Assessment of the current ecological integrity of the uMngeni River, KwaZulu-Natal, South Africa, using fish community structures and attributes of the *Labeobarbus natalensis* (Castelnau, 1861) populations

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ABSTRACT

Rivers are the main source of freshwater water for human communities and provide people with numerous ecosystem services such as water purification, transportation, power generation, food supply, and water for domestic, agricultural and industrial use. Water resources, and the ecosystem services they provide, are particularly important in developing countries, such as South Africa. The uMngeni River, is a strategic resource that provides water to two of the largest cities in KwaZulu-Natal Province (the uMgungundlovu and eThekwini municipalities), with more than four million people, making it socio-economically important. As such, to maintain sustainability the protection of the river is important. However, in South Africa and KwaZulu-Natal, the impact of anthropogenic activities has made riverine ecosystems one of the most threatened types of ecosystems in the world. The use of fish as key indicators of the ecological state of aquatic ecosystems is well established as their vulnerability to environmental change, mobility, longevity and relative ease of species identification make them good indicators.

This study evaluated the current ecological integrity of the uMngeni River in KwaZulu-Natal using multiple lines of evidence including fish communities and the state of *Labeobarbus natalensis* (the KwaZulu-Natal yellowfish) populations, and environmental variables. The research was undertaken in the major man-made lakes (dams) in the uMngeni River (namely Midmar, Albert Falls, Nagle and Inanda Dams) and in the rivers of the uMngeni Catchment. Abiotic lines of evidence investigated included water quality and habitat, while the biotic lines of evidence included fish community structures and attributes of the population of *L. natalensis*.

Fish community structures at eight selected River Eco-status Monitoring Programme (REMP) sites in the uMngeni catchment were considered. This included consideration of how the fish communities responded to changes in a range of environmental variables and alien

fishes using the Fish Response Assessment Index (FRAI), we were able to determine that the ecological integrity of the uMngeni River decreases in a downstream gradient from the upper reaches of the catchment to lower reaches, due the synergistic effect of multiple anthropogenic stressors. The multivariate analyses indicated that the anthropogenic impacts responsible for shifts in fish community structures, and the associated ecological integrity of the river were related to changes in instream habitats and water quality stressors primarily. Most of the environmental changes identified can be linked to flow modifications and land use activities throughout the uMngeni catchment.

Assessments of attributes of the *L. natalensis* populations from large instream impoundments in the uMngeni River (namely Midmar, Albert Falls, Nagle and Inanda Dam) resulted in diminishing wellbeing of the populations of this endemic migratory fish progressively both in abundance and structure, down the length of the catchment. The quality and quantity of water diminished down the catchment gradient with this gradient and the effect of the barriers themselves can partially be attributed to the impaired state of the populations. Impoundments are not preferred by juvenile and young *L. natalensis* that prefer shallow riffle habitats that are lacking in dams, the occurrence of many predatory alien fishes in the dam can also be attributed to the absence of small yellowfish in the dams.

The outcomes of this study can contribute to the sustainable management and development of conservation plans for the rivers and dams in the uMngeni catchment. Major stressors that should be mitigated include the barrier effect and operation or flow releases from the large dams and smaller weirs etc. that cause river fragmentation in the catchment. It is recommended that management plans for the conservation of the fishes in the catchment should be developed which is achievable as the current supply of resources in the catchment is balanced with the demand for use. Fish passages should be established in all of the dams in the uMngeni River to allow migratory fish free passage along the river and to re-establish river connectivity processes. Additionally, the removal of redundant weirs or partial man-made barriers is recommended to alleviate the effects of fragmentation particularly on the yellowfish in the catchment. More research is required to understand the migratory requirements of fishes in the catchments and the cost-benefit of mitigating river fragmentation to achieve a sustainable balance between the use and protection of resources in the catchment. Finally, the study has identified water quality and flow stressors that are negatively affecting the wellbeing of the fish communities in the catchment. The water quality stressors derived from land-based activities and associated management of flows in the catchment must be improved to attain a sustainable balance between the use and protection of the resources of the uMngeni Catchment.

PREFACE

The data described in this thesis were collected in KwaZulu-Natal, Republic of South Africa from May 2017 to July 2018. Experimental work was carried out while registered at the School of Life Sciences, University of KwaZulu-Natal, Pietermaritzburg, under the supervision of Professor Colleen T. Downs and Dr Gordon O'Brien.

This thesis, submitted for the degree of Master of Science in the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, School of Life Sciences, Pietermaritzburg campus, represents original work by the author and has not otherwise been submitted in any form for any degree or diploma to any University. Where use has been made of the work of others, it is duly acknowledged in the text.

…………………………….
Pumla Vanessa Dlamini

November 2019

I certify that the above statement is correct and as the candidate's supervisor I have approved this thesis for submission.

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Professor Colleen T. Downs
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DECLARATION 1 - PLAGIARISM

I, Pumla Vanessa Dlamini, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

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DECLARATION 2 - PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this thesis.

Publication 1 (Formatted for submission to African Journal of Aquatic Sciences)

PV Dlamini, CT Downs, MJ Burnett & G O'Brien

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Author contributions:

PVD conceived paper with MJB, CTD and GO. PVD collected and analysed data and wrote the paper. MJB, CTD and GO contributed valuable comments to the manuscript.

Publication 2 (Formatted for submission to African Journal of Aquatic Sciences)

PV Dlamini, CT Downs, MJ Burnett & G O'Brien

Assessing the state of *Labeobarbus natalensis* (Castelnau, 1861) populations in impoundments along the uMngeni River, KwaZulu-Natal Province, South Africa

Author contributions:

PVD conceived paper with MJB, CTD and GO. PVD collected and analysed data and wrote the paper. MJB, CTD and GO contributed valuable comments to the manuscript.

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CHAPTER 1:

Introduction

1.1 Importance of rivers

Water is considered by many to be earth's most vital natural resource and it is made even more precious by its scarcity (Vörösmarty et al. 2010; Kanyerere et al. 2018). Although 71% of the earth's surface is covered by water, freshwater makes up only 2.5% of all water on earth (USGS 2019). Furthermore, less than 1% of freshwater is available for human use as most of it is locked up in polar ice caps (Geise et al. 2010; USGS 2019). The main source of the freshwater water accessible for human use comes from rivers, which also provide numerous ecosystem services (Costanza et al. 1997; Yeakley et al. 2016). Ecosystem services provided by rivers include water purification, transportation, power generation, food supply, and water supply (for domestic, agricultural and industrial use) (Tejerina-Garro et al. 2005; Yeakley et al. 2016). Unfortunately, despite their value to us, riverine ecosystems are one of the most endangered ecosystems in the world, as a result of human activities (Tejerina-Garro et al. 2005; Dudgeon 2014; Rodell et al. 2018; Du Plessis 2019).

With an ever-growing human population worldwide, there is also an increase in urbanisation to accommodate the growing numbers (Wigginton et al. 2016; UN WUP 2018). The South African urban population, in particular, has grown from 7.8 million in 1960 to 38.3 million in 2018 (UN WUP 2018). This results in increased demand for land, agriculture, and infrastructure, thus putting a strain on the country's natural resources (Giannecchini et al. 2007; Hsu et al. 2013; Jewitt et al. 2015; Fouchy et al. 2018). The strain of increased urban populations in South Africa has had great impacts on aquatic habitats and ecosystems through physical disturbance of aquatic systems and physicochemical pollution from urban development such as mining, infrastructure and dam construction, which alters flow regimes (Sibanda et al. 2015; Jewitt et al. 2015; Fouchy et al. 2018; O'Brien et al. 2019). Drastic land use changes have transformed more than 50% of land cover in most provinces and led to over 57% of all rivers in South Africa being in a threatened or unsustainable ecological state (Jewitt et al. 2015; O'Brien et al. 2019). Rural land use, such as agriculture and rangelands, also impact habitats through water consumption and deforestation (Jewitt et al. 2015). In Africa, irrigated agriculture, as well as domestic and municipal water use, are responsible for the most water consumption (Fouchy et al. 2018).

1.2 Importance of river connectivity

When a river can flow freely it allows for the movement and exchange of water, organisms, sediments, organic matter, nutrients and energy throughout the river system (Grill et al. 2019). Flow modification by humans is one of the greatest threats to freshwater ecosystems and has altered natural river connectivity so intensively that only about a third of the world's large rivers (>1000 km in length) remain free-flowing (Dugan et al. 2010; Grill et al. 2019). The construction of impoundments (dams and/ weirs) causes a disturbance in natural aquatic systems by altering sedimentation processes, flooding, channelisation and temperature regulations (Dugan et al. 2010; Hall et al. 2011; McIntyre et al. 2016; Grill et al. 2019). Additionally, by interrupting migration pathways of migratory fish between spawning and feeding sites, natural nutrient processes are also affected by dams (Hall et al. 2011; Gao et al. 2019; Fouchy et al. 2018). There is still much debate as to whether the benefits of dams outweigh the negative impacts dams can have on river systems (Joyce 1997; Altinbilek 2002; Kuby et al. 2005; Rufin et al. 2019; Schulz and Adams 2019).

1.3 Importance of dams for water security

Despite their detriment to riverine ecosystems, dams have become very important because of the services they provide such as water supply, irrigation, flood control and the production of hydropower in anthropogenically modified landscapes (ICOLD 2016). Water storage is often crucial in developing countries, such as South Africa, as it guarantees water supply, especially during droughts (ICOLD 2016). This makes water security a vital component in promoting sustainable economic and social development (Steyn et al. 2019). South Africa's dry climate and uneven distribution of water resources have driven both the government and the private sector to build large dams and implement irrigation and inter-basin transfer scheme projects (Steyn et al. 2019).

1.4 Environmental monitoring

The social and economic value of water resources, coupled with its scarcity, makes it very important for regularly monitoring of the wellbeing of waterways, especially when subjected to anthropogenic ills (Kleynhans 2003; Rodríguez-Romero et al. 2018). Information gathered from environmental monitoring can be used for environmental regulation and management purposes (Meybeck and Helmer 1996; Baldwin 2019). When monitoring the environment and its ecosystems, one has to systematically sample various lines of evidence as ecosystems are sensitive to a host of stressors (Reece and Richardson 1999; Artiola et al. 2004; Burns and Wiersma 2004; Wepener et al. 2011; Myers-Smith 2019). Multiple lines of evidence can be used to measure the integrity of an aquatic ecosystem (or any other ecosystem) and these include both abiotic (e.g. air, water, soil, etc.) and biotic (e.g. microorganisms, invertebrates, and vertebrates) lines of evidence (Todd and Roux 2000; Weston 2011; Nõges et al. 2016).

1.5 Abiotic indicators

1.5.1 Water quality (physicochemical characteristics)

Water quality is the term used to describe the chemical, physical, biological and aesthetic properties of water, all of which are influenced by elements that are either dissolved or suspended in the water (DWAF 1996b; Boyd 2015; Mandal et al. 2019). Knowing the water quality of a system is useful when protecting the integrity of the ecosystem and can be used to determine a system's fitness for various uses (Canter 1985/2018; DWAF 1996b; Dallas and Day 2004; Boyd 2015; Heibati et al. 2017; Abbasnia et al. 2019; Chen et al. 2019; Mandal et al. 2019). Water quality is monitored by measuring the core variables which include system variables (temperature, dissolved oxygen, salts, pH and turbidity), nutrients (phosphate, nitrite and nitrate), toxic substances and non-toxic inorganic substances (total dissolved solids and electrical conductivity) (Canter 1985/2018; DWAF 1996a; 1996b; Dallas and Day 2004; Palmer et al. 2005; Boyd 2015; Abbasnia et al. 2019).

Urbanisation and land-use changes (such as agriculture) can significantly alter water quality, deteriorating the integrity of a riverine ecosystem (Johnson and Dawson 2005; Dabrowski et al. 2015; Sibanda et al. 2015; Sharpley 2016; Selemani et al. 2018). Changes in water quality can affect biotic indicators, such as fish, and so monitoring changes in water quality can play an important role in maintaining ecosystem integrity (DWAF 1996b; Bilotta and Brazier 2008; O'Brien et al. 2009; Li et al. 2010; Ramesh et al. 2018). Poor water quality conditions can also lead to an increase in invasive species, which are often more tolerant of deteriorated and polluted waters (Bunn and Arthington 2002; Dudgeon 2014; Gao et al. 2019).

1.5.2 Habitat

Although river modifications mostly result in water abstraction and deteriorated water quality, they can also cause physical alterations in aquatic habitats (Kleynhans 1999). This is important as one of the most determining factors in the survival of organisms in an ecosystem is the quality and availability of habitat (Hubert and Bergersen 1999; O'Brien et al. 2009; Venter 2013; O'Brien et al. 2014, Ramesh et al. 2018). The importance of habitat in the survival of biota makes it an important factor to consider when managing fishes and the ecosystems in which they occur as well as when assessing the ecological integrity of a riverine system (Mangold 2001; O'Brien et al. 2013; Burnett et al. 2018; Ramesh et al. 2018). For fish, habitat can be defined as the physical and chemical features that individuals, population or communities require to survive (Hubert and Bergersen 1999). Different habitats are distinguishable from one other by their physical, chemical and biological properties, not excluding basic life requirements of food, water and cover/shelter (Bain and Stevenson 1999). River habitat consists of three components: substrate type (silt, mud, sand, gravel, cobbles, boulders and bedrock), cover type (undercutting- banks, roots, marginal vegetation, overhanging vegetation, depth and substrate) and flow type (still marginal, deep pool, shallow pool, deep glide, shallow glide, run, riffle and rapids/torrent) (Kleynhans 2007; Malherbe 2008).

1.6 Biotic indicators

1.6.1 Fish

Fish have often been used to as key indicators when assessing the ecological state of aquatic ecosystems (Karr 1981; Barbour et al. 1999; Maceda-Veiga and De Sostoa 2011; Burnett et al. 2018; Ramesh et al. 2018). However, studies that only look at a single level of biological organisation may not always provide sufficient information for a thorough evaluation of ecological impact, hence why it has become widely accepted to use different levels of organisation (Clements 2000; Van der Oost et al. 2003; Richardson et al. 2011; Murphy et al. 2013; Rohr et al. 2016; 2017; Valesini et al. 2017; Murphy et al. 2018). The stress responses in organisms can be observed at different levels of biological organisation, from sub-cellular to organism, population, community and eventually at the ecosystem level (Munkittrick and McCarthy 1995; Adams and Greeley 2000; Murphy et al. 2013; Rohr et al. 2016; Murphy et al. 2018). Lower levels of biological organisation respond more rapidly to stressors and so give a better understanding of cause-and-effect pathways, while the higher-level responses highlight broader ecological implications of environmental and anthropogenic stressors (Valesini et al. 2017).

1.6.2 Fish communities

The ability to sustain a balanced biotic community is one of the best indicators of a healthy aquatic ecosystem (Karr 1981). Fish communities are very useful when assessing the biotic integrity of an aquatic ecosystem as they are relatively easy to identify, incorporate both species composition and abundance (unlike single species studies that only focus on abundance), can be linked to the effects of stress and toxicity and are usually present in even the smallest streams (Karr 1981; Jowett and Richardson 2003). There are, however, some disadvantages associated with using fish as indicators of ecological integrity such as their high tolerance to environmental change (including habitat degradation) and pollution and bias nature of sampling methods because of time constraints (Whitfield and Elliott 2002; Harrison and Whitfield 2004; Cabral et al. 2012; Gamito et al. 2012; Rohr et al. 2016). However, the advantages of using fish as indicators outweigh these disadvantages (Harrison and Whitfield 2004; Cabral et al. 2012; Gamito et al. 2012; Rohr et al. 2016).

Fish communities can be defined or classified in numerous ways depending on the aims of the study, the characteristics of the fish community that the study focuses on and the type of quantitative analysis that is used (Jackson et al. 2001). One of the methods used to classify fish community (and other species communities) is multivariate statistical approaches.

Multivariate statistics not only summarise and predict community patterns, but they also provide an objective approach in identifying fish assemblages and the impact that environmental conditions have on them (Jackson et al. 2001; O'Brien et al. 2009; Wepener et al. 2011; Dempsey 2019). Another approach to studying riverine fish communities is by using the Fish Response Assessment Index (FRAI) (Kleynhans 1999 2007; Wepener et al. 2011; Venter 2013; Levin et al. 2019).

The FRAI is regularly used to determine the wellbeing of fish communities in Southern African freshwater ecosystems by assessing the response of fish assemblages to changes in environmental conditions (Kleynhans 2007; Wepener et al. 2011; Venter 2013; Zdanow et al. 2014; Levin et al. 2019). Habitat integrity and water quality are usually the environmental variables used when using the FRAI (and similar indices) and multivariate statistics to assess fish community changes in an ecosystem (Dickens and Graham 2002; Thirion 2007; Kleynhans 2007: Venter 2013; Levin et al. 2019). The FRAI uses information from these environmental variables, together with a database of the intolerance and preference ratings for a variety of southern African freshwater species, to determine changes in fish assemblages from the natural state and the underlying reasons for these changes (Kleynhans 1999, 2003, 2007; Levin et al. 2019). Metric categories assessed in FRAI include habitat availability (velocity-depth classes), flow modification, migration, cover, physico-chemical metric and introduced species (Kleynhans et al. 2005; Kleynhans 2007; Venter 2013; Levin et al. 2019).

1.6.3 Fish populations (*Labeobarbus natalensis,* Castelnau, 1861)

The KwaZulu-Natal yellowfish, *Labeobarbus natalensis* forms part of the Cyprinidae family and is one of seven different yellowfish species (*Labeobarbus* spp.) in South Africa (Skelton 2001; Impson et al. 2008). It is endemic to KwaZulu-Natal and is widely distributed, occurring in all major catchments from the Mtamvuna River (Eastern Cape border) to the Mkuze River in the north. It is the most widespread of the yellowfish species (and possibly freshwater fish species) in KwaZulu-Natal Province (Karssing 2007). *Labeobarbus natalensis* can be found in a range of different habitats but prefer habitats in the middle reaches of rivers that have a combination of deep pools and fast-flowing rapids and riffles and is especially selective when spawning (Karssing 2007; Jacobs 2017).

Labeobarbus natalensis spawn in fast-flowing riffles (high oxygen content) over a gravel and cobble substrate and mature breeding adults, sub-adults, and juveniles migrate seasonally (spring and early summer) upstream in search of suitable spawning and feeding sites (Karssing 2007). *Labeobarbus natalensis* migrate in search of silt-free (gravel) spawning as the larvae are unable to burrow in silt-covered gravel and thus would be susceptible to predation or displacement (Wright and Coke 1975a; 1975b). However, impenetrable barriers (such as dams) impede migration, especially into the upper reaches (Wright and Coke 1975a; Karssing 2007).

Despite the relatively tolerant nature of *L. natalensis*, it is still vulnerable to anthropogenic impacts associated with anthropogenic land use change including urbanisation such as habitat change, chronic pollution, siltation, and increased water abstraction (Karssing 2007). Instream dams and weirs throughout KwaZulu-Natal Province have slowed down floods that would otherwise wash away silt, particularly silt that has formed as a result of erosion from poor agricultural practices (Karssing 2007). Dams also trap sediment from naturally turbid water, releasing a discharge that is relatively clear (Poff et al. 1997; Hall et al. 2011; Hohensinner et al. 2018), making the fish downstream more vulnerable to predation (Figueiredo et al. 2016).

In addition to the aforementioned threats, *L. natalensis* is also vulnerable to illegal netting, particularly at spawning grounds, as well as hybridisation with translocated Orange-Vaal smallmouth yellowfish (*Labeobarbus aeneus*) in the upper Thukela catchment (Karssing

2007; Swartz 2008). As noted by Karssing (2007), inter-basin water transfers and direct stocking for angling purposes may result in intraspecific hybridisation with genetically distinct *L. natalensis* from different river systems. There is now some genetic evidence (though limited) of intraspecific hybridisation between *L. natalensis* populations in the Thukela and uMngeni catchments (Stobie et al. 2018). Another source of concern is the increasing threat by alien fish, such as largemouth bass (*Micropterus salmoides*) and common carp (*Cyprinus carpio*), on native fish like *L. natalensis*. Likewise, extralimital species, such as the *L. aenues*, compete directly with *L. natalensis* for food and habitat and prey on *L. natalensis* juveniles (Koehn 2004; Karssing 2007; Swartz 2008).

Labeobarbus natalensis is currently regarded as least concern (Cambray et al. 2017), however, the species may be in decline because of the continual pressure placed on the aquatic environment and fragmentation of the population because of barriers (both chemical and physical barriers) (Skelton 2001; Karssing 2007). Karssing (2007) recommends regular surveys in order to monitor the state of the *L. natalensis*, particularly in areas where they are most vulnerable, such as the uMngeni River (Stobie et al. 2018).

1.7 The River Eco-Status Monitoring Programme

The River Eco-Status Monitoring Programme (REMP) has evolved from, and replaced, the River Health Programme (RHP) in 2016 and forms part of the National Aquatic Ecosystem Health Monitoring Programme (NAEHMP) (DWS 2016). The REMP was developed by the Department of Water and Sanitation, (DWS) South Africa, and focuses on monitoring the ecological condition of river ecosystems by characterising the response of instream and riparian biota to abiotic drivers of a system (Dallas 2000; DWS 2016). The REMP uses FRAI and other similar indices to produce an overall measure of the ecological integrity of a river as a whole. Similar to the RHP, the rationale of REMP is that by measuring the integrity of biota in a river ecosystem, we are provided with a direct measure of the health of the river ecosystem as a whole (Dallas 2000; WRC 2002).

1.8 Study area: The uMngeni River

The uMngeni River is one of the major rivers in the KwaZulu-Natal Province (Van der Zel 1975; Agunbiade and Moodley 2014). The uMngeni River catchment originates at the uMngeni Vlei wetland, a protected conservation area, flowing 225 km from source to mouth, emptying into the Indian Ocean at the Blue Lagoon (WRC 2002; Matongo et al. 2015). The Msunduzi River is a major tributary of the uMngeni River and smaller tributaries include the Lions River, Karkloof River, Mpolweni Stream, and Palmiet River. The uMngeni catchment also has several large dams which were constructed for water supply, namely Nagle Dam (constructed in 1948), Midmar Dam (1965), Albert Falls Dam (1976) and Inanda Dam (1989) (Agunbiade and Moodley 2014; Matongo et al. 2015; Hay 2017).

The uMngeni catchment area is 4 440 km^2 with a mean annual rainfall of ~674 million cubic meters and supports South Africa's third-largest regional economy, the Durban–Pietermaritzburg urban area (Hay 2017; Sutherland and Mazeka 2019). According to the eThekwini Municipality IDP (2017), the region has an estimated population of 3.81 million people in 2019. The uMgungundlovu Municipality has a population of just over 1 million people (uMgungundlovu District Municipality IDP 2017) and so the uMngeni catchment supports ~4.8 million people. Water demand in the uMngeni catchment has exceeded the river's supply and has had to be supplemented by the Mooi River transfer scheme which transfers water to supplement Midmar Dam (Snaddon et al. 1999; WRC 2002; Markowitz 2016; Meissner et al. 2019). One of greatest impacts on the uMngeni catchment is anthropogenic land-use transformation with 17% of natural vegetation being reduced in the upper uMngeni catchment (Namugize et al. 2018) and as much as 50% of land in the uMgungundlovu municipality has been transformed for agricultural, industrial, commercial and residential use (Hay 2017). Other issues affecting this catchment include alien invasive plants, increased nutrient loads from agricultural activity, and pollution (WRC 2002; Lin et al. 2012; Van Deventer 2012; Mahlobo 2016; Hay 2017; Namugize et al. 2018; Namugize and Jewitt 2018). Although the uMngeni River system is highly productive, it is also under a lot of strain from numerous anthropogenic impacts, thus presenting an opportunity to study and monitor this river system. The outcomes of such studies help to enforce management strategies that establish a balance between water resource use and riverine ecosystem protection.

1.9 Hypothesis and predictions

We hypothesised that fish communities in the uMngeni River and *L. natalensis* populations in dams along the river act as ecological indicators, responding to environmental change (abiotic drivers), namely changes in habitat and water quality. We predicted that 1) the uMngeni River would generally be in a poor state, largely because of the anthropogenic activities prevalent in and around the river, and 2) the wellbeing of *L. natalensis* populations in the major uMngeni dams would be compromised as a result of migratory barriers and a lack of habitat diversity.

1.10 Aims and objectives

The first aim of this study was to determine the present ecological integrity of fish communities in the uMngeni River in KwaZulu-Natal, using multiple lines of evidence. The second aim was to update the state of *L. natalensis* wellbeing in the major uMngeni River dams considering river fragmentation caused by the dams. To achieve these aims, the following objectives were established:

1) Characterise fish community structures at eight selected River Eco-status Monitoring Programme (REMP) sites on the uMngeni River using the Fish Response Assessment Index (FRAI).
2) Determine shifts in fish community structures and environmental drivers of change in these communities using multivariate analysis techniques.
3) Survey *L. natalensis* population structures Midmar Dam, Albert Falls Dam, Nagle Dam, and Inanda Dam and update the state of *L. natalensis* populations in KwaZulu-Natal.

1.11 Study layout

This thesis is structured with stand-alone chapters; each of the data chapters are written in a manuscript format with the intention of submission to an international peer reviewed journal. The chapters are as follows:

Chapter 1: Literature review

Chapter 2: Assessment of the current ecological integrity and fish community structures of the uMngeni River, KwaZulu-Natal, South Africa.

Chapter 3: Assessing the state of *Labeobarbus natalensis* (Castelnau, 1861) populations in impoundments along the uMngeni River, KwaZulu-Natal Province, South Africa

Chapter 4: Conclusions

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CHAPTER 2:

Assessment of the current ecological integrity and fish community structures of the uMngeni River, KwaZulu-Natal, South Africa

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Running header: Current ecological integrity and fish community structures

2.1 Abstract

Providing water to two of the largest cities in KwaZulu-Natal Province, South Africa, means that the uMngeni River is of great economic importance. As such, protecting the river and the life within it is also of great importance. In this study, fish community structure was used as an indicator of ecosystem health by assessing how fish communities responded to changes in habitat composition and water quality as a consequence of anthropogenic activity using the Fish Response Assessment Index (FRAI). Multivariate statistical analyses were used to determine differences in fish communities and drivers of change in these communities. The results of this study showed that the ecological integrity of the uMngeni River (and its tributaries) tended to degrade from upper to lower reaches in response to various anthropogenic activities. Deterioration in sites along the uMngeni River was a result of various anthropogenic activities ranging from flow modification and migration barriers from dams and weirs, the introduction of invasive species and water quality alterations from rural and urban settlements. Multivariate analyses showed that variation among the sites selected in this study was significantly driven by changes in velocity-depth classes, substrate type, and water quality, all of which can be influenced by flow modifications.

Keywords: Ecological integrity, fish community, FRAI, multivariate analysis, anthropogenic

2.2 Introduction

Freshwater makes up just 2.5% of all water on earth, and of that less than 1% is available for human use as most freshwater is contained in polar ice caps (Geise 2010). Most of the freshwater water available for human use comes from rivers, which also provide a plethora of other ecosystem services on which they rely (Costanza et al. 1997; Yeakley et al. 2016). River anthropogenic services include water purification, transportation, power generation, food supply, and water supply (for domestic, agricultural and industrial use) (Tejerina-Garro et al. 2005; Yeakley et al. 2016). Unfortunately, riverine ecosystems are one of the most intensively affected by anthropogenic activities (Tejerina-Garro et al. 2005; Dudgeon 2014). In South Africa particularly, increased urbanisation and industrialisation have caused increasing deterioration of the water quality of most river systems (Sibanda et al. 2015), the effects of which have only been exacerbated by water storage reservoirs and human use (Ashton 2007; Ashton 2010; Wepener and Chapman 2012; Fouchy et al. 2018).

The pressures and demands of a growing economy and human population, such as South Africa's, have great impacts on riverine habitat structure, natural flow regimes, water quality and fish diversity (Saunders et al. 2002; Vidal 2008; Fouchy et al. 2018; O'Brien et al. 2019). The introduction of invasive species also has detrimental effects on ecosystem health and biodiversity of its rivers (Vander Zanden 1999; Rahel 2000; Gao et al. 2019). This has resulted in, sometimes, drastic reductions of certain species (Ashton 2010). The severity of the impact of anthropogenic activities on rivers makes the assessment of the state and health of these ecosystems of upmost importance. There are various ways to assess ecosystem health, including environmental components (abiotic) and the use of different biological organisms (biotic), at various levels of biological organisation (Richardson et al. 2011; Fouchy et al. 2018). The levels of biological organisation that can be used range from the molecular level all the way to the community level (Richardson et al. 2011; Wepener and Chapman 2012).

The ability to sustain a balanced biotic community is one of the best indicators of a healthy aquatic ecosystem (Karr 1981; O'Brien et al. 2014). Fish communities are considered extremely useful when assessing the biotic integrity of an aquatic ecosystem as they are relatively easy to identify, include an array of species (representing a range of trophic levels), are sensitive to water quality and are usually present in even the smallest streams (Karr 1981; Wepener et al. 2011; O'Brien et al. 2019). Additionally, fish, in general, are good environmental indicators as they are widely distributed in aquatic systems and have a relatively long-life span (DWAF 1999; Gamito et al.,2012; O'Brien et al. 2011; Levin et al. 2019). There are, however, some disadvantages associated with using fish as indicators of ecological integrity such as their high tolerance to environmental change (including habitat degradation) and pollution and the bias nature of sampling methods (Whitfield and Elliott 2002; Harrison and Whitfield 2004; Cabral et al. 2012; Gamito et al. 2012; Collins et al. 2017). However, the advantages of using fish as indicators outweigh these disadvantages (Harrison and Whitfield 2004; Cabral et al. 2012; Gamito et al. 2012; O'Brien et al. 2019).

Fish communities can be defined or classified in numerous ways depending on the aims of the study, the characteristics of fish community that the study focuses on and the type of quantitative analysis that is used (Jackson et al. 2001; Dempsey 2019). One of the methods used to classify fish community (and other species communities) is multivariate statistical approaches (O'Brien et al. 2009; Wepener et al. 2011). Multivariate statistics not only summarise and predict community patterns, but they also provide an objective approach in identifying fish assemblages and the impact that environmental conditions have on them (Taylor et al. 1993; Magnuson et al. 1998; Jackson et al. 2001; Wepener et al. 2011). Another approach to studying riverine fish communities is by using the Fish Response Assessment Index (FRAI) (Kleynhans 1999).

The FRAI is used to routinely determine the wellbeing of fish communities in southern African freshwater ecosystems by assessing the response of fish communities to changes in environmental conditions (Kleynhans 2007; Zdanow et al. 2014; Levin et al. 2019). The environmental conditions in question normally include water quality and habitat integrity (Kleynhans 2007; Levin et al. 2019). The uMngeni River, KwaZulu-Natal, South Africa, is one of the most socio-economically important rivers in the region but is under great anthropogenic pressure (WRC 2002; Ramulifho 2015; Namugize et al. 2018).

The aim of our study was to assess the current ecological integrity of fish communities in the uMngeni River using FRAI and multivariate statistical techniques. We predicted that the uMngeni River would generally be in a poor state, largely because of the anthropogenic activities prevalent in and around the river. In this study, we evaluated the current ecological integrity and fish community structures of the uMngeni River using multiple lines of evidence including community metric measures (FRAI) and multivariate statistical analyses of differences in fish communities and drivers of changes in these communities.

2.3 Methods

2.3.1 Study area

The uMngeni catchment, in KwaZulu-Natal, area is 4 440 km^2 with a mean annual rainfall of 921 mm (UW 2016; Hughes et al. 2018). It is a summer rainfall region, ranging from an alpine-type climate in and along the Drakensberg Mountains, to a more temperate summer rain climate of the Midlands region and subtropical perennial rainfall area along the coast (UW 2016). Mean annual ambient temperatures range between 14 and 22°C and the catchment is generally characterised by grassland, with areas of thicket and bushland and forest patches, although a lot of this area has been cultivated (UW 2016; Hughes et al. 2018). The study area for this study comprised of eight sites in the uMngeni catchment and included sites on the uMngeni (including tributaries) and Msunduzi Rivers (Fig. 2.1). The sites selection coincides with sites used in the National River Eco-Status Monitoring Programme (REMP).

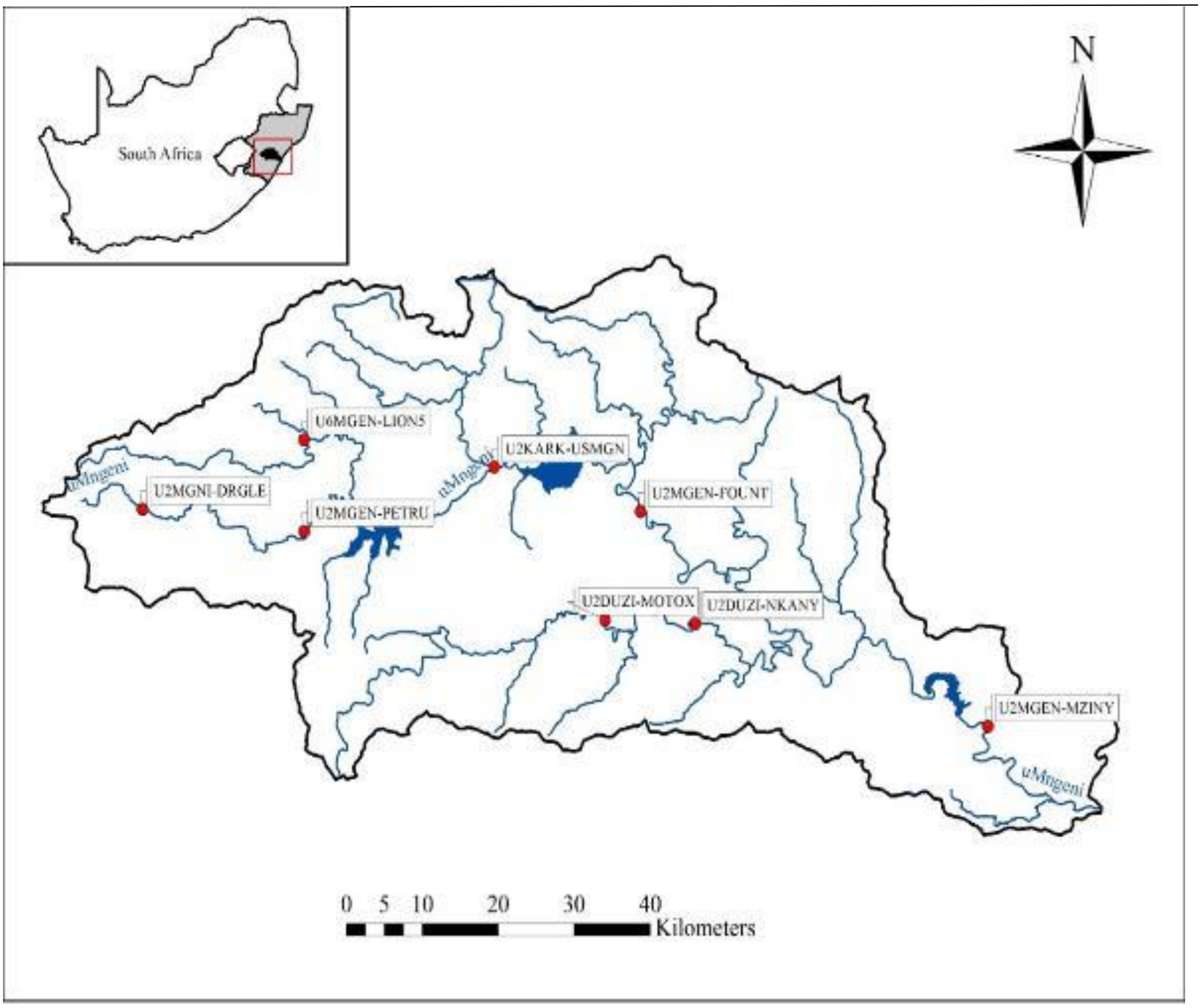

Fig. 2.1: Map of sampling sites on the uMngeni River, KwaZulu-Natal Province, South Africa, in the present study. Site coordinates are presented in the Supplementary Table S1.

2.3.1.1 U2MGNI-DRGLE

Situated about 30 km from Midmar Dam, this sampling site was in the area of Dargle Valley in the KwaZulu-Natal Midlands (Fig. 2.1, Supplementary information Fig. S2.1a). The area surrounding this site is comprised mainly of pastoral grasslands and some forests (including indigenous forests and exotic timber plantations). The trees lining the riverbank at this site include the invasive black wattle (*Acacia mearnsii*), which were later cut down during the study. The entire area of Dargle Valley is a conservancy (Dargle Conservancy).

2.3.1.2 U2MGEN-PETRU

The sampling site U2MGEN-PETRU was in the Howick area (Fig. 2.1, Supplementary information Fig. S2.1b). The site is situated in an agricultural area and is directly (about 50 m) below a weir. Impacts of agricultural activity may occur at this site (pers. obs.).

2.3.1.3 U2MGEN-LIONS

The sampling site U2MGEN-LIONS was in Caversham Valley, near Howick (Fig. 2.1, Supplementary information Fig. S2.1c). The site location is surrounded by agriculture, exotic timber plantations and a few scattered residential areas (including Caversham Mill restaurant). A waterfall and arch bridge are less than 300 m upstream of the site.

2.3.1.4 U2KARK-USMGN

The U2KARK-USMGN site was located at the base of the Karkloof River, right before it joins the uMngeni River (Fig. 2.1, Supplementary information Fig. S2.1d). There are numerous bridge crossings and a weir within about 3.5 km upstream of this site. The site is surrounded by agricultural land, exotic timber plantations, and savannah.

2.3.1.5 U2MGEN-FOUNT

This sampling site was in Fountainhill Estate in the Midlands, outside Wartburg (Fig. 2.1, Supplementary information Fig. S2.1e). Fountainhill Estate forms part of a conservancy (Central Umgeni Conservancy) and is mostly surrounded by a mix of bush and grassland, though there is also some agricultural activity in the area. Site U2MGEN-FOUNT is also about 20 km below Albert Falls Dam. Impacts from flow regulation may be present at this site (pers. obs.).

2.3.1.6 U2DUZI-MOTOX

Sampling site U2DUZI-MOTOX was on the Msunduzi River which flows through the urban area of Pietermaritzburg and is generally littered with anthropogenic waste (pers. obs.) Wartburg (Fig. 2.1, Supplementary information Fig. S2.1f). The site is less than 2 km below Darvill Wastewater Treatment Works and about 12 km below Camps Drift. This site is also about 36 km downstream of Henley Dam. There is also sugarcane agricultural activity in the surrounding area. There may be impacts at this site associated with the pollution from surrounding urbanised area as well as flow modifications.

2.3.1.7 U2DUZI-NKANY

Sampling site U2DUZI-NKANY was also on the Msunduzi River in the rural area of Nkanyezini (Fig. 2.1, Supplementary information Fig. S2.1g). The site is often used by the local community for sand mining and watering their cattle. There is also an *Eichhornia crassipes* (water hyacinth) presence at this site. This site is generally impacted negatively by sand mining, cattle presence and the invasion of *E. crassipes* (pers. obs.).

2.3.1.8 U2MGEN-MZINY

Sampling site U2MGEN-MZINY was located within the township of iNanda (Fig. 2.1, Supplementary information Fig. S2.1h). The site is just less than 5 km below the iNanda Dam wall. The area surrounding the site is predominately township settlements as well as natural forest. This site may possibly be impacted by modified flow caused by the dam and runoff from the surrounding human settlements (pers. obs.).

2.3.2 Field sampling

Fish communities were sampled from all eight riverine sites also used within the National River Eco-Status Monitoring Programme (REMP) in the uMngeni and Msunduzi Rivers, KwaZulu-

Natal (Fig. 2.1). Fish were collected using electro-fishing techniques and active and passive netting techniques (Meador et al. 1993; Barbour et al. 1999; Rodtka et al. 2015). Netting techniques included the use of a 6 m long, 1.5 m deep seine net with a bag that was pulled through both shallow (< 1 m) and deep (> 1 m) habitats. The habitats that were sampled according to established REMP velocity depth categories including: include slow (< 0.3 m/s) deep (> 0.5 m) and shallow (> 0.5 m), fast (> 0.3 m/s) deep (> 0.3 m) and shallow (< 0.3 m) (James and King 2010). All available substrate and cover features including marginal and aquatic vegetation, undercut banks and root wads were sampled. Fish were measured (SL) and identified on-site using Skelton (2001) and returned to the river alive. Fish samples were collected between May and November 2017 and surveys comprised of two high flow seasons and one low flow season.

2.3.3 Water physico-chemical characteristics (Water quality)

Physico-chemical characteristics were measured *in situ* at each site concurrent with fish sampling. Water quality was measured using a calibrated Eutech PCD 650 multimeter (EUTECH Instruments Ltd, Singapore) and the variables measured include oxygen concentration and saturation, temperature, pH, electrical conductivity and total dissolved solids (TDS). Water clarity was also measured using a clarity tube (Kilroy and Biggs 2002)

During each fish survey, sub-surface water samples were collected for laboratory analyses. Water samples were collected in clean polyethylene plastic bottles, making sure that there were no air bubbles in the sample. Samples included a 2L bottle (or 1L x 2) for water quality analyses and a 500 ml bottle for microbial analyses. Once collected the water samples were refrigerated at 4^{o}C (not frozen) until they were delivered to Umgeni Water's Laboratory (Pietermaritzburg, South Africa) for analyses. The following variables were analysed: System variables (chemical oxygen demand (COD); electrical conductivity (mS/m); alkalinity

($CaCO_3$); turbidity (ntu)); salts (Chlorides (Cl); Sulphates (SO_4); Calcium (Ca); Sodium (Na)); nutrients (Nitrates (NO_3); Nitrite (NO_2); Phosphorus (SRP and TP)); toxicants (Ammonia (NH_3)) ; microbial (Coliforms; *Escherichia coli*; heterotrophic plate count (HPC 37)); Chlorophyll a and Fluorine (F).

2.3.4 Habitat

Habitat condition and availability were assessed using a visual scoring system that considers the relative availability of and scores the suitability of substrate, cover and flow biotope types and (O'Brien et al. 2012). Velocity-depth was measured using a transparent velocity head rod (Fonstad et al. 2005). The substrate available was categorised into different types, namely bedrock, boulders, cobbles, gravel, sand, mud and silt (Kleynhans 1999). Habitat parameters also included cover which comprised of undercut banks, root wads, marginal vegetation, overhanging vegetation, aquatic vegetation, substrate, depth/column (Kleynhans 1999) and woody debris.

2.3.5 Fish response assessment index (FRAI)

The FRAI is an assessment of the effect of environmental changes on fish communities to determine the wellbeing of said fish communities (Kleynhans 2007; Avenant 2010; Wepener et al. 2011). The index is specific to southern African freshwater ecosystems (Kleynhans 2007). The environmental variables used in FRAI and other similar indices usually include habitat integrity and water quality (Dickens and Graham 2002; Thirion 2007), together with a database of the intolerance and preference ratings for a variety of southern African freshwater species (Kleynhans 1999, 2003). The metrics that are assessed in FRAI are categories of these preferences and intolerances (Kleynhans and Louw 2007). The following metric categories assessed in FRAI (Kleynhans et al. 2005; Kleynhans 2007) include: habitat availability (velocity-depth classes); flow modification (volume, timing and flow duration); migration; cover (undercut banks; overhanging vegetation; aquatic vegetation; water column (depth); substrate; root wads); physicochemical metric (water quality); and introduced species.

Assessing the response of fish species to changing environmental conditions can either be done through direct measurement (surveys) or inferred from changing environmental conditions (habitat) (Kleynhans 2007). In this study the assessment was conducted via direct measurement – fish sampling. In FRAI, ecological responses are interpreted by linking changes in environmental conditions (drivers) to fish stress (Kleynhans 2007). The index is based on a combination of fish sample data and fish habitat data in which the response of fish species to habitat changes is assessed based on knowledge of each fish species' ecological requirements (preferences and intolerances) (Kleynhans 2007). The FRAI assessment of the ecological integrity state of fish communities that were sampled is represented in the form of ecological categories (Table 2.1; Kleynhans 2007).

Table 2.1: FRAI ecological category (EC) descriptions (Source: Kleynhans 2007)

Ecological Categories	Name	Description	Acceptable/ Unacceptable	Score (%)
A	Natural	Unmodified natural	Acceptable	90 - 100
B	Good	Mostly natural with few modifications	Acceptable	80 - 89
C	Fair	Moderately modified	Acceptable	60 - 79
D	Poor	Largely modified	Unacceptable	40 - 59
E	Seriously modified	Seriously modified	Unacceptable	20 - 39
F	Critically modified	Critically or extremely modified	Unacceptable	0 - 19

The FRAI results are in the form of both an automatic and adjusted score. The automatic score is based solely on the differences in frequency of occurrence (FROC) between expected and observed fish species at each specific site (Kleynhans 2007), however it does not account for habitat (velocity-depth, cover, flow modification, and physico-chemical) and sampling effort and hence there is an adjusted score which can be manually altered to accommodate the variations in these factors. Manually adjusting the FRAI score allows the user to evaluate the state of environmental drivers according to each site's habitat availability and sampling effort.

2.3.6 Multivariate statistical analyses

The use of multivariate statistical analyses techniques to evaluate biological communities in different ecosystems is common (Ter Braak 1994; O'Brien et al. 2009; Wepener et al. 2011) and in this study multivariate statistics were used to evaluate the response of fish assemblages to driving environmental variables (driver components), which included water quality and habitat. To analyse the data collected, a principal component analysis (PCA) approach (using CANOCO for Windows Version 4.53) was used. The PCA is based on a linear response model relating species and environmental variables (van den Brink et al. 2003). The outcomes of the analysis (ordination) are represented as two-dimensional maps of the samples, where the placements of the samples indicate the (dis)similarities between samples (O'Brien et al. 2009). In the case of this study, the samples in question are fish community samples based on the diversity and abundance of communities observed.

In addition to the PCA, various redundancy analyses (RDAs - a derivative of PCAs) were conducted to determine which species or environmental variables likely had the greatest influence on the structure or groupings reflected in the PCA. To do this, the fish species and environmental variables (water quality and habitat) were overlaid onto the original PCA. With the use of Canoco for Windows Version 4.53 (Ter Braak and Smilauer 2004), the RDA allows for the selection of the driving variables which are then overlaid onto the PCA (O'Brien et al. 2009).

The RDA analyses use best-fit values (rather than the original data) which have been estimated from a multiple linear regression between each variable in turn and a second matrix of complementary biological or environmental data (O'Brien et al. 2009). The outcome of the RDA is interpreted through two-dimensional bi-plots that indicate the similarities or dissimilarities between the samples (Shaw 2003; Van den Brink et al. 2003; O'Brien et al. 2009).

In the tri-plots that contain the overlaid environmental and species data, each arrow represents an environmental variable and points in the direction of the steepest increase of values for the corresponding variable. The angles between arrows indicate the sign (+ or -) of the correlation between the variables; the approximated correlation is positive when the angle is less than 90° and negative when the angle is larger than 90° (O'Brien et al. 2009). The distance between the sampling sites in the diagram approximates the (dis)similarity of the variables as measured by their Euclidean distance (Shaw 2003). Species data were transformed using a $LogX^2$ transformation (because abundance data were available) (Van den Brink et al. 2003).

2.4 Results

A total of 14 fish species were collected over the duration of this study (which consisted of three assessments of eight REMP sites and a total of 160 efforts). This resulted in a total abundance of 295 fish of which *Labeobarbus natalensis* was most common (n = 87), followed by *Pseudocrenilabrus philander* (n = 46) and *Tilapia sparrmanii* (n = 43). These three most common fish were collected 75%, 50% and 63% of sites, respectively. Uncommon species included *Amphilius natalensis* (n = 6), *Awaous aeneofuscus* (n = 5), *Clarias gariepinus* (n =

2), *Enteromius anoplus* (n = 1), *Enteromius viviparus* (n = 1) and the invasive species *Oncorhynchus mykiss* (n = 1) (Table 2.2). The other invasive species collected in this study was *Micropterus salmoides* (n = 27). Translocated indigenous species were also collected at U2MGEN-LIONS and U2KARK-USMGN (Table 2.2).

Table 2.2: Summary of fish species caught in the uMngeni River in the present study (May. August and November 2017) and their abbreviations. Translocated indigenous species are written in bold.

Species name	Abbr.	U2MGNI-DRGLE	U2MGEN-PETRU	U2MGEN-LIONS	U2KARK-USMGN	U2MGEN-FOUNT	U2DUZI-MOTOX	U2DUZI-NKANY	U2MGEN-MZINY	Species abundance
Labeobarbus natalensis	LNAT	0	5	0	11	21	5	44	1	87
Pseudocrenilabrus philander	PPHI	0	0	0	0	1	2	4	39	46
Oreochromis mossambicus	OMOS	0	0	0	10	0	0	0	3	13
Coptodon rendalli	CREN	0	0	**1**	1	0	0	8	5	15
Enteromius pallidus	EPAL	0	0	**2**	**26**	0	0	0	0	28
Tilapia sparrmanii	TSPA	0	0	**10**	13	3	13	4	0	43
Enteromius gurneyi	EGUR	0	0	0	20	0	0	0	0	20
Amphilius natalensis	ANAT	0	0	0	4	2	0	0	0	6
Micropterus salmoides	MSAL	0	0	23	0	0	0	2	2	27
Oncorhynchus mykiss	OMYK	1	0	0	0	0	0	0	0	1
Enteromius anoplus	EANO	0	0	0	1	0	0	0	0	1
Awaous aeneofuscus	AAEN	0	0	0	0	0	0	0	5	5
Clarias gariepinus	CGAR	0	0	0	0	1	0	0	1	2
Enteromius viviparus	EVIV	0	0	0	**1**	0	0	0	0	1
Abundance		1	5	36	87	28	20	62	56	
Diversity		1	1	4	9	5	3	5	7	

2.4.1 Fish Response Assessment Index (FRAI)

The assessment of the ecological integrity of fish assemblages using adjusted FRAI scores indicated a general downward trend from source/upper catchment to mouth/lower catchment, with FRAI Ecological Categories (ECs) ranging from moderately modified (C) to largely/severely modified (D/E) (Table 2.3).

U2MGNI-DRGLE

Indigenous species *Anguilla mossambica, A. natalensis, E. anoplus* and *L. natalensis* were expected in this region, according to the site's reference species in Present Ecological State, Ecological Importance & Ecological Sensitivity (PESEIS) (DWS 2014a). However, none of the reference species for site U2MGNI-DRGLE were ever caught and instead a single *O. mykiss* was caught in the November 2017 (high flow) survey. The EC score at this site was C (moderately modified). The metric groups with the most weights in this site were the impact of introduced species, migration, and flow modification, indicating that they had the most influence on fish assemblages at this site (see Table 2.4).

U2MGEN-PETRU

According to the PESEIS reference species, the indigenous species *A. mossambica A. natalensis, E. anoplus* and *L. natalensis* are naturally occurring and expected in U2MGEN-PETRU (Skelton 2001; DWS 2014a). In the present study, however, only a single *L. natalensis* was caught in the May 2017 (high flow) survey. The adjusted EC score for this site was C (moderately modified). The metric groups with the most weights in this site were velocity-depth classes, flow-modification, and migration.

U2MGEN-LIONS

None of the expected reference species were caught in site U2MGEN-LIONS, but instead quite a few invasive *M. salmoides* (more than any other site) and several translocated indigenous fish species (*T. sparrmanii*, *E. pallidus* and *C. rendalli*) were caught over the course of this study. The outcome of the fish assemblage assessment (FRAI) in the U2MGEN-LIONS site indicated that this site was largely modified (EC score was D). The top three metric groups identified to have the greatest impact on fish assemblage at this site were the impact of introduced species, flow modification, and migration.

U2KARK-USMGN

Based on the outcome of the fish assemblage assessment (FRAI), the site U2KARK-USMGN was moderately modified (ecological category C). Seven out of ten reference species (DWS 2014a) were caught at this site (although the frequency of occurrence was lower than the reference) as well as two indigenous translocated species, namely *E. pallidus* and *E. viviparus*, making this site the richest in both diversity and abundance over the course of this study (see Table 2.2). The fish assemblage assessment indicated that velocity-depth classes, flow modification, and physico-chemical characteristics (water quality) were the main drivers of change in fish community at this site.

U2MGEN-FOUNT

There were fifteen expected reference species at the U2MGEN-FOUNT site and of these, five species were caught over the duration of this study. Sampled fish species include *A. natalensis*, *L. natalensis*, *C. gariepinus*, *P. philander*, and *T. sparrmanii* and all species had a low frequency of occurrence. No invasive or translocated species were caught at this site and the

FRAI assessment indicated that the site was moderately/largely modified (EC score was C/D). According to the FRAI assessment, velocity-depth classes, flow modification, and physico-chemical characteristics were the metric groups with the most weight at this site, and hence the biggest drivers of change in fish community structure.

U2DUZI-MOTOX

The fish assemblage assessment (FRAI) of U2DUZI-MOTOX indicated that this site was largely modified (EC score was D). Of the thirteen reference species that were expected at this site, only three (*L. natalensis*, *P. philander*, and *T. sparrmanii*) were sampled, and at lower frequencies of occurrence than the reference. Metric weights in the FRAI assessment indicated that velocity-depth classes, flow modification, and physico-chemical characteristics had the most significant influence on changes in fish community structure in this site.

U2DUZI-NKANY

There were thirteen expected reference at this site, five of which were sampled over the course of this study. Sampled species include *L. natalensis*, *P. philander*, *C. rendalli*, *T. sparrmanii* and the invasive species *M. salmoides*. Based on the outcome of the FRAI assessment of site U2DUZI-NKANY, this site was largely modified (EC score D) and metric weights indicated that flow modification, velocity-depth classes, and physico-chemical characteristics were the main drivers of change in fish community structure at this site.

U2MGEN-MZINY

Site U2MGEN-MZINY was the farthest down the uMngeni River and has the greatest number of expected reference species. There were 26 expected reference species at this site (DWS

2014a) and only seven of these were sampled (at low frequencies of occurrence) throughout the duration of the study, one of which is the invasive *M. salmoides*. Several of the reference fish that were not sampled inhabit both estuaries and freshwaters (Skelton 2001). The FRAI assessment of fish communities revealed that this site was largely modified (EC score D), the May 2017 survey even indicated it to be seriously modified (EC score E). Metric weights at this site indicated that migration, flow modification, and velocity-depth classes had the most significant influence on changes in fish community structure at this site.

Table 2.3: Adjusted FRAI scores and Ecological Categories of uMngeni River REMP sites

	May		Aug		Nov	
Site name	**FRAI Score**	**EC**	**FRAI Score**	**EC**	**FRAI Score**	**EC**
U2MGNI-DRGLE	74.3	C	75.6	C	69	C
U2MGEN-PETRU	62.3	C	69.5	C	69.7	C
U2MGEN-LIONS	48.3	D	46.9	D	48.7	D
U2KARK-USMGN	-	-	70.4	C	69.6	C
U2MGEN-FOUNT	61.1	C/D	53.4	D	-	-
U2DUZI-MOTOX	-	-	47.6	D	43.4	D
U2DUZI-NKANY	54.0	D	44.1	D	40.3	D/E
U2MGEN-MZINY	37.2	E	44.1	D	44.0	D

Table 2.4: Weights of metric groups used in FRAI in the present study.

Metric group weights (%)	Velocity-depth	Cover	Flow modification	Physico-chemical	Migration	Impact of introduced
U2MGNI-DRGLE	75.00	73.44	76.56	68.75	81.25	100.00
U2MGEN-PETRU	100.00	71.93	94.74	85.96	94.74	64.91
U2MGEN-LIONS	81.67	68.33	98.33	55.00	90.00	100.00
U2KARK-USMGN	100.00	78.57	100.00	89.29	78.57	82.14
U2MGEN-FOUNT	100.00	78.57	100.00	92.86	82.14	75.00
U2DUZI-MOTOX	100.00	75.00	100.00	89.29	85.71	78.57
U2DUZI-NKANY	100.00	77.78	100.00	92.59	88.89	88.89
U2MGEN-MZINY	92.86	78.57	96.43	78.57	100.00	82.14

Table 2.5: Water physico-chemical characteristics (water quality) of the uMngeni River sites sampled in the present study (May, August and November 2017).

	Temperature (°C)	pH	DO (Mg/l)	DO (%)	Conductivity (mS/m)	Clarity (cm)	Turbidity (ntu)	Alkalinity (mg CaCO3/L)	Cl (mg Cl/L)	NO2 (mg N/L)	NO3 (mg N/L)	SO4 (mg SO4/L)	Ca (mg Ca/L)	Chlorophyll a (µg/L)	COD (mg O2/L)	Coliforms (MPN/100mL)	E.coli (MPN/100mL)	F (µg F/L)	HPC 37 (cfu/mL)	Na (mg Na/L)	NH3 (mg N/L)	SRP (ug P/L)	TP (ug P/L)
HF-NOV-U2MGEN-MZINY	22.7	8.10	7.8	90.6	33.4	75	2.1	74	42	0.1	0.49	22	14	1.5	20	1414	2	163	1000	36	0.1	5	15
HF-NOV-U6DUZI-MOTOX	19.6	7.37	8.18	89.4	42.7	55	3.2	100	50	0.1	1.04	34	20	4.1	20	2250	69	100	1000	40	7.3	335	460
HF-NOV-U2DUZI-NKANY	22.3	8.25	8.03	91.3	38.6	29	9.1	69	47	9.1	7.12	35	19	35	20	2420	147	100	1000	39	0.98	241	350
HF-NOV-U2MGEN-DRGLE	15.1	7.33	8.67	86.2	5.01	88	0.9	19	2.7	0.1	0.33	2	3.8	1	20	179	12	100	292	3.1	0.1	5	15
HF-NOV-U2MGEN-LIONS	19	7.17	8.15	87.8	13.2	54	7.5	48	8.3	0.1	0.42	2.1	9.1	0.1	20	613	7	100	228	7.8	0.1	7.21	24.1
HF-NOV-U2KARK-USMGN	19.7	7.33	8.02	87.6	9.5	49	6.8	35	5.3	0.1	0.42	3.1	6.3	0.3	20	2420	117	100	1000	5.5	0.1	5	16.5
HF-NOV-U2MGEN-PETRU	18.7	6.0	8.23	88.3	6.46	76	4.5	26	3	0.1	0.19	1.9	5	0.7	20	4352	1233	100	1000	4.2	0.1	5	20
LF-AUG-U2MGEN-PETRU	13.8	7.26	7.99	76	7.14	90	2.5	30	3	0.1	0.18	1.6	4.8	0.4	20	261	101	100	55	2.9	0.1	5	20
LF-AUG-U2MGEN-DRGLE	9.8	7.62	8.26	75	4	90	0.5	21	2.6	0.1	0.35	1.2	3.9	0.3	20	157	9	100	46	2.3	0.1	5	24.1
LF-AUG-U2MGEN-FOUNT	17	7.21	7.55	-	8.7	36	34	31	9.2	0.1	0.38	5.5	4.4	1.7	20	2420	219	100	1000	5.9	0.1	12.6	62.3
LF-AUG-U2DUZI-MOTOX	16.5	7.3	7.5	-	40.2	60	3.2	116	49.6	0.1	1	37	22	4	20	2420	72	100	1000	45	8.09	354	472
LF-AUG-U2KARK-USMGN	13.6	7.12	7.95	77	8	65	6.2	38	6.1	0.1	0.29	2.1	5.6	1.3	20	308	36	100	1000	4.1	0.1	5	35.6
LF-AUG-U2MGEN-LIONS	12.5	7.43	7.82	77	9.1	65	4.9	45	7.6	0.1	0.23	1.7	8	0.3	20	411	7	100	1000	6.2	0.1	5	27.6
LF-AUG-U2DUZI-NKANY	14.1	6.93	7.96	-	36.3	50	9.2	70	47	0.1	7.03	36	20	35	20	2420	138	100	1000	39	0.89	241	350

LF-AUG-U2MGEN-MZINY	19.4	7.89	7.95	86	25.7	95	1.6	70	36	0.1	0.83	17	19	1.5	20	387	15	149	1000	40	0.1	8.02	33.8
HF-MAY-U2MGEN-PETRU	16.1	6.94	8.7	-	5.95	88	4.2	25	2.8	0.1	0.1	1	5.3	0.8	20	579	83	100	269	5	0.1	5	111
HF-MAY-U2DUZI-NKANY	20.5	6.93	7.23	85	30.7	21	38	58	31	0.34	4.94	15	23	2.6	20	24196	763	100	1000	29	0.45	208	373
HF-MAY-U2MGEN-MZINY	20.8	7.1	9.74	101	190	80	2	37	0.1	0.22	15.4	14	0.6	20	1300	39	29.4	155	32.3	0.1	5	23	1.7
HF-MAY-U2MGEN-LIONS	12.2	6.46	8.08	-	8.436	53	17	181	6.7	0.1	0.46	1	5.9	0.7	20	4839	775	100	318	7.5	0.1	17.2	32.1
HF-MAY-U2MGEN-DRGLE	9.3	6.05	8	-	3.945	44	12	11	3.8	0.1	0.12	1.1	2.7	0.2	20	4839	1034	100	1000	4	0.1	5.49	57.3
HF-MAY-U2MGEN-FOUNT	15	6.74	7.96	91	10.93	29	20	32	8.9	0.1	0.2	5.3	7.4	2.1	25	4839	300	100	421	11	0.1	21.1	82.5

Table 2.6: Overall (average) habitat features of the uMngeni River sites sampled in the present study (May, August and November 2017).

	Depth			**Velocity**			**Substrate**								**Cover**									
	Average depth (mm)	**Min depth (mm)**	**Max depth (mm)**	**Average velocity (m/s)**	**Min velocity (m/s)**	**Max velocity (m/s)**	**Silt (%)**	**Mud (%)**	**Sand (%)**	**Gravel (%)**	**Cobble (%)**	**Boulder (%)**	**Bedrock (%)**	**Other (%)**	**Undercut bank (%)**	**Roots (%)**	**Marginal veg (%)**	**Overhanginh veg (%)**	**Substrate (%)**	**Column (%)**	**Debris (%)**	**Aquatic veg (%)**	**Other (%)**
HF-NOV-U2MGEN-MZINY	312.0	236	358	0.23	0.07	0.33	6	2	16	4	0	46	13	13	0	0	38	0	38	16	0	0	8
HF-NOV-U2DUZI-MOTOX	329.6	257.1	284.3	0.13	0.05	0.20	7.86	2.86	0	0	0	0	85	4.29	7.14	11.43	20	14.29	15.71	12.86	11.43	0	7.14
HF-NOV-U2DUZI-NKANY	365.0	258	462	0.4	0.3	0.4	2	20	3	1	24	50	0	0	0	0	20	0	41	28	3	8	0
HF-NOV-U2MGEN-DRGLE	312.3	263	351	0.3	0.2	0.4	12	11	9.6	0	11	43	14	0	8.3	0	0	5.83	40	15	25	0	5.8
HF-NOV-U2MGEN-LIONS	270.4	187	340	0.3	0.3	0.4	13	0	0	0	7.5	18	61	0	6.7	0	28	11.7	30.8	20.8	1.67	0	0
HF-NOV-U2KARK-USMGN	526.6	391	684	0	0	0.1	0	16	14	0	0	69	0	0	0	1.25	28	0	37.5	34.4	1.25	0	0
HF-NOV-U2MGEN-PETRU	685.0	540	848	0.1	-0	0.2	15	34	0	0	1.3	50	0	0	0	0	18	0	36.3	46.3	0	0	0
LF-AUG-U2MGEN-PETRU	464.3	356	556	0.2	0.1	0.2	0	0	1.4	5.7	2.9	37	53	0	0	0	0	0	64.3	34.3	1.43	0	0

LF-AUG-U2MGEN-DRGLE	393	333	468	0.2	0.1	0.3	0	6.3	16	13	8.1	51	5	0	3.8	3.75	0	1.25	53.8	2.5	35	0	0
LF-AUG-U2MGEN-FOUNT	407	332	483	0.3	0.2	0.3	0	17	0	10	3.3	30	40	0	0	0	37	0	21.7	28.3	13.3	0	0
LF-AUG-U2DUZI-MOTOX	290	213	383	0.2	0.1	0.3	0	2.2	0.6	0.6	0	11	86	0	0	0	28	5.56	0	44.4	0	0	22
LF-AUG-U2KARK-USMGN	433	357	512	0.1	0.1	0.1	0	27	0.5	4	0	69	0	0	3	0	16	0	46.5	29	6	0	0
LF-AUG-U2MGEN-LIONS	524	421	614	0	-0	0.1	14	19	0	0	2.7	52	13	0	0	0	12	0	45.9	41.8	0	0	0
LF-AUG-U2DUZI-NKANY	302	219	376	0.4	0.2	0.5	1	2	6	28	47	16	0	0	0	0	0	0	59.5	24.5	0	16	0
LF-AUG-U2MGEN-MZINY	408	327	493	0.2	0.1	0.3	6	22	14	1	9	37	11	0.7	0	0	27	0	35.7	35.7	0	1.3	0
HF-MAY-U2MGEN-PETRU	464	405	505	-	0	-	0	0	0	2.5	5	45	48	0	0	0	0	0	70	27.5	2.5	0	0
HF-MAY-U2DUZI-NKANY	275	136	410	0.5	0.3	0.6	0	0	6	28	57	9	0	0	0	0	14	1	52	33	0	0	0
HF-MAY-U2MGEN-MZINY	416	329	494	0.3	0.2	0.4	14	7.5	19	0	2.5	30	24	3.8	0	0	26	0	58.8	12.5	0	0	2.5
HF-MAY-U2MGEN-LIONS	359	293	460	0.2	0.2	0.3	0	2.5	0	7.5	39	50	0	1.3	0	0	28	11.3	46.3	17.5	0	0	0
HF-MAY-U2MGEN-DRGLE	542	473	655	0.6	0.4	0.7	0	10	0	1.3	7.5	79	0	2.5	5	0	1.3	8.75	36.3	48.8	0	0	0
HF-MAY-U2MGEN-FOUNT	351	246	453	0.4	0.3	0.6	0	0	0	5	5.7	86	3.6	0	0	0	5.7	0	66.4	27.9	0	0	0

Results of the application of the FRAI approach include a deteriorating trend in the state of the fish communities of the Umgeni River downstream. This trend decreased from a moderately modified fish community observed in the upper reaches of the catchment associated with water quality and flow stressors because of land use changes, and alien invasive species that compete with and predate on indigenous species. The ecological integrity state of the fishes deteriorates to a largely modied "D" state and on occasion in the Msunduzi River the ecological integrity of the fish community has deteriorated to an unststainable Severely Modified "D/E" and "E" state. This deterioration was representative of excessive changes to the water quality, flows and habitats of the rivers associated with land use changes. Indicator species identified through the application of FRAI that were expected to be more common in the catchment included the five *Enteromius spp*. in particular. All of these fish species have a high preference for good water quality which appears to be a major contributor to the deteriorated state of the FRAI scores.

2.4.2 Multivariate statistical analyses

2.4.2.1 Fish communities based on site

Redundancy analyses (RDA) of intersite community comparisons related to environmental variables including water quality, quantity (flow) and habitat (Tables 2.5 and 2.6). Fish community structures at the various sites sampled in this study were generally significantly unique ($p = 0.0010$, Fig. 2.2). A total of 65.5% of the total variation of data were presented in this ordination, with 39% of the variation on the first axis and 26.5% on the second axis (Fig. 2.2). The only sites whose community structures were similar to one another were U2MGEN-PETRU and U2MGEN-MZINY ($p = 0.062$) as well as U2DUZI-NKANY and U2MGEN-FOUNT ($p = 0.903$, Fig. 2.2). Site U2KARK-USMGN had the greatest species diversity followed by U2MGEN-MZINY which had a completely different fish assemblage. Invasive species *M. salmoides* (MSAL), and *O. mykiss* (OMYK) were closely associated with U2MGEN-LIONS and U2MGNI-DRGLE, respectively. *Labeobarbus natalensis* (LNAT) was associated with three (out of eight) sites in this study, namely, U2KARK-USMGN, U2DUZI-NKANY and U2MGEN-FOUNT. *Tilapia sparrmanii* (TSPA) was also associated with three sites; U2MGEN-LIONS, U2KARK-USMGN and U2DUZI-MOTOX.

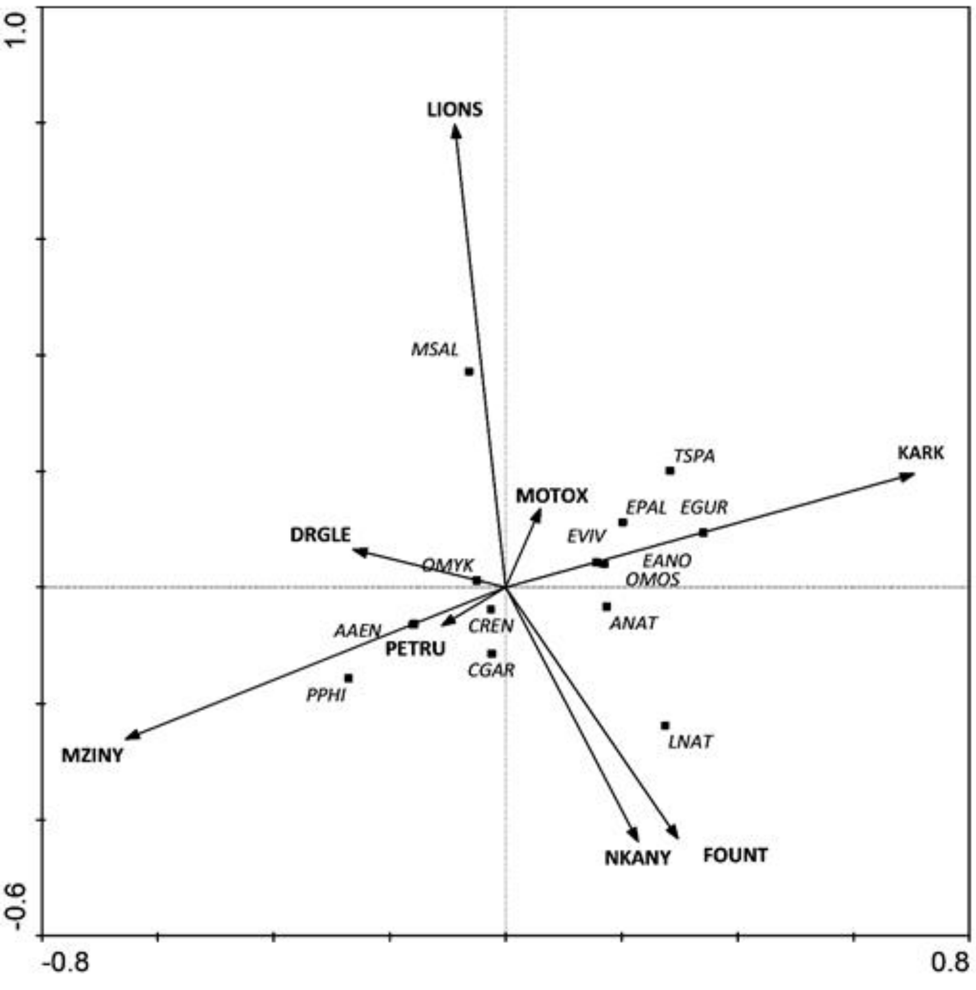

Fig. 2.2: Redundancy analysis tri-plot of fish species and sites showing dissimilarity among sites (arrows) in the uMngeni River in the present study. The fish species (squares) were overlaid onto the RDA to show potential driving variables. (Abbreviations as per Table 2.2).

2.4.2.2 Fish communities based on seasonal river flow (High flow vs. Low flow)

The results comparing fish community structures in high and low flow seasons indicated that fish community structures during the two flow seasons were significantly different in the uMngeni River in the present study (p = 0.0220, Fig. 2.3) and thus, flow had a significant influence on fish assemblages in this study. 100% of the variation of data were presented in this ordination, all of which was on the first axis (Fig. 2.3). Fish species that were associated with flow seasons include *E. viviparus* (EVIV), *T. sparrmanii* (TSPA), *E. gurneyi* (EGUR) and *M. salmoides* (MSAL), while *E. anoplus* (EANO), *E. pallidus* (EPAL), *O. mossambicus* (OMOS), *C. rendalli* (CREN), *A. aeneofuscus* (AAEN) and *O. mykiss* (OMYK) were associated with high flow seasons. Species that were not necessarily related to either season included *L. natalensis* (LNAT), *P. philander* (PPHI), *C. gariepinus* (CGAR) and *A. natalensis* (ANAT). though the high flow season had slightly greater species diversity (Fig. 2.3).

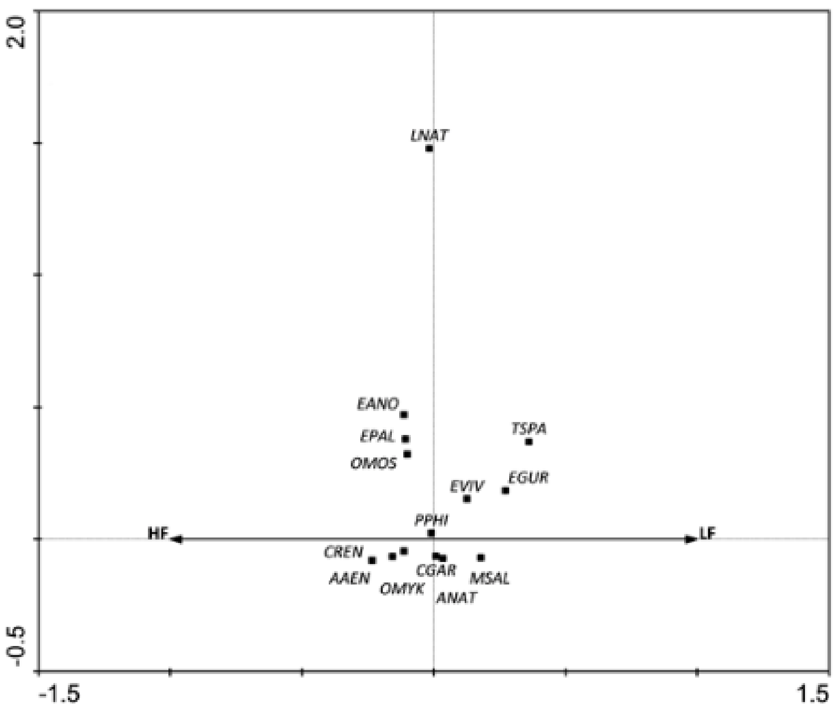

Fig. 2.3: Redundancy analysis tri-plot of fish species. sites and flow showing dissimilarity between high and low flows (arrows) uMngeni River in the present study. The fish species

(squares) and sites (triangles) were overlaid onto the RDA to show potential driving variables. (Abbreviations as per Table 2.2).

2.4.2.3 Fish communities based on velocity and depth

Velocity-depth was found to have a significant influence on fish community structure in the uMngeni River in the present study (p = 0.0090; Fig. 2.4). In this ordination 76% of the variation within the data were presented, with 48% of the variation on the first axis and 28% on the second (Fig. 2.4). Mean velocity (X (m/s)) accounted for the greatest variation (F = 4.15, p = 0.001). Maximum depth (Max (mm); F = 2.19, p = 0.047) and minimum depth (Min (mm); F = 3.60, p = 0.004), were also significant drivers of fish community structures in this study. Although some of the individual variables, namely minimum and maximum velocity and average depth, did not have a significant influence on fish community structure, there was a clear distinction between fish species that were more associated with depth variables and those that were more associated with velocity variables.

In this study, water depth was associated with species *M. salmoides* (MSAL), *T. sparrmanii* (TSPA), *O. mykiss* (OMYK), *E. gurneyi* (EGUR), *E. pallidus* (EPAL), *E. viviparus* (EVIV), *E. anoplus* (EANO), *A. natalensis* (ANAT) and *O. mossambicus* (OMOS) and sites U2MGEN-LIONS, U2KARK-USMGN and U2DUZI-MOTOX. Velocity was associated with species *A. natalensis* (ANAT), *E. anoplus* (EANO), *C. gariepinus* (CGAR), *A. aeneofuscus* (AAEN), and *C. rendalli* (CREN) and especially had a relatively strong positive correlation with *L. natalensis* (LNAT) and sites U2DUZI-NKANY and U2MGEN-FOUNT.

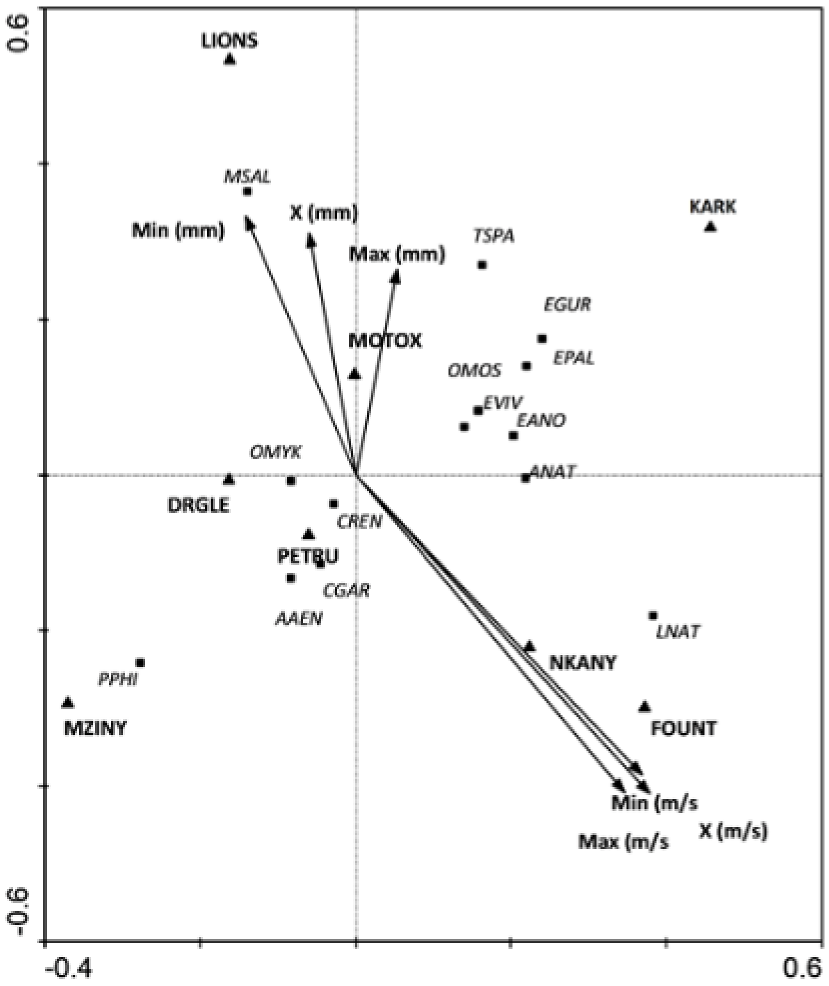

Fig. 2.4: Redundancy analysis tri-plot of fish species, sites and velocity-depth showing dissimilarity between velocity and depth variables (arrows) in the uMngeni River in the present study. The fish species (squares) and sites (triangles) were overlaid onto the RDA to show potential driving variables. (Note: Min (mm) is minimum depth. Max (mm) is maximum depth. X (mm) is average depth. Min (m/s) is minimum velocity. Max (m/s) is maximum velocity and X (m/s) is average velocity). (Other abbreviations as per Table 2.2)

2.4.2.4 Fish communities based on substrate type

Statistical comparisons between fish communities and substrates found substrate to be a significant driver of fish community structures in the uMngeni River in the present study ($p = 0.0380$, Fig. 2.5). In this ordination 70.4% of the variation within the data were presented, with

49.5% of the variation on the first axis and 20.9% on the second axis (Fig. 2.5). Of all the substrate types, silt accounted for the greatest variation in fish community structure ($F = 5.16$, $p = 0.003$) followed by mud ($F = 2.76$, $p = 0.017$) and cobbles ($F = 2.15$, $p = 0.046$).

Awaous aeneofuscus (AAEN), *P. philander* (PPHI) and sites U2MGNI-DRGLE and U2MGEN-MZINY were closely associated with silt, while other associations with silt included *C. gariepinus* (CGAR), *C. rendalli* (CREN), *M. salmoides* (MSAL) and sites U2MGEN-PETRU and U2MGEN-LIONS. Site U2MGEN-LIONS, *M. salmoides* (MSAL) and *O. mykiss* (OMYK) were closely associated with mud. Also associated with mud substrate was site U2DUZI-MOTOX and species *O. mossambicus* (OMOS), *E. pallidus* (EPAL), and *T. sparrmanii* (TSPA). Cobble substrate was strongly associated with *L. natalensis* (LNAT), *A. natalensis* (ANAT) and sites U2MGEN-FOUNT and U2DUZI-NKANY. Also associated with cobble (to a lesser degree) were *E. viviparus* (EVIV), *E. anoplus* (EANO), *E. gurneyi* (EGUR), *E. pallidus* (EPAL), *T. sparrmanii* (TSPA) and site U2KARK-USMGN.

In addition to cobble substrate, *L. natalensis* (LNAT) was also closely associated with gravel, as were sites U2MGEN-FOUNT and U2DUZI-NKANY. *Pseudocrenilabrus philander* (PPHI), *A. aeneofuscus* (AAEN), *C. rendalli* (CREN) and sites U2MGEN-MZINY, U2MGEN-PETRU and U2MGNI-DRGLE were associated with sand (Fig. 2.5). Boulder and bedrock substrate types both shared associations with *O. mossambicus* (OMOS), *E. pallidus* (EPAL), *T. sparrmanii* (TSPA), *E. gurneyi* (EGUR), *E. viviparus* (EVIV), *E. anoplus* (EANO), *A. natalensis* (ANAT) and sites U2DUZI-MOTOX and U2KARK-USMGN. Additionally, boulder substrate was associated with *M. salmoides* (MSAL) and U2MGEN-LIONS and bedrock was associated with *L. natalensis* (LNAT).

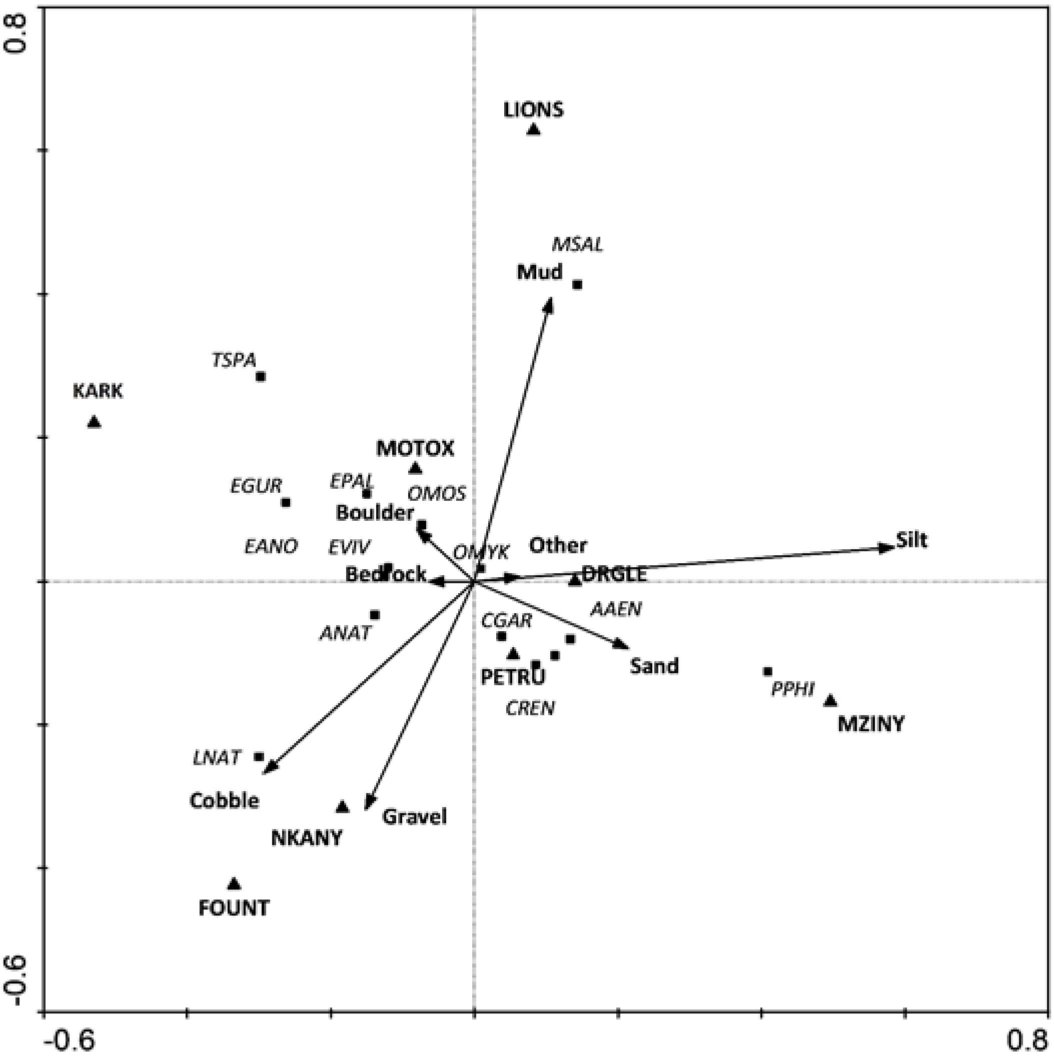

Fig. 2.4: Redundancy analysis tri-plot of fish species, sites and substrate showing dissimilarity between substrate types (arrows) in the uMngeni River in the present study. The fish species (squares) and sites (triangles) were overlaid onto the RDA to show potential driving variables. (Abbreviations as per Table 2.2).

2.4.2.5 Fish communities based on cover feature type

In the present study, cover features had no significant influence on fish community structure in the uMngeni River (p = 0.5330. Fig. 2.6). This ordination showed 80.5% of the variation within the data, with 61% of the variation on the first axis and 19.5% on the second axis (Fig. 2.6).

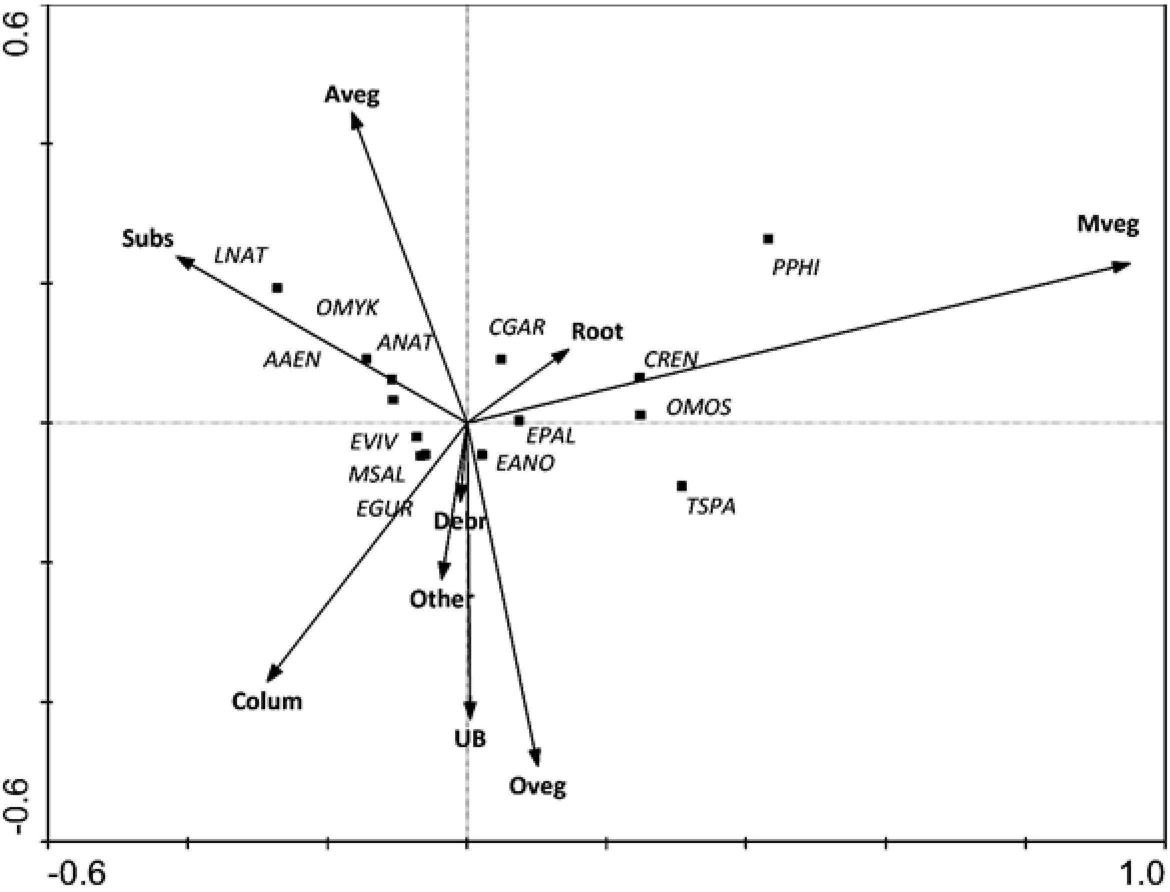

Fig. 2.5: Redundancy analysis tri-plot of fish species and cover features showing dissimilarity between cover features (arrows) in the uMngeni River in the present study. The fish species (squares) were overlaid onto the RDA to show potential driving variables. (Abbreviations as per Table 2.2).

2.4.2.6 Fish communities based on water quality

Water quality was a significant driver of fish community structure in the uMngeni River in the present study (p = 0.0010, Fig. 2.7). This ordination presented 57.2% of the variation within the data, with 32.7% of the variation on the first axis and 24.5% on the second axis (Fig. 2.7). Numerous water quality variables that had a significant influence on fish community structure included turbidity (ntu, p = 0.001), fluoride (F, p = 0.001), alkalinity ($CaCO_3$, p = 0.035), Sodium (Na, p = 0.016), heterotrophic plate count (HPC 37, p = 0.004), sulphate (SO_4, p =

0.048), total phosphorus (TP, $p = 0.031$), conductivity ($p = 0.031$), nitrate (NO_3, $p = 0.001$) and ammonia (NH_3, $p = 0.021$).

The results showed that *L. natalensis* (LNAT) was associated with turbidity (ntu) and coliforms (Fig. 2.7). *Oreochromis mossambicus* (OMOS) was associated with SO_4, while *C. gariepinus* (CGAR) was associated with elevated Na (sodium) and *P. philander* (PPHI) was associated with conductivity (Fig. 2.7). Sites U2DUZI-MOTOX and U2MGEN-MZINY were associated with $CaCO_3$ and F, respectively (Fig. 2.7).

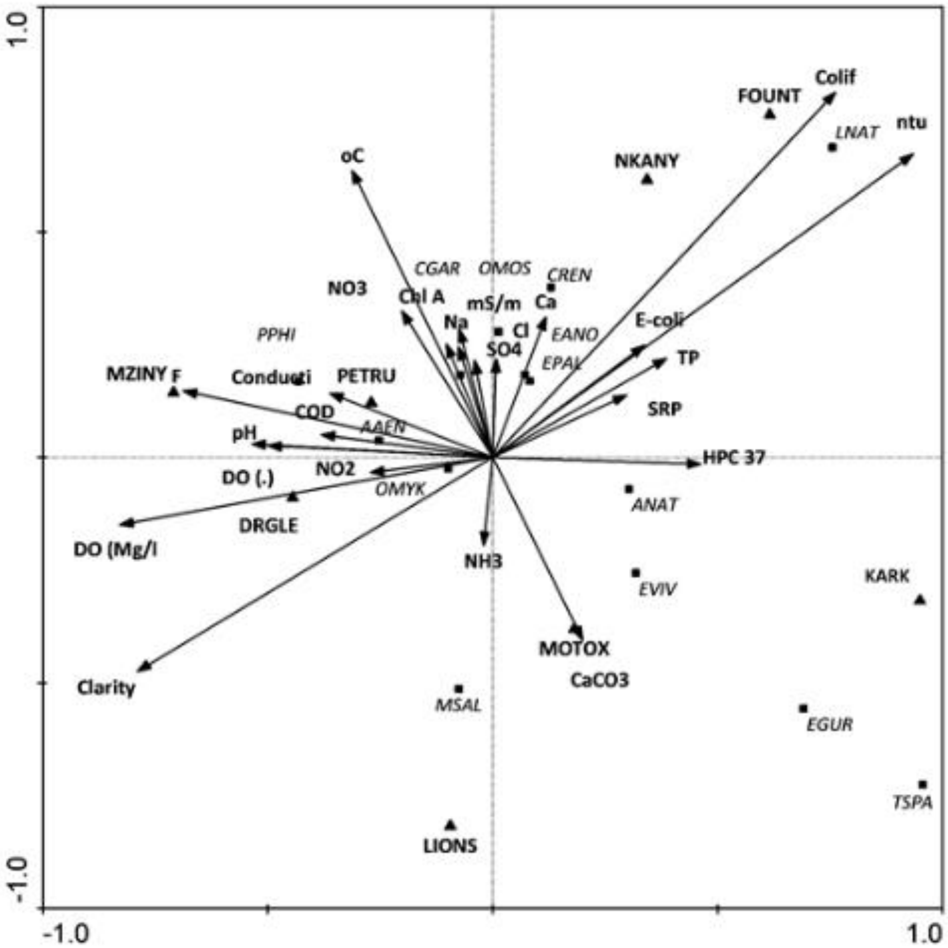

Fig. 2.6: Redundancy analysis tri-plot of fish species. sites and substrate showing dissimilarity between water quality variables (arrows) in the uMngeni River in the present study. The fish species (squares) and sites (triangles) were overlaid onto the RDA to show potential driving variables. (Abbreviations as per Table 2.2).

2.5 Discussion

The overall ecological integrity of the uMngeni was shown to be in a poor state. In comparison to other catchments (the Mvoti and Elands River) faced with simlar impacts and fish species the uMngeni is in a poorer ecological state (O'Brien et al. 2013; O'Brien et al. 2009). In KwaZulu-Natal, the uMngeni River has been shown to be the most anthropogenic impacted river (Evans 2017). The ecological assessment in this study did show that the system in highly stressed negatively impacting the ecological integrity of the uMngeni River. Using multivariate statistics and FRAI to assess both the impacts and drivers of fish communities provided insight into where the ecological integrity can be addressed within the catchment and what drives these fish communities in order to improve on the systems ecological integrity.

2.5.1 Multivariate analyses

For the most part, the eight sites that were sampled in this study were unique in their fish community structure and the high flow season had a greater species diversity which was to be expected as in other studies (Schlosser, 1985). Of the eight sites, six had *L. natalensis* present, commonly used as an indicator of ecosystem wellbeing (Impson et al. 2008; O'Brien et al. 2019), though in U2MGEN-MZINY only one *L. natalensis* was ever caught. *Labeobarbus natalensis* was not caught at the sites U2MGEN-LIONS and U2MGNI-DRGLE in this study. Although *L. natalensis* was present in most of the sites sampled in this study, the low numbers in which it occurs is concerning and, given that it is a migratory species (Karssing 2007), this is most likely a consequence of the uMngeni River being so heavily regulated and impounded by large instream dams; making it the most fragmented river in KwaZulu-Natal (Ramulifho 2015; O'Brien et al. 2019).

Velocity-depth parameters were found to have an influence on fish community structure in this study. Decreased water velocity, for instance, would result in a shift in fish community structure as species such as *L. natalensis* and *A. natalensis* showed a preference for high velocity, which is to be expected (Skelton 2001; Karssing 2007). The community structure shifted to include species such *M. salmoides* which generally prefer slow-flowing water. The velocity-depth classes of habitat are greatly influenced by the flow dynamics of a river (Kleynhans 2007), which in turn is subject to regulation by dams (Poff et al. 1997; Dugan et al. 2010; Fouchy 2019). Site U2MGEN-FOUNT included habitats with fast-flowing water and as such was associated with *L. natalensis*. Deep waters were associated with *M. salmoides* and *O. mykiss* in this study, both of which are invasive species. Similar to the findings in this study, Gao et al. (2019) found that dam regulation in the Yangtze River (China) caused significant shifts in fish assemblages, even gradually increasing the number of non-native fishes.

The presence of gravel, cobbles and boulders is very ecologically important as numerous KwaZulu-Natal fishes rely on these substrates as breeding and feeding grounds (Skelton 2001) and as such, also had an influence of fish assemblages in this study. For instance, *L. natalensis* showed a preference for cobbles and gravel (which it uses to spawn) (Karssing 2007). Noticeably, sites U2MGEN-FOUNT and U2DUZI-NKANY were both associated with these substrates and so had the two highest *L. natalensis* abundances. Certain substrate types can also act as a form of cover for fish (such as *A. aeneofuscus*) to hide from predators (Skelton 2001; Smokorowski, and Pratt 2007). *Awaous aeneofuscus* is known to bury itself in the sand for cover (Skelton 2001) and is seen in this study to be associated with this substrate. Gravel, cobbles and boulders all have the potential to act as cover for fish, but when these substrates are buried under fine silt or mud (as found in sites U2MGEN-LIONS and U2MGNI-DRGLE), they are no longer useful for cover (Kleynhans 2007). In a systematic review of studies that look at the effect of habitat alterations, Taylor et al. (2019) found substrate type (e.g., gravel, cobble) to have a significant effect on the abundance of substrate-spawning fish.

The main sources of sediment in rivers are generally anthropogenically facilitated through agriculture, commercial forestry and urban development such as dams, road construction and infrastructure (Waters 1995; Dugan et al. 2010; McIntyre et al. 2016). As sedimentation results in reduced fish biodiversity (Poff et al. 1997; Hall et al. 2011; Hohensinner et al. 2018), having these activities near a river is detrimental to ecosystem health. In the present study, water quality had a significant influence on fish community structure, though not as much as the other environmental variables as it only explained 57.2 % of the variation. The indicator species *L. natalensis* showed a preference for waters of relatively high turbidity as well as an association with microbial coliforms. None of the species showed a preference for water clarity and this was expected as it can make fish more susceptible to predators (Skelton 2001; Figueiredo et al. 2016). Salts such as sulphates (SO_4), sodium (Na) and chlorine (Cl) had an influence of fish community structure as species such as *O. mossambicus*, *C. gariepinus*, *C. rendalli*, *E. anoplus* and *E. pallidus* were associated with them. *Pseudocrenilabrus philander* also showed a preference for high conductivity, which is an indicator of ions in the water (DWAF 1996). The sites U2MGEN-PETRU and U2MGEN-MZINY were also associated with elevated conductivity. One of the main sources of conductivity is sedimentation, which may result from run-off from agricultural activity (Walser and Bart 1999). Considering that the U2MGEN-PETRU site is surrounded by agricultural activity, this may be the reason for its elevated electrical conductivity. The effects of water quality changes on aquatic ecosystems has been studied quite extensively (Peters and Meybeck 2000; O'Brien et al. 2009; Peters 2009; DWS 2014b; Yavuzcan Yildiz 2017). Poor water quality often results in a decline in fish species, not only because of the intolerances of the fishes, but also because the organisms that they feed on may decline (DWAF 1996; Bilotta and Brazier 2008). Unfavourable water quality conditions can also give rise to an increase in invasive species which are often more tolerant of deteriorated and polluted waters (Bunn and Arthington 2002; Dudgeon 2014; Gao et al. 2019).

2.5.2 Fish response assessment index (FRAI)

Based on the outcome of fish response assessment index (FRAI), the fish assemblage in the surveyed sections of the uMngeni River can be considered to be largely modified in the lower reaches and moderately modified in the upper reaches of the river. This is a common occurrence in KwaZulu-Natal and many reaches of South Africa where resources are being developed (O'Brien et al. 2019). In the eight sites that were surveyed over the course of this study, a combined total of 26 indigenous reference species were expected and of this, only 14 were caught.

The site U2MGNI-DRGLE was shown to be moderately modified as none of the four expected reference species were caught here. Migration and flow modification were shown to be some of the greatest influences of fish community structure at this site. Given the high dependence that the lifecycles of *A. mossambica*, *E. anoplus* and *L. natalensis* have on migration (Wallace et al. 1984; Skelton 2001; Impson et al. 2008), the presence of weirs and Midmar Dam downstream may be the reason for the absence of these species (Dugan et al. 2010; O'Brien et al. 2019). The alterations in flow that are caused by debris from cut down trees in some parts of this site may also play a role in the absence of *A. natalensis* which is particularly intolerant of habitats with no flow. Namugize et al. (2018) showed that land-use changes in the upper uMngeni catchment reduced natural vegetation by 17% and this too has clearly influenced the river's ecological state, including the state of fish (Jewitt et al. 2015). The presence of the invasive *O. mykiss* likely has the greatest influence on fish community structures at this site. *Oncorhynchus mykiss* inhabits cool (< 21 °C), clear and well-aerated waters and breed in cold (< 15 °C) water flowing water in winter (Skelton 2001), thus making

U2MGNI-DRGLE a relatively suitable habitat for *O. mykiss*. This, together with the predatory nature of this species (Skelton 2001), is the likely reason it can completely dominate this site. The relatively good water quality (which is shown by the multivariate analysis to have a significant influence on fish community structure in this study) and minimal human modification in this site was the reason why it had a fairly good adjusted FRAI score.

Site U2MGEN-PETRU was found to be in moderately modified state primarily because of modified flow conditions and barriers that hinder fish migration (i.e. the weir that is present at this site), both of which have been shown to be detrimental to fish biodiversity (Dudgeon et al. 2006; Grill et al. 2019). Additionally, the multivariate statistics performed in this study indicated that velocity-depth classes have a significant influence on fish community structures, further indicating that habitat modifications that alter flow and depth have a detrimental effect on fish communities.

One of the reference species, *A. mossambica*, prefers flowing water although it is also moderately tolerant of non-flowing water (Skelton 2001). *Labeobarbus natalensis* also prefers flowing waters and is moderately intolerant of no flow because of the importance that flowing plays in their breeding (Skelton 2001; Karssing 2007). *Amphilius natalensis* is relatively intolerant of non-flowing waters and prefers fast-flowing water. Being able to freely migrate between habitats is also important for these fish species, especially *A. mossambica* and *L. natalensis* which migrate >100 km and between 20 km and 100 km, respectively, for breeding and reproductive purposes (Wallace et al. 1984; Skelton 2001; Karssing 2007). The presence of a weir at this site has modified natural flow patterns and impedes on fishes' ability to freely migrate, thus resulting in a decline of fish species that should otherwise occur in high frequencies in this site.

Site U2MGEN-LIONS was shown to be largely modified and, according to the FRAI assessment, fish species with a high preference for flowing water and an affinity for migration decreased in frequency of occurrence compared to the reference frequencies of occurrence. It can, therefore, be suspected that the decrease in fish community integrity at this site is primarily because of competition and predation by invasive and translocated fish species, modified flow conditions, and migration barriers. Additionally, invasive species (such as those found at this site) have been shown to be more tolerant of unfavourable conditions such as increased temperatures and flow modifications (Bunn and Arthington 2002; Dudgeon 2014). *Micropterus salmoides,* in particular, is tolerant of a wide temperature range (below 10 °C to 32 °C) and is catholic in its feeding habits (Skelton 2001) and so the increased presence of this invasive species, is a further indication of this site's deteriorated state.

The relatively poor availability of water in some parts of this site (especially in low flow seasons) may also contribute to the lack of reference species, especially those that prefer flowing waters (such as *A. natalensis* and *L. natalensis*) as well as those whose life cycle relies on the ability to migrate (such as *A. mossambica*, *E. anoplus*, *L. natalensis*, *E. viviparus* and *C. gariepinus*) (Skelton 2001; DWS 2014a). The significance of velocity-depth classes and high/low flow seasons in the differences in fish communities among sites is further evidence of the influence of water availability at this sire.

Translocated species, particularly *T. sparrmanii* and *C. rendalli*, most likely thrive at this site because they are tolerant of a wide range of habitats (Skelton 2001). It is, however, surprising that a species as widespread and tolerant as *C. gariepinus* (Willoughby and Tweddle 1978; Koehn 2004) was absent at this site.

Site U2KARK-USMGN (which had the greatest fish diversity) was shown to be moderately modified with velocity-depth classes, flow modification, and physico-chemical characteristics (water quality) being the main drivers of change in fish community structure. These findings are further corroborated by the multivariate analysis performed in this study which showed velocity-depth classes and physico-chemical characteristics to have a significant influence on fish community variation among sites surveyed. The presence of a weir and several bridge crossings upstream of this site may be the reason behind flow modifications and changes in velocity-depth classes from the natural state (Ramulifho 2015; O' Brien et al. 2019). Another factor that had a significant influence on fish community structures in this study (according to the multivariate analysis) was substrate type. Substrate type, and how it is distributed across habitats in any particular site, can affect the presence or absence of fish based on the various physiological needs that different substrate may fulfil over the fish's lifespan (Skelton 2001). For instance, gravel substrate is relatively important for *L. natalensis* as they spawn over gravel beds and *A. natalensis* lives among cobbles and rocks (Skelton 2001; Karssing 2007). This site, however, was associated with mud according to the multivariate analysis results. Water quality samples taken at this site show elevated microbial levels (*E. coli*, coliforms and HPC 37), indicating that there may be faecal matter present in the water, most likely from the wildlife present in the area (DWAF 1996; Zhu et al. 2019) or nearby wastewater treatment.

Moving into the lower parts of the uMngeni catchment to site U2MGEN-FOUNT, the site is shown to be moderately/largely modified. According to the FRAI assessment, species with a high preference for clear, flowing water decreased in frequency of occurrence compared to reference as velocity-depth classes, flow modification, and physico-chemical characteristics are the metric groups with the most weight at this site. All these metrices are related to flow modification (Kleynhans 2007; Mantel et al. 2010; Jewitt 2015) and at the U2MGEN-FOUNT site, this can be attributed to the unnatural flow pattern caused by Albert Falls Dam upstream of this site (WRC 2002). Flow alterations can negatively affect habitats, sediment deposition, migration and life history/physiological cues such as fish recruitment and growth (Poff et al. 1997; Bunn and Arthington 2002; Hall et al. 2011). The water quality at this site was relatively good, with just slight elevations in microbial activity, namely *E. coli*, coliforms and HPC 37.

Multivariate analysis also indicated that velocity-depth classes and physico-chemical characteristics were indeed drivers of change in fish community structure in this study.

For most reference species, the habitats that they inhabit or prefer to inhabit were present at U2MGEN-FOUNT, with just a few exceptions. There was essentially no sand in U2MGEN-FOUNT (Table 2.6), which is vital for *A. aeneofuscus* which uses the sand for cover (Skelton 2001; DWS 2014a). The lack of vegetated pools, which *E. viviparus* and *T, sparrmanii* inhabit and prefer, respectively, meant that these species were lacking from the site sampled. *Coptodon rendalli* prefers quiet, vegetated backwaters (Skelton 2001) a habitat type that is not present at U2MGEN-FOUNT and hence this species was also not sampled at this site.

Site U2DUZI-MOTOX, which is in the Msunduzi River (a tributary of the uMngeni River) was shown to be largely modified and most influenced by changes in that velocity-depth classes, flow modification, and physico-chemical characteristics. This site (which occurs in the most urbanised location in this study) is about 12 km downstream of Camps Drift, a canalised section of the Msunduzi River, and 36 km below Henly Dam, impacting the river's natural flow. Weirs on the Msunduzi River also affect the river's flow as well as fish migration (Foucy et al. 2019). The consequences of urbanisation are most obvious at this site and Levin et al. (2019) showed similar results by directly linking increased urbanisation to poor FRAI EC scores (i.e. ecological degradation). The Msunduzi River passes through the urban area of Pietermaritzburg which further contributes pollution to the river (WRC 2002; Matongo et al. 2015) and site U2DUZI-MOTOX was no exception (pers. obs.).

The multivariate analyses indicated that velocity-depth classes and physico-chemical characteristics were significant drivers of fish community variation among sites surveyed. Multivariate analyses also showed substrate type to have a significant influence on community structure. This may be why species that rely on substrate types that were absent in this site (such as *L. natalensis*) or occurreds in low frequencies (lower than expected). As *L. natalensis* requires gravel with no silt to breed and this was lacking at site U2DUZI-MOTOX which was predominated by bedrock, boulders, and mud. Extensive urbanisation, such as is present along the Msunduzi River, has been shown to alter flow and sedimentation, thus altering the habitat (Poff et al. 1997; Hall et al. 2011; Hohensinner et al. 2018). Other species such *A. aeneofuscus* prefer sandy substrate which it uses for cover, while *A. natalensis* lives among cobbles and rocks and fast-flowing water (Skelton 2001). *Enteromius pallidus* inhabits pools in clear, rocky streams (Skelton 2001), and the water in U2DUZI-MOTOX was quite murky.

Some of the water quality characteristics at this site may contribute to the absence of reference species and poor fish species diversity. For instance, elevated concentrations of Chlorine may be a result of the Darvill Wastewater Treatment Works which is less than 2 km upstream of this site. Chlorine has detrimental effects on fish and other river organisms (DWAF 1996). The high electrical conductivity at this site is also an indication of high total dissolved salts concentration (i.e. ions in the water such as chloride, sulphate, nitrate, sodium, and calcium), indicative of an impacted site (DWAF 1996). Additionally, the ratio of Nitrogen (NO_3) to Phosphorous (SRP) at this is about 3:1, which is considered typical for impacted sites (DWAF 1996). It should be noted, however, that water leaving the Darvill Wastewater Treatment Works has also been shown to be of better quality than it was before treatment (WRC 2002; Matongo et al. 2015).

The second Msunduzi River site, U2DUZI-NKANY, was largely modified and metric weights indicated that flow modification, velocity-depth classes, and physico-chemical characteristics were the main drivers of change in fish community structure at this site. As such, species with a high preference for clear, flowing water decreased in frequency of occurrence. Multivariate analyses also indicated that velocity-depth classes and physic-chemical characteristics had a significant influence on fish community variation among sites in this study. Once again, flow regulation was one of the main influences on the deteriorated state of this site. Alterations to the Msunduzi River's natural flow are caused by Henly Dam, weirs and canalisation (Camps Drift) upstream (Hall et al. 2011; Hohensinner et al. 2018). The riparian zone (which includes marginal vegetation and banks) at this site is also heavily deteriorated by anthropogenic activity. The riparian zone is important for the maintenance of freshwater biodiversity and a compromised riparian zone leaves a lot of fish species without cover, especially juvenile fish (Skelton 2001; Pusey and Arthington 2003). Such species include *L. natalensis*, *C. rendalli*, *P. philander* and *E. pallidus*, most of which were absent or occurred in low frequencies at this site. The riparian zone is home to the invertebrates and small vertebrates that fish feed on and also provides shade and cover for fish (Pusey and Arthington 2003).

The riparian zone at this site may be damaged by cattle grazing and trampling which has been shown to compromise riparian zones (Amy and Robertson 2001; Campbell et al. 2019). Cattle faeces also act as a water contaminant (Zhu et al. 2019) and this was observed in the elevated faecal coliform count at this site, although *E. coli* is within the general limit of 1000 mpn per 100 ml (DWAF 1996). Additionally, sand mining at this site has compromised the riverbank and riparian zone, which is detrimental to fish and other freshwater species (Padmalal et al. 2008; Kori and Mathada 2012; pers. obs.). At this site, there is also the invasive aquatic plant *Eichhornia crassipes* (water hyacinth) which is scattered across the site. The dense mats that *E. crassipes* forms can alter water quality which has a detrimental effect on other aquatic life (Cilliers 1991; Fouchy et al. 2018). At this site, however, *E. crassipes* appeared to have not altered water quality (most likely because it does not occur in dense mats) and instead water quality alterations appear to be a result of sand mining and cattle (pers. obs.).

Site U2MGEN-MZINY, which was the farthest site down the uMngeni River in this study, was shown to be largely/severely modified, with migration, flow modification, and velocity-depth classes having the most significant influence on changes in fish community structure. This means that, according to the EC scores of the FRAI assessment, fish species that migrate and have a high preference for flowing water decreased in frequency of occurrence. Flow alterations at this site are caused by iNanda Dam, which also acts as a barrier for migratory fish (Dugan et al. 2010; McIntyre et al. 2016). Migratory fishes depend on a range of habitats along a river ecosystem, and so connectivity between habitats is important in order to maintain healthy biodiversity (O'Brien et al. 2019).

Water quality below iNanda Dam was relatively fine because of water purification in the dam. Multivariate analyses, however, indicated that this site was associated with sand and elevated silt levels. Multivariate analyses also indicated that this site was associated with high conductivity, an indication of total dissolved salts concentration (i.e. ions in the water such as chloride, sulphate, nitrate, sodium, and calcium) (DWAF 1996). Alterations in nutrient and sediment dynamics at this site may be a result of the flow alterations caused by iNanda Dam upstream (Poff et al. 1997; Hall et al. 2011; Hohensinner et al. 2018).

2.6 Conclusions

The results of the present study showed that the ecological integrity of the uMngeni River tends to degrade from upper to lower reaches in response to various anthropogenic activities. Assessments of fish communities in eight sites in the uMngeni and Msunduzi Rivers showed that the ecological states of most sites in the upper reaches of uMngeni River (above Albert Falls Dam) to be moderately modified, with one site on the Lions River being classified as largely modified. The Ecological integrity of sites on this portion of the uMngeni River was largely driven by flow modifications and migration barriers, from Midmar Dam and weirs in the upper uMngeni, as well as the impact of invasive species. The site in Fountainhill Estate was moderately/largely modified mostly because of the effects of flow modifications caused by Albert Falls Dam. Moving down the uMngeni River (including the Msunduzi tributary) the ecological state deteriorated further as sites here were largely modified because of flow and water quality alterations. This deterioration was largely because of flow modifications from dams and channelisation as well as water quality alterations from urban and rural activities. The application of the multi-metric index was successful and identified the stressors driving fish communities that were all attributed to anthropogenic land use activities. These outcomes conformed with the multivariate analyses that identified significant changes in communities.

Using multivariate analyses, the present study also showed that variations among the sites selected in this study were significantly driven by changes in velocity-depth classes, substrate type and water quality (physico-chemical), all of which can be influenced by flow modifications. Cover type, however, was shown to not be a significant driver of fish community variations in this study. The outcomes include new evidence of altered fish communities associated with multiple stressors in the Umgeni River Catchment that need to be mitigated.

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2.9 Supplementary Information

Fig. S2.1a: Photographs of site U2MGNI-DRGLE.

Fig. S2.1b: Photographs of site U2MGEN-PETRU.

Fig. S2.1c: Photographs of site U2MGEN-LIONS.

Fig. S2.1d: Photographs of site U2KARK-USMGN

Fig. S2.1e: Photographs of site U2MGEN-FOUNT.

Fig. S2.1f: Photographs of site U2DUZI-MOTOX.

Fig. S2.1g: Photographs of site U2DUZI-NKANY

Fig. S2.1h: Photographs of site U2MGEN-MZINY.

Table S2.1: River Eco-status monitoring Programme (REMP) sites sampled and their coordinates in the present study.

REMP site name	River	Latitude	Longitude
U2MGNI-DRGLE	uMngeni	-29.488805	29.903036
U2MGEN-PETRU	uMngeni	-29.512469	30.094401
U2MGEN-LIONS	Lions	-29.414572	30.094375
U2KARK-USMGN	Karkloof	-29.443797	30.319403
U2MGEN-FOUNT	uMngeni	-29.491252	30.492632
U2DUZI-MOTOX	Msunduzi	-29.607	30.4508
U2DUZI-NKANY	Msunduzi	-29.611	30.5578
U2MGEN-MZINY	uMngeni	-29.720833	30.903937

Table S2.2: FRAI Ecological Categories (Kleynhans 2007) and justification sheets for each survey conducted over the course of this study. Lists of expected species were taken from the Department of Water and Sanitation's PESEIS documents (DWS 2014a).

Ecological Categories	Name	Description	Acceptable/ Unacceptable	Score (%)
A	Natural	Unmodified natural	Acceptable	90 - 100
B	Good	Mostly natural with few modifications	Acceptable	80 - 89
C	Fair	Moderately modified	Acceptable	60 - 79
D	Poor	Largely modified	Unacceptable	40 - 59
E	Seriously modified	Seriously modified	Unacceptable	20 - 39
F	Critically modified	Critically or extremely modified	Unacceptable	0 - 19

Site Name	U2MGNI-DRGLE	**Assessor**	P Dlamini		
River	uMngeni	**Reviewed**	G O'Brien		

ABR	SPECIES	REFERENCE FROC	OBSERVED FROC		
			May	Aug	Nov
AMOS	ANGUILLA MOSSAMBICA PETERS 1852	5.00	0	0	0
ANAT	AMPHILIUS NATALENSIS BOULENGER. 1917	5.00	0	0	0
BANO	BARBUS ANOPLUS WEBER. 1897	5.00	0	0	0
BNAT	BARBUS NATALENSIS CASTELNAU. 1861	3.00	0	0	0

Response of species with a preference/tolerance to		May	Aug	Nov
Velocity Depth Metric	Fast-Deep	-2	-2	-1
	Fast-Shallow	-2	-2	-2
	Slow-Deep	-1	-1	-1
	Slow-Shallow	0	0	0
Cover features	Overhanging veg	2	3	3
	Undercut banks	2	1	1

		May	Aug	Nov
	Substrate	0	0	0
	Instream veg	3	1	3
	Water column	1	1	2
Response of species that are		May	Aug	Nov
Flow dependance	Intolerant to no flow	-2	-2	-2
	Moderately intolerant to no flow	-1	-1	-1
	Moderately tolerant to no flow	-1	-1	-1
	Tolerant to no flow	0	0	0
Response of species that are		May	Aug	Nov
Physico-chemical conditions	Intolerant to modified physico-chemical conditions	-1	-1	-1
	Moderately intolerant to modified physico-chemical conditions	0	0	0
	Moderately tolerant to modified physico-chemical conditions	-1	-1	-1
	Tolerant modified to physico-chemical conditions	0	0	0
Response of which require		May	Aug	Nov
Migration	Catchment scale movement	2	2	2
	Movement between reaches	2	2	2
	Movement within a reach	0	0	0
Extent of the following in the reach		May	Aug	Nov
Changes in connectivity	Weirs and causeways	2	2	2
	Impoundments	2	2	2
	Physico-chemical barriers	1	1	1
	Flow modifications	1	1	1
Introduced/alien species		May	Aug	Nov
Introduced/alien species	Introduced/alien predacious species 1	-	-	OMYK
	Introduced/alien predacious species 2	-	-	-
	Introduced/alien predacious species 3	-	-	-
	Introduced/alien habitat modifying species 1	-	-	-
	Introduced/alien habitat modifying species 2	-	-	-
	The impact of introduced competing spp?	0	0	5
	FROC of introduced competing spp?	0	0	0.5
	The impactof introduced habitat modifying spp?	0	0	0
	FROC of habitat modifying spp?	0	0	0
AUTOMATED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		16.6	15.3	9.5

EC: FRAI	F	F	F
ADJUSTED FISH RESPONSE ASSESSMENT INDEX SCORE			
FRAI (%)	74.3	75.6	69
EC: FRAI	C	C	C

Site Name	U2MGEN-PETRU	**Assessor**	P Dlamini
River	uMngeni	**Reviewed**	G O'Brien

ABR	SPECIES	REFERENCE FROC	OBSERVED FROC		
			May	Aug	Nov
AMOS	ANGUILLA MOSSAMBICA PETERS 1852	5.00	0	0	0
ANAT	AMPHILIUS NATALENSIS BOULENGER. 1917	5.00	0	0	0
BANO	BARBUS ANOPLUS WEBER. 1897	5.00	0	0	0
BNAT	BARBUS NATALENSIS CASTELNAU. 1861	3.00	0	1	0
Response of species with a preference/tolerance to			May	Aug	Nov
Velocity Depth Metric	Fast-Deep		-2	-1	-1
	Fast-Shallow		-2	-2	-1
	Slow-Deep		0	0	0
	Slow-Shallow		0	0	0
Cover features	Overhanging veg		1	1	1
	Undercut banks		2	2	2
	Substrate		3	2	3
	Instream veg		2	2	2
	Water column		2	1	1
Response of species that are			May	Aug	Nov
Flow dependance	Intolerant to no flow		-2	-2	-2
	Moderately intolerant to no flow		-1	-1	-1
	Moderately tolerant to no flow		-1	-1	-1
	Tolerant to no flow		0	0	0
Response of species that are			May	Aug	Nov
Physico-chemical conditions	Intolerant to modified physico-chemical conditions		-3	-2	-2
	Moderately intolerant to modified physico-chemical conditions		0	0	0
	Moderately tolerant to modified physico-chemical conditions		-2	-2	-2
	Tolerant modified to physico-chemical conditions		0	0	0
Response of which require			May	Aug	Nov

Migration	Catchment scale movement	3	3	3
	Movement between reaches	3	3	3
	Movement within a reach	1	1	1
Extent of the following in the reach		May	Aug	Nov
Changes in connectivity	Weirs and causeways	4	4	4
	Impoundments	2	2	2
	Physico-chemical barriers	1	1	1
	Flow modifications	1	1	1
Introduced/alien species		May	Aug	Nov
Introduced/alien species	Introduced/alien predacious species 1	-	-	-
	Introduced/alien predacious species 2	-	-	-
	Introduced/alien predacious species 3	-	-	-
	Introduced/alien habitat modifying species 1	-	-	-
	Introduced/alien habitat modifying species 2	-	-	-
	The impact of introduced competing spp?	0	0	0
	FROC of introduced competing spp?	0	0	0
	The impactof introduced habitat modifying spp?	0	0	0
	FROC of habitat modifying spp?	0	0	0
AUTOMATED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		12.6	12.7	7.5
EC: FRAI		F	F	F
ADJUSTED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		62.3	69.5	69.7
EC: FRAI		C	C	C

Site Name U6MGEN-LIONS **Assessor** P Dlamini
River uMngeni **Reviewed** G O'Brien

ABR	SPECIES	REFERENCE FROC	OBSERVED FROC		
			May	Aug	Nov
AMOS	ANGUILLA MOSSAMBICA PETERS 1852	3.00	0	0	0
ANAT	AMPHILIUS NATALENSIS BOULENGER. 1917	3.00	0	0	0
BANO	BARBUS ANOPLUS WEBER. 1897	5.00	0	0	0
BGUR	BARBUS GURNEYI GÜNTHER. 1868	3.00	0	0	0
BNAT	BARBUS NATALENSIS CASTELNAU. 1861	3.00	0	0	0

BVIV	BARBUS VIVIPARUS WEBER. 1897	3.00	0	0	0
CGAR	CLARIAS GARIEPINUS (BURCHELL. 1822)	3.00	0	0	0
Response of species with a preference/tolerance to			May	Aug	Nov
Velocity Depth Metric	Fast-Deep		-1	-1	-1
	Fast-Shallow		-2	-1	-1
	Slow-Deep		-3	-3	-3
	Slow-Shallow		-3	-3	-3
Cover features	Overhanging veg		1	3	3
	Undercut banks		2	3	3
	Substrate		3	3	3
	Instream veg		3	3	3
	Water column		2	0	2
Response of species that are			May	Aug	Nov
Flow dependance	Intolerant to no flow		-4	-4	-4
	Moderately intolerant to no flow		-3	-3	-3
	Moderately tolerant to no flow		-2	-2	-2
	Tolerant to no flow		-1	0	0
Response of species that are			May	Aug	Nov
Physico-chemical conditions	Intolerant to modified physico-chemical conditions		-1	-1	-1
	Moderately intolerant to modified physico-chemical conditions		-1	0	0
	Moderately tolerant to modified physico-chemical conditions		0	0	0
	Tolerant modified to physico-chemical conditions		0	0	0
Response of which require			May	Aug	Nov
Migration	Catchment scale movement		3	3	3
	Movement between reaches		4	3	3
	Movement within a reach		1	3	3
Extent of the following in the reach			May	Aug	Nov
Changes in connectivity	Weirs and causeways		2	2	2
	Impoundments		1	1	1
	Physico-chemical barriers		0	0	0
	Flow modifications		1	1	1
Introduced/alien species			May	Aug	Nov
Introduced/alien species	Introduced/alien predacious species 1		MSAL	MSAL	MSAL
	Introduced/alien predacious species 2		-	-	-

	Introduced/alien predacious species 3	-	-	-
	Introduced/alien habitat modifying species 1	-	-	-
	Introduced/alien habitat modifying species 2	-	-	-
	The impact of introduced competing spp?	4	4	4
	FROC of introduced competing spp?	2.5	3	1
	The impactof introduced habitat modifying spp?	0	0	0
	FROC of habitat modifying spp?	0	0	0
AUTOMATED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		4	1.2	3.9
EC: FRAI		F	F	F
ADJUSTED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		48.3	46.9	48.7
EC: FRAI		D	D	D

Site Name U2KARK-USMGN **Assessor** P Dlamini
River uMngeni **Reviewed** G O'Brien

ABR	SPECIES	REFERENCE FROC	OBSERVED FROC May	Aug	Nov
AMAR	ANGUILLA MARMORATA QUOY & GAIMARD 1824	5.00	-	0	0
AMOS	ANGUILLA MOSSAMBICA PETERS 1852	5.00	-	0	0
ANAT	AMPHILIUS NATALENSIS BOULENGER. 1917	5.00	-	1	0
BANO	BARBUS ANOPLUS WEBER. 1897	5.00	-	0	1
BGUR	BARBUS GURNEYI GÜNTHER. 1868	3.00	-	3	2
BNAT	BARBUS NATALENSIS CASTELNAU. 1861	5.00	-	2	2
CGAR	CLARIAS GARIEPINUS (BURCHELL. 1822)	5.00	-	0	0
OMOS	OREOCHROMIS MOSSAMBICUS (PETERS. 1852)	5.00	-	0	2
TREN	TILAPIA RENDALLI (BOULENGER. 1896)	3.00	-	0	1
TSPA	TILAPIA SPARRMANII SMITH. 1840	5.00	-	4	0

Response of species with a preference/tolerance to		May	Aug	Nov
Velocity Depth Metric	Fast-Deep	-	-1	-1
	Fast-Shallow	-	-1	-2
	Slow-Deep	-	-3	-2
	Slow-Shallow	-	-2	-1
Cover features	Overhanging veg	-	0	1

		May	Aug	Nov
	Undercut banks	-	2	2
	Substrate	-	2	2
	Instream veg	-	1	1
	Water column	-	1	1
Response of species that are		May	Aug	Nov
Flow dependance	Intolerant to no flow	-	-2	-2
	Moderately intolerant to no flow	-	-1	-1
	Moderately tolerant to no flow	-	-3	-3
	Tolerant to no flow	-	-1	-1
Response of species that are		May	Aug	Nov
Physico-chemical conditions	Intolerant to modified physico-chemical conditions	-	0	-2
	Moderately intolerant to modified physico-chemical conditions	-	-1	0
	Moderately tolerant to modified physico-chemical conditions	-	-3	-2
	Tolerant modified to physico-chemical conditions	-	-2	-2
Response of which require		May	Aug	Nov
Migration	Catchment scale movement	-	3	2.5
	Movement between reaches	-	2	1
	Movement within a reach	-	0	1
Extent of the following in the reach		May	Aug	Nov
Changes in connectivity	Weirs and causeways	-	1	1
	Impoundments	-	1	1
	Physico-chemical barriers	-	0	0
	Flow modifications	-	0	0
Introduced/alien species		May	Aug	Nov
Introduced/alien species	Introduced/alien predacious species 1	-	-	-
	Introduced/alien predacious species 2	-	-	-
	Introduced/alien predacious species 3	-	-	-
	Introduced/alien habitat modifying species 1	-	-	-
	Introduced/alien habitat modifying species 2	-	-	-
	The impact of introduced competing spp?	-	0	0
	FROC of introduced competing spp?	-	0	0
	The impactof introduced habitat modifying spp?	-	0	0
	FROC of habitat modifying spp?	-	0	0
AUTOMATED FISH RESPONSE ASSESSMENT INDEX SCORE				

FRAI (%)	-	34.7	29.1
EC: FRAI	-	E	E

ADJUSTED FISH RESPONSE ASSESSMENT INDEX SCORE

FRAI (%)	-	70.4	69.6
EC: FRAI	-	C	C

Site Name U2MGEN-FOUNT **Assessor** P Dlamini
River uMngeni **Reviewed** G O'Brien

ABR	SPECIES	REFERENCE FROC	OBSERVED FROC		
			May	Aug	Nov
AAEN	AWAOUS AENEOFUSCUS (PETERS 1852)	5.00	0	0	-
ALAB	ANGUILLA BENGALENSIS LABIATA PETERS. 1852	3.00	0	0	-
AMAR	ANGUILLA MARMORATA QUOY & GAIMARD 1824	3.00	0	0	-
AMOS	ANGUILLA MOSSAMBICA PETERS 1852	5.00	0	0	-
ANAT	AMPHILIUS NATALENSIS BOULENGER. 1917	5.00	1	0	-
BGUR	BARBUS GURNEYI GÜNTHER. 1868	3.00	0	0	-
BNAT	BARBUS NATALENSIS CASTELNAU. 1861	5.00	2	2	-
BPAL	BARBUS PALLIDUS SMITH. 1841	1.00	0	0	-
BVIV	BARBUS VIVIPARUS WEBER. 1897	5.00	0	0	-
CGAR	CLARIAS GARIEPINUS (BURCHELL. 1822)	5.00	1	0	-
OMOS	OREOCHROMIS MOSSAMBICUS (PETERS. 1852)	5.00	0	0	-
PPHI	PSEUDOCRENILABRUS PHILANDER (WEBER. 1897)	3.00	1	0	-
TREN	TILAPIA RENDALLI (BOULENGER. 1896)	5.00	0	0	-
TSPA	TILAPIA SPARRMANII SMITH. 1840	5.00	0	2	-

Response of species with a preference/tolerance to		May	Aug	Nov
Velocity Depth Metric	Fast-Deep	-2	-2	-
	Fast-Shallow	-2	-2	-
	Slow-Deep	-4	-4	-
	Slow-Shallow	-3	-3	-
Cover features	Overhanging veg	2	2	-
	Undercut banks	2	2	-
	Substrate	2	3	-
	Instream veg	2	2	-
	Water column	2	2	-

	Response of species that are	May	Aug	Nov
Flow dependance	Intolerant to no flow	-1	-3	-
	Moderately intolerant to no flow	-1	-1	-
	Moderately tolerant to no flow	-3	-3	-
	Tolerant to no flow	-2	-2	-
	Response of species that are	May	Aug	Nov
Physico-chemical conditions	Intolerant to modified physico-chemical conditions	1	-3	-
	Moderately intolerant to modified physico-chemical conditions	-3	-3	-
	Moderately tolerant to modified physico-chemical conditions	-4	-2	-
	Tolerant modified to physico-chemical conditions	-2	-2	-
	Response of which require	May	Aug	Nov
Migration	Catchment scale movement	1.5	2	-
	Movement between reaches	1	1	-
	Movement within a reach	1	2	-
	Extent of the following in the reach	May	Aug	Nov
Changes in connectivity	Weirs and causeways	1	1	-
	Impoundments	2	2	-
	Physico-chemical barriers	0	0	-
	Flow modifications	3	3	-
	Introduced/alien species	May	Aug	Nov
Introduced/alien species	Introduced/alien predacious species 1	-	-	-
	Introduced/alien predacious species 2	-	-	-
	Introduced/alien predacious species 3	-	-	-
	Introduced/alien habitat modifying species 1	-	-	-
	Introduced/alien habitat modifying species 2	-	-	-
	The impact of introduced competing spp?	0	0	-
	FROC of introduced competing spp?	0	0	-
	The impactof introduced habitat modifying spp?	0	0	-
	FROC of habitat modifying spp?	0	0	-
AUTOMATED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		28.2	21.1	-
EC: FRAI		E	E/F	-
ADJUSTED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		61.1	53.4	-

EC: FRAI			C/D	D	-

Site Name	U2DUZI-MOTOX	Assessor	P Dlamini
River	uMngeni	Reviewed	G O'Brien

ABR	SPECIES	REFERENCE FROC	OBSERVED FROC		
			May	Aug	Nov
AAEN	AWAOUS AENEOFUSCUS (PETERS 1852)	3.00	-	0	0
ALAB	ANGUILLA BENGALENSIS LABIATA PETERS. 1852	3.00	-	0	0
AMOS	ANGUILLA MOSSAMBICA PETERS 1852	5.00	-	0	0
ANAT	AMPHILIUS NATALENSIS BOULENGER. 1917	1.00	-	0	0
BGUR	BARBUS GURNEYI GÜNTHER. 1868	5.00	-	0	0
BNAT	BARBUS NATALENSIS CASTELNAU. 1861	5.00	-	1	0
BPAL	BARBUS PALLIDUS SMITH. 1841	1.00	-	0	0
BVIV	BARBUS VIVIPARUS WEBER. 1897	5.00	-	0	0
CGAR	CLARIAS GARIEPINUS (BURCHELL. 1822)	5.00	-	0	0
OMOS	OREOCHROMIS MOSSAMBICUS (PETERS. 1852)	5.00	-	0	0
PPHI	PSEUDOCRENILABRUS PHILANDER (WEBER. 1897)	5.00	-	0	1
TREN	TILAPIA RENDALLI (BOULENGER. 1896)	5.00	-	0	0
TSPA	TILAPIA SPARRMANII SMITH. 1840	5.00	-	2	0

Response of species with a preference/tolerance to		May	Aug	Nov
Velocity Depth Metric	Fast-Deep	-	-3	-3
	Fast-Shallow	-	-3	-4
	Slow-Deep	-	-4	-4
	Slow-Shallow	-	-3	-3
Cover features	Overhanging veg	-	2	3
	Undercut banks	-	3	3
	Substrate	-	3	4
	Instream veg	-	2	3
	Water column	-	2	2

Response of species that are		May	Aug	Nov
Flow dependance	Intolerant to no flow	-	-3	-2
	Moderately intolerant to no flow	-	-2	-2
	Moderately tolerant to no flow	-	-3	-3
	Tolerant to no flow	-	-3	-2

Response of species that are		May	Aug	Nov
Physico-chemical conditions	Intolerant to modified physico-chemical conditions	-	-4	-4
	Moderately intolerant to modified physico-chemical conditions	-	-3	-3
	Moderately tolerant to modified physico-chemical conditions	-	-3	-3
	Tolerant modified to physico-chemical conditions	-	-2	-2
Response of which require		**May**	**Aug**	**Nov**
Migration	Catchment scale movement	-	2	3
	Movement between reaches	-	1	3
	Movement within a reach	-	2	2
Extent of the following in the reach		**May**	**Aug**	**Nov**
Changes in connectivity	Weirs and causeways	-	2	2
	Impoundments	-	3	3
	Physico-chemical barriers	-	4	4
	Flow modifications	-	3	3
Introduced/alien species		**May**	**Aug**	**Nov**
Introduced/alien species	Introduced/alien predacious species 1	-	-	-
	Introduced/alien predacious species 2	-	-	-
	Introduced/alien predacious species 3	-	-	-
	Introduced/alien habitat modifying species 1	-	-	-
	Introduced/alien habitat modifying species 2	-	-	-
	The impact of introduced competing spp?	-	0	0
	FROC of introduced competing spp?	-	0	0
	The impactof introduced habitat modifying spp?	-	0	0
	FROC of habitat modifying spp?	-	0	0
AUTOMATED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		-	17.7	10.3
EC: FRAI		-	E/F	F
ADJUSTED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		-	47.6	43.4
EC: FRAI		-	D	D

Site Name U2DUZI-NKANY **Assessor** P Dlamini

River uMngeni **Reviewed** G O'Brien

ABR	SPECIES		OBSERVED FROC

		REFERENCE FROC	May	Aug	Nov
AAEN	AWAOUS AENEOFUSCUS (PETERS 1852)	3.00	0	0	0
ALAB	ANGUILLA BENGALENSIS LABIATA PETERS. 1852	3.00	0	0	0
AMOS	ANGUILLA MOSSAMBICA PETERS 1852	3.00	0	0	0
ANAT	AMPHILIUS NATALENSIS BOULENGER. 1917	1.00	0	0	0
BGUR	BARBUS GURNEYI GÜNTHER. 1868	3.00	0	0	0
BNAT	BARBUS NATALENSIS CASTELNAU. 1861	3.00	3	1	1
BPAL	BARBUS PALLIDUS SMITH. 1841	1.00	0	0	0
BVIV	BARBUS VIVIPARUS WEBER. 1897	5.00	0	0	0
CGAR	CLARIAS GARIEPINUS (BURCHELL. 1822)	3.00	0	0	0
OMOS	OREOCHROMIS MOSSAMBICUS (PETERS. 1852)	3.00	0	0	0
PPHI	PSEUDOCRENILABRUS PHILANDER (WEBER. 1897)	3.00	0	0	1
TREN	TILAPIA RENDALLI (BOULENGER. 1896)	3.00	1	0	0
TSPA	TILAPIA SPARRMANII SMITH. 1840	3.00	1	1	0
Response of species with a preference/tolerance to			May	Aug	Nov
Velocity Depth Metric	Fast-Deep		-2	-2	-2
	Fast-Shallow		-2	-2	-2
	Slow-Deep		-3	-4	-4
	Slow-Shallow		-2	-3	-3
Cover features	Overhanging veg		4	3	3
	Undercut banks		3	3	2
	Substrate		3	3	3
	Instream veg		1	3	4
	Water column		1	3	3
Response of species that are			May	Aug	Nov
Flow dependance	Intolerant to no flow		-1	-1	-1
	Moderately intolerant to no flow		0	-1	-1
	Moderately tolerant to no flow		-4	-4	-4
	Tolerant to no flow		-3	-3	-3
Response of species that are			May	Aug	Nov
Physico-chemical conditions	Intolerant to modified physico-chemical conditions		-2	-2	-2
	Moderately intolerant to modified physico-chemical conditions		-2	-4	-4
	Moderately tolerant to modified physico-chemical conditions		-3	-4	-4
	Tolerant modified to physico-chemical conditions		-3	-4	-3

Response of which require		May	Aug	Nov
Migration	Catchment scale movement	1.5	1	1
	Movement between reaches	1	1	1
	Movement within a reach	2.5	2.5	2.5
Extent of the following in the reach		May	Aug	Nov
Changes in connectivity	Weirs and causeways	2	2	2
	Impoundments	1	1	1
	Physico-chemical barriers	3	3	3
	Flow modifications	1	1	1
Introduced/alien species		May	Aug	Nov
Introduced/alien species	Introduced/alien predacious species 1	-	-	MSAL
	Introduced/alien predacious species 2	-	-	-
	Introduced/alien predacious species 3	-	-	-
	Introduced/alien habitat modifying species 1	-	-	-
	Introduced/alien habitat modifying species 2	-	-	-
	The impact of introduced competing spp?	0	0	4
	FROC of introduced competing spp?	0	0	1
	The impactof introduced habitat modifying spp?	0	0	0
	FROC of habitat modifying spp?	0	0	0
AUTOMATED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		30.6	20.7	16.2
EC: FRAI		E	E/F	F
ADJUSTED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		54.0	44.1	40.3
EC: FRAI		D	D	D/E

Site Name U2MGEN-MZINY **Assessor** P Dlamini
River uMngeni **Reviewed** G O'Brien

ABR	SPECIES	REFERENCE FROC	OBSERVED FROC		
			May	Aug	Nov
AAEN	AWAOUS AENEOFUSCUS (PETERS 1852)	5.00	1	1	0
ABER	ACANTHOPAGRUS BERDA (FORSSKÅL. 1775)	3.00	0	0	0
ALAB	ANGUILLA BENGALENSIS LABIATA PETERS. 1852	5.00	0	0	0
AMAR	ANGUILLA MARMORATA QUOY & GAIMARD 1824	5.00	0	0	0

AMOS	ANGUILLA MOSSAMBICA PETERS 1852	5.00	0	0	0
ANAT	AMPHILIUS NATALENSIS BOULENGER. 1917	5.00	0	0	0
BANO	BARBUS ANOPLUS WEBER. 1897	5.00	0	0	0
BGUR	BARBUS GURNEYI GÜNTHER. 1868	5.00	0	0	0
BNAT	BARBUS NATALENSIS CASTELNAU. 1861	5.00	0	0	1
BPAL	BARBUS PALLIDUS SMITH. 1841	5.00	0	0	0
BVIV	BARBUS VIVIPARUS WEBER. 1897	5.00	0	0	0
CGAR	CLARIAS GARIEPINUS (BURCHELL. 1822)	5.00	0	1	0
GAES	GILCHRISTELLA AESTUARIA (GILCHRIST. 1913)	3.00	0	0	0
GCAL	GLOSSOGOBIUS CALLIDUS SMITH. 1937	3.00	0	0	0
GGIU	GLOSSOGOBIUS GIURIS (HAMILTON-BUCHANAN. 1822)	3.00	0	0	0
LMCR	LIZA MACROLEPIS (SMITH. 1846)	3.00	0	0	0
MARG	MONODACTYLUS ARGENTEUS (LINNAEUS. 1758)	3.00	0	0	0
MBRA	MICROPHIS BRACHYURUS BLEEKER. 1853	3.00	0	0	0
MCAP	MYXUS CAPENSIS (VALENCIENNES. 1836)	3.00	0	0	0
MCEP	MUGIL CEPHALUS LINNAEUS. 1758	3.00	0	0	0
MFLU	MICROPHIS FLUVIATILIS (PETERS. 1852)	1.00	0	0	0
OMOS	OREOCHROMIS MOSSAMBICUS (PETERS. 1852)	5.00	0	1	0
PPHI	PSEUDOCRENILABRUS PHILANDER (WEBER. 1897)	5.00	2	3	1
RDEW	REDIGOBIUS DEWAALI (WEBER. 1897)	3.00	0	0	0
TREN	TILAPIA RENDALLI (BOULENGER. 1896)	5.00	1	0	0
TSPA	TILAPIA SPARRMANII SMITH. 1840	5.00	0	0	0

Response of species with a preference/tolerance to		May	Aug	Nov
Velocity Depth Metric	Fast-Deep	-3	-3	-2
	Fast-Shallow	-3	-3	-2
	Slow-Deep	-4	-3	-3
	Slow-Shallow	-4	-3	-3
Cover features	Overhanging veg	3	3	3
	Undercut banks	4	3	3
	Substrate	4	4	4
	Instream veg	4	4	4
	Water column	4	4	3

Response of species that are		May	Aug	Nov
Flow dependance	Intolerant to no flow	-2	-2	-2
	Moderately intolerant to no flow	-3	-3	-2

		May	Aug	Nov
	Moderately tolerant to no flow	-4	-4	-4
	Tolerant to no flow	-2	-2	-4
Response of species that are		May	Aug	Nov
Physico-chemical conditions	Intolerant to modified physico-chemical conditions	-2	-2	-2
	Moderately intolerant to modified physico-chemical conditions	-3	-3	-3
	Moderately tolerant to modified physico-chemical conditions	-4	-4	-2.5
	Tolerant modified to physico-chemical conditions	-3	-3	-3
Response of which require		May	Aug	Nov
Migration	Catchment scale movement	2.5	2.5	3
	Movement between reaches	2.5	2	3
	Movement within a reach	2	2	3
Extent of the following in the reach		May	Aug	Nov
Changes in connectivity	Weirs and causeways	3	3	3
	Impoundments	3	3	3
	Physico-chemical barriers	1	1	1
	Flow modifications	3	3	3
Introduced/alien species		May	Aug	Nov
Introduced/alien species	Introduced/alien predacious species 1	MSAL		
	Introduced/alien predacious species 2	-		
	Introduced/alien predacious species 3	-		
	Introduced/alien habitat modifying species 1	-		
	Introduced/alien habitat modifying species 2	-		
	The impact of introduced competing spp?	4		
	FROC of introduced competing spp?	1		
	The impactof introduced habitat modifying spp?	0		
	FROC of habitat modifying spp?	0		
AUTOMATED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		12.3	17.2	14.3
EC: FRAI		F	F	F
ADJUSTED FISH RESPONSE ASSESSMENT INDEX SCORE				
FRAI (%)		37.2	44.1	44.0
EC: FRAI		E	D	D

CHAPTER 3:

Assessing the state of *Labeobarbus natalensis* (Castelnau, 1861) populations in impoundments along the uMngeni River, KwaZulu-Natal Province, South Africa

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Running header: State of *Labeobarbus natalensis* in impoundments.

3.1 Abstract

Impoundments (dams) play a relativelyimportant role in anthropogenic developments through the many services they provide, such as water supply, irrigation and the production of hydropower. However, there is still much debate as to whether the benefits of impoundments outweigh the negative impacts, they can have on river systems. Barriers in rivers caused by impoundments and weirs are especially harmful to migratory fish because of the restriction these barriers have on their longitudinal movement. In this study we assessed the population structures of the endemic migratory fish, the KwaZulu-Natal yellowfish *Labeobarbus natalensis*, in four large instream impoundments (namely Midmar, Albert Falls, Nagle and Inanda Dam) on the uMngeni River, KwaZulu-Natal Province, South Africa, in order to update the state of *L. natalensis* wellbeing in the uMngeni River. This study showed how *L. natalensis* populations in these four large instream impoundments progressively diminished, both in abundance and structure, as both the quality and quantity of water diminished down the catchment gradient. The absence of juvenile and smaller adult *L. natalensis* in all the impoundments illustrated how the nature of water impoundments were not well suited for small fish because impoundments lack the suitable habitat they require (namely shallow riffles) and often harbour alien and larger predatory fishes that prey on small fish. The possible construction of fish passages and removal of redundant weirs or partial man-made barriers is recommended in order to mitigate the many negative effects of fragmentation on *L. natalensis*. We also recommend further studies on migration cues to assist water resource managers when to release flood flows as well as *L. natalensis* population genetics studies to understand the full extent of impoundment fragmentation.

Keywords: *Labeobarbus natalensis, uMngeni River,* dam fragmentation, state of wellbeing.

3.2 Introduction

The construction of impoundments (dams) has played a relatively major role in anthropogenic infrastructure development and local communities through the services that they provide, such as water supply, irrigation and the production of hydropower (Kuby et al. 2005; ICOLD 2016). The water supply that impoundments provide is especially important in developing countries such as South Africa, given the dry climate (ICOLD 2016; Steyn et al. 2019). There is still much debate as to whether the benefits of impoundments out way the negative impacts they have on river systems (Joyce 1997; Altinbilek 2002; Kuby et al. 2005; Rufin et al. 2019; Schulz and Adams 2019). Such impacts include loss of river connectivity, changing instream habitat and altered flow regimes, all of which can have several detrimental effects on river ecosystems (Kuby et al. 2005; Dugan et al. 2010; McIntyre et al. 2016; Grill et al. 2019).

Most river systems have lost their original connectivity as a result of barriers in the form of impoundments and weirs (Jager et al. 2001; Birnie-Gauvin et al. 2018; Grill et al. 2019) with over 60% of all large rivers (i.e. >1000 km in length) around the world affected by fragmentation (ICOLD 2016). Impoundments alter aquatic ecosystems through water temperature changes, channelisation, sediment deposition and flooding (Poff et al. 1997; Poff and Hart 2002; Walter and Merritts 2008; Hall et al. 2011; McIntyre et al. 2016; Grill 2019). These environmental changes also mean that the fragmentation that impoundments cause in rivers is a threat to the diversity, abundance, and sustainability of aquatic species in river ecosystems (Saunders et al. 1991; Dynesius and Nilsson 1994; Nilsson et al. 2005; Seliger and Zeiringer 2018). River fragmentation is especially harmful to migratory fish species (Hall et al. 2011; Gao et al. 2019; Fouchy 2019).

Barriers in rivers caused by impoundments and weirs are harmful to migratory fish because of the restriction these barriers have on the fishes' longitudinal movement (Fagan 2002; Fullerton et al. 2010). Impoundments hinder fish migration between feeding and spawning sites, thus altering food webs (Pringle et al. 2000; Hall et al. 2011; McIntyre et al. 2016). The habitat loss that impoundments cause further results in population loss caused by fragmentation, altered food webs and loss of aquatic biodiversity (Rosenberg et al. 2000; Jackson et al. 2001; Pess et al. 2008; Morita et al. 2009; Seliger and Zeiringer 2018).

Not maintaining river connectivity can have great detrimental effects on fish community structures (Joy and Death 2001; Freeman et al. 2003; Park et al. 2003; Gao et al. 2019). When Santos et al. (2013) compared fish community structures in impoundments to those in the river stretch below the impoundment, they found that the community structure downriver had greater diversity and more migratory species. Similarly, in a study on the migration of brown trout (*Salmo trutta*), it was found that the removal of barriers increased spawning success of adults, fry survival, recruitment, and smolt migration success (Birnie-Gauvin et al. 2018).

Fish are regularly used as key indicators when assessing the ecological state of aquatic ecosystems (Karr 1981; Barbour et al. 1999; Maceda-Veiga and De Sostoa 2011; Burnett et al. 2018; Ramesh et al. 2018). Yellowfish (*Labeobarbus* spp), in particular, are good indicators of freshwater ecosystem health, as they are abundant throughout KwaZulu-Natal Province and are considered to be a hardy species towards water quality (Impson et al 2008; Burnett et al. 2018).

The KwaZulu-Natal yellowfish, *Labeobarbus natalensis* (Castelnau, 1861), commonly known as the scaly, forms part of the Cyprinidae family (Skelton 2001). This species is one of seven different yellowfish (*Labeobarbus* spp.) in South Africa (Skelton 2001; Impson et al. 2008). This South African yellowfish is endemic to KwaZulu-Natal Province and is widely distributed, occurring in all major catchments from the Mtamvuna River (Eastern Cape border) to the Mkuze River in the north. It is the most widespread yellowfish (and possibly freshwater fish) in KwaZulu-Natal Province (Karssing 2007). *Labeobarbus natalensis* can be found in a range of different habitats but prefers habitats in the middle reaches of rivers that have a combination of deep pools and fast-flowing rapids and riffles (Karssing 2007; Jacobs 2017).

Labeobarbus natalensis are long-living and can grow to up to ~640 mm (maximum length) and ~4.6 kg (Skelton 2001). Adult fish colour may vary, however commonly are olive above with bronze sides and a cream ventral, while fry are silver with dark spots (which they lose as juveniles) (Karssing 2007). *Labeobarbus natalensis* are opportunistic, omnivorous feeders, feeding on filamentous algae, diatoms, organic waste, aquatic plants, insect larvae, and crabs (Roux 2007). *Labeobarbus natalensis* can thrive in a range of river conditions and habitats (such as pools and impoundments), but are more selective when spawning and as such, migrate upstream into rivers for suitable sites (Karssing 2007).

Labeobarbus natalensis migrates seasonally (spring and early summer) upstream from the low and middle reaches into rivers in order to search for spawning and feeding sites (Karssing 2007). *Labeobarbus natalensis* spawn in fast-flowing riffles (high oxygen content) over a gravel and cobble substrate free of any silt because larvae are unable to burrow in silt-covered gravel and thus would be susceptible to predation or displacement (Wright and Coke 1975a; 1975b). Unfortunately, the presence of instream impoundments and weirs throughout KwaZulu-Natal Province has slowed down floods that would otherwise wash away silt, particularly silt that has formed as a result of erosion from poor agricultural practices (Karssing 2007). Additionally, impoundments trap sediment from naturally turbid water, resulting in a discharge that is relatively clear. This makes the fish in the river stretch downstream of the impoundments more vulnerable to predation (Figueiredo et al. 2016). When it is migrating season (normally October/November) and temperatures and habitat are favourable, mature breeding *L. natalensis* adults, sub-adults and juveniles migrate upstream. However, when there are impenetrable barriers (such as impoundments) migration is not possible, especially into the upper reaches (Wright and Coke 1975a; Karssing 2007).

Labeobarbus natalensis is currently regarded as least concern (Cambray et al. 2017), however, the species may be in decline because of the continual pressure placed on the aquatic environment and fragmentation of the population because of barriers (both chemical and physical barriers) (Skelton 2001; Karssing 2007). Karssing (2007) recommended regular surveys in order to monitor the state of the *L. natalensis*, particularly in areas where they are most vulnerable, importantly the uMngeni River (Karssing 2007; Stobie et al. 2018). *Labeobarbus natalensis* is fairly tolerant of anthropogenic habitat change, however, it is still threatened by chronic pollution, siltation, physical habitat changes, and increased water abstraction, all of which are mostly associated with urbanisation (such as in Durban and Pietermaritzburg) (Karssing 2007). Pollution is known to cause disfigured fins, scales and mouthparts in the *L. natalensis* (Impson et al. 2008). The fungal infection *Saprolegnia* (an indication of stress) is also known to develop in *L. natalensis* that are found in polluted water, particularly near the end of winter (Oldewage 1987). This has been evident in the Msunduzi River where several fish kills have been observed over the last decade because of pollution events (Karssing 2007; pers. obs.). These pollution events that happen in the upper catchment may threaten the quality of the water supply to Durban if not mitigated (Graham and Dickens 1998; Nel et al. 2007). River fragmentation can also affect the presence or absence of fish and reduces genetic variance within populations, this is concerning because of the presence of four large in-stream impoundments in the uMngeni River (namely Midmar Dam, Albert Falls Dam, Nagle Dam, and Inanda Dam) (Neraas and Spruell 2001; Hartfield 2010; Helms et al. 2011; Zhai et al. 2019). These impoundments further reduce and or release irregular out of season downstream flows, altering downstream water quality, habitat and biotic integrity (WRC 2006; Karssing 2007).

Other threats to the *L. natalensis* include illegal netting, particularly at spawning grounds, as well as hybridisation with translocated Orange-Vaal smallmouth yellowfish

(*Labeobarbus aeneus*) that are now present in the upper Thukela catchment. Karssing (2007) also noted that inter-basin water transfers or direct stocking for angling purposes may result in intraspecific hybridisation with genetically distinct *L. natalensis* from different river systems. There is now some genetic evidence (though limited) of intraspecific hybridisation between *L. natalensis* populations in the Thukela and uMngeni catchments (Stobie et al. 2018). The increasing threat by alien fish such as largemouth bass (*Micropterus salmoides*), and common carp (*Cyprinus carpio*) on native fish, including *L. natalensis*, is also a source of major concern, similarly with extralimital species such as the *L. aenues* (Impson et al. 2008; Swartz 2008). These species compete directly for food resources, habitat and will prey on juvenile *L. natalensis* (Koehn 2004; Karssing 2007).

Our aim in the present study was to update the state of *L. natalensis* wellbeing in the major uMngeni River dams considering river fragmentation caused by the impoundments themselves. We, therefore, surveyed *L. natalensis* population structures in the four large instream impoundments on the uMngeni River, namely Midmar Dam, Albert Falls Dam, Nagle Dam and Inanda Dam, and assessed fish community structures within the impoundments. We hypothesised that *L. natalensis* populations in dams along the uMngeni River act as ecological indicators, responding to environmental change (abiotic drivers), namely changes in habitat and water quality caused by artificial impoundments. We predicted that the wellbeing of *L. natalensis* populations in the major uMngeni dams would be compromised and that they would be further affected by migratory barriers.

3.3 Methods

3.3.1 Study area

The study area comprised four instream impoundments (Midmar, Albert Falls, Nagle, and Inanda Dam) in the uMngeni River, within the uMngeni catchment (Fig. 3.1). Midmar Dam is located at the highest point in the catchment (relative to the other three impoundments) and is supplied by the uMngeni River, as well as the Lions River, and streams Gqishi and Nguklu. Downstream of Midmar Dam, the uMngeni River is joined by the Karkloof River tributary after which it flows into Albert Falls Dam in the Midlands area, near Pietermaritzburg. After Albert Falls Dam, the uMngeni River is joined by the Mpolweni tributary and after flowing through the Wartburg area is joined by Mkabela River before finally flowing into Nagle Dam (the smallest of the four impoundments) in Nonzila, KwaZulu-Natal. Downstream of Nagle Dam, the uMngeni River is joined by the Msunduzi tributary, and after moving through the Rural area of Valley of a 1000 Hills, it enters Inanda Dam. Below Inanda Dam the uMngeni River flows through the city of Durban and out to sea at Blue Lagoon.

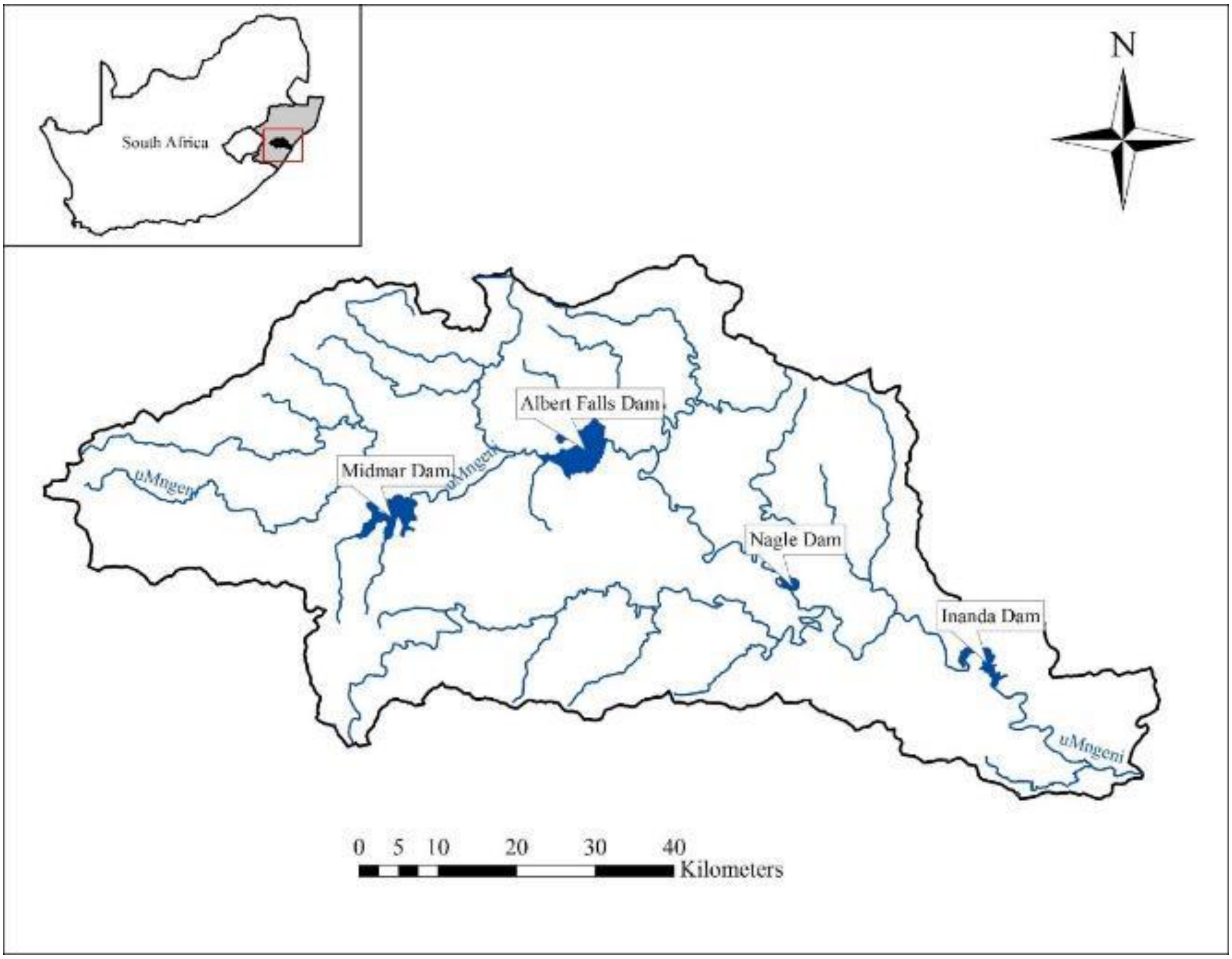

Fig. 3.1: Map of the four study impoundments, on the uMngeni River in KwaZulu-Natal, South Africa in the present study.

Table 3.1: Impoundment capacity at the time of the present study (adapted from DWA 2018).

Impoundment	Full storage capacity (million m^3)	Percentage (%)	Outflow (m^3/s)	Accessed
Midmar Dam	325.4	99.09	3.04	27 June 2018
Albert falls Dam	290	51.99	3.04	27 July 2018
Nagle Dam	24.6	73.46	0.61	11 July 2018
Inanda Dam	251.6	73.04	0.54	4 July 2018

3.3.2 Field sampling

Fish sampling at all the impoundments took place between 24 June and 28 July 2018 (low-flow season). The surveys in this study were carried out with the approval from Ezemvelo KZN Wildlife (permit number: OP143-2018) and management at each impoundment. Fish were collected using gill nets, fyke nets and seine nets (Tables 3.2 - 3.5) according to suitable areas. At each impoundment, samples were taken at the inlet (or upper reach) area, middle reach and at the wall (or lower reach) in order to get a good representation of fish in the entire impoundment (Fig. 3.2 - 3.5). In each of the three impoundment areas (inlet/middle/wall), five fyke nets were deployed during a daytime session and an evening session. The nine gill nets were randomly joined together into three sections which were deployed during the daytime sessions. Only the 57 mm and 93 mm bar mesh gill nets were used in the evenings in order to minimise fish mortality. Where there was suitable shallow habitat, a medium seine net (7 m, 1 m bag, 4 mm mesh) was used to collect fish. During each survey, several water quality variables were collected *in situ* using a calibrated Eutech PCD 650 multimeter (EUTECH Instruments Ltd, Singapore). Each fish collected was measured for standard length (SL), which was used to analysis population structures according to age groups/classes (Russell and Skelton 2005). The available habitat was visually assessed and described as best as possible according to cover and substrate type and velocity/depth (Kleynhans 1999) in each impoundment area sampled.

Table 3.2: Sampling efforts at Midmar Dam in the present study.

Sampling method		Specifications	Efforts	Inlet/Upper reach		Middle reach		Wall/Lower reach	
				Daytime	**Overnight**	**Daytime**	**Overnight**	**Daytime**	**Overnight**
Gill nets	16 mm	25 m weighted and floated segment	Hours in the water	2	-	4	-	2.5	-
	28 mm			3	-	3	-	3.5	-
	35 mm			3	-	3	-	3.5	-
	45 mm			2	-	4	-	2.5	-
	57 mm			3	20	4	16	3.5	17
	73 mm			2	-	4	-	2.5	-
	93 mm			3	20	4	16	3.5	17
	105 mm			3	-	4	-	3.5	-
	125 mm			3	-	3	-	3.5	-
Fyke nets	Large (x 5)	2 × 6 m trap, 1 m x 1.5 m opening, 1 × 10 m single leader, 18 mm mesh	Hours in the water	4	17.5	4	19	4	16.5
				4.5	17	3	19.5	4	16.5
				4	18	3	19	3.5	15.5
				3.5	18.5	4	18.5	3.5	15
				4	19.5	4	19	3.5	14.5
Seine nets		7 m, 1 m bag, 4mm mesh	Pulls	3	-	3	-	3	-

Table 3.3: Sampling efforts at Albert falls Dam in the present study.

Sampling method		Specifications	Efforts	Inlet/Upper reach		Middle reach		Wall/Lower reach	
				Daytime	Overnight	Daytime	Overnight	Daytime	Overnight
Gill nets	16 mm	25 m weighted and floated segment	Hours in the water	4	-	3	-	4	-
	28 mm			4.5	-	3.5	-	4.5	-
	35 mm			4.5	-	3.5	-	4.5	-
	45 mm			4	-	3	-	4	-
	57 mm			2	15	4	18	4	17
	73 mm			4	-	3	-	4	-
	93 mm			2	15	4	18	4	17
	105 mm			2	-	4	-	4	-
	125 mm			4.5	-	3.5	-	4.5	-
Fyke nets	Large (x 5)	2 × 6 m trap, 1 m x 1.5 m opening, 1 × 10 m single leader, 18 mm mesh	Hours in the water	4.5	18	4	18	4.5	17
				4	18	4	18.5	4.5	16.5
				4.5	18	3	19	4	16
				4	18	2.5	19	4	16
				6	17.5	2.5	19.5	3.5	16
Seine nets		7 m, 1 m bag, 4mm mesh	Pulls	3	-	-	-	-	-

Table 3.4: Sampling efforts at Nagle Dam in the present study.

Sampling method		Specifications	Efforts	Inlet/Upper reach		Middle reach		Wall/Lower reach	
				Daytime	Overnight	Daytime	Overnight	Daytime	Overnight
Gill nets	16 mm	25 m weighted and floated segment	Hours in the water	3	-	3	-	4	-
	28 mm			3	-	3	-	4.4	-
	35 mm			3	-	3	-	4.5	-
	45 mm			3	-	3	-	4	-
	57 mm			2.5	16	4	14.5	4	20.5
	73 mm			3	-	3	-	4	-
	93 mm			2.5	16	4	14.5	4	20.5
	105 mm			2.5	-	4	-	4	-
	125 mm			3	-	3	-	4.5	-
Fyke nets	Large (x 5)	2 × 6 m trap, 1 m x 1.5 m opening, 1 × 10 m single leader, 18 mm mesh	Hours in the water	4	17	4	19	4	18.8
				4	17.5	4	19	4	19
				4	17	4	18	4	19
				4	17	3.5	19.5	4	-
				4.5	16.5	3.5	18.5	4	-
Seine nets		7 m, 1 m bag, 4mm mesh	Pulls	3	-	3	-	3	-

Table 3.5: Sampling efforts at Inanda Dam in the present study.

Sampling method		Specifications	Efforts	Inlet/Upper reach		Middle reach		Wall/Lower reach	
				Daytime	**Overnight**	**Daytime**	**Overnight**	**Daytime**	**Overnight**
Gill nets	16 mm	25 m weighted and floated segment	Hours in the water	2.5	-	5.5	-	3	-
	28 mm			2.5	-	6	-	3	-
	35 mm			2.5	-	6	-	3	-
	45 mm			2.5	-	5.5	-	3	-
	57 mm			3	17	6	16	2.5	15
	73 mm			2.5	-	5.5	-	3	-
	93 mm			3	17	6	16	2.5	15
	105 mm			3	-	6	-	2.5	-
	125 mm			2.5	-	6	-	3	-
Fyke nets	Large (x 5)	2 × 6 m trap, 1 m x 1.5 m opening, 1 × 10 m single leader, 18 mm mesh	Hours in the water	5	16	5	16.5	5	15
				4	17	5	16	5	15
				5.5	16	5	16	4.5	15
				5	17	5.5	16	4	15
				5	17	-	-	5	16
Seine nets		7 m, 1 m bag, 4mm mesh	Pulls	-	-	3	-	3	-

Fig. 3.2: Satellite image of survey sites on Midmar Dam, KwaZulu-Natal, adapted from Google. (n.d.).

Fig. 3.3: Satellite image of survey sites on Albert Falls Dam, KwaZulu-Natal, adapted from Google. (n.d.).

Fig. 3.4: Satellite image of survey sites on Nagle Dam, KwaZulu-Natal, adapted from Google. (n.d.).

Fig. 3.5: Satellite image of survey sites on Inanda Dam, KwaZulu-Natal, adapted from Google. (n.d.).

3.3.3 Statistical analyses

The data collected (count data), violated the assumptions of the analysis of variance (ANOVA) (even when transformed) and so Generalised Linear Models (Poisson distribution) (in SPSS version 25, IBM Inc. 2017) were used instead to analyse the data (Quinn and Keough 2002).

3.4 Results

3.4.1 Catch effort

A total of 10 fish species were collected in this study during a single assessment of the three sites (inlet, middle and lower reach) per impoundment. This resulted in a total abundance of 228 fish, of which *L. natalensis* was most common (n = 70), followed by *Lepomis macrochirus* (n = 42), *Oreochromis mossambicus* (n = 34), *Coptodon rendalli* (n = 27) and *Clarias gariepinus* (n = 24) (Table 3.6). *Oreochromis mossambicus*, *C. gariepinus* and *Micropterus salmoides* were caught in all the impoundments, while *Lepomis macrochirus* was not caught in Albert falls Dam and *C. rendalli* and *Cyprinus carpio* were not caught in Midmar Dam. Other uncommon species in this study included *Tilapia sparrmanii*, of which only a single individual was caught in Nagle Dam, as well as *Micropterus punctulatus* and *Anguilla mossambica* that were limited in both numbers and distribution among the impoundments surveyed (Table 3.6). Midmar Dam had the most *L. natalensis* caught there (n = 51) followed by Albert falls Dam (n = 13) and Nagle Dam (n = 6). No *L. natalensis* were caught in Inanda Dam (Fig. 3.6).

Table 3.6: Summary of fish species caught in, Midmar, Albert falls, Nagle and Inanda Dam, KwaZulu-Natal, South Africa in the present study.

Species name	FRAI Abbreviations	Midmar	Albert Falls	Nagle	Inanda	Species abundance
Labeobarbus natalensis	LNAT	51	13	6	-	70
Oreochromis mossambicus	OMOS	8	20	1	5	34
Lepomis macrochirus	CMAC	6	-	17	19	42
Coptodon rendalli	CREN	-	3	10	14	27
Tilapia sparrmanii	TSPA	-	-	1	-	1
Clarias gariepinus	CGAR	5	15	1	3	24
Cyprinus carpio	CCAR	-	10	1	3	14
Micropterus salmoides	MSAL	2	2	1	2	7
Micropterus punctulatus	MPUN	1	-	-	3	4
Anguilla mossambica	AMOS	-	-	1	4	5
Impoundment total abundance		**73**	**63**	**39**	**39**	
Impoundment species richness		**6**	**6**	**9**	**8**	

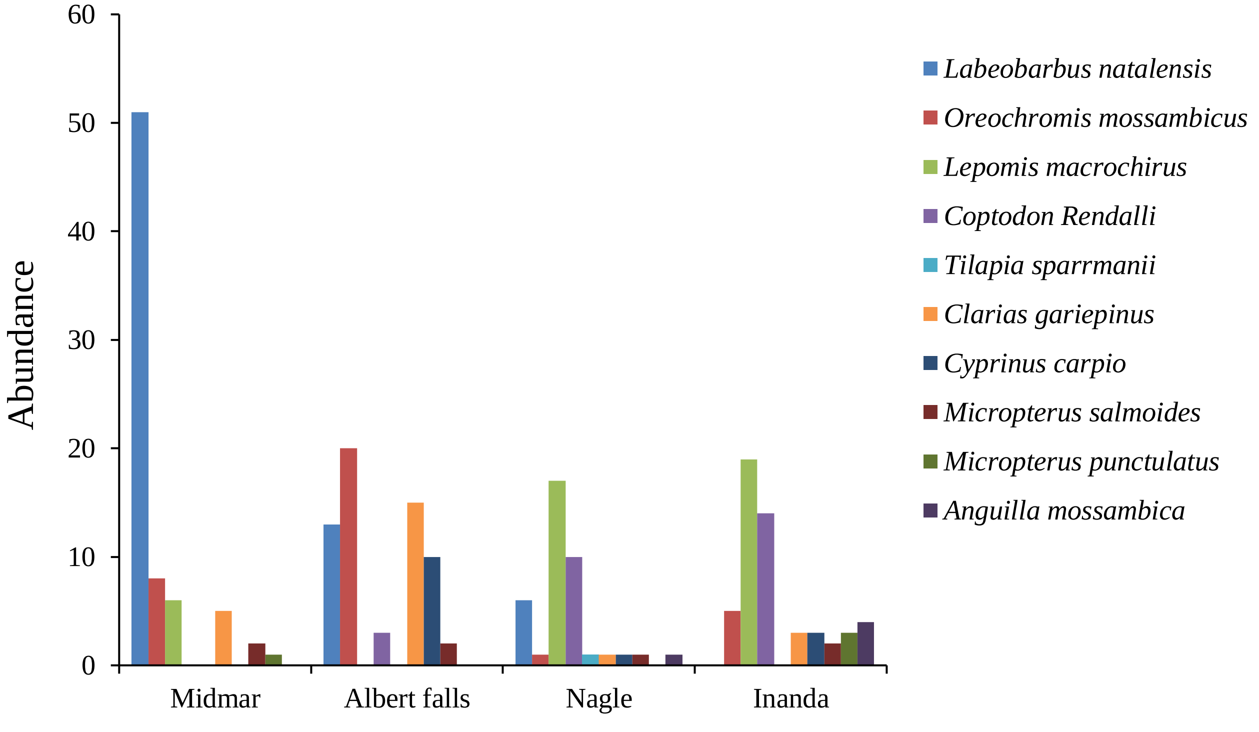

Fig. 3.6: Species abundance and richness of fish caught in Albert Falls Dam, Midmar Dam, Inanda Dam and Nagle Dam, KwaZulu-Natal, South Africa in the present study.

3.4.2 Labeobarbus natalensis abundance (overall) and populations

In this study, a total of 70 *L. natalensis* individuals were caught between Midmar Dam, Albert Falls Dam and Nagle Dam. *Labeobarbus natalensis* was not evenly distributed between the four impoundments ($P < 0.0001$) with 51 *L. natalensis* individuals caught from Midmar Dam, 13 individuals from Albert Falls Dam, six from Nagle Dam and none from Inanda Dam (Fig. 3.7). Midmar Dam had a significantly higher *L. natalensis* abundance than all the other impoundments ($P < 0.0001$). Albert Falls Dam had an *L. natalensis* abundance that was greater than that of Inanda Dam ($p = 0.002$), however, it was not significantly greater than that of Nagle Dam ($p = 0.685$). Although there were no *L. natalensis* caught in Inanda, the *L. natalensis* abundance found in Nagle was so low that there was no significant difference between the two Dams ($p = 0.083$).

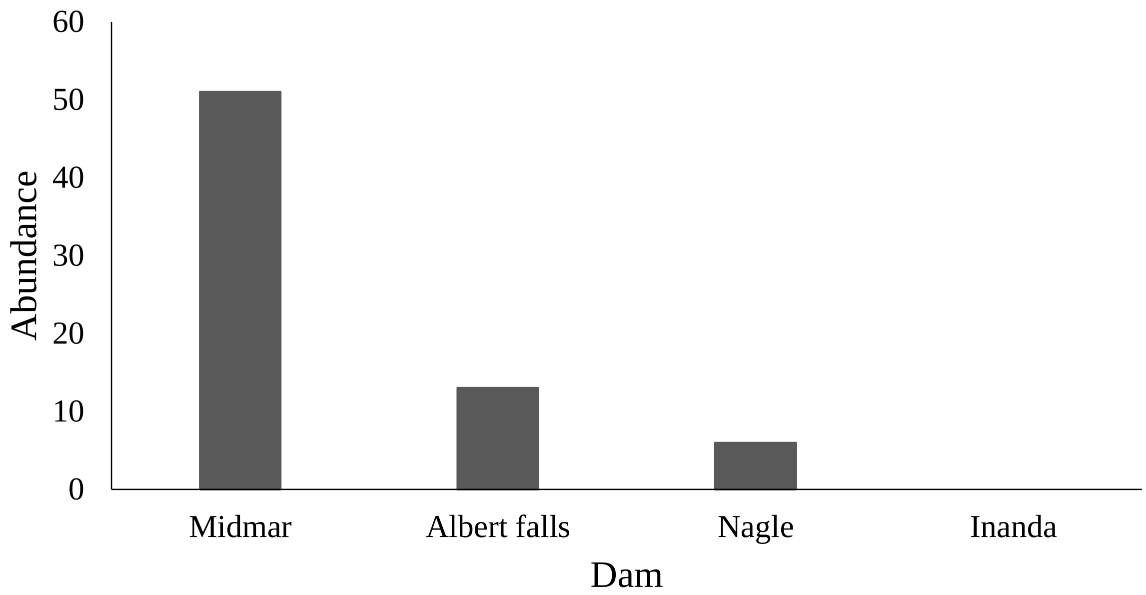

Fig. 3.7: Abundance of *L. natalensis* caught in Albert Falls Dam, Midmar Dam, Inanda Dam and Nagle Dam, KwaZulu-Natal, South Africa in the present study.

3.4.3 Labeobarbus natalensis population structure

Of the 70 *L. natalensis* caught, 66 were large adult fish (>350 mm) and these were dominant in all three impoundments (P < 0.0001). A few individuals that fell within the 150-199 mm and 200-249 mm range were also caught in Midmar Dam. The population structure of *L. natalensis* caught in Midmar was heavily weighted towards the adult size class, most of which were above 350 mm in length (SL) with just a few individuals in the 150-199 mm and 200-249 mm ranges (Fig. 3.6). *Labeobarbus natalensis* catches in Nagel Dam were minimal and, again, mainly within the adult size class (n = 6) (Table 3.6; Fig. 3.6).

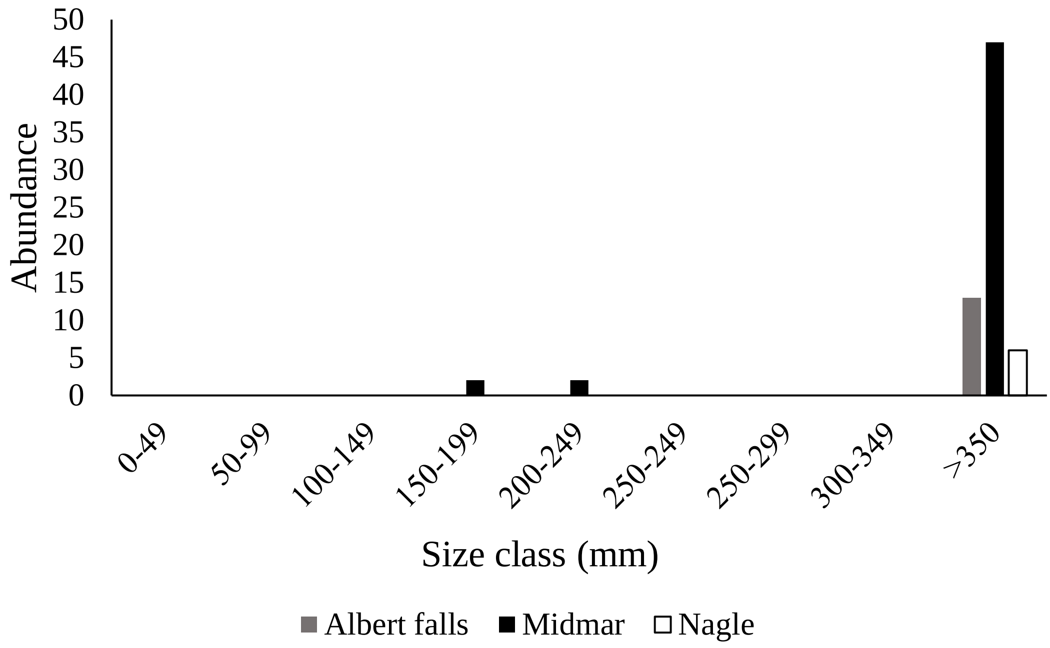

Fig. 3.8: Population structure of *L. natalensis* in Albert Falls Dam, Midmar Dam and Nagle Dam, KwaZulu-Natal, South Africa in the present study.

3.5 Discussion

Labeobarbus natalensis are good indicators of freshwater ecosystem health, as they are generally abundant throughout KwaZulu-Natal Province and considered to be a hardy species towards water quality (Karssing 2007). Their migratory nature, however, makes them potentially vulnerable to the effects of river fragmentation by impoundments and their sensitivity to flow changes as is the case with other *Labeobarbus* species (O'Brien et al. 2013; Burnett et al. 2018). *Labeobabrus natalensis* are known to move between refugia habitat in the winter, often large instream pools to spawning habitat within faster flowing rapid habitats (Karssing 2007). Large impoundments can serve the same purpose as these instream pools, providing refuge habitat for aquatic organisms, including fish (Tonkin et al. 2014; Beatty et al. 2017). However, the size of these pools needs to be sufficient to support a population and whether large impoundments can negatively affect refugia habitat for *L. natalensis* in winter remains unclear. The overall abundances of *L. natalensis* that were observed in this study indicated that the species could adapt well to some impoundment environments, although it was concerning that no *L. natalensis* were caught in Inanda Dam. Another major concern is that the population structure mainly comprised of individuals from size classes greater than 350 mm. This is problematic because the absence of smaller individuals means that recruitment was compromised in these dams.

Overall, the results suggest that adult *L. natalensis* may use some impoundments as refugia during winter or unfavourable conditions, where they likely find suitable deep habitat where large adults can survive and grow because of the cover features associated with impoundments, however, they still need to migrate into rivers to find suitable spawning habitat (Wright and Coke 1975a). Thus *L. natalensis* will move upstream from refugia habitat occupied in impoundments to breed and the state of the river upstream would affect recruitment success. The cues for when adult *L. natalensis* move upstream are still to be fully understood and could not be determined during this study. The river surveys conducted upstream of Midmar, Albert Falls and Nagel Dam (in Chapter 2), indicated the presence of *L. natalensis,* though in low numbers (Supplementary information, Fig. S3.1). *Labeobarbus natalensis* individuals caught in these river reaches were juvenile to small adults (150-199 mm) (Supplementary information, Fig. S3.2). The presence of juveniles indicated successful recruitment and the presence of small adults making recruitment possible despite poor abundances within impoundments (Karssing 2007). Noticeably, there were no large adults caught in the river surveys in these reaches (Supplementary information, Fig. S3.2), indicating the use of impoundments as refugia until migration cues are met. The exception being the reach between Albert Falls Dam and Nagle Dam where healthy abundances of differing size classes were found, despite low abundances found in Nagel Dam. The presence of weirs upstream of all the impoundments surveyed (Ramulifho 2015) is likely a big contributing factor in the poor population structure of *L. natalensis* in both the impoundments and the rivers that feed into them.

The lack of *L. natalensis* juveniles in all the surveyed impoundments indicated that juveniles most likely remain in rivers upstream because of the absence of suitable habitat and/or the presence of predatory fish such as *M. punctulatus* and *M. salmoides* (popular angling species, especially *M. salmoides*) (Skelton 2001). Other invasive alien fish in these dams included *L. macrochirus* which preys on indigenous fish and competes with them for resources as they tend to overpopulate waters as well as *C. carpio* which has destructive feeding habitats but is a valued aquaculture and angling species (Skelton 2001). The presence of alien fishes is known to have negative consequences for ecosystems, further adding stress to *L. natalensis* (particularly juveniles, which were lacking within the study) (Karssing 2007; Lopez 2018). Additionally, the type of habitat required by juveniles, i.e. fast-flowing riffles with gravel substrate free from silt (Wright and Coke 1975a; Karssing 2007), is lacking in these impoundments and they tend to naturally silt-up (Auerswald and Geist 2017).

Our results showed a clear difference between the impoundments for the abundances of *L. natalensis*. Each impoundment is placed in different reaches and altitudes in order to meet service delivery requirements for the eThekwini and uMgungundlovu municipalities respectively (Breen et al. 1985; Hay 2017). Abundances in catch increased the higher up the catchment the impoundment was situated, with Midmar having a significantly higher number of *L. natalensis*.

Although the *L. natalensis* numbers caught in Midmar Dam had the highest abundances, the population structure was not well represented across all sizes. The population structure of *L. natalensis* caught in Midmar was heavily weighted towards the adult size class, most of which were above 350 mm in length (SL). The *L. natalensis* populations in the Midmar Dam and upstream rivers may benefit from the generally good habitat and water quality in this region (Still et al. 2010), although streams Gqishi and Nguklu have been shown to have relatively poor water quality (Mahlobo 2016). However, the presence of alien fish and numerous small farm impoundments in the catchment (Ramulifho 2015) are detrimental. The many farm impoundments and weirs present in this area alter water flow (WRC 2002; Poff et al. 2010) and this, in turn, affects the habitats leading to Midmar Dam (McIntyre et al. 2016; Grill et al. 2019).

Down the catchment gradient of the uMngeni River from Midmar Dam to Albert Falls Dam, the presence of *L. natalensis* diminished. Similar to Midmar Dam, Albert Falls Dam catches consisted of only adult individuals, with significantly lower abundances. This is concerning as the movement of *L. natalensis* between Midmar Dam and Albert Falls Dam is restricted by several barriers and one natural barrier in the form of Howick falls (96 m high) (Ramulifho 2015). This greatly affects the connectivity between refugia habitat and spawning habitat. The lower abundances and poor population structure of *L. natalensis* in this impoundment suggests that perhaps the effects of river connectivity are greater here than in Midmar Dam. Furthemorer, one must consider the effects of discharge from Midmar Dam into this reach. The drought during the present study meant that no flood flows were able to be released, despite the maintenance of base flows. This is particularly concerning as the genus is known to be sensitivity changes in flow (Karssing 2007; Burnett et al. 2018).

The diversity of alien fish species present in Inanda Dam were higher than any other impoundment surveyed in this study. The alien fish caught in this dam included *M. punctulatus*, *M. salmoides*, *C. carpio*, and *L. macrochirus*. Invasive fish compete with *L. natalensis* for food resources and potentially prey on juvenile *L. natalensis* (Skelton 2001; Karssing 2007; Kimberg et al. 2014) and this is likely one of the reasons for the absence of *L. natalensis* in Inanda Dam and low presence in Nagle Dam and Albert Falls Dam.

Catches of *L. natalensis* in Nagel Dam were minimal and, again as in Midmar Dam mainly within the adult size class. The presence of gauging weirs around the impoundment and within the reach between Nagel Dam and Albert Falls Dam limit the movement of *L. natalensis* in and out of the impoundment (Ramulifho 2015). Within the impoundment, there are weirs segregating the inflow and outflow to the impoundment (Graham et al. 1998; pers obs.). This could be the main contributing factor for the low presence of *L. natalensis* considering that this reach is regarded as one of the healthiest reaches in the catchment, with enough tributaries to assist with naturalised flows (Dickens and Graham 1998; Ramulifho 2015). Interestingly one *A. mossambica* was caught in Nagle Dam and this species along with the presence of alien fishes could have negatively impacted the presence of *L. natalensis* as its diet includes fish (Skelton 2001).

The lack of *L. natalensis* surveyed within Inanda Dam is concerning, however, the trend found in this study (of diminishing *L. natalensis* abundances in impoundments moving down the catchment) suggests that *L. natalensis* are more mid-reach specific than previously thought (Karssing 2007), as they are so scarce in the lower reach dams. However, it must be noted that Inanda Dam had a high presence of *A. mossambica* sampled, and this species is highly predatory and seemingly with the presence of other alien fishes could have a greater negative effect on the presence of *L. natalensis*. All *Anguillid* spp. have migratory requirements that are hindered by the presence of large instream impoundments such as the ones in this study. Further, between Nagle Dam and Inanda Dam there is a total of 11 barriers in the uMngeni and Msunduzi River (Ramulifho 2015). These barriers include five weirs in the uMngeni River, four weirs on the Msunduzi River, excluding Henley Dam in the upper catchment of the Msunduzi River (Ramulifho 2015). In addition to these barriers, the Msunduzi is further impounded by Camps Drift, which is a canalised reach, altering the river's natural flow patterns. The degree to which this section of the uMngeni River is disconnected from other reaches in the catchment could be a contributing factor for the absence of *L. natalensis* in the Inanda Dam. This is because impoundments and barriers in the uMngeni River have altered natural flow regimes (Still et al. 2010), which can cause siltation and physical habitat change (Poff et al. 2010; Auerswald and Geist 2017), both of which are major threats to *L. natalensis* (Karssing 2007; Cambray et al. 2017).

Similar to the reaches between the other impoundments, *L. natalensis* was found within the river reach between Nagle and Inanda Dam (Chapter 2). This suggests that the population of *L. natalensis* is not entirely dependent on the presence of impoundments for refugia habitat, although the presence of large adult fish is important to the well-being of any population structure (Skelton 2001). This is also the longest reach between impoundments, if one includes the Msundzi River, which contains the Darvill wastewater treatment works and effluent received by the city of Pietermaritzburg, this does recover prior to entering the Inanda Dam.

3.6 Conclusions

The present study showed how *L. natalensis* populations in the four large instream impoundments on the uMngeni River progressively diminished, both in abundance and structure, down the catchment gradient. This supported the suggestion by Karssing (2007) that they are mid-reach species found between altitudes of 100 m to 1500 m above sea level, however, the water quality and quantity issues faced within the catchment have seemingly limited the species' presence in lower reaches (Chapter 2; pers. obs.). The further down the catchment the greater the compounded impact of water quality and quantity has on the system, despite ecosystem services provided by the river when given the chance (Jewitt 2002). The absence of juvenile and smaller adult *L. natalensis* in all the impoundments illustrated how the nature of water impoundments are not well suited for small fish. This is because impoundments lack the suitable habitat they require (namely shallow riffles) and harbour alien and larger predatory fishes that prey on small fish. The study also illustrated how the many impoundments and weirs in the uMngeni river system, the most fragmented in KwaZulu-Natal Province (Ramulifho 2015), has many negative effects on the systems as water impoundments severely alter aquatic habitats by altering natural flow regimes, change sedimentation dynamics and alter water quality. The reduction in flow that is often associated with rivers downstream of impoundments also causes siltation and algal blooms. The anthropogenic high demand for water is the main reason these four impoundments were built and is a case in which providing water resources for human well-being has taken precedence over the ecological functioning of the ecosystem. This is understandable given South Africa's uneven water distribution, but to what detriment to the ecosystem? The plight of *L. natalensis* in the uMngeni river catchment is relatively bleak and compounded by the introduction of alien fishes, in particular *Micropterus* spp. The fragmentation caused by barriers within the river system needs urgent attention to determine the effects of these barriers on, not only the genetic resilience of the species in question, but also the movement of other endangered species such as the *Anguillid* spp. Furthermore, these barriers should be mitigated; the lack of fish passages on all the four impoundments studied is concerning as no provision is made for river connectivity with the catchment. The removal of redundant weirs or partial man-made barriers should also be looked at to encourage the movement of *L. natalensis* within the river. Finally, the ecological flow requirements, with particular attention to flood releases, also need particular attention to know when and how to release these flows in order to maximise on benefiting the local fish populations. Further studies understanding migration cues of *L. natalensis,* as well as population genetics, are required to inform water resource managers on when to release flood flows.

3.7 Acknowledgements

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3.9 Supplementary Information

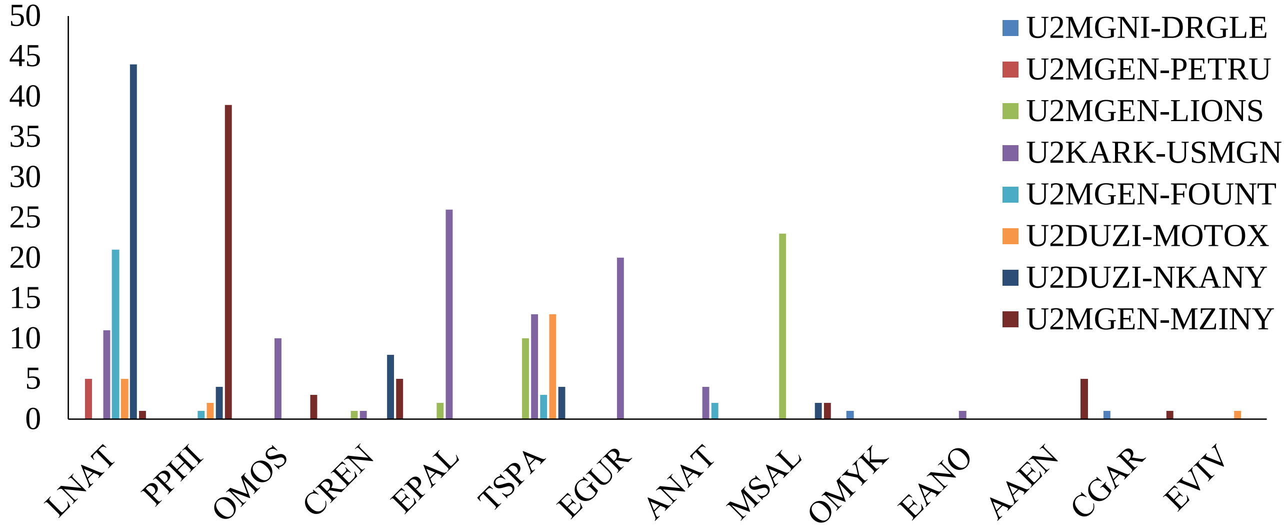

Fig. S3.1: Species abundance and richness of fish caught in river integrity assessment of uMngeni River, KwaZulu-Natal, South Africa. (Abbreviations as per Table S3.1)

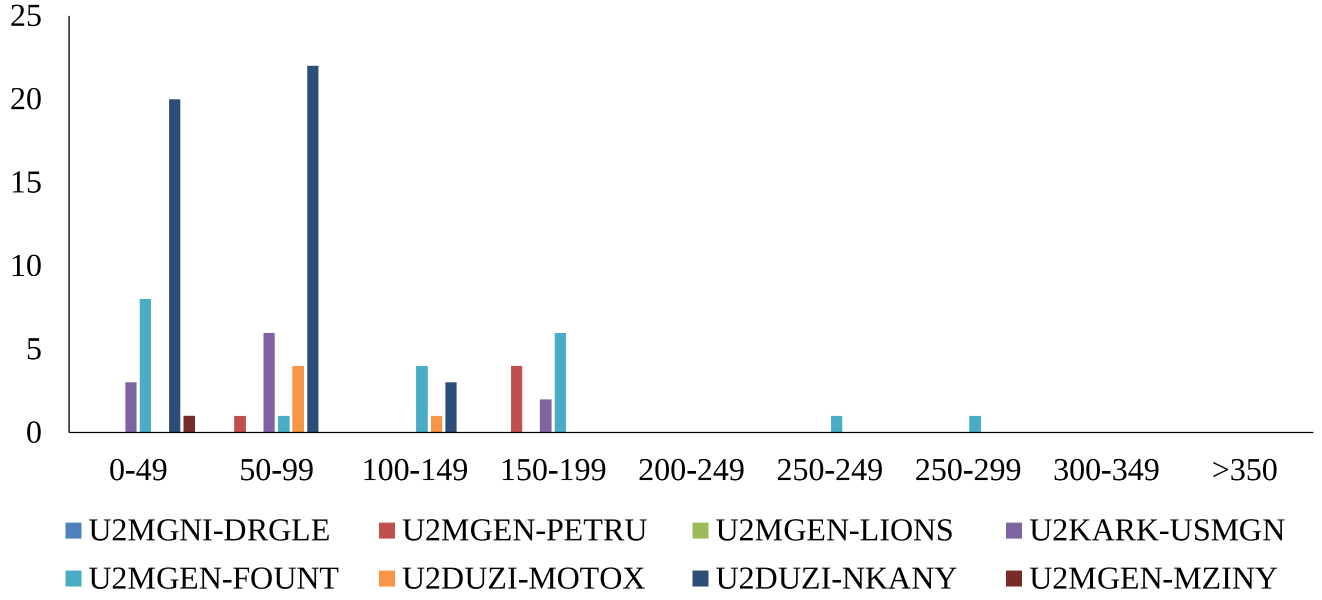

Fig. S1.2: Abundance of *L. natalensis* caught in river integrity assessment of uMngeni River, KwaZulu-Natal, South Africa. (Abbreviations as per Table S3.1)

Table S3.1: Species abbreviations.

Species name	Abbreviation
Labeobarbus natalensis	LNAT
Pseudocrenilabrus philander	PPHI
Oreochromis mossambicus	OMOS
Coptodon rendalli	CREN
Enteromius pallidus	EPAL
Tilapia sparrmanii	TSPA
Enteromius gurneyi	EGUR
Amphilius natalensis	ANAT
Micropterus salmoides	MSAL
Oncorhynchus mykiss	OMYK
Enteromius anoplus	EANO
Awaous aeneofuscus	AAEN
Clarias gariepinus	CGAR
Enteromius viviparus	EVIV

CHAPTER 4:

Conclusions

The main source of freshwater water for human use comes from rivers that are distributed throughout the landscape. They provide us with a range of ecosystem services such as water purification services, transportation, power generation, food supply, and water for domestic, agricultural and industrial use (Tejerina-Garro et al. 2005; Yeakley et al. 2016). The availability of water resources, and the ecosystem services that they provide, are especially important in developing countries, such as South Africa (ICOLD 2016; Steyn et al. 2019). The uMngeni River, for instance, provides water to two of the largest municipalities in KwaZulu-Natal province, namely the uMgungundlovu and eThekwini municipalities, making socially and economically valuable (Hay 2017; Sutherland and Mazeka 2019). To ensure that our access to resources in the uMngeni River is sustainable, the protection of this valuable freshwater resouce is important. Unfortunately, the impact of anthropogenic activities has resulted in riverine ecosystems becoming one of the most endangered ecosystems in the world (Rodell et al. 2018; Du Plessis 2019). And this is the case of parts of the uMngeni River (Namugize et al. 2018). To achieve sustainability, knowledge of the resource, its dynamics and requirements to protect it is required. One of the ways we can assess the ecological state of an aquatic ecosystem is through the use of fish species, which have often been used as key indicators owing to their sensitivity to environmental change, mobility, relatively long lifespan, and relative ease of species identification (Karr 1981; O'Brien et al. 2019; Chapter 1).

The present study evaluated the current ecological integrity of the uMngeni River in KwaZulu-Natal Province using multiple lines of evidence and by assessing the state of the KwaZulu-Natal yellowfish *Labeobarbus natalensis* wellbeing in the major instream dams in the uMngeni River. The ecological integrity was determined by driver and responder lines of evidence. The abiotic lines of evidence included water quality and habitat, while the biotic lines of evidence included fish community and *L. natalensis* population assessments.

The first main hypothesis for this study was that fish communities in the uMngeni River would act as ecological indicators, responding to environmental change (abiotic drivers), namely changes in habitat and water quality (Chapter 2). This hypothesis was accepted as the results in Chapter 2 indicated that the ecological integrity of the uMngeni River can be assessed by assessing changes in fish assemblages. The Fish Response Assessment Index (FRAI) showed that the ecological integrity of the uMngeni River tended to degrade from upper to lower reaches in response to various anthropogenic activities (Chapter 2). Multivariate analyses indicated that the anthropogenic impacts responsible for shifts in community structure (and therefore ecological integrity) were changes in velocity-depth classes, substrate type, and water quality (physico-chemical); all of which can be linked to flow modifications in most sites surveyed (Chapter 2).

The second main hypothesis of this study was that populations of *L. natalensis* in impoundments along the uMngeni River also act as ecological indicators, responding to environmental change (abiotic drivers), namely changes in habitat and water quality caused by artificial impoundments (Chapter 3). This hypothesis was accepted as the results of the study showed how *L. natalensis* populations in the four large instream impoundments on the uMngeni River progressively diminished, both in abundance and structure, down the catchment gradient as the compounded impact of water quality and quantity changes in the system increased (Chapter 3). The absence of juvenile and smaller adult *L. natalensis* in all the impoundments illustrated how the nature of water impoundments are not well suited for small fish as they lack the suitable habitat they require (namely shallow riffles) and harbour alien and larger predatory fishes that prey on small fish (Chapter 3). This study illustrated how the numerous impoundments and weirs in the uMngeni river system, the most fragmented in

KwaZulu-Natal Province (Ramulifho 2015), has many negative effects on the systems as water impoundments severely alter aquatic habitats by altering natural flow regimes, change sedimentation dynamics and alter water quality.

The high anthropogenic demand for water resources needed for human well-being and development is the main reason these four impoundments were built, and this is understandable given South Africa's uneven water distribution. However, the question that remains is how much are we willing to compromise/alter the ecological functioning of our river ecosystems in order to satisfy water demand? The plight of *L. natalensis* in the uMngeni river catchment is relatively bleak, but there are steps that can be taken to remedy the effects of human impacts on this species and the river system as a whole.

4.2 Recommendations

- Although the use of community level measures to evaluate fish health there are additional tools or methods that include consideration of indicator species and the biology and ecology of these species for example. In the Umgeni River where there are low diversities of fish species, especially in the upper reaches of the catchment, these methods should also be considered to evaluate fish health and drivers of changes in their wellbeing.
- It is recommended that attention be paid to the driving forces that have led to the deteriorated state of the uMngeni sites that were sampled. These sites are largely characterised by modified flow, alien fish species, and poor water quality. Efforts to mitigate these issues would likely result in an improvement of river health, and subsequently the health of fish communities.
- Fish passages need to be constructed in all dams on the uMngeni River to allow migratory fish such as *L. natalensis* and *Anguillid* spp. to migrate between habitats.

- The removal of redundant weirs or partial man-made barriers needs to also be looked at to encourage the movement of *L. natalensis* within the river.
- The effects of fragmentation on the genetic resilience of the *L. natalensis* and *Anguillid* spp. needs to be studied to further investigate the detrimental effects of river fragmentation on fish populations and the health of the uMngeni River (and other rivers) as a whole.
- Finally, studies on migration cues the ecological flow requirements of *L. natalensis* are needed to inform water resource managers on when to release flood flows in order to maximise on benefiting the local fish populations.

The findings of this study can be of great use when considering management and conservation plans in the uMngeni catchment. Evidence presented in this study on the overarching effects of river fragmentation can help inform decision-makers on the appropriate management plans (e.g. constructing fish passages) that mitigate anthropogenic impacts on the ecological functioning of our aquatic resources, while still maintaining water security that promotes sustainable economic and social development. On a more local scale, the finding of this study can inform local municipalities on the ills that pollution and sand mining have on our aquatic resources and how important it is to create awareness around this and initiate campaigns that discourage such activities.

4.3 References

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