.06	0.06
U10B	0.00	0.08	0.08
U10D	0.00	0.27	0.27
U10E	0.00	0.33	0.33
U10F	0.04	0.35	0.39
U10G	0.00	0.56	0.56
U10H	0.08	0.42	0.50
U10J	0.12	0.32	0.44
U10K	0.00	0.55	0.55
U10L	0.00	0.31	0.31

U10M	0.16	0.34	0.50
U20B	0.00	1.00	1.00
U20C	0.21	0.81	1.02
U20D	0.00	0.69	0.69
U20E	0.55	0.69	1.24
U20F	0.00	0.72	0.72
U20G	0.67	0.65	1.32
U20H	0.13	0.34	0.47
U20J	0.33	0.67	1.01
U20K	0.00	0.51	0.51
U20L	0.83	0.42	1.25
U20M	1.00	0.56	1.56
U30A	0.08	0.45	0.53
U30B	0.21	0.50	0.71
U30C	0.00	0.40	0.40
U30D	0.04	0.56	0.60
U40B	0.00	0.76	0.76
U40D	0.00	0.38	0.38
U40E	0.00	0.40	0.40
U40F	0.00	0.57	0.57
U40G	0.00	0.28	0.28
U40H	0.00	0.34	0.34
U40J	0.20	0.52	0.72
U60B	0.03	0.66	0.69
U60C	0.25	0.90	1.15
U60D	0.29	0.51	0.81
U60E	0.00	0.48	0.48
U60F	0.00	0.48	0.48
U70A	0.00	0.42	0.42
U70B	0.00	0.71	0.71
U70C	0.00	0.51	0.51
U70D	0.00	0.33	0.33
U70F	0.00	0.59	0.59
U80B	0.00	0.41	0.41
U80C	0.00	0.32	0.32
U80F	0.04	0.37	0.41
U80J	0.00	0.41	0.41
U80K	0.04	0.41	0.45
V11B	0.00	0.08	0.08
V11C	0.04	0.15	0.19
V11D	0.12	0.18	0.30
V11E	0.13	0.07	0.20
V11G	0.05	0.09	0.14
V11H	0.04	0.11	0.15

V11J	0.60	0.48	1.08
V11L	0.65	0.67	1.32
V11M	0.00	0.14	0.14
V12A	0.00	0.17	0.17
V12B	0.00	0.16	0.16
V12C	0.00	0.25	0.25
V12E	0.00	0.20	0.20
V12F	0.00	0.44	0.44
V12G	0.11	0.53	0.63
V13C	0.00	0.17	0.17
V13D	0.08	0.44	0.52
V13E	0.00	0.46	0.46
V14A	0.00	0.32	0.32
V14B	0.76	0.14	0.90
V14D	0.00	0.26	0.26
V14E	0.00	0.15	0.15
V20D	0.08	0.69	0.77
V20E	0.11	0.46	0.56
V20G	0.15	0.67	0.82
V20H	0.19	0.60	0.79
V20J	0.23	0.37	0.60
V31A	0.00	0.16	0.16
V31B	0.17	0.23	0.40
V31C	0.00	0.19	0.19
V31D	0.23	0.25	0.47
V31E	0.13	0.44	0.57
V31G	0.21	0.25	0.47
V31K	0.25	0.22	0.47
V32B	0.27	0.27	0.54
V32C	0.31	0.29	0.60
V32D	0.35	0.21	0.55
V32E	0.39	0.70	1.09
V32F	0.00	0.62	0.62
V32H	0.00	0.46	0.46
V33A	0.43	0.76	1.19
V33B	0.00	0.55	0.55
V33C	0.00	0.44	0.44
V33D	0.00	0.48	0.48
V40A	0.00	0.53	0.53
V40B	0.00	0.32	0.32
V40C	0.00	0.49	0.49
V40D	0.00	0.31	0.31
V40E	0.00	0.32	0.32
V50A	0.00	0.24	0.24

V50B	0.00	0.23	0.23
V50C	0.00	0.45	0.45
V50D	0.08	0.33	0.41
V60B	0.00	0.55	0.55
V60C	0.00	0.36	0.36
V60E	0.04	0.60	0.64
V60F	0.00	0.54	0.54
V60G	0.84	0.31	1.15
V60H	0.88	0.57	1.45
V60J	0.00	0.41	0.41
V60K	0.00	0.44	0.44
V70A	0.01	0.04	0.05
V70C	0.09	0.12	0.21
V70E	0.27	0.13	0.40
V70F	0.00	0.29	0.29
V70G	0.00	0.45	0.45
W11A	0.04	0.48	0.52
W11B	0.00	0.41	0.41
W11C	0.08	0.24	0.32
W12A	0.00	0.46	0.46
W12B	0.00	0.31	0.31
W12C	0.01	0.36	0.38
W12D	0.17	0.37	0.54
W12E	0.29	0.17	0.46
W12F	0.55	0.21	0.75
W12H	0.05	0.20	0.26
W12J	0.00	0.20	0.20
W13A	0.00	0.30	0.30
W13B	0.00	0.23	0.23
W21A	0.13	0.37	0.51
W21B	0.17	0.37	0.54
W21D	0.00	0.45	0.45
W21E	0.00	0.63	0.63
W21F	0.00	0.38	0.38
W21G	0.21	0.56	0.78
W21H	0.00	0.54	0.54
W21J	0.00	0.56	0.56
W21K	0.04	0.50	0.54
W21L	0.08	0.20	0.28
W22A	0.12	0.37	0.49
W22B	0.00	0.35	0.35
W22C	0.20	0.30	0.50
W22E	0.00	0.36	0.36
W22F	0.24	0.55	0.79

W22G	0.28	0.61	0.89
W22H	0.00	0.50	0.50
W22J	0.32	0.38	0.70
W22K	0.07	0.27	0.34
W22L	0.36	0.15	0.51
W23A	0.00	0.23	0.23
W23B	0.00	0.12	0.12
W23C	0.00	0.10	0.10
W23D	0.48	0.19	0.67
W31B	0.08	0.32	0.40
W31D	0.16	0.35	0.51
W31E	0.20	0.40	0.60
W31F	0.25	0.61	0.86
W31G	0.31	0.44	0.75
W31H	0.48	0.48	0.96
W31K	0.00	0.58	0.58
W31L	0.00	0.13	0.13
W32A	0.00	0.15	0.15
W32B	0.20	0.12	0.32
W32C	0.00	0.55	0.55
W32D	0.00	0.14	0.14
W32E	0.17	0.22	0.39
W32G	0.00	0.26	0.26
W32H	0.32	0.17	0.49
W41B	0.00	0.33	0.33
W41D	0.00	0.32	0.32
W41E	0.21	0.32	0.53
W41F	0.00	0.26	0.26
W41G	0.00	0.24	0.24
W42B	0.00	0.38	0.38
W42D	0.00	0.42	0.42
W42E	0.00	0.41	0.41
W42G	0.00	0.29	0.29
W42H	0.00	0.26	0.26
W42J	0.00	0.41	0.41
W42L	0.00	0.33	0.33
W42M	0.00	0.44	0.44
W43F	0.00	0.12	0.12
W44A	0.04	0.42	0.46
W44B	0.16	0.39	0.55
W44C	0.00	0.49	0.49
W44D	0.20	0.35	0.55
W44E	0.00	0.25	0.25
W45A	0.33	0.11	0.45

W45B	0.45	0.08	0.54
W57J	0.00	0.16	0.16

Appendix E

Names of free-flowing and conditional free-flowing river segments, where "conditional" means impounded rivers with flow recovered to natural condition.

Free- flowing River Segments	Conditional free-flowing rivers segments
1. Bloed River	1. Bivane River
2. Bloukrans River	2. Black Mfolozi
3. Dorpspruit River	3. Boensmans River
4. Eland River	4. Mdloti River
5. Great Usutu River	5. White Mfolozi River
6. Hlazane River	6. Mkuze River
7. Hlimbitwa River	7. Mooi River
8. Hlonyane River	8. uMzimkhulu River
9. Ithalu River	9. Mzintlava River
10. Kinira River	10. Ngagane River
11. Krom River	11. Ngwangwane River
12. Lotheni River	12. Pongolo River
13. Mbokodweni River	13. Tongati River
14. Mfonos River	14. Tugela River
15. Mhlatuzana River	15. Wasbank River
16. Mlalazi River	
17. Mozana River	
18. Mpembeni River	
19. Mquke River	
20. Msunduzi River (North)	
21. Mvozana River	
22. Mvunyane River	
23. Mzinyashana River	
24. Mzumbe River	
25. Ngogo River	
26. Ngudwine River	
27. Nhlavini River	
28. Nkunzana River	
29. Nondweni River	
30. None Mavuya River	
31. Nseleni River	
32. Nsuze River	
33. Ntinini River	
34. Nwavuma River	
35. Nzinga River	
36. Riet River	
37. Sand River	
38. Sandspruit River	
39. Sikoto River	
40. Sikwebezi River	

41. Sitilo River 42. Spekboom River 43. Sterkspruit River 44. Sundays River 45. Toleni River 46. Tswereka River 47. Umngwenya River	

Appendix F

Family species occurrence at different RHP sites (geo-position given) of selected rivers, mean instantaneous temperature and ratio of sensitive to non-sensitive families.

RHP Site Code	River Basin	Sampling Date	Latitude °S	Longitude °E	Temp (°C)	A	B	C	D	E	F	G	Ratio
T3MZVB-JNSBR	uMzimkhulu	2010/07/22	-30.15797	29.11462	11.30	No	No	No	No	Yes	Yes	Yes	0:3
U1QUNU-NGB06	Mkomazi	2004/08/13	-30.01568	30.06088	08.90	Yes	No	Yes	Yes	Yes	No	Yes	3:2
U2KARK-DMB02	uMngeni	2003/07/17	-29.26060	30.18663	14.30	No	No	Yes	Yes	Yes	Yes	No	2:2
V1SITU-WTN02	Tugela	2003/07/03	-28.90352	29.39890	14.60	No	No	No	No	Yes	No	No	0:1
V2LITT-DSHLA	Mooi	2006/11/21	-29.23111	29.92556	22.00	No	No	No	No	Yes	No	No	0:1
V3SAND-CTSWL	Buffels	2011/11/02	-28.09882	30.31853	24.10	No	No	No	No	No	No	Yes	0:1
W1LENJ-NAT29	Mfolozi	2008/12/17	-27.86365	31.06208	20.80	No	No	No	No	Yes	No	No	0:1
W4TSAK-NAT25	Pongolo	2008/12/16	-27.44042	30.50351	17.70	No	No	No	No	Yes	No	No	0:1
U6MHLA-BOOTC	Mlazi	2008/04/08	-29.82420	30.77580	21.00	Yes	No	No	Yes	No	No	Yes	2:1

Legend (Sensitive Family in Bold)

A= Amphipoda B= Blephariceridae C= Notonemouridae D= Philopotamidae **E= Gyrinidae F = Heptageniidae G= Simulidae**