Evaluating multiple stressors on aquatic ecosystems in an urban environment

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ABSTRACT

The issue of compromised aquatic ecosystems is a global dilemma; with existing and new stressors emerging, freshwater ecosystems continue to degrade tremendously. Multiple stressors exist in aquatic ecosystems, from invasive species to overexploitation of aquatic resources, habitat degradation, flow modifications and pollution. The uMsunduzi catchment in Pietermaritzburg, KwaZulu-Natal Province, South Africa, is one such stressed freshwater body. The present study was undertaken to determine the major threats to aquatic ecosystems and the possible strategies to mitigate the factors that compromise freshwater biodiversity, health, and ecological status. The first problem was to investigate the impact of anthropogenic barriers along the longitudinal pathway of the rivers. Hence, an extensive literature review on managing river barriers was conducted. This systematic review showed a need for river connectivity restoration projects in Africa, particularly in South Africa. The Northern Hemisphere countries are more advanced in restoring river connectivity by removing barriers or retrofitting fishways. A prevalence of physical barriers in the uMsunduzi catchment was found, and most barriers did not have fishways or fish passage structures. The fish communities, together with their associated habitat features, within the uMsunduzi mainstem and tributaries, were assessed to deduce which environmental factors influence the fish communities' structures in the system. There was a clear indication of a decline in species diversity and deterioration of the ecological health of the uMsunduzi catchment. Of the 18 expected fish species, according to the Freshwater Biodiversity Information System (2023), only 50% of these were caught. This is concerning, especially as the “near threatened” (IUCN status) *Enteromius gurneyii* (redtail barb) was not caught, and *Amphilius natalensis* (Natal mountain catfish) was caught once in low abundance. The uMsunduzi River had a highly deteriorated ecological integrity per the Fish Response Assessment Index (FRAI) scores, especially close and downstream of the city centre where the industrial areas are concentrated. Similarly, there is a great deal of microbial contamination, putting the uMsunduzi River in a matter of public health. There was also a significant presence of magnesium, calcium and fatty acids. In conclusion, the connectivity, ecological health and water quality of the uMsunduzi catchment were compromised, giving a clarion call for mitigation and management actions on the systems.

PREFACE

The data described in this thesis were collected in KwaZulu-Natal, Republic of South Africa, from 2021 to 2023. Experimental work was carried out while registered at the School of Life Sciences, University of KwaZulu-Natal, Pietermaritzburg, under the supervision of Prof Colleen T. Downs and Dr Matthew J. Burnett.

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.

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Signed:………………………………………

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January 2024

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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Prof Colleen T. Downs

Supervisor

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DECLARATION 1 - PLAGIARISM

I, Nolwazi Blessed Ngcobo, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    a. Their words have been re-written but the general information attributed to them has been referenced
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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- not submitted

Unleashing the flow: A systematic review of longitudinal river connectivity and restoration strategies

Ngcobo, N.B., Burnett, M.J., Downs, C.T.

Author contributions:

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

PUBLICATION 2- provisionally accepted

Assessment of the impact of anthropogenic structures in streams of a city: Pietermaritzburg, KwaZulu-Natal, South Africa

Ngcobo, N.B., Burnett, M.J., Hanzen, C., Downs, C.T.

Author contributions:

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

PUBLICATION 3- not submitted

Drivers of fish communities between the mainstem and tributaries in the urban uMsunduzi catchment, KwaZulu-Natal

Ngcobo, N.B., Burnett, M.J., Hanzen, C., Downs, C.T.

Author contributions:

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

PUBLICATION 4- not submitted

A case study: Monitoring seasonal changes in water quality in the uMsunduzi catchment, KwaZulu-Natal Province, South Africa

Ngcobo, N.B., Burnett, M.J., Downs, C.T.

Author contributions:

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

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“I can do all things through Christ who strengthens me”

Philippians 4:13

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CHAPTER 1

INTRODUCTION

1.1 Background

Although they form the smallest portion of the planet, freshwater ecosystems are the most diverse ecosystems (Closs et al., 2016; Carrizo et al., 2017; Barbarossa et al., 2020). Concomitantly, these systems are the most threatened ecosystems globally (Forio and Goethals, 2020; Chakona et al., 2022). Common threats to freshwater biodiversity are habitat degradation, invasion of alien species, water pollution, flow modification and overexploitation of freshwater resources (Dudgeon et al., 2006). Freshwater ecosystems are becoming more and more threatened, with known stressors and continuously emerging threats (Stendera et al., 2012; Craig et al., 2017; Chakona et al., 2022). Anthropogenic changes in land use and land cover is one of the continuously emerging threats and is considered the major driver of extinction in freshwater species (Abell et al., 2019). Urbanisation and changes in natural vegetation for industrial or agricultural practices disrupt the natural composition of the river, which in turn compromises the balance of freshwater ecosystems (Cerqueira et al., 2020).

Freshwater ecosystems are essential for a wide range of services, including nutrient and energy cycling, climate regulation, and water quality maintenance (Castello and Macedo, 2016; Teichert et al., 2017). The increased pressures on urban rivers caused by anthropogenic activities have resulted in compromised ecological functioning and loss of other essential ecosystem services (Covarrubia et al., 2016). In KwaZulu-Natal, South Africa, over 10% of natural land cover has been transformed as a result of urbanisation (Evans et al., 2022). Furthermore, South African rivers are susceptible to multiple threats that arise because of land use changes, urbanisation, flow modification, habitat disturbance and water pollution (O'Brien et al., 2019)

The impact of urbanisation on freshwater systems results in several issues, mainly excess nutrient disposal, microbial pollution, and sedimentation (Cerqueira et al., 2020). All these factors alter aquatic habitats for freshwater fauna such as fish and macroinvertebrates (Gal et al., 2019). Over 70% of the World's population is either experiencing water insecurity or incidental biodiversity threat, and these populations are generally located near intensive agricultural lands or overcrowded settlements (Vorosmarty et al., 2010; Carpenter et al., 2011; Davis et al., 2015).

1.2 Importance of longitudinal river connectivity

Well-governed river connectivity should be permeable for water, sediments, nutrients, organisms, organic matter and energy on all river dimensions (Grill et al., 2019). Just as the connectivity in terrestrial landscapes is important, so is the connectivity of riverscapes, which is essential for maintaining biodiversity in freshwater bodies (Baldan et al., 2022). River connectivity is complex and has multiple dimensions, including vertical connectivity, which is the connection between ground water and surface water systems; lateral connectivity, which is a fundamental connection between the mainstream and the floodplain; and lastly, longitudinal connectivity, which is the connection between the upstream and downstream of the river (Grill et al., 2019; Lehner et al., 2019).

Longitudinal connectivity supports the free movement of organisms and nutrients (Shao et al., 2019; Hu et al., 2020). However, it has been widely documented that the construction of obstacles such as dams and weirs in river systems results in a substantial population decline in freshwater biodiversity (White et al., 2011; Barbarossa et al., 2020), and over 50% of the global river systems show compromised connectivity (Grill et al., 2019). Although the construction of weirs and impoundments or dams is deemed necessary for water security, it should also consider how these impoundments affect freshwater biota (Ramulifho et al., 2018; Grill et al., 2019; O’Brien et al., 2019). Migrating fish species are better indicators of a well-connected system, especially the potamodromous and catadromous species that migrate within different freshwater habitats (Birnie-Gauvin et al., 2018). Freshwater migratory fish species inhabit a wide range of ecological niches and thus help maintain the ecological integrity of the rivers and the ecosystem services (O’Brien et al., 2019). For this reason, the longitudinal connectivity of the river is important for maintaining the ecological functioning of freshwater ecosystems (Costa et al., 2023).

1.3 Fish communities in compromised ecosystems

Due to the factors affecting rivers and their health, freshwater fish species are declining at an unprecedented rate (Costa et al., 2021). Fish assemblages are driven by multiple factors that act together and determine which type of species can reproduce and survive at a certain river locality (Boddy et al., 2020). The multiple factors include hydrogeomorphics of the river, ecological and physiological aspects of different species and physicochemical influences (Closs et al., 2016; Ramya et al., 2021). With the multiple pressures that act upon the natural drivers of the ecosystem, there is a drastic change in the functional diversity of the freshwater fish species (Stefani et al., 2020).

Over 40% of the IUCN red-listed species are aquatic species (Teichert et al., 2017). Amongst these species, potamodromous and diadromous fish are the most threatened (Costa et al., 2021). In South Africa, over 30% of the native freshwater fish species are threatened (Chakona et al., 2022). Of the 45 threatened freshwater native species, 36% are impacted by invasive species, 27% are impacted by chemical pollution from agricultural practices, 26% are impacted by compromised river connectivity and excessive water abstraction, 16% species are impacted by wastewater pollution, and lastly, the least significant threat is degraded habitat impacting 14% native freshwater fish species (Chakona et al., 2022).

To assess the ecological status of the stressed freshwater ecosystems, ecologists have used different sources and tools like the Fish Response Assessment Index (FRAI) (Wepener et al., 2011; Malherbe et al., 2016; Evans et al., 2022), a tool used to assess the status of fish populations in a particular region or area. It is typically used to evaluate the impact of human activities on fish populations (Kleynhans, 2007). FRAI uses multiple factors to generate the scores, including the present fish communities, migration requirements, habitat structures, presence of invasive species and water quality indices (Evans et al., 2022). The FRAI method requires historical and ecological data to formulate the trends and determine the scores of river health (Kleynhans, 2007). In South Africa, the FRAI has been used to evaluate the fish communities' response to various anthropogenic disturbances, including compromised water quality and habitat disruption (Malherbe et al., 2016; Evans et al., 2022), This study showed that most sites in the uMsunduzi River had a compromised ecological status, similar to other parts of KwaZulu-Natal Province (Evans et al., 2022).

1.4 River health and water quality

Water insecurity is a global dilemma, and mitigating the effects affecting water security and freshwater ecosystems' health should be a globally integrated effort (Hoekstra et al., 2018). The main goals for aquatic ecosystem management and restoration are to have protected aquatic biodiversity and sustainable water delivery systems (Meissner et al., 2019). To achieve these goals, there must be initiatives to determine all the primary threats on local to global scales (Vorosmarty et al., 2010). The efforts to minimise water insecurity should be a government mandate and other general citizens like the private sector, local communities, scientists, and media personalities (Meissner et al., 2019).

Urbanisation and agricultural practices, where chemical fertilisers are disposed of into water, are some of the common human impacts that disrupt water quality (Williams et al., 2016), and therefore, water tends to be highly polluted in regions closer to residential and industrial areas or near agricultural land use (Carpenter et al., 2011; Davis et al., 2015). The relationship between various land uses and water quality in the Kororoit stream in Melbourne, Australia, was studied (Covarrubia et al., 2016). The water quality parameters, such as pH, turbidity, dissolved oxygen, and electrical conductivity, were monitored (Covarrubia et al., 2016). There was no clear indication of the relationship between water quality and land use along the river for all these variables (Covarrubia et al., 2016). However, several other studies have deduced a significant negative correlation between water quality and land use at a catchment level in Africa (du Plessis et al., 2014; Kibena et al., 2014; Namugize et al., 2018). Therefore, there is a consensus that river health and water quality degrade as land use changes increase.

1.5 Pietermaritzburg and its rivers

Pietermaritzburg is a highly urbanised city in KwaZulu-Natal, South Africa, with condensed residential areas and a high population along the uMsunduzi River in the uMngeni catchment area (Beires, 2010). In KwaZulu-Natal, 20% of natural vegetation was transformed into cultivated land between 1995 and 2005 (Jewitt, 2012). The deteriorated habitat and water quality in the uMngeni River are caused by urbanisation, industrial pollution and agricultural augmentation, and *Escherichia coli* levels have exceeded the recommended levels (Gemmell and Schmidt, 2013; Namugize et al., 2018). Although the issue of organic pollution was emerging in the 1970s (Nash et al., 1971), in the early 1980s, the uMsunduzi had a satisfactory water quality and was considered to be a good source of potable domestic water; overmore the city of Pietermaritzburg was a good tourist destination for recreational activities such as the river canoeing (Wills, 1982). However, three decades later, the river was documented to be in the worst state for domestic and recreational use because of the high infestation of microbes

(Gemmel and Schmidt, 2013). In 2017, another study indicated a high occurrence of hydrocarbons in the uMsunduzi River. This was assumed to be associated with human activities, including industrial works around the river (Munyengabe et al., 2017). Furthermore, there has also been evidence of steroid hormones in the wastewater effluent in the uMsunduzi River; these steroid hormones are known to harm fish and humans (Manickum and John, 2014).

1.6 Aims and objectives

There is relatively little literature on the effect of land use change, river connectivity, fish assemblages and water quality in KwaZulu-Natal, particularly in Pietermaritzburg. Hence, the overall aim of this study was to evaluate the stressors that are degrading the ecological integrity and water quality of the uMsunduzi catchment. Literature review was first conducted on the effect of anthropogenic impoundments on river longitudinal connectivity and restoration measures. Secondly, the presence of barriers that affect the river connectivity in the uMsunduzi River and its tributaries were evaluated. Thirdly, the drivers of fish communities in the uMsunduzi River and tributaries were assessed to evaluate the state of water quality at selected sites in the uMsunduzi catchment. To achieve these aims, the following objectives were outlined:

1. Review global longitudinal river connectivity restoration strategies together with biomonitoring studies in freshwater ecosystems to make river management recommendations for African countries that have compromised longitudinal river connectivity.
2. To assess the prevalence of barriers in the uMsunduzi catchment using the Barrier Tracker application developed for the Adaptive Management of Barriers in European Rivers (AMBER) project to track artificial impoundments in rivers.

3. To assess the fish community assemblages in different habitat structures to infer which environmental factors support fish diversity in urban rivers.
4. To use uMsunduzi River historical fish and habitat structure data to deduce the ecological function of the ecosystem.
5. Monitor microbial and chemical contamination to determine the impact of industrial and agricultural activities on water quality in urban rivers.

1.7 Thesis structure

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

Chapter 1: This is the present chapter, which gives an overview and general background of the study covering the concepts that Chapters 2 to 5 focused on.

Chapter 2: This is a systematic review following the PRISMA method about longitudinal connectivity in rivers and the restoration approaches that have been shown to be effective.

Chapter 3: This is an assessment of the impact of anthropogenic structures in streams of Pietermaritzburg, KwaZulu-Natal.

Chapter 4: This is an assessment of fish communities and their response to human activities in Pietermaritzburg, KwaZulu-Natal

Chapter 5: This is a case study on the state of water quality in the uMsunduzi catchment

Chapter 6: This is a synthesis and makes recommendations.

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CHAPTER 2

Unleashing the flow: A systematic review of longitudinal river connectivity and restoration strategies

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Running header: Review on restoring river connectivity

2.1 Abstract

River connectivity is essential for the movement of species within the system. However, introducing barriers such as weirs and dams has disrupted global river connectivity. We conducted a systematic review following the PRISMA method to deduce which river restoration strategies are more effective in improving river connectivity and habitat restoration. We used various databases, such as Google Scholar, Web of Science, and Science Direct, to access peer-reviewed journals from 1975 to 2023. The literature search results were biased towards European and North American countries, comprising 66% of all the literature obtained. The African continent was far behind in river connectivity restoration implementation projects. Our results showed that barrier removal was the most effective approach to improving river connectivity and supporting species recruitment, distribution, and survival. However, this approach has its setbacks. Hence, it is crucial to understand species' life histories, phenotypic make-up, behavioural ecology and the control of alien invasive species before removing the barrier or retro-fitting a fish passage. There is also a consensus that one can observe the impact of barrier removal approximately two years after its removal. The overall efficacy of fishways is low because the current designs tend to support specific individuals, groups or species. We concluded that African countries could adopt graph-based models to mitigate disconnectivity in longitudinal pathways of their rivers.

Keywords: Barrier removal, Fishway, River connectivity restoration.

2.2 Introduction

In the 1980s, researchers introduced the concept of connectivity in landscapes to understand metapopulations and the continuity of landscape structure (Merriam, 1984). This concept was deemed a significant factor in species distribution (Kondolf et al., 2006). Connectivity between mosaic landscapes is essential to maintaining biodiversity and species' survival (Rincon et al., 2017). The connectivity phenomenon in riverscapes is often overlooked because of their natural linear pathways (Panagiotou et al., 2022). However, river networks are more susceptible to loss of connectivity because of 1.) their hydraulic factors that change with space and time (Kondolf et al., 2006), 2.) their directional bifurcating structure allows minimal redundancy for dispersal between patches because the movement can either be upstream or downstream, and 3.) rivers are prone to human-induced stressors like the introduction of barriers such as impoundments/ dams, weirs, culverts, and sluices (Lee et al., 2022; Panagiotou et al., 2022). Degraded habitats and lack of connectivity in rivers are considered the most common factors impacting biodiversity globally (Baldan et al., 2022; Panagiotou et al., 2022).

The presence of artificial barriers in rivers and streams often disrupts the natural flow of water, hence inhibiting the transference of matter, nutrients, energy, and organisms along the spatial and temporal scales (Ward and Stanford, 1995; O'Hanley, 2011; King and O'Hanley, 2016; Wohl, 2017; Shao et al., 2019; Baldan et al., 2022). Disturbance in river connectivity, therefore, reduces the amount of nutrients in the system and thus compromises the maintenance of biological diversity and distribution in the system (Gardner et al., 2013; Kaus et al., 2019; Shao et al., 2019). Moreover, the presence of barriers and their lack of fishway structures hinders the movement of aquatic species, especially migrating fish species (Hogg et al., 2015; Yu et al., 2023). Compromised river connectivity has an impact on the resilience of species in aquatic ecosystems (Wohl, 2017; Thieme et al., 2023).

River connectivity can have three categories: vertical, lateral and longitudinal connectivity. The relationship between river connectivity in aquatic ecosystems was established in the late 1900s (Hynes, 1975; Vannote et al., 1980), where it was first understood that lateral and longitudinal connectivity act together to support hyporheic zones (Tockner et al., 2000). Changes in longitudinal connectivity affect the water storage capacity, natural drainage, and primarily ecological function of the system (Branco et al., 2014; Yu et al., 2023).

To further understand the ecological implications of connectivity, it is better to distinguish structural connectivity from functional connectivity, i.e., connectivity defined by aquatic biotic factors (Branco et al., 2014; Harvey et al., 2019; Lee et al., 2022). Furthermore, migrating fish species are factors that can determine connectivity in a system (Birnie-Gauvin et al., 2018; O'Brien et al., 2019) for feeding, reproduction, and colonisation (Branco et al., 2014). Mainly, diadromous fish species are more prone to the effects of loss of connectivity (Rodeles et al., 2020a). For example, a decline in the recruitment of the European eel (*Anguilla anguilla*) resulted from multiple barriers along the river channels (Nunn and Cowx, 2012). Barriers such as dams, weirs and culverts tend to affect the structural longitudinal connectivity of the river (Jager et al., 2001; Wasserman et al., 2011; Duarte et al., 2021) and potentially also affect the populations' distribution and diversity (Saunders et al., 1991; Nunn and Cowx, 2012; Kukula and Bylak, 2022).

Globally, the drastic increase in water insecurity has demanded the construction of dams for water supply and the production of renewable energy (Duarte et al., 2021). In 2005, over 65% of rivers globally were fragmented by introducing barriers (Nilson et al., 2005). River restoration is needed to restore river continuity for migratory species, and presently, the two most common restoration measures used are barrier removal and retrofitting of fishways or fish passages (King, 2015).

Our study aimed to review studies where each or both river connectivity restoration strategies (barrier removal and retrofitting fishways) have been undertaken, together with biomonitoring projects. We then deduced the best restoration approaches the African continent can adopt in their river systems, which have compromised river connectivity. We predicted that barrier removal would be the most suitable strategy, given that when the barrier is removed correctly, there is no physical obstruction to the fishways, which reduces connectivity to a small percentage of the width of a river and may not be adequately designed for species where biology and ecology of species are pauce.

2.3 Methods

2.3.1 Literature search strategy

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method to conduct a systematic review using peer-reviewed journals (Moher et al., 2009). We used the Publish or Perish (version 8) (O’Dea et al., 2021) to access peer-reviewed journals from various science databases such as Google Scholar©, Web of Science©, Scopus© and Science Direct©. The search terms included "restoring river connectivity through barrier removal", "restoration of river connectivity through retrofitting fishways", "fish assemblages pre and post-dam removal", "the effectiveness of river connectivity restoration", the efficacy of fishways in migrating fish species”, and “biomonitoring fish densities in a newly restored river connectivity”.

2.3.2. Analyses

We used Microsoft Excel© spreadsheet and assigned metrics to screen the publications, using the web link for each journal provided by Publish or Perish. We added columns for countries and continents where the studies were undertaken, and the focus of the study. We also used the conditional formatting feature on Excel to remove the duplicated articles. For the publications on biomonitoring post-dam removal or after the construction of a fishway, we created a spreadsheet that included the region, type of barrier, name of the river, restoration strategy, study species, study outcome, and reference. We summarised trends using descriptive statistics, using the number and percentages of the publications removed or included in the study.

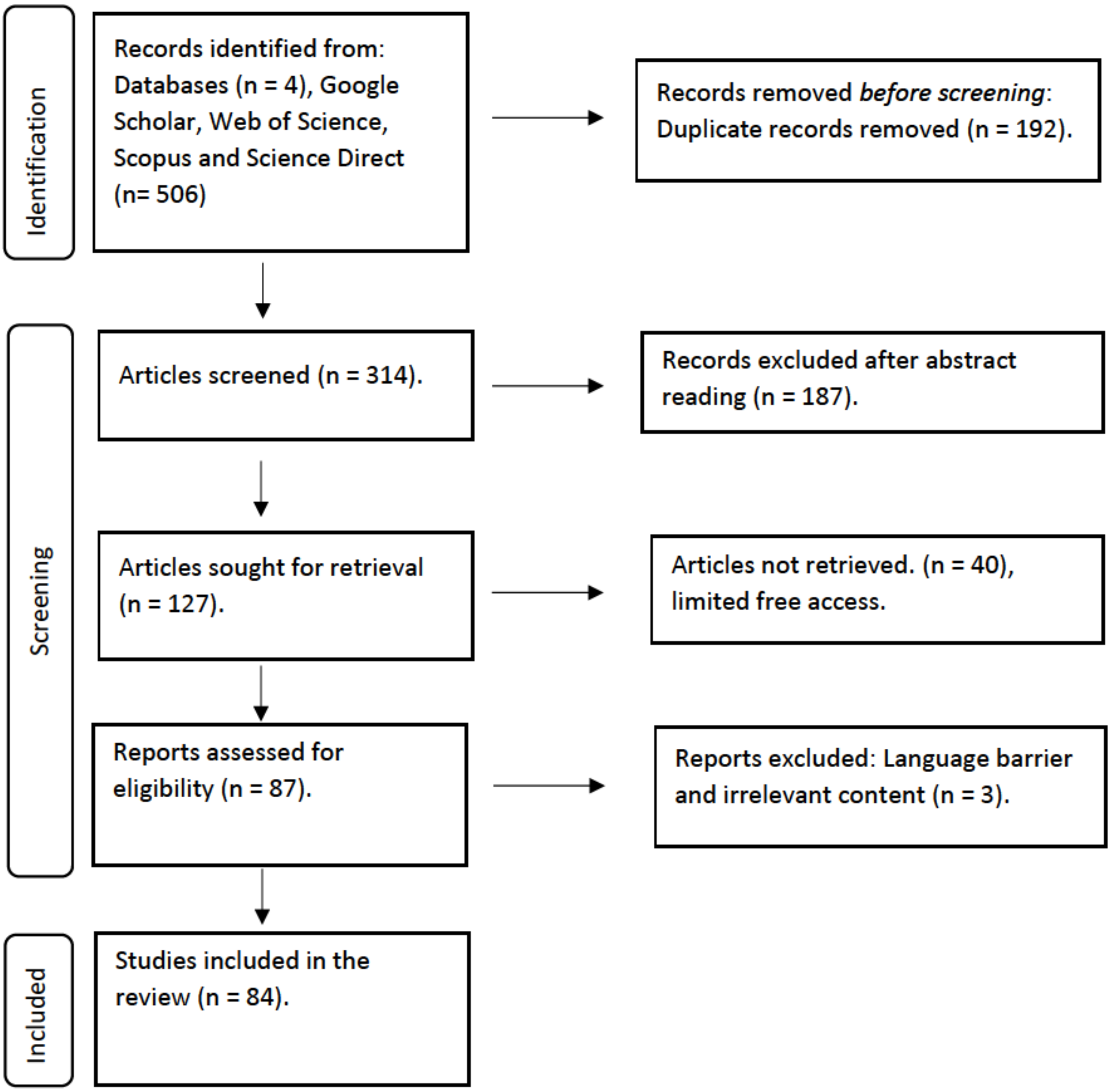

Figure 2.1: A flow chart based on PRISMA protocols shows how publications were discarded or included in the review (O'Dea et al., 2021).

2.4 Results

The literature search on Publish or Perish produced 506 peer-reviewed articles published from 1975 to 2023. Of the 506 peer-reviewed articles, 38% were duplicated and removed from the records. A total of 314 peer-reviewed articles were screened through abstract reading, and 60% of those were removed because they were not relevant as they did not incorporate river connectivity restoration measures through barrier removal and retrofitting of fishways. Forty papers were not accessible because of online limited free access, and they were then not included in the study. We then assessed the 87 remaining articles, and 4% were irrelevant or had a language barrier. Hence, 84 peer-reviewed articles were included in this review (Supplementary information Table S2.1).

Most publications of the 506 peer-reviewed publications were biased towards North American and European studies, with 35% and 32%, respectively. South America had the least publications (1.2%), followed by Africa (3.2%); Asia and Oceania (including Australia) had 7.5% and 7.3% of publications, respectively—the remaining 14% comprised unknown publication locations and/ or global reviews (Supplementary information Table S2.1)). Most publications focused on barrier removal as a river connectivity restoration measure, while a few focused on retrofitting fishways. Over 96% of the biomonitoring studies that evaluated the effectiveness of barrier removal and the efficacy of fishways were only published in the past 11 years (2012-2023) (Table 2.1)). Barrier removal has been a more common restoration measure in Europe and North America, forming 60% of the reviewed biomonitoring studies, while retrofitting fishways contributed 40% (Table 2.1). Only six publications from African studies, particularly South Africa, were included in this review.

Table 2.1: Outcomes or possible outcomes for two restoration strategies (barrier removal and retro fitting) in pursuit of river connectivity and habitat restoration.

Region	Barrier type	Barrier size (m)	River/ stream	Removal	Retro fit	Study species	Outcome/potential outcome	Reference
North America	Dam	32	Elwha River	X		Pacific Salmon	Return of Pacific salmon	Tonra et al., 2015
Oceania	Weir	2.6	Murray River		X		Accommodated passing of a wide range of fish sizes (31-1030 mm) long	Stuart et al., 2008
Australia	Dam		Rushy Creek		X	Various species	Passing and recruitment of native fish species	Beatty et al., 2012
Australia	Weir	0.75	Hillards Creek		X	Various species	The fishway was successful in passing 178 fish individuals of different sizes (15 -800 mm)	Moore, 2017
Europe	Dam		Tagus River	X		Cyprinid fish species	Removing barriers that will allow species to have access to resources they need is more crucial than randomly choosing barriers for removal.	Branco et al., 2014
Europe	Weir	1.85	Lugg River	X		Salmonid	No changes in fish communities before and after barrier removal	Muha et al., 2021
North America	Dam	3	Sedgeunkedunk Stream	X			There was a significant increase in fish populations above the former dam	Gardner et al., 2013
Europe	Weir	2.4	Claxton Beck	X		European eel	Increased fish density, particularly a notable increased density of the European eel from 0.5/100 m^2 to 32/100 m^2	Jingrui et al., 2021
Europe	Multiple small barriers		Holubla catchment	X		Various species	Increased fish populations and higher abundances of new generations	Kukula and Bylak, 2022)

North America	Multiple Dams	1-38	Multiple streams	X		Salmonid	58% of removed barriers resulted in an increased distribution of anadromous salmonid species	Brewitt, 2016
Europe	Multiple small barriers		Villestruo river	X		Trout	Improved the distribution of trout, down and upstream	Birnie-Gauvin et al., 2018)
North America	Small Dams		Elhwa and Snake Rivers			Salmonid	Potential regulation of water temperature, flow, and flood dynamics for migrating fish species	Gregory et al., 2002
Asia	Dam		Liuxi river		X	Various species	Over 30 species of 10 different families could pass through fishway successfully.	Hu et al., 2020
North America	Dam		Sedgeunke dunk Stream	X		Various species	1. Dam removal provided access to required habitats by anadromous fish species 2. Recolonisation of sea lampreys, which was beneficial in habitat restoration with their nest-building technique.	Hogg et al., 2013
North America	Multiple small Dams	2.1, 3.7 and 4	Little River	X		*Alosa sapidissima* (American Shad) and *Pylodictis olivaris* (flathead catfish)	Over 70% of pit-tagged individuals passed through the former dam site and were moved extensively to the upper and lower reaches of the previous dam site.	Raabe, 2014
Europe	Dam		River Vesdre		X	Various Cyprinid species	Overall efficiency of fishways was 69%, which suggested that most of the species can use the fishway from downstream to upstream habitats.	Ovidio et al., 2020
Europe	Dam	26	River Vester	Pseudo-dam removal		*Salmo trutta*	Improved recruitment of brown trout in the upstream site, with densities similar to unaffected sites.	Birnie-Gauvin et al., 2020

South America	Dam		Parana River		X	Various species	Improved similarity in fish assemblages upstream and downstream of the dam after construction of the fishway.	Marques et al., 2018
North America	Multiple Dams		Klamath River	X		*Oncorhynchus* spp (Salmonids)	Allowed for access to upstream habitat and improved conservation status for salmonids.	Quinones et al., 2015
Europe	Dam	34	Rhone River		X	*Barbus barbus, Squalius cephalus* and *Salmo trutta*	1. The fishway had a lower efficiency for salmonids compared with cyprinids. 2. Some individuals could not detect the entrance for a prolonged period of time.	Grimardias et al., 2022
North America	Dam	1.5	Eightmile River	X		Various species	Significant spatiotemporal changes were observed in fish communities below and above the previous dam site post dam removal.	Poulos et al., 2014
Asia	Dam		Jidu river	X		Various species	Increased species richness, density, and diversity both upstream and downstream post dam removal	Ding et al., 2019
North America	Dam		Scioto River	X		Various species	Reduced fish communities' diversity shortly after dam removal, however expected to increase after two to five years.	Dorobek et al., 2015
Europe	Multiple Dams		River Mouse and River Ourthe		x	Various species	The vertical slot fishway induced the ability of both the potamodromous and diadromous species to access optimum habitats which were not available prior.	Benitez et al., 2018
North America	Dam		Pahsimeroi River	X		*Oncorhynchus tshawytscha* (*Chinook salmon*)	Increased habitat availability for salmon juveniles and resulted in non-density dependent survival.	Copeland et al., 2020
Europe	Weir	2.4	Claxton Beck Stream	X		Various species	Immediate increase of habitat and fish density upstream of the former weir site.	Sun et al., 2021

North America	Two Dams	32 and 64	Elwha River	X		Salmonids	After the removal of dams, eight (in Elwha dam) and seven (in Glines Canyon dam) salmonid species which were previously rare upstream were observed in high densities.	Duda et al., 2021

2.5 Discussion

2.5.1 Barrier removal

The construction of fishways or fish passages was most common from 1910 to 1940's before barrier removal became prevalent (Zielinski and Freiburguer, 2021). Barrier removal is the most common management strategy that previous studies have followed to improve river connectivity since the late 1900's (Gardner et al., 2013; Hogg et al., 2015; Magilligan et al., 2023). In some cases, the barriers were removed, redesigned and rebuilt in a way that regulated flow properly and supported aquatic life (O'Hanley, 2011; Poulos et al., 2014; Duda and Bellmore, 2022). Removing small barriers or weirs results in variable restoration action for trout (*Salmo trutta*) movement down and upstream in Villestrup River, Denmark (Birnie-Gauvin et al., 2018). However, large barrier removal, such as dams, is relatively complex because each barrier has a different magnitude and operational process than other barriers. Hence, barrier removal assessment has to be done on a case-by-case basis or on a "barrier-by-barrier basis" (Hart et al., 2002; Duda and Bellmore, 2022).

Various methods have been adopted to identify barriers to remove (O'Hanley and Tomberlin, 2005). Firstly, the use of the physical attributes (such as height, fish passage slope and available habitat) of each barrier, species movement (upstream or downstream movement) and the probability of connectivity for each barrier to determine the contribution each barrier has on the overall loss of river connectivity (O'Hanley and Tomberlin, 2005; Nunn and Cowx, 2012). With this method, a matrix can be built to determine the overall connectivity index (CI) (range 0-1), with 1 being maximum passability and 0 minimum passability (Rincon et al., 2017). The barriers with the CI value of 0 are removed or reconstructed. Similarly, barriers for removal can be identified by building temporal dams and removing them sequentially (step by step in a backward manner) to determine where the barrier affects functional connectivity (Segurado et al., 2013; Branco et al., 2014).

Furthermore, this method helps prioritise river connectivity interventions (Segurado et al., 2013).

Secondly, a linear model-based approach can be designed with minimal data, such as the length of the river, barrier location, and the impact of the barrier on potamodromous fish species (O'Hanley, 2011; Lin et al., 2019). This method is cost-effective because the required attributes can be easily attained. Since budget is the most common limiting factor in barrier mitigation, a linear model can solve that issue by providing a management strategy that is within the budget limits (King and O'Hanley, 2016; Marsden et al., 2023), and this is particularly pertinent for African countries. Thirdly, a spatial graph-based method can be used to depict the impact of each barrier on the overall connectivity in the catchment. With this approach, the ecological system's individual elements (in this case, barriers) are presented as nodes with links to each other, and the relationship between the nodes is determined (Segurado et al., 2013; King, 2015; Rincon et al., 2017). A study conducted in the Truckee River, Nevada, United States of America (USA), highlighted the effectiveness of the graph theory approach in enhancing fish passages (McKay et al., 2013). This study used hypothetical watershed simulations to test the index of each watershed in the system under different conditions, such as the number, passability and dam locations, to outline which barrier is a high priority for restoration (McKay et al., 2013).

Some setbacks are also possible after barrier removal. The changes brought about by removing a barrier may negatively impact habitat structures, and the ecological response of species can not be easily predicted (Hart et al., 2002; Hogg et al., 2015; Panagiotou et al., 2022). Barrier removal may be suitable for redistributing native species but could also allow for the unintended spreading of invasive species (Bennett et al., 2015; Grimardias et al., 2022). After dam removal in the Heishui River, China, there were unintended consequences on the riverbed, such as an excess amount of silt downstream, and although there was an increase in water depth and velocity, which promoted spawning, the new habitat structure did not support juvenile growth (Lu et al., 2022). Nonetheless, these impacts are relatively short-term, and if the system is given enough time, it does recover and support biodiversity (Bednarek, 2001; Duda and Bellmore., 2022). However, the fish assemblages before and after barrier removal need to be monitored rigorously, and all the baseline conditions of the river need to be evaluated thoroughly before removing a barrier (Gardner et al., 2013; Duda and Bellmore, 2022). Species life histories are essential to understand before restoring habitats (Teichert et al., 2022); this can similarly be said when fitting a fishway (Williams et al., 2011; Grimardias et al., 2022). For instance, species that lack homing behaviour may not respond to or benefit from barrier removal (Lin and Robinson, 2019). Barrier removal should improve the ecological integrity of the system (Branco et al., 2014), which means assessing which barriers will allow for the recruitment, distribution and survival of species is essential (Garcia de Leaniz et al., 2023). In the Tagus catchment, which runs through Portugal and Spain, over 471 fish species could not pass the 934 barriers along the river and tributaries (Hermoso et al., 2021). Removing barriers allows species to locate the services they require (Branco et al., 2014; Duda et al., 2021).

Hart et al. (2002) outlined that in the United States of America (USA), only 5% of the barrier removal projects were coupled with biomonitoring in the systems. While in 2020, over 1100 barriers were removed in the USA, only 12% showed ecological improvement (Habel et al. 2020). This is mainly because there is a gap in biomonitoring studies post-dam removal (Duda and Bellmore, 2022). While in the Sedgeunkedunk Stream, USA, an immediate redistribution of resident species was observed (Gardner et al., 2013). The complete effect of barrier removal is more likely to be observed after two or more years post-dam removal (Birnie-Gauvin et al., 2017; Duda et al., 2021). Two years after Gardner et al. (2013) noted the redistribution of resident species, Hogg et al. (2015) continued to monitor the diversity and abundance, and the results were significant.

Lin et al. (2019) emphasised that other temporal factors may influence the responses observed in a 2-3-year post-dam removal period. Hence, biomonitoring should continue until the habitat stabilises to avoid any ecological loops that may surface over time (Lin and Robinson, 2019; Rodeles et al., 2020b).

2.5.2 Controversy in dam removal

According to our results, the African continent still needs to catch up with mitigation implementations for river connectivity restoration, and because there are socio-political limiting factors in developing and developed countries (Marsden et al., 2023). In European and North American countries, most dams that have been successfully removed are typically small dams (5 m in height). However, generally, the dams that have more effect on the freshwater ecosystem are larger barriers (≥ 15 m height of the dam wall) (Hart et al., 2002; Marsden et al., 2023). While dam removal approaches vary, it is empirical to quantify and analyse the tradeoffs between ecological gain in terms of improving river connectivity and economic loss of dam removal (Kuby et al., 2005). For successful migration by catadromous migrators, all the barriers along the longitudinal pathway of the river should be removed, which may be too far-fetched in terms of achievement in anthropogenically modified landscapes (Kuby et al., 2005). Hence, various models have been developed to balance the tradeoffs between ecological services, economic drain and river safety; these approach models allow for better decision-making in dam removal since they involve multiple stakeholders and broaden the decision-making scale of dam removal (Roy et al., 2018). For instance, aligning river connectivity restoration with infrastructure maintenance would minimise the cost of barrier removal while benefitting the aquatic ecosystem (Fitzpatrick and Neeson, 2018; Neeson et al., 2018; Lin et al., 2019).

Water insecurity is a global issue and one of the main reasons dams were and still are constructed; however, there was and still is little consideration of freshwater species and their habitat in these construction projects (O'Brien et al., 2019). As the demand for water increases, there is a necessity to make choices between utilising ecosystem services (e.g. clean water) and preserving the ecosystems that provide these services (Evans et al., 2022).

In a case study conducted in Myanmar, Asia, where they used the Fish Barrier Prioritisation and Screening System (FBPSS), which is usually used to identify high-priority barriers in river restoration) to assess and prioritise fish passage barriers for remediation (Marsden et al., 2023). They followed a multi-stage approach: 1. identification of barriers, 2. global information system (GIS) analysis, 3. field validation for ground-truthing the barriers, and 4. biological assessment and socio-economic evaluation (Marsden et al., 2023). This method is relatively low-cost and can be adopted in developing countries where financial costs are limiting river connectivity restoration (Marsden et al., 2023).

An important question before barrier removal is, why is the barrier being removed? Do we want to take the system back to its pristine state? Bellmore et al. (2019) argued that after barrier removal, the system may or may not recover, and if it does recover, it is not guaranteed to return to its original state. When the barrier is introduced, it changes the structure of the ecosystem, which may favour the spread of invasive species; hence, fish communities that assemble after barrier removal may differ from historical data of expected species distribution (Bellmore et al., 2019; Lin et al., 2019; Habel et al., 2020; Duda and Bellmore, 2022). The impact of dam construction on freshwater species and their habitat is a complex issue, and careful consideration must be given to the trade-offs between utilising ecosystem services and preserving the ecosystems that provide them (Habel et al., 2020).

2.5.3 Retrofitting of fishways

Designing a fishway is a broad field of science that needs collaboration from different fields of science like biology, ecology, environmental engineering and ecohydraulics (Silva et al., 2017). For an effective fishway fitting, it is imperative to understand fish behaviour in different hydrodynamics across the waterways (Williams et al., 2011; Grimardias et al., 2022). From an economic point of view, barrier removal is the best logical action if the barrier no longer serves its purpose (Walter et al., 2021). On the other hand, retrofitting fishways is another solution for restoring river connectivity, but it could also benefit invasive species (Grimardias et al., 2022). One solution would be selective restoration, whereby the restoration action benefits the native species that need to be conserved (Thieme et al., 2023). Similar to barrier removal restoration, fitting a fishway also requires a complete understanding of species' life histories (Birnie-Gauvin et al., 2018), and presently, most retrofitting caters to anadromous fish species and does not consider differences in sizes of individuals, species and even populations (Birnie-Gauvin et al., 2018; Ovidio et al., 2020). In an experimental study using Anguillid eels, it was observed that fish passing on a fishway structure may depend on the phenotypic make-up of an individual, with large individual eels being better climbers with higher passage successes (Mensinger et al., 2021), in another study of brown trout (*Salmo trutta*) the results were similar (Lothian et al., 2020a). However, some fishways accommodate a wide range of fish body sizes; for instance, the fishway in Murray River, Australia, accommodated the passing of 31-1030 m body sizes of fish (Table 2.1, Stuart et al., 2018).

2.5.4 The overall efficacy of the fishways

Most fishways that have been constructed have limiting factors to the efficacy of the fishways (Grimardias et al., 2022); depending on the size of each individual, species morphology and behaviour, attraction to the fish passage and migratory behaviour (Ovidio et al., 2020; Mensinger et al., 2021; Grimardias et al., 2022). Although fishways are effective, they usually only cater to recreational species that are good swimmers, while most temperate south species are not recreational or good swimmers (Wilkes et al., 2017). Hence, it is recommended that designs for fishways should consider all the native species, including potamodromous species that are found in such regions (Wilkes et al., 2017; Ovidio et al., 2020). Another notable feature of the most common designs is that they do not support movement during low-flow seasons (Lothian et al., 2020b).

Moreover, fishway construction is becoming more and more expensive, but the efficacy of these fishways remains low (Silva et al., 2017). In South Africa, fishway construction is becoming more common (Heath et al., 2005). Of the South African fishways where monitoring studies have been conducted, the Nhlabane fishway in Richards Bay, KwaZulu-Natal Province, tends to allow a certain size of individuals to pass through (Heath et al., 2005) while the Xikundu weir, Limpopo Province, allows over 70% of fish species to pass through the fishway so enough to declare a good efficacy of the fishway (Heath et al., 2005). In 2004-2006, the functionality of the fishway in the Luvuvhu River in Limpopo, South Africa, was evaluated, and the fishway was found to be efficient only during low discharge and turbulence seasons (Fouche and Heath, 2013). In uThukela River, South Africa, a vertical slot fishway had partial fish and invertebrate passage such that some species like *Varuna litterata* could not pass through the fishway (Burnett et al., 2023). Therefore, the design and functionality of fishways should be carefully considered to effectively cater to a wide range of native species and ensure efficient passage during all seasons.

2.5.5 Conclusions

Barrier removal has been the most common restoration measure undertaken in European and North American countries since the late 1900's (Zielinski and Freiburger, 2021). Most of the short-term (2-3 years) biomonitoring studies have significant success in fish movement, recruitment and recolonisation upstream and downstream of the former barriers (Brewitt, 2016; Rodeles et al., 2020b). On the other hand, pre- and post- dam removal monitoring studies are essential in determining the significance of dam removal, and they should at least be done within 10 years, five years before and five years after dam removal (Poulos et al., 2014). To better understand the mitigation measures, it is necessary to study and understand fish communities in terms of their ecological behaviour before restoration (Gardner et al., 2013; Rodeles et al., 2020b). Some, but not all, fishways are efficient for fish movement; even those that allow for passing only allow certain individuals, groups, or species depending on their phenotypic makeup.

The African continent can adopt the graph-based model using the multistage approach for barrier removal to determine which barriers are completely obstructing fish movement. This method would be convenient in the South African context because it allows for partial removal of barriers, which is less cost effective. Barriers that are no longer in use can also be removed, if the barriers cannot be removed, then a better design for the fishway is required and should involve multiple stakeholders from different fields of science for better innovation of fish passages. Both mitigation measures require adequate knowledge of the biology and ecology of the fish species queried, and such studies must be continued across Africa to inform both the removal of barriers and the design of fishways.

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2.8 Supplementary information

Supplementary information Table S2.1. Summary of publications used in the systematic review of longitudinal river connectivity and restoration strategies.

Note: This is presented in the Appendix at the end of the thesis

CHAPTER 3

Assessment of anthropogenic structures in the streams of a city: Pietermaritzburg, KwaZulu-Natal, South Africa

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Running header: Evaluating the instream barriers in urban streams and rivers

3.1 Abstract

The freshwater ecosystems are classified as one of the most threatened ecosystems. Due to the natural linearity of the river, there are limited niche habitats where species can find refuge when a river is threatened. Artificial barriers like culverts, weirs, dams, and fords may threaten fish movement because they alter the habitat and fragment rivers. Losing longitudinal connectivity in streams can negatively impact migrating diadromous and potamodromous fish species. With the increased anthropogenic land-use change, especially urbanisation, the connectivity of many streams is impacted and poorly documented. Our study aimed to evaluate anthropogenic structures impacting mainstem uMsunduzi River connectivity and its tributaries in Pietermaritzburg, KwaZulu-Natal Province, South Africa. We mapped the barriers on eight watercourses using the Adaptive Management of Barriers in European Rivers (AMBER) "Barrier Tracker" application. We logged different types of instream obstacles, recorded their description, and uploaded relevant photographs. Our results showed that the Wilgerfontein and Dorpspruit Streams had a higher density of barriers per kilometre stretch. Nevertheless, their lengths from up to downstream were short. The number of barriers in the Dorpspruit, Wilgerfontein streams and uMsunduzi River were similar. However, the uMsunduzi is the mainstream and four times longer than the Dorpspruit and Wilgerfontein. Hence, the Wilgerfontein and Dorpspruit showed great disconnectivity in their longitudinal waterways. This has implications for the persistence of the freshwater fauna in these rivers, especially those that migrate seasonally.

KEYWORDS: River connectivity; instream barriers; fishway; river management

3.2 Introduction

Freshwater ecosystems are among the most impacted systems by various factors imposed by human activities (Dudgeon, 2019). This includes introducing alien species, water extraction, habitat modification, land use change, pollution, artificial barriers and more (Vaughn & Taylor, 1999). The connectivity between the river and its tributaries is essential because it allows for nutrient exchange (Larrieu et al., 2020), access to diverse habitats and promotes biodiversity and community assemblages within the catchment (Shao et al., 2019). Sometimes, the transference of sediment from one zone to another can also determine the level of connectivity in the river channel (Hooke, 2003). The introduction of artificial impoundments compromises the connectivity in the main river and the neighbouring streams, mostly the longitudinal connectivity, which allows for the natural continuity of the river (Panagiotou et al., 2022). Over 65% of the perennial rivers in the world are fragmented by artificial barriers (Grill et al., 2019; Thieme et al., 2023). There is poor documentation of in-stream artificial barriers in many countries, including South Africa (Panagiotou et al., 2022).

The different land uses can affect the ecosystem's functions, resulting in habitat fragmentation (Maloney & Weller, 2011; van Puijenbroek et al., 2018; Panagiotou et al., 2022). Humans play a considerable role in landscape fragmentation and influencing the ecosystem's functioning (Branco et al., 2017). Aquatic ecosystems are complex and driven by various biotic and abiotic factors (Fuller et al., 2015). Various anthropogenic structures have been built in natural habitats, leading to the fragmentation and habitat alterations of terrestrial and aquatic ecosystems (van Puijenbroek et al., 2018). Inland aquatic ecosystems are declining at three times the rate of terrestrial systems (Tickner et al., 2020; Evans et al., 2022). About 25% of all living vertebrates are fish species, and most have been identified as endangered (IUCN, 2016). Over 60% of South African endemic fish taxa are threatened, and according to the assessment of the decline in native freshwater species, introducing artificial physical barriers such as dams, weirs, fords, and culverts in freshwater ecosystems reduces river connectivity and alters habitat. It may be one of the drivers behind the decline in freshwater fish species (Jackson et al., 2001; Harris et al., 2015; Hanzen et al., 2022). Diadromous fish species are more prone to the effect of the artificial barriers, as it has been previously noted that the decline of European eel, *Anguilla anguilla* has been because of the obstruction caused by the hydropower artificial barrier (Silva et al., 2018).

The connectivity in a stream is essential for migrating fish as they need to access different habitats for various purposes, such as breeding, feeding, or taking refuge (Branco et al., 2017). Freshwater fauna are more vulnerable to habitat loss because of their linear confinement in rivers and streams (Coleman et al., 2018). For example, barriers create more lentic habitats (Maitland et al., 2016; Birnie-Gauvin et al., 2017; Consuegra et al., 2021), and consequently, such stretches of rivers become more favourable to invasive species (Johnson et al., 2008; Alexandre & Almeida, 2010; Chakona et al., 2022). The accumulation of lentic habitats can affect the water quality by inducing sediment mobilisation and deposition and impacting the life cycle of fish species occupying the habitat (Birnie-Gauvin et al., 2017). Artificial barriers have been observed to influence the productive potential of rheophilic fish species (Birnie-Gauvin et al., 2017). Rheophilic fish species have specific habitat requirements that they are adapted to, such as substrates, depth, and water velocity (Alexandre & Almedia, 2010; Consuegra et al., 2021).

Losing connectivity among freshwater habitats may prevent species from migrating or breeding, resulting in population decline and possibly leading to localised extinction (Deinet et al., 2020; Thieme et al., 2023). In the case of diadromous species that migrate between freshwater and seawater (Bok et al., 2004; Branco et al., 2017), the presence of a single barrier along the longitudinal dimension of the river may pose a significant threat to them (Branco et al., 2012). Multiple barriers may cause even more drastic impacts (Branco et al., 2017). Such effects have already been shown for African freshwater eels in KwaZulu-Natal, South Africa (Hanzen et al., 2022). For potamodromous fish, which migrate within freshwater habitats, there has been a remarkable decline in their abundance, indicating the disturbance in the rivers of Australia (Harris et al., 2016).

With the increasing pressure of anthropogenic stressors in South Africa, for rivers like the uMngeni River, there is a concern for the decline of migrating *L. natalensis* populations (Impson et al., 2008; Burnett et al., 2021). The red-tailed barb *Enteromius gurneyi* is a South African endemic in decline, and its decline may be related to multiple stressors within rivers, particularly those associated with urban areas (O'Brien et al., 2019). Small artificial barriers such as culverts and low-head weirs tend to be more numerous in rivers than larger barriers and are believed to have a far more significant impact on migrating freshwater fish (Branco et al., 2017). Moreover, it has been outlined that the loss of river connectivity may threaten genetic diversity in aquatic species (van Leeuwen et al., 2017).

In the KwaZulu-Natal Province, South Africa, some rivers have been observed to have compromised ecological connectivity (Dlamini, 2019). One such river is the uMngeni River, which is the system that has lost connectivity the most (Dlamini, 2019; Hanzen et al., 2022). The issue is that the barriers in the uMngeni River do not facilitate fish migrations, and migratory species such as *L. natalensis* and freshwater eels cannot pass through these barriers (Dlamini, 2019; Evans et al., 2022; Hanzen et al., 2022). The uMsunduzi River, a tributary to uMngeni River, is no exception, as the prevalence of barriers is also as high. Adaptive management is required to improve river connectivity in rivers such as the uMngeni River (Erős et al., 2018). Continued innovation is needed to ensure the passage is suitable for all the migrating fish in such rivers (Silva et al., 2018). Barrier management through barrier removal has been more common in European and North American countries. These practices have yielded promising results in terms of the conservation of aquatic fauna (Magilligan et al., 2023).

Unfortunately, in South Africa, issues regarding river connectivity have not been addressed and have not been of utmost priority in the water management areas (O'Brien et al., 2019; Munhzhelele et al., 2024).

Our study aimed to evaluate the number of undocumented and documented artificial barriers that impact the river connectivity in the uMsunduzi River and its tributaries in Pietermaritzburg, KwaZulu-Natal, South Africa. We were interested in seeing the difference between an urban environment and a conservancy area in terms of the presence and, therefore, impact of artificial in-stream barriers. We predicted that the Mpushini Stream would have a lower density of barriers per kilometre because it runs through a conservancy area.

3.3 Methods

3.3.1 Study area

Our study took place in the uMsunduzi catchment in Pietermaritzburg, KwaZulu-Natal Province, South Africa. With a population of ~922,000 (Statistics South Africa, 2022, Figure 3.1), the city is a mosaic urban landscape with rural, semi-urban and urban areas, as well as natural and managed green spaces and dominated by the grassland biome (Josiah & Downs, 2023). Our study covered semi-urban and rural areas. The average annual precipitation ranges from 700 mm to 1550 mm in the greater uMngeni catchment (Kusangaya et al., 2018; Ramulifho et al., 2018). The uMsunduzi and its tributaries flows are highly responsive to rainfall events and flow higher in summer than in winter (Hlahla et al., 2022). The average annual temperature was 23.4 °C as of 2022, with warmer seasons from November to March and cold seasons from May to August (SAWS, 2022). The KwaZulu-Natal area, or Southern Africa at large, experiences severe floods and droughts because of the El Nino Southern Oscillation (Kusangaya et al., 2018). However, the country experienced the La Nina oscillation between 2021 and 2022, and the drought levels decreased (SAWS, 2022). Just like most provinces, KwaZulu-Natal is prone to climate change, with predicted extreme hydrological events (Kusangaya et al., 2018).

The South African economy faced challenges in achieving environmental sustainability due to its heavy reliance on natural resource-based industries such as mining and agriculture, leading to environmental degradation. Additionally, environmental economic development is demand-driven, with a need for more investments in environmental sustainability. Nonetheless, the South African Department of Environmental affairs is working towards balancing economic growth with environmental protection (Statistics South Africa, 2023).

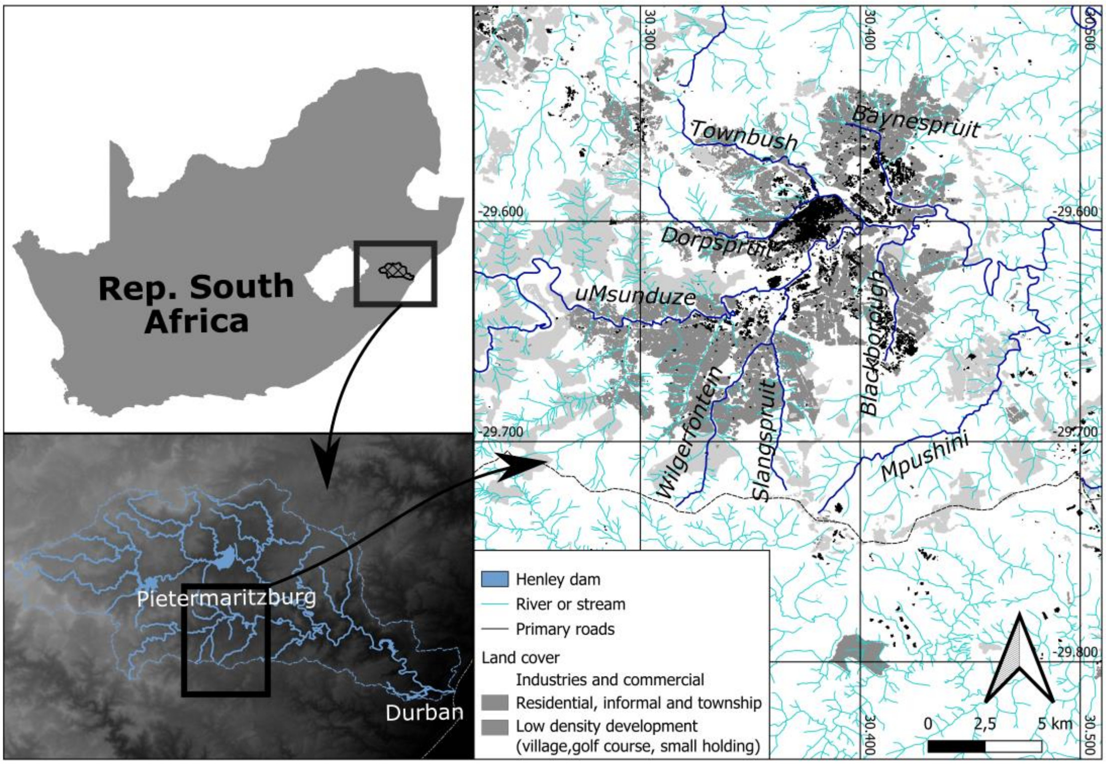

Figure 3.1: Study area map showing the eight waterways of interest and the surrounding land cover features in Pietermaritzburg, KwaZulu-Natal, South Africa, including the digital elevation model for the uMngeni Catchment.

Our study area included the uMsunduzi River, five of its tributaries; Wilgerfontein, Dorpspruit, Blackborough, Baynespruit, Mpushini; and two sub-tributaries, Townbush and Slangspuit, in and around the city of Pietermaritzburg (Figure 3.1, Table 3.1). The tributaries of the uMsunduzi River flow through different land uses: residential, commercial, and industrial areas, including the Pietermaritzburg city centre. The uMsunduzi River is 115 km long and is a major tributary of the greater uMngeni River. For this study, we assessed ca. 44 km of the uMsunduzi River from Henley Dam downstream to the Mpushini tributary's confluence (Figure 3.1).

The most upstream tributary we examined was the Wilgerfontein Stream, covering about ~11.0 km in length. Both the Wilgerfontein and Slangspruit Streams start south of Pietermaritzburg and flow through the peri-urban residential areas of Willowfountain and Imbali (Figure 3.1). The uMsunduzi tributary, the Dorpspruit Stream, which is ~11.7 km long, was examined. The Dorpspruit starts north-west of Pietermaritzburg and flows south through the residential suburbs and exotic tree plantations of Pietermaritzburg, such as Prestbury, Winterskloof, Wylie Park, Clarendon and, importantly, the city centre (Figure 3.1). The Townbush Stream is an uMsunduzi sub-tributary, and it flows into the Dorpspruit Stream north of Pietermaritzburg city and is ~5.9 km in length. The Townbush Stream flows through a mosaic of exotic tree plantations and the Pietermaritzburg residential suburbs of Cascades and Montrose, entering the Dorpspruit Stream before the city's centre. The stream has two major shopping centres along its course (Figure 3.1). The uMsunduzi tributary, the Blackborough Stream (Figure 3.1), which flows through the Mkondeni industrial area and the residential suburbs of Scottsville and is ~6.2 km long, was examined. The uMsunduzi River tributary, the Baynespruit Stream (Figure 3.1), was assessed. It is ~9.0 km in length and starts north-east of Pietermaritzburg and flows from Nansindlela Socio Eco Park, Willowton and Sobantu informal settlements before entering the uMsunduzi River downstream of the city centre (Figure 3.1).

The most downstream uMsunduzi River tributary we studied was the Mpushini Stream, a perennial river in a protected environment southeast of Pietermaritzburg (Figure 3.1). The stream runs from the Bisley Nature Reserve, and flows through Ashburton to the uMsunduzi River for ~20.0 km. Natural areas surround this stream with little anthropogenic land use, and it runs through the Mpushini Conservancy, which is dedicated to the natural protection of the area. The Mpushini stream is sourced from five tributaries along its course, and we recorded artificial barriers on or close to the main stem for the present study (Figure 3.1).

The geomorphological zonation of South African rivers is influenced by regional geology, tectonic events, and long-term fluvial action (Rowntree and du Plessis, 2003). The East and South coasts have experienced widespread rejuvenation due to uplift and tilting during the Miocene and Pliocene (Rowntree et al., 2000). The distribution of sediment input is not uniform along the length of the channel, with significant sediment supply lower down the catchment due to decreased vegetation cover and increased rural population densities (Rowntree et al., 2000). The greater uMngeni river flows through various geological zonations, however, the uMsunduzi river is within the single sedimented profile (Jordaan et al., 2016). Studies show that different types of river reaches responded differently to flood events, with sediment-dominated systems undergoing lateral migration and avulsion, and bedrock-confined systems experiencing sediment erosion (Holmes et al., 2016).

Table 3.1: The uMsunduzi and tributaries length, altitude, and gradient statistics.

River	**Total length (km)**	**Assessed length (km)**	**Altitude upstream (m)**	**Altitude downstream (m)**	**Height above sea level (km)**	**Gradient**
uMsunduzi	115.0	44.0	925.7	521.1	0.4	0.01
Wilgerfontein	11.0	11.0	818.3	628.2	0.2	0.02
Slangspruit	6.3	6.3	921.9	680.9	0.2	0.04
Dorpspruit	11.7	11.7	1065.1	639.6	0.4	0.04
Townbush	5.9	5.9	1080.2	638.1	0.4	0.08
Blackboroughspruit	6.2	6.2	733.7	621.9	0.1	0.02
Baynespruit	9.0	9.0	761.6	599.2	0.2	0.02
Mpushini	20.0	20.0	882.9	551.0	0.3	0.02

3.3.2 Sampling methods

To record artificial barriers, we visited each barrier and logged them onto a barrier tracking application (Barrier tracker), a tool used to record artificial barriers in the Adaptive Management of Barriers in European Rivers (AMBER) project, installed on a smartphone for data collection between 2021 and 2022. The logging of instream barriers on the application included a geographical location, a photograph, and physical characteristics of the barrier. The physical characteristics included the barrier type, barrier height, presence of fishway through visual analysis of these structures, extent across the watercourse, river width, river name, river flow levels, and if the barrier was in working condition. Data were downloaded into a workable Microsoft Excel© spreadsheet, and additional barriers we were aware of but could not access were added. For inaccessible barriers (n = 8), we used Google Earth (version 7.3.3 for Windows (64-bit)), satellite imagery of 2022, to record their physical location and used for mapping analyses and barrier-type data only.

The density of barriers per kilometre stretch was then calculated using the number of barriers per stream and the distance of the river.

$$\text{Barrier Density/unit length} = \frac{n}{x};$$

Where n represents the number of barriers per stream and x represents the longitudinal distance of the stream in kilometres. The total length of the mainstem was used for all streams except for the uMsunduzi River, where the defined 44 km reach of the river was used and assessed for barriers.

3.3.3 Statistical analyses and geo-visualisation

We used descriptive statistics to summarise some of our data. To assess if there was a significant difference between different barrier heights, we used the independent-samples t-test, 95% (critical alpha value = 0.05) confidence interval (IBM SPSS version 28). We used the height of each barrier and the availability of fish passage structure as a proxy to determine the most suitable management action required for each barrier towards the ecological restoration of rivers. After the AMBER project approved all the logged barriers, we created a database for the analyses of the artificial barriers recorded. We further categorised artificial barriers based on their need for fishways to improve connectivity and the required management actions (Table 3.2). We geo-visualised these categories using QGIS version 3.12 (an Open-Source Geospatial Foundation Project, qgis.osgeo.org). We also included urban landcover for visualisation purposes. We used the South African National Land-Cover 2019 dataset, which was available on an open licence agreement (South African Department of Forest, Fisheries and the Environment. The land use categories we used included 1. water (natural), 2. sugarcane, semi-commercial, commercial, emerging farmers, irrigated and dryland, 3. mines and quarries, 4. built-up dense settlements, 5. golf courses, 6. low-density settlements, 7. small holdings, 8. KwaZulu-Natal national roads and district roads, 9. water (dams) and 10. KwaZulu-Natal railways.

Table 3.2: Proposed management action required for each barrier in pursuit of river ecological restoration.

Management action	**Action required**	**Category**
Nothing	No action required	The barrier is in use but does not need a fishway
Fit a Fishway	To retrofit a fishway onto the artificial structure	The barrier is in use and needs a fishway to improve river connectivity
Fit/remove	Removal of the artificial barrier or retrofitting a fishway onto the instream structure	The barrier use is unknown; therefore, management action can only be determined once it is known
Remove	Removal of the artificial barrier	The barrier is clearly not in use and does not have a fishway
Fishway?	Research for a fishway is needed	The barrier use is unknown and the need for a fishway is not clear

3.4 Results

3.4.1 Barrier types

Different barrier types were observed in different streams, classified into six categories: culverts, river channels, dams, fords, weirs, and others (Figure 3.2). We recorded a total of 86 barriers among the eight waterways, with over 50% being weirs and culverts, which were the overall dominating barriers (Figures 3.2 – 3.5)

There was a significant difference between the number of culverts and other barriers except for canal and weir (Independent samples T-test, Table 3.3). There was also a significant difference between weir*dam and weir*other mean height comparison (Table 3.3). Fords were significantly different from dams and others (Table 3.3). Only one river canal was recorded, and hence, there was no variation in the heights of barriers; similarly, the fords showed less variation in their heights (Figure 3.6, Table 3.3).

The concentration of barriers was high along the city centre, industrial, commercial, residential and township areas (Figure 3.3). After Dorpspruit, which had the highest number of barriers (n = 19), the uMsunduzi and Wilgerfontein had the second highest number of barriers (n = 17) per stream. Henley Dam (Figure 3.2C) was constructed in 1942 for water supply purposes (both domestic and irrigation); this dam is, however, no longer used for these purposes (Umgeni Water, 2020). In 1983, there was a demand for industrial development in the city of Pietermaritzburg; hence, there was a need to control floods in the uMsunduzi catchment (Regional award for civil engineering excellence, 1989). There was an initiative to construct gauging weirs, including the major project of the Camps drift wear in the uMsunduzi River (Figure 3.2E). This weir has a paddler ramp constructed to act as a fishway structure (Figure 3.2E).

Figure 3.2: Examples of different barriers observed, where (A) is a canal, (B) a culvert, (C) a dam, (D) a ford, (E) a weir and (F) other in the assessed waterways in Pietermaritzburg, South Africa.

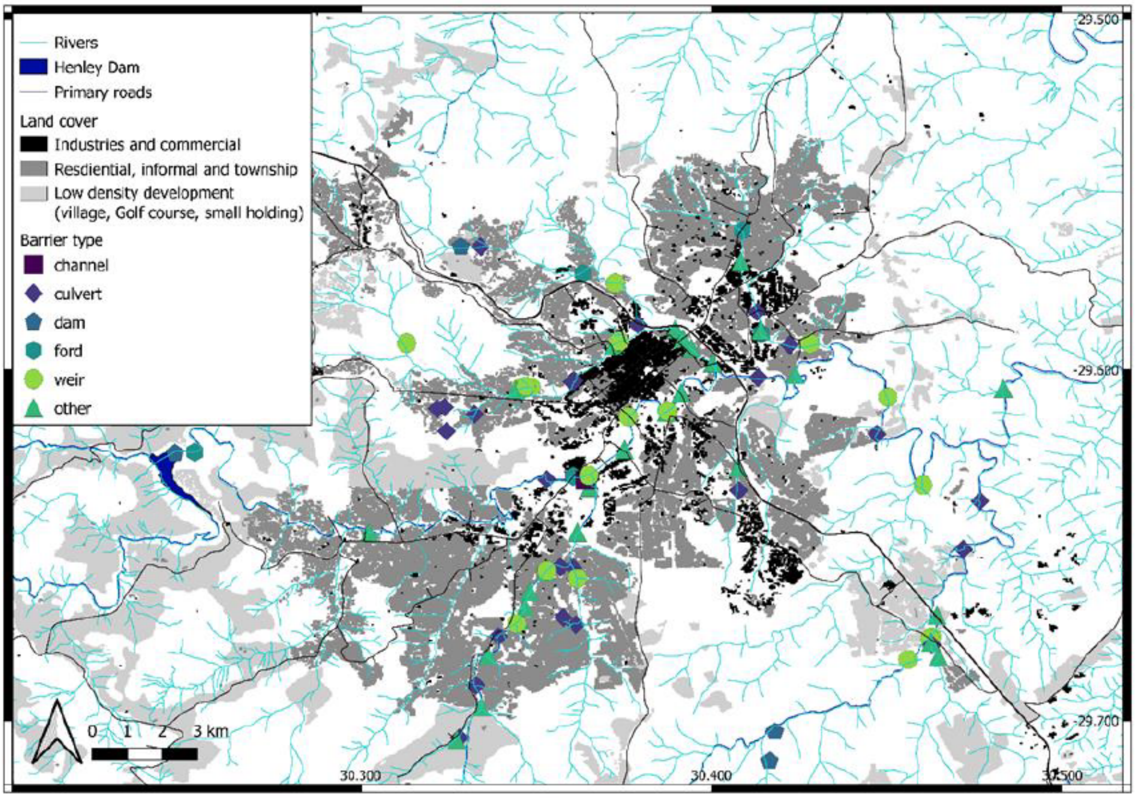

Figure 3.3: Different artificial barrier types found in the eight streams in the uMsunduzi catchment during the present study in 2021 and 2022.

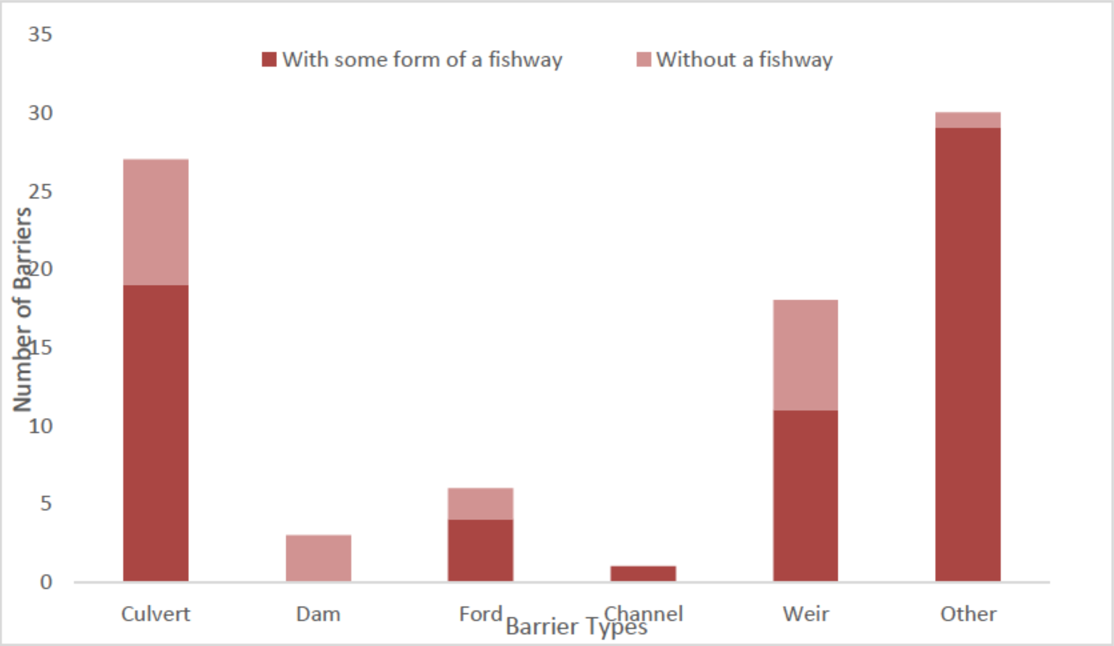

Figure 3.4: Bar graph representing the number of the barrier-types and the barrier types that lack or need fish passage structures in our study of eight waterways in Pietermaritzburg, South Africa.

Table 3.3: Independent samples T-test results comparing different barrier heights in the present study.

Barriers in comparison	P-value	Test statistic (t)	Degrees of freedom (df)
Culvert*Weir	0.280	1.095	42
Culvert*Dam	0.016^{sd}	-2.569	28
Culvert*Channel	0.447	0.773	25
Culvert*Other	<0.001^{sd}	-3.484	54
Culvert*Ford	0.039^{sd}	2.54	30
Weir*Ford	0.079	1.843	22
Weir*Dam	0.007^{sd}	-2.977	20
Weir*Channel	0.548	0.614	17
Weir*Other	<0.001^{sd}	-3.899	46
Dam*Other	0.561	0.588	32
Dam*Channel	0.464	0.836	3
Dam*Ford	0.040^{sd}	2.456	8
Other*Ford	0.002^{sd}	3.265	34
Other*Channel	0.217	-1.263	29
Channel*Ford	0.437	0.845	5

† sd~Significant difference between groups

3.4.2 Barrier density

The density of barriers varied from one stream to the next. Our results showed that Wilgerfontein had the highest barrier density compared with the other streams, followed by Dorpspruit, Townbush, and Baynesspruit streams (Figure 3.5). Although the uMsunduzi had the same number of barriers as the Wilgerfontein Stream, the density was lower for uMsunduzi because the longitudinal distance of the river was longer (Figure 3.1, Table 3.1). Mpushini Stream runs through a conservancy area; hence, it was expected to be the least dense stream (Figure 3.5). The height of culverts and weirs ranged from 0.5 to 5 m.

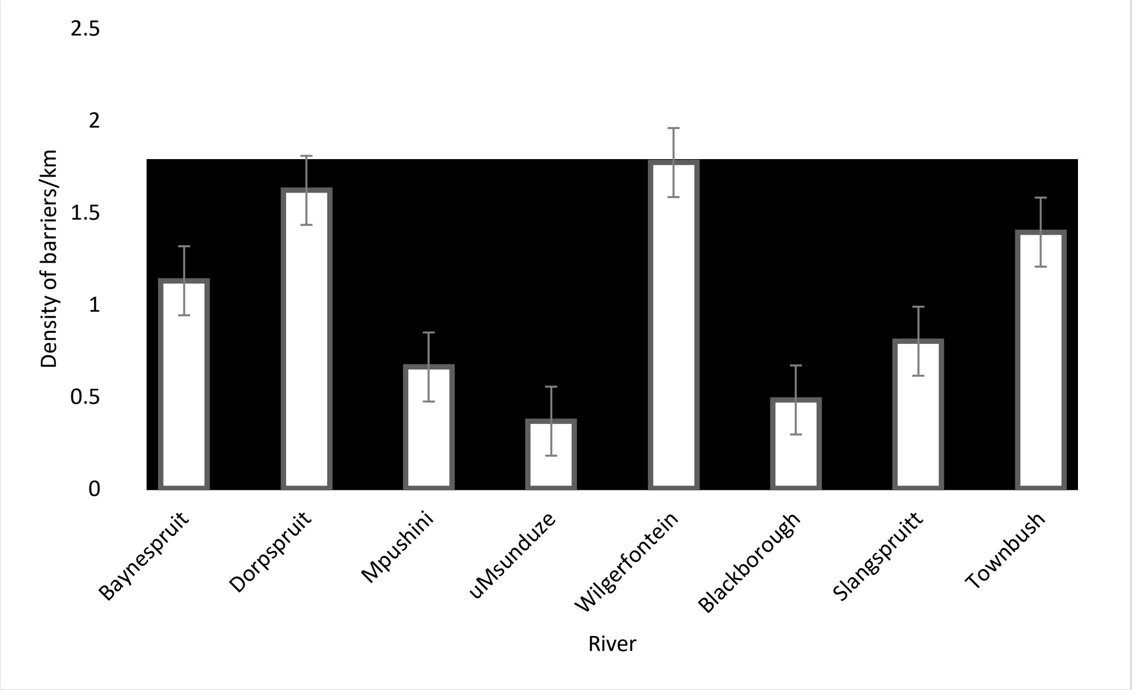

Figure 3.5: Mean (+ SD) barrier density per kilometre for the different streams in our study.

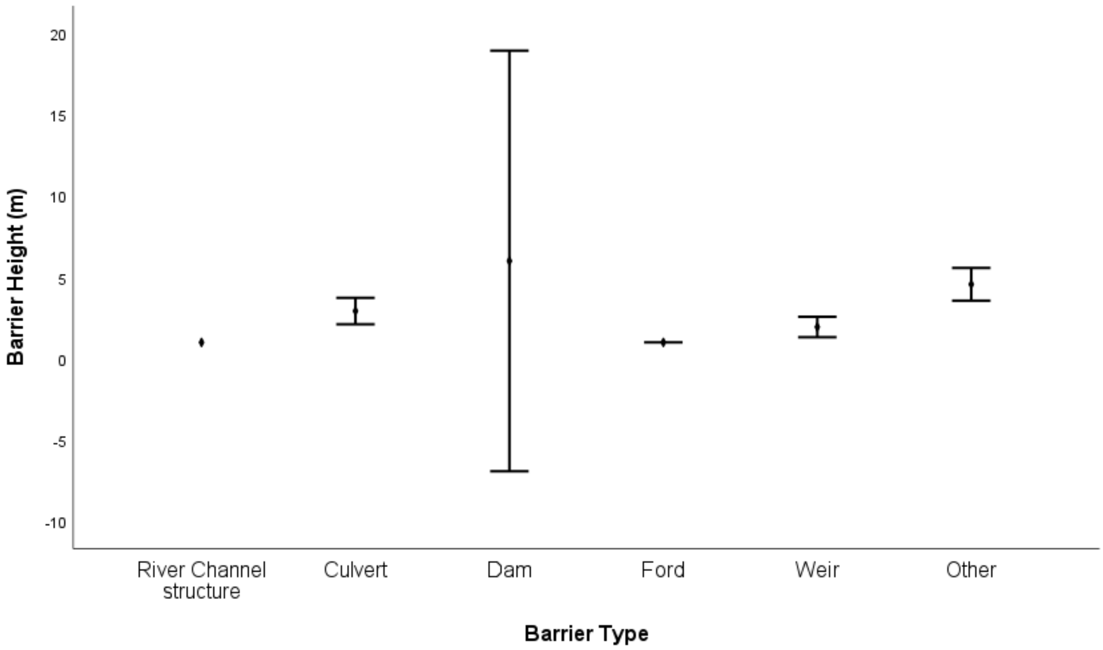

Figure 3.6: Mean variations (± SD) in barrier heights between different barrier types in our study.

3.4.3 Fish passage structures

Our key observation was to note the presence and absence of fish passage structures in the recorded structures. The results indicated that 24% of the barriers required fish passages; of that, over 70% were culverts and weirs (Figure 3.4). The absence of fish passage structures indicated the lack of ecological connectivity for most fish species. However, in some barriers, we could not indicate whether the fish passage structure was present or not; hence, the fish passibility is "unknown" for those barriers (Figure 3.7). The categorised artificial barriers based on their need for fishways to improve connectivity and the types of management actions that are required are shown in Table 3.2. The recommendations are further shown in Table 3.2 and Figure 3.8.

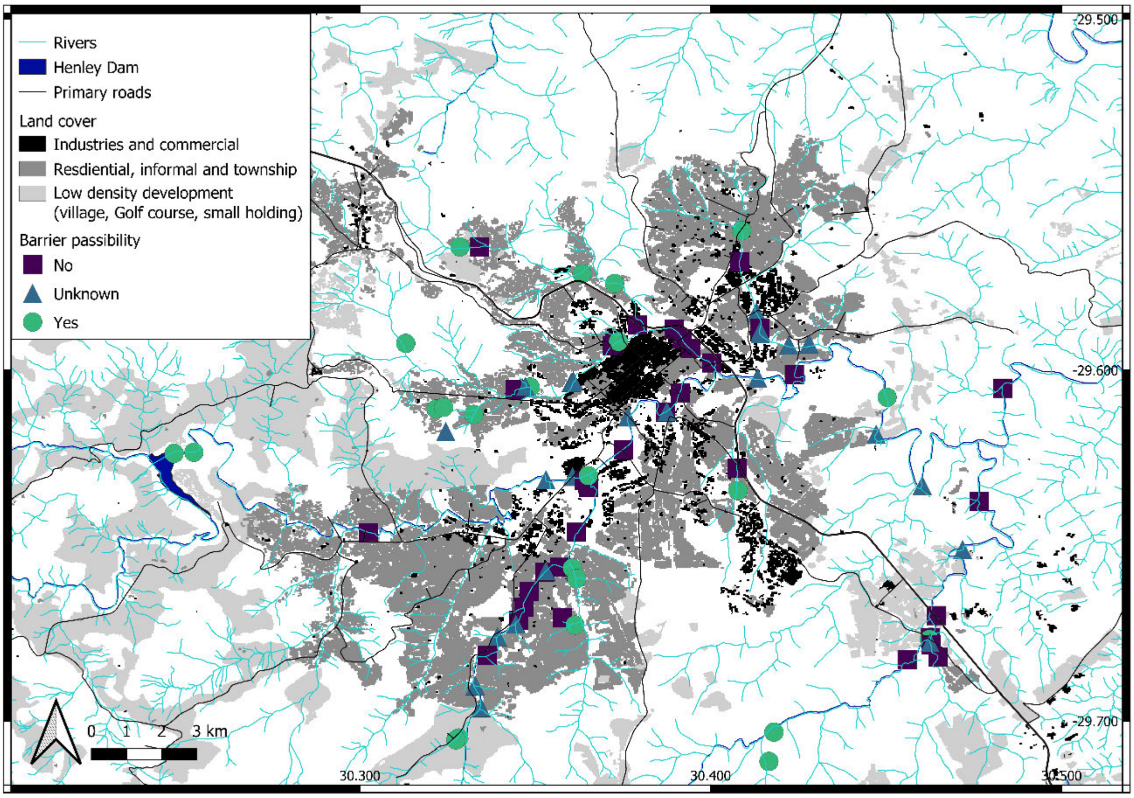

Figure 3.7: Mapping of barriers that require fish passage structures in our study.

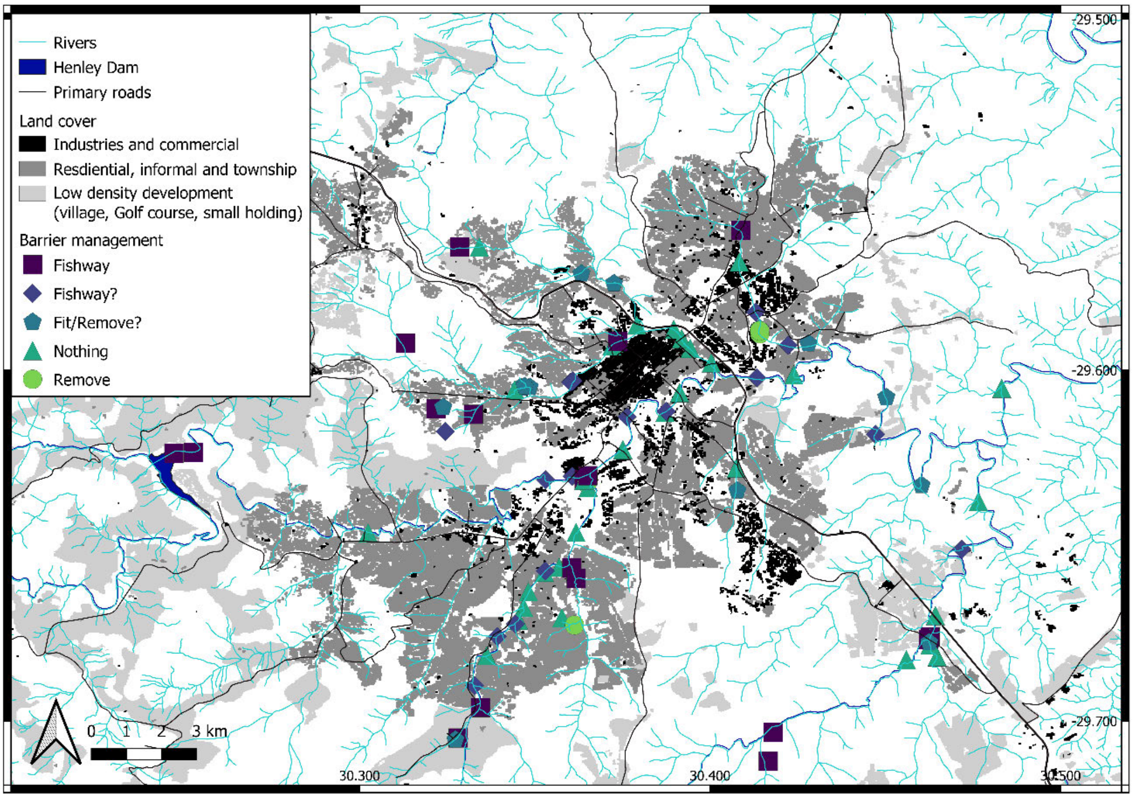

Figure 3.8: Recommended management actions for different barriers in the present study.

3.5 Discussion

Our results showed a high number of barriers in the Pietermaritzburg waterways, with all the waterways having a notable disruption in longitudinal connectivity. The Wilgerfontein stream was the most compromised waterway. It is important to note that it is possible that several other in-stream barriers could not have been detected because of limited accessibility to the entirety of the streams, nor detected using satellite imagery from Google Earth. This is partly because of difficulty accessing private land and security risks to researchers when visiting areas with higher crime rates in the city, as portions of the streams are often out of sight to the general public and overgrown with dense vegetation.

The disruption in river connectivity alters the hydraulics, water chemistry and sediment dynamics, resulting in fragmented habitats for freshwater biota (Jones et al., 2020). In addition, the absence of fishways in most culverts, weirs, and dams, as found in the present study, indicated that migrating freshwater species might not be able to pass at those points of the rivers. In the present study, about 24% of the barriers needed fishways, and 70% were weirs and culverts. Although the height of culverts and weirs ranged from 0.5 to 5 m, their impact may still be as significant as the greater height barriers found in other studies (Jones et al., 2020).

Small barriers were more abundant than large barriers. The impact of the small barriers may be more critical than large barriers because the constant encounters the migrating fish may have with these barriers can cause the population to decline, as found in other studies (Jones et al., 2021; Panagiotou et al., 2021). The Henley Dam in the uMsunduzi River is located upstream, further away from other small barriers. With its upstream location, it may be possible that the dam has less impact on the movement of fish in the study area but may negatively impact river connectivity on a catchment scale.

The Wilgerfontein and Dorpspruit waterways had as many barriers as the uMsunduzi River, almost four times longer than the two waterways. This suggests a significant disruption in the longitudinal connectivity of the Wilgerfontein and Dorpspruit Streams. The recommended mitigation actions are removing barriers or installing fishways (King & O’Hanley, 2016).

These recommendations align with other studies (Figure 3.9; Erős et al., 2019), where the conservation and restoration of rivers were achieved by removing non-significant barriers. Management action varies from barrier to barrier according to the fish passage structures, usage, and availability (Table 3.2; Figure 3.8). For all the barriers that are in use but do not have a fishway structure, we recommend that the fishway be fitted; however, if the barrier is no longer in use, we recommend removing the barrier (Figure 3.8). Culverts should be fitted with buffers to aid fish passage or upgraded to mitigate culverts impeding river connectivity and connectivity considered in the design.

Culverts have been observed to restrict the species and sediment movement in the longitudinal pathway of the rivers in North America (Maitland et al., 2016). In our study, most culverts we observed need to be upgraded as they compromise water flow upstream to downstream (Figure 3.2B, Figure 3.9). Culverts tend to disrupt the water flow by increasing the water flow velocity because water is channelled through smaller areas (Wasserman et al., 2011). High water velocity may prevent fish from passing through the barrier (Wasserman et al., 2011; Consuegra et al., 2021). Barriers have a dire impact on rheophilic habitats; the more barriers are introduced, the greater the loss of habitats (Birnie-Gauvin et al., 2017; O’Brien et al., 2019).

FIGURE 3.9: A poorly management culvert that was blocked during our study, showing water flowing over the culvert and not under it in Baynespruit Stream.

The decline in migrating species indicates a pressured ecosystem and its provided services (Branco et al., 2017). For instance, the anguillid eel species in east and southern Africa migrate from marine to freshwater environments at the early stages of their lifecycle; they spend a few years in freshwater and then return to the sea to breed and die (Hanzen et al., 2019, 2022). These eel species are the only known large vertebrates that connect the freshwater and marine ecosystems through the circulation of energy and nutrients on the African continent (McIntyre et al., 2016). Because of the loss of connectivity, a local decline in their distribution has been observed in KwaZulu-Natal (Verheist et al., 2018; Hanzen et al., 2022), leading to the near-threatened status of the endemic longfin eel, *Anguilla mossambica* (Pike et al., 2020). In

KwaZulu-Natal, there has been a notable decline in *Enteromius gurneyii* (Evans et al., 2022), a species that has a vulnerable status (IUCN), and *Amphilius natalensis* which is near threatened (Chakona et al., 2022).

A shortfall when retrofitting a fishway is that it is a "quick-fix" solution to river connectivity that does not consider the possible loss of habitat by the impoundment created by the in-stream barrier. To retrofit fishways is pointless if the habitats have already been lost, and in some cases, it is better ecologically to remove the barrier altogether (Birnie-Gauvin et al., 2017). Most of the barriers we mapped in this study were built over 30 years ago (Department of Water and Sanitation, 2021); therefore, should management actions be taken, habitat availability and the long-term maintenance cost of these structures should also be considered. If the habitat is compromised, there should be management actions for habitat restoration prior to or with connectivity management actions. This may involve stakeholder meetings to repurpose the reach of the river that is more ecologically beneficial without losing social-ecological benefits.

Loss of connectivity threatens migrating species and the recruitment and dispersal mechanisms of freshwater species (Panagiotou et al., 2021; Thieme et al., 2023). Per our results, various management actions should be undertaken to improve connectivity in the Pietermaritzburg waterways. Although the mechanisms of migratory fish are understudied in South Africa, over 100 fish species are estimated to require longitudinal movements to complete life cycles (O'Brien et al., 2019). One redundant artificial barrier disrupting river connectivity should be sufficient for management actions to be taken, regardless of the status of other barriers (King & O'Hanley, 2016). The management actions for improving river connectivity should be prioritised for all the artificial barriers (Segurado et al., 2013). With some barriers not being used, the cost and benefit of installing a fishway or removing a barrier should be weighed first (O'Hanley, 2011). In South Africa, the Department of Water and

Sanitation has proposed that the construction of weirs and dams should include convenient fishways for migrating fish; however, existing infrastructure needs to be addressed (Branco et al., 2012; O'Brien et al., 2019).

The ongoing projects in pursuit for water security in KwaZulu-Natal have not directly considered the fisheries component in terms of river connectivity. Even though the proposed module for environmental impact assessment in the uMkhomazi Water Project has earmarked 32% of the uMkhomazi catchment for ecological water requirements . However, it was decided that the implementation of a fishway in this dam was not feasible due to operational, economical, technical and topographical limitations (DWS, 2016). Consequently, the Smithsfield Dam will be a permanent barrier for migrating fish species in the uMkhomazi river. Distinctly the raising of Hazelmere dam in uMdloti river catered for the movement of eel species by constructing a fishway that facilitated the upstream movement of juvenile eel species (Nemai Consulting, 2008).

3.5.1 Conclusions

In the present study, we concluded that excessive anthropogenic structures in Pietermaritzburg impound the waterways and that management actions are required to restore and improve river connectivity. Contrary to our prediction, artificial barriers did not seem to be restricted to urban areas and included the Mpushini River in a conservancy. The management, or lack thereof, of artificial barriers to maintained infrastructure (flood mitigation, water resource use) seemingly neglects the need for fish to move in their freshwater environment. This is coupled with the paucity of local studies examining how instream barriers impact native fish movements (O’Brien et al. 2019). It is recommended that redundant artificial barriers that are considered to hinder the movement of fish be removed. While culverts and other roadway infrastructure that potentially hinders fish movement should be regularly maintained for flood mitigation and protection of infrastructure and fish movement. It is important to consider fish movement in the development of new infrastructure in rivers to reduce how these would act as barriers, for example, the fitting or incorporation of fishways or a structure that enables fish movement. The present study is the first of its kind in southern Africa; hence, the novelty of the study has some limitations in finding similar studies to compare with. However, European and North American studies have recommended and implemented various ways for barrier management through barrier removal and retrofitting of fishways, which has yielded positive results in the ecological function of the aquatic systems. Using the Barrier Tracker application successfully outside the context of Europe can be used in the region to map instream barriers as a citizen science tool for managing instream barriers in South Africa. Lastly, there is a need to address the paucity of knowledge on the biological and ecological of native fish and how artificial barriers impact them in South Africa, especially considering urbanisation and increased development along South African waterways.

3.6 Acknowledgements

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CHAPTER 4

Drivers of fish communities between the mainstem and tributaries in the Urban uMsunduzi Catchment, KwaZulu-Natal

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Running header: Evaluating Fish communities in the uMsunduzi catchment.

4.1 Abstract

Various factors drive the decline of freshwater vertebrate biodiversity. These include changing landscape and urbanisation, introduced invasive species, altered habitat, water quality deterioration, instream barriers, and climate change. In the present study, we evaluated the impact of different habitat features on the fish community assemblages using the Catch Per Unit Effort (CPUE) as a proxy for fish assemblage per site and season. We sampled 17 main sites and 21 ad-hoc sites in the uMsunduzi catchment in Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, South Africa, during 2022-2023. We collected data using an electro-shocker, fyke nets and gill nets, and we also recorded and calculated habitat features such as substrate types, biotopes, in-situ water quality, ecohydraulics, average depth and velocity. We used Generalised Linear Models to determine the habitat features driving fish communities. We calculated the Shannon-Weiner and Pielou diversity indices to compare between rivers. We used the Fish Response Assessment Index (FRAI) tool to understand each site's ecological integrity per season. Our results indicated that various features, including substrate (mud, sand, gravel), fast intermediate and fast deep ecohydraulics, electrical conductivity, habitat (glide, pool) and average velocity significantly impacted the CPUE of fish. There was no variation in diversity indices between tributaries, but there was a significant difference in fish diversity between the uMsunduzi mainstem and its tributaries. The FRAI scores showed great deterioration in the system’s ecological health, and most sites, especially the mainstem sites, were critically or extremely modified. We suggest that the relevant bodies take action to mitigate the pressures compromising the uMsunduzi catchment's ecological integrity. There is an urgent need for conservation measures for the two “near threatened” species, *Enteromius gurneyii* and *Amphilius natalensis.*

Keywords: Fish communities, habitat features, ecological integrity, urban

4.2 Introduction

Freshwater vertebrate biodiversity is declining at a higher rate than terrestrial organisms, and multiple factors are driving these declines (Radinger et al. 2018; Toth et al. 2019; Costa et al. 2021). Among these factors is the alteration of landscapes through land use change, such as urbanisation along rivers (Radinger et al. 2019; Toth et al. 2019; Cruz and Pompeu 2020), the introduction of invasive species (Pool et al. 2010; Toth et al. 2019; Lavery et al. 2022), in-stream habitat alteration and loss (Pool et al. 2010; Ramirez et al. 2012; Levin et al. 2019; Brain and Posser 2022), water pollution (Sarkar and Islam 2020), deteriorating water quality (Ramirez et al. 2012; Mondal and Bhat 2020; Lavery et al. 2022), discharge of effluent and poorly managed wastewater (Sarkar and Islam 2020), construction of dams and impoundments (Brain and Posser, 2022; Lavery et al. 2022), climate change and changes in ambient temperature (Evans et al. 2022; Lavery et al. 2022) and changes in physico-chemical parameters (Levin et al. 2019). The survival of fish and other freshwater biota depends on mitigating the impacts, as mentioned earlier, to maximise the survival ability of freshwater vertebrates in these highly modified freshwater environments (Gupta et al. 2012; Katopodis 2012; Reid et al. 2018).

Various environmental and spatial attributes influence fish community structures, and each plays an independent role in shaping freshwater fish meta-community assemblages (Helms et al. 2009; Gebrekiros 2016). The use of fish biological responses to understand the stability of the freshwater ecosystem has been widely adopted in aquatic ecology (Li et al. 2010; Costa et al. 2021). This is done by assessing the functional diversity within the ecosystem, for example, understanding a fish's biological traits to its habitat preference (Li et al. 2010; Stefani et al. 2020; Sha Esmaeili et al. 2021). Functional diversity refers to the diverse traits prevailing within the ecosystem, and more functionally diverse communities tend to be more resilient to environmental stressors (Lamothe et al. 2017). With the broad responses that freshwater fish have to various anthropogenic impacts, using them to study the ecological integrity of rivers and streams has been effective (Radinger et al. 2019). Using functional diversity to evaluate prevailing functional traits in the ecosystem is a convenient approach to determining the likelihood of species persistence in the ecosystem (Sha Esmaeili et al. 2021).

Variation in flow regimes in rivers and streams is predominantly the primary driver of fish community structures and assemblages (Stocks et al. 2021). Consequently, various studies have used hydrodynamic habitat models to assess the impact of physical habitat as a flow function to determine the effect of flow variations on fish assemblages (Wegscheider et al. 2020). Fish assemblages and community structures vary according to flow regimes (Shukla and Bhat 2018). Impoundment or dam introduction has a major impact on river flows, which alters the river's hydro-morphological processes (Boavida et al. 2020; Wegscheider et al. 2020). This includes the changes in water depth, water turbulence and flow velocity, which then affect the substrate composition, hence impairing fish growth and survival (Boavida et al. 2020).

The increase in the human population is a major contribution to the alteration of land use cover and the resulting urbanisation through industrial works, deforestation, wastewater treatments, agricultural development, residential habitation and recreational grounds (Keppeler et al. 2017; Chen and Olden 2020). As a result, urbanisation has influenced over 80% of the land cover near freshwater systems (Vorosmarty et al. 2010; Arthington et al. 2016). Threatened fish species proportions are higher in areas with high human population density (Gloss et al. 2016; Chakona et al. 2022). In KwaZulu-Natal, South Africa, there have been numerous alterations in natural land cover, especially in the past 12 years, because of urbunisation (Evans et al. 2022) and several threatened fish species are listed as a result (Chakona et al. 2022).

The alteration of land use cover causes a decline in freshwater fish diversity (Meador et al. 2005; Levin et al. 2019). It also reduces functional diversity (Keppeler et al. 2017), supported by the decrease in the ecological integrity of rivers and streams (Levin et al. 2019), which is measured using the Fish Response Assessment Index (FRAI). This tool is widely used in South Africa to determine the ecological state of aquatic ecosystems (Kleynhans 2007; Wepener et al. 2011; Malherbe et al. 2016; Evans et al. 2022). In the northern hemisphere, freshwater fish species have been studied and determined to be sensitive organisms to sub-catchment urbanisation (Chen and Olden 2020). Alteration in land cover features near the rivers and streams affects the physio-chemical conditions of the system (Helms et al. 2009). Physio-chemical parameters such as water temperature, pH, turbidity, total dissolved solids (TDS), dissolved oxygen (DO) and electrical conductivity (EC) influence the diversity of freshwater fish populations (Akhi et al. 2020).

In this study, we assessed various factors correlating with fish communities in the mainstem and tributaries of the uMsunduzi catchment in Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, South Africa. Our study aimed to quantify the functional diversity of fish species found in the mainstem and its tributaries. In addition, we assessed the fish's biological traits and habitat associated with fish assemblages. We also assessed the differences between fish assemblages between the mainstem and tributaries. We predicted that species' functional diversity would be higher in tributaries than in the mainstem, which is highly fragmented and polluted (Chapter 3 and Chapter 5).

4.3 Methods

4.3.1 Sampling sites

We surveyed 17 sites in seven rivers of the uMsunduzi catchment in Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, South Africa. This area is a mosaic urban landscape (Josiah and Downs 2022), with high-density urban areas to low-density semi-rural small holder farmers (Figure 4.1). The rivers include the uMsunduzi mainstem, five tributaries and one sub-tributary. The mainstem had six sites, three in Mpushini, two in Wilgerfontein, Dorpspruit and

Baynespruit per stream, and one in Townbush and Blackborough streams (Figure 4.1). The uMsunduzi mainstem runs through the peri-urban urban areas (Henley, Imbali and Edendale) and further passes through the periphery of the Pietermaritzburg city centre; downstream of the city, it runs through urban areas (Bishopstowe and Eastwood), followed by the wide area of agricultural land use and lastly it joins the greater uMngeni River in Emvini rural area (Figure 4.1).

The most upstream tributary we surveyed was the Wilgerfontein stream, which runs through peri-urban areas of Willowfountain and Imbali. The Dorpspruit Stream was the second tributary and included areas of exotic tree plantations to urban areas (Prestbury, Winterskloof, Wylie Park, and Pietermaritzburg National Botanical Garden). Lastly, it passes through the city centre, where it then joins the uMsunduzi mainstem. We also surveyed one Dorpspruit tributary, Townbush Stream, which flows through the exotic tree plantations and urban residential areas (Cascade, Montrose and Woodlands) and joins Dorpspruit just before Pietermaritzburg's city centre. The third uMsunduzi tributary was Blackborough Spruit, a reasonably short stream that runs through the industrial and urban areas of Mkondeni and Scottsville. Baynesspruit flows through the Northdale urban area and various industrial areas. The last and most downstream tributary assessed was Mpushini, which flows through Bisley Nature Reserve and Mpushini Conservancy and has minimal anthropogenic pressures (Figure 4.1).

We had 21 additional ad-hoc sites sampled once during the study that included other minor tributaries. These were Sinathingi, Mvubukazi, KwaPata, Slangspruit and Foxhillspruit, which flow through moderate urban densities. Five sites on the main stem of the uMsunduzi were included (Figure 4.1).

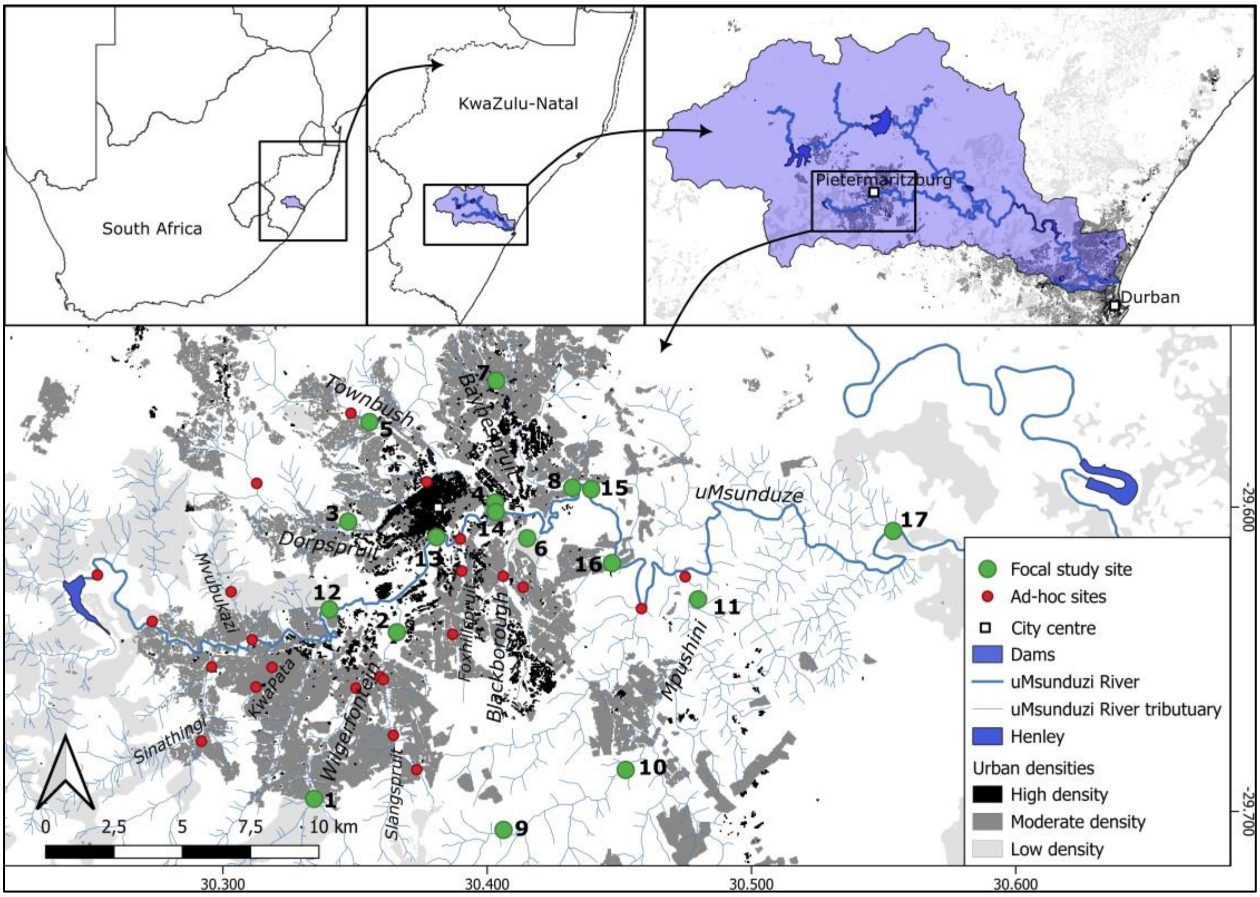

Figure 4.1: The graphical representation of the sites surveyed for the focal study sites and ad-hoc study sites in the uMsunduzi catchment in Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, South Africa.

4.3.2 Sampling techniques

We used three methods for sampling fish: electro-shocking (SAMUS 725M, Electro-fisher, SAMUS Special Electronics, Poland), fyke nets (2 m traps x 700mm opening, 6 m wing and 23 mm mesh size, T&L Netmaking, Mooroolbark, Australia) and gill nets (48 mm mesh size, Eigevis group of companies, Cape Town, South Africa) in the mainstem sites that had deep pools (> 2 m deep). All sites were sampled using the electro-shocking technique. We placed temporary barriers in small streams by running sein nets (2 mm mesh size, 50 cm height) upstream and downstream of the sampled area. We did two passes with the electro-shocking, which constituted an effort for each pass with the time taken for each effort recorded. In addition, two fyke nets were deployed only at the Mpushini main sites and Dorpspruit upstream site (Figure 4.1). We conducted our surveys quarterly in March, June, August, and November of 2022, and ad-hoc sites were sampled during January 2023 to coincide with high flows, where we found the presence of fish in the tributaries to be the greatest. We then used the guide to the freshwater fishes of southern Africa to identify species (Skelton, 2012). We measured the standard length for all fish collected, and recorded their species' abundances for each site together with effort. When we had sampled all the fish, we returned them to the river at their capture sites.

At all the main sites and where we caught fish at the ad-hoc sites, the habitat was recorded, including the total length of the surveyed river stretch and the cross-section every five meters. For each cross-section, five points were collected perpendicular to the flow of the river as per Ellender et al. (2012), with depth, velocity, substrate, and respective biotopes recorded. For velocity and depth, the transparent velocity head rod (TVHR) was used (Desai et al. 2021; Evans et al. 2022). The substrate types recorded were bedrock, boulders, cobbles, gravel, sand, and mud. We recorded the hydraulic biotopes, such as pool, still margin, glide, run and rapid, as defined by Wadeson (1995). We converted depth and velocity readings per point into eco-hydraulic classes as per James and King (2010). The ecohydraulics were classified into seven classes: fast very shallow (FVS), fast shallow (FS), fast intermediate (FI), fast deep (FD), slow very shallow (SVS), slow shallow (SS) and slow deep (SD) (James and King 2010).

4.3.3 Data analyses

We calculated the Catch Per Unit Effort (CPUE) as functional space by fish per m^3, using the following formula:

$$CPUE = \frac{\sum(x_1 + x_2 + x_3 + \cdots x_\infty)}{\sum(L \times B \times H)}$$

Where $X_{1-\infty}$ represented the number of individuals per species. L x B x H, is a calculation for the area per cross-section where L represents the length of along the riverbank, B represents the width of the respective cross-section, and H stands for average depth in each cross-section. Therefore, the CPUE is presented by the relative abundance of fish per area surveyed in each quarter sampled (Ellender et al. 2012).

We used analysis of variance (ANOVA) multivariate statistical analysis performed in R (version 4.2.2) to determine which habitat feature had a significant impact on the functional diversity of fish communities within the catchment. To evaluate the impacts of habitat features, we ran many generalised linear models (GLMs) using the mvabund package (Desai et al. 2021). For the GLMs, CPUE was used as a function of each factor within the habitat features. We ran several models where CPUE was a function of substrate (mud, sand, gravel, cobbles, boulders and bedrock), biotopes (still margin, pool, glide, run and rapids), in-situ water quality (water temperature, pH, electric conductivity, salinity and total dissolved solvents), ecohydraulics (FVS, FS, FI, FD, SVS, SS, SD), average depth and velocity, and barrier density per kilometre (Chapter 3).

To measure the diversity and evenness of fish species communities per river, we calculated the Shannon-Weiner diversity index (H') and the Pielou's evenness index (J'). The Shannon-Weiner index was calculated from the species abundance data using vegan packages in R (v.4.2.2). The Pielou's evenness is the natural logarithm of the Shannon index {(ln (H')}. We conducted a Kruskal-Wallis test to determine if there was a significant difference in species diversity between rivers.

Lastly, to determine the ecological class for each site per season, we used the Fish Response Assessment Index (FRAI) (Kleynhans 2007), a tool designed to quantify the ecological integrity of the river site. This tool uses historical data on species distribution and their intolerance of environmental changes in habitat features over time. We obtained historical fish species distribution from the Freshwater Biodiversity Information System (2023), and for all our sites, we used the uMsunduzi catchment species distribution. The FRAI tool gives the results as adjusted and general ecological scores and classes to describe the state of the river (Table 4.1).

Table 4.1: The ecological classes, scores and description of ecological integrity as depicted by Kleynhans et al. (2005).

Ecological Class	**Name**	**Ecological Score**	**Description**
A	Natural	90-100	Natural
B	Good	80-89	Mostly natural but with light modification
C	Fair	70-79	Moderately modified
D	Poor	40-59	Largely modified
E	Seriously Modified	20-39	Seriously modified
F	Critically Modified	0-19	Extremely modified

4.4 Results

We caught a total of 1920 fish from nine species and seven families during the study. The most common species we caught were *Clarius gariepinus*, *Labeobarbus natalensis*, *Oreochromis mossambicus*, *Pseudocrenilabrus philander* and *Tilapia sparmanii*. The other species were only caught once or relatively few times and in smaller abundance. These included *Amphilius natalensis* caught during the ad-hoc survey; *Anguilla mossambica* and *Micropterus salmoides* had only one individual of each caught once; and *Enteromius viviparus* was caught once in the upstream Townbush and downstream Mpushini sites (Figure 4.2).

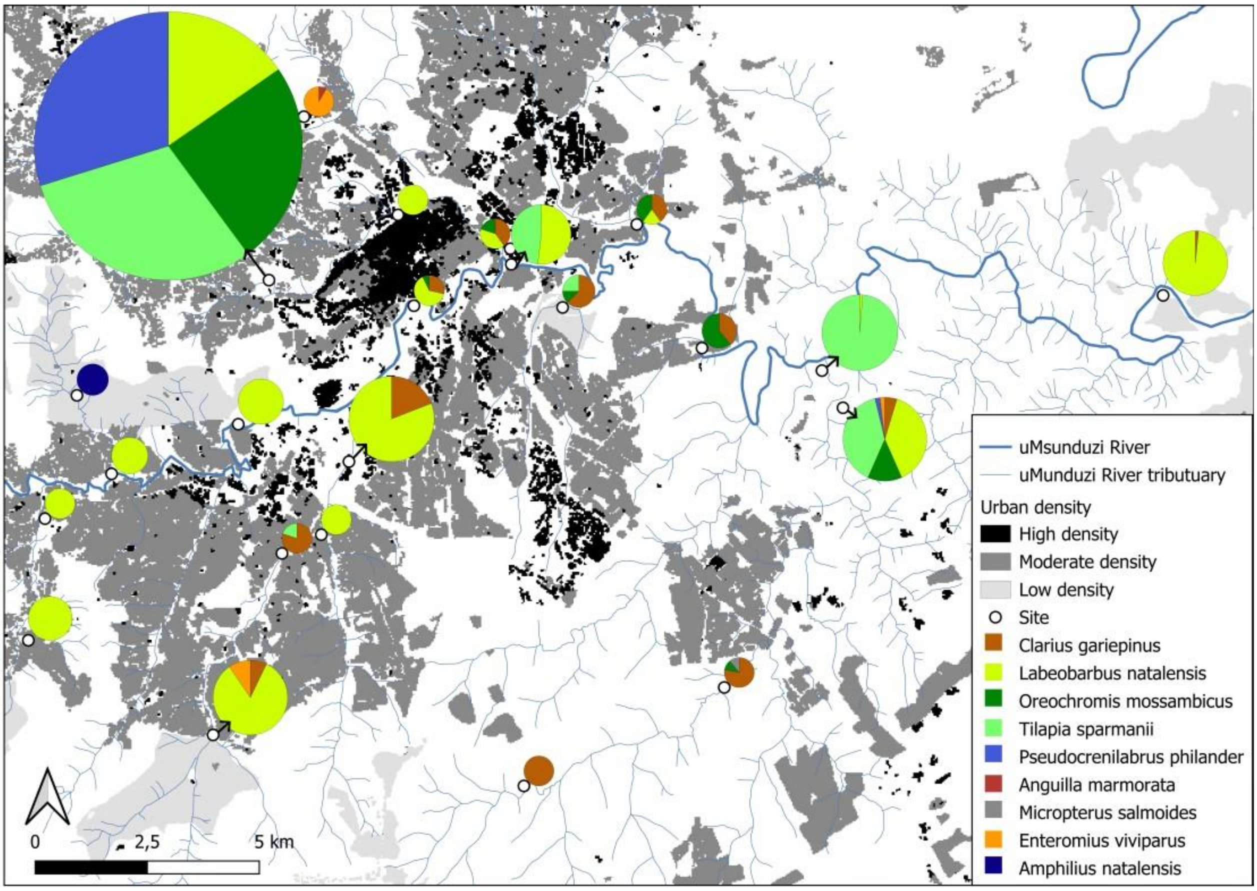

Figure 4.2: Spatial representation of fish species abundances on different rivers and sites in the uMsunduzi catchment, Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, South Africa, for the main and ad-hoc surveys- Pie charts representing species diversity per site.

According to the IUCN Red listing, two native species, *Amphilius natalensis* and *Enteromius gurneyii* are near threatened, and one species, *O. mossambicus* has a vulnerable status in southern Africa (Table 4.2). *Enteromius gurneyii* was not found during the study, and *Amphilius natalensis* was only caught once during the ad-hoc survey (Table 4.2; Figure 4.2). We expected to find 18 species in the uMsunduzi catchment using the Freshwater Biodiversity Information System, but we only caught 50% of these species in the present study (Table 4.2, Figure 4.2)

Table 4.2: List of expected and observed species and their IUCN listing, as outlined by Chakona et al. (2022) for native species and IUCN for alien species, in the uMsunduzi catchment in Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, South Africa.

Expected Species	**Native/Invasive**	**Historical Presence**	**Current occurrence**	**IUCN listing**
Amphilius natalensis	Native	X	X	NT
Anguilla bengalensis	Native	X		LC
Anguilla mossambica	Native	X		LC
Carassius auratus	Alien	X		LC
Clarius gariepinus	Native		X	LC
Cyprinus carpio	Alien	X		LC
Enteromius gurneyii	Native	X		NT
Enteromius toppini	Native	X		NT
Enteromius viviparus	Native	X	X	NT
Labeo molybdinus	Native	X		LC
Labeobarbus natalensis	Native	X	X	LC
Lepomis macrochirus	Alien	X		LC
Micropterus punctulatus	Alien	X		LC
Micropterus salmoides	Alien	X	X	LC
Oreochromis mossambicus	Native	X	X	VU
Pseudocrenilabrus philander	Native	X	X	LC
Tilapia sparmanii	Native	X	X	LC

There were significant impacts in the habitat variables on the CPUE (ANOVA, F = 3.966; DF = 4 ; P = 0.029). Substrate variables included mud (P = 0.003), sand (P = 0.001) and gravel (P = 0.017) (Figure 4.3). The biotopes glide (P = 0.001) and pool (P = 0.027) significantly impacted the CPUE (Figure 4.4). Most ecohydraulics did not show significance, but fast deep (P = 0.003) and fast intermediate (P = 0.035) were significant (Figure 4.4). Only electric conductivity was significant within the in-situ water quality (P = 0.045) (Figure 4.5). Average velocity significantly impacted the CPUE (P = 0.033) (Figure 4.5). Lastly, the barrier density per kilometre significantly impacted the CPUE; as a result, the CPUE increased as the barrier density increased (Figure 4.6).

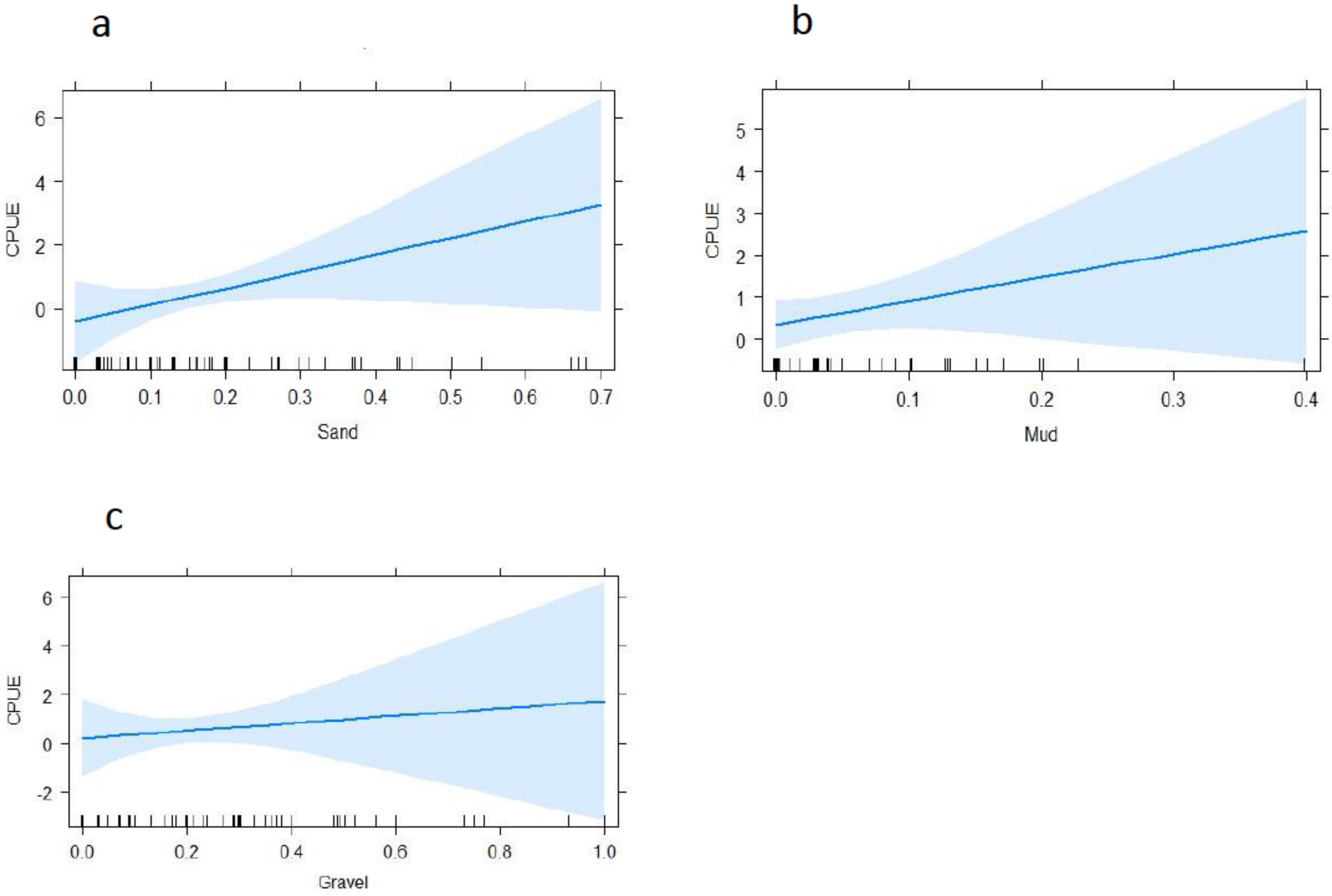

Figure 4.3: Generalised linear model outputs presenting the significant factors in catch per unit effort (CPUE) of fish for substrate types a) sand, b) mud and c) gravel in the uMsunduzi catchment in Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, South Africa.

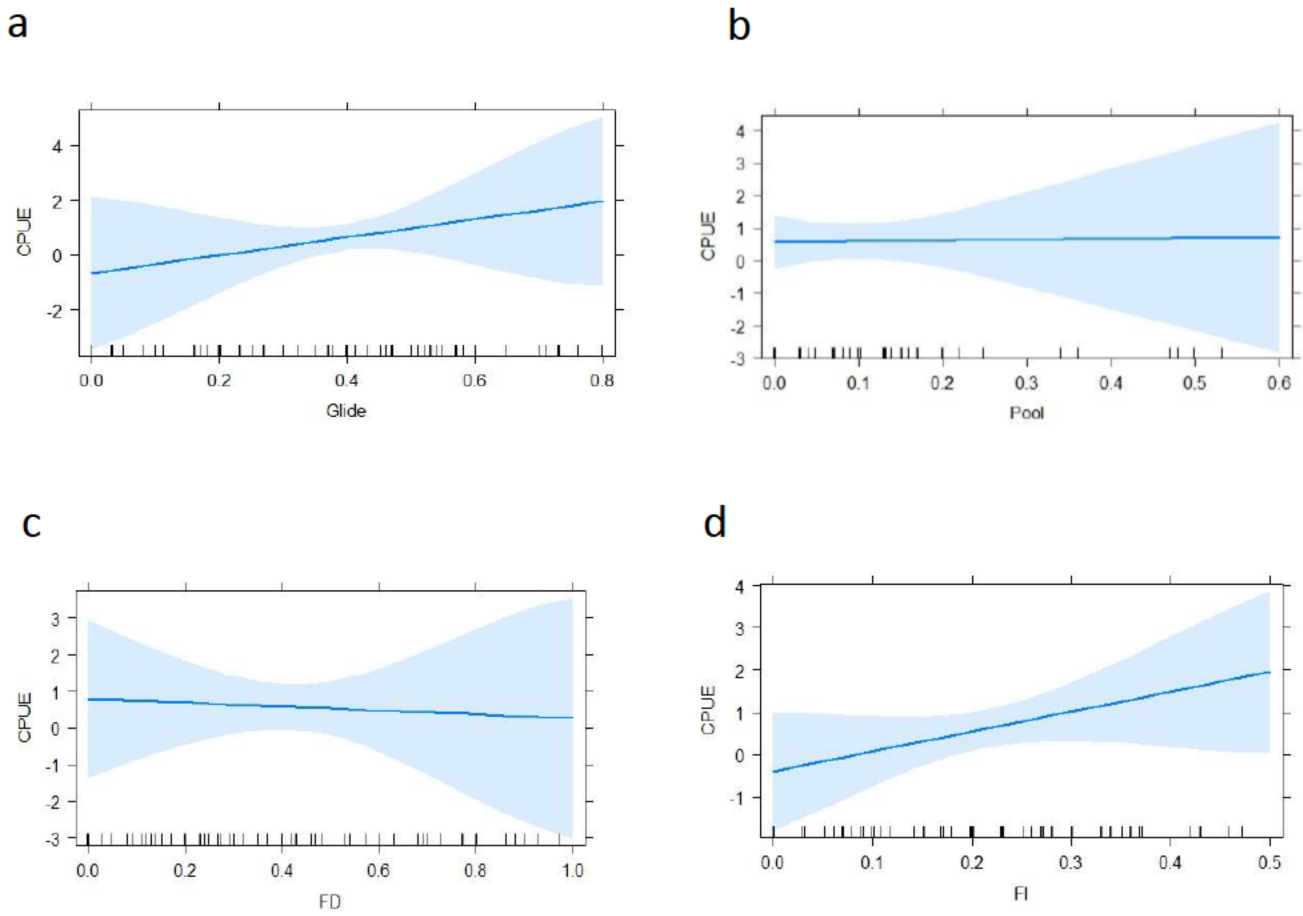

Figure 4.4: The generalised linear model outputs depicting the significance of glide and pool factors among the biotopes' habitat features where a) is glide, and b) pool, and showing the significant attributes of ecohydraulics on the catch per unit effort of fish where d) shows fast deep (FD), and e) fast intermediate (FI), in the uMsunduzi catchment in Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, South Africa.

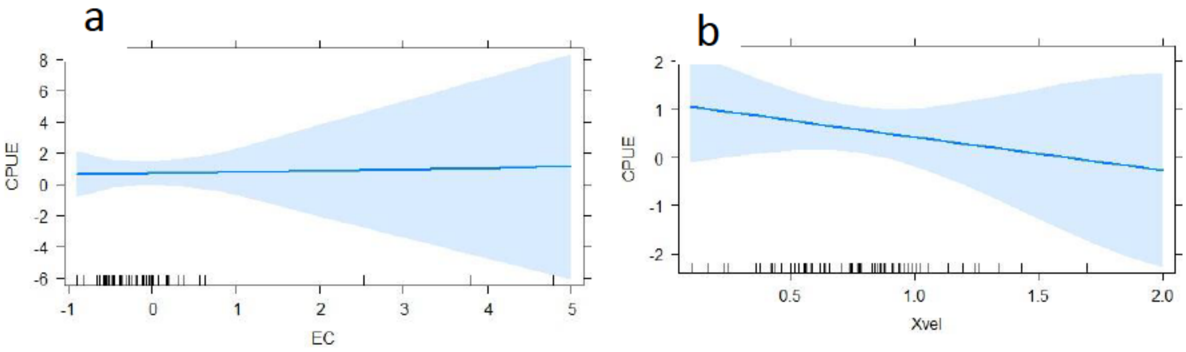

Figure 4.5: Generalised linear model output showing a.) the significance of electric conductivity on the catch per unit effort of fish under the in-situ water quality parameters, and b.) the impact of water velocity on the catch per unit effort (CPUE), in the uMsunduzi catchment in Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, South Africa.

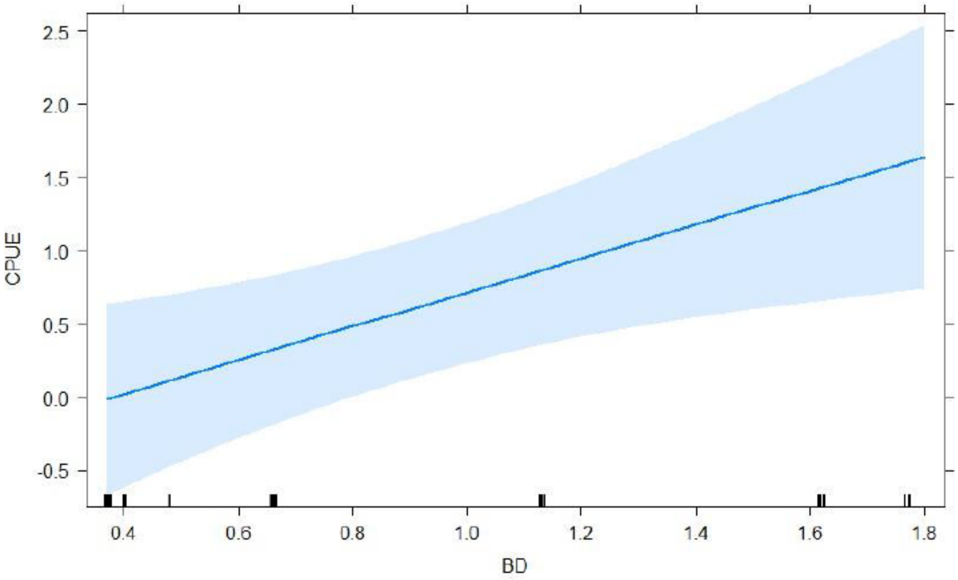

Figure 4.6: Generalised linear model showing the significance of catch per unit effort (CPUE) response to physical barrier density/km in the uMsunduzi catchment in Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, South Africa.

Both the Shannon-Weiner and Pielou evenness diversity indices for fish communities were variable (Figure 4.7). There were no significant differences between the rivers; Shannon diversity 'H' (Kruskal-Wallis Chi squared = 10.535, df = 8, P > 0.2295) and Pielou evenness J' (Kruskal-Wallis Chi squared = 10.535, df = 8, P > 0.2295). However, there was a significant difference between the uMsunduzi and Dorpspruit diversity indices (Pairwise comparison Wilcoxon rank, P = 0.024). The uMsunduzi mainstem did not show significant diversity in both Shannon-Weiner and Pielou diversity indices (Figure 4.7). In contrast, there was relatively high diversity in the tributaries. Dorpspruit showed the highest species diversity, followed by Mpushini, Blackborough and Wilgerfontein streams, while all other tributaries showed no significant diversity (Figure 4.7). Our results showed that the sites with the highest diversity and evenness also had the highest fish abundances (Figures 4.2 and 4.7).

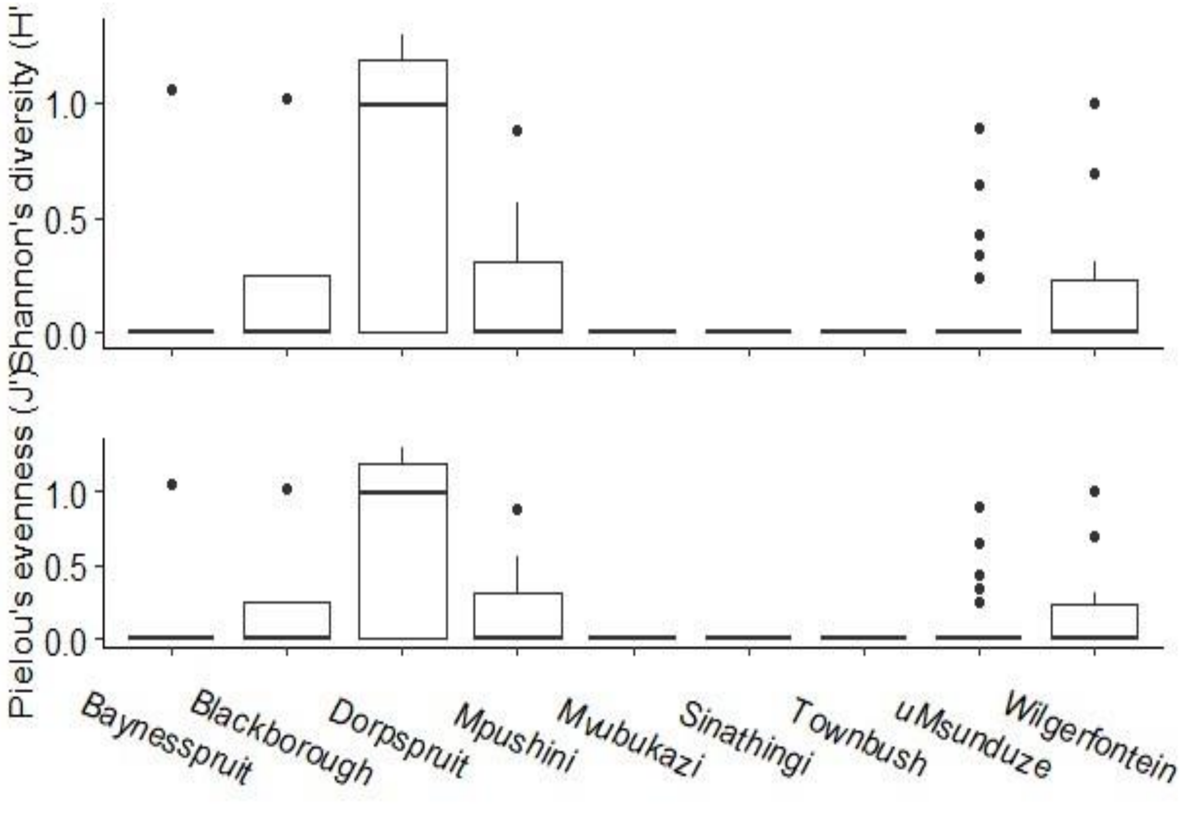

Figure 4.7: The Shannon-Weiner diversity index (H') and Pielou evenness index (J') for the focal study tributaries, ad-hoc surveys, and the uMsunduzi mainstem.

Table 4.3: The seasonal changes in the Fish Response Assessment Index ecological scores for each site over the four quarters sampled in the uMsunduzi catchment in Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, South Africa. (See Figure 4.1 for localities).

			Seasonal Quarters		
River	**Site no.**	**March**	**June**	**August**	**November**
Wilgerfontein	1	63.2	63.6	56.7	62
Wilgerfontein	2	64.8	56.8	48.6	53.4
Dorpspruit	3	82.7	68.8	70.4	71.2
Dorpspruit	4	35.2	34.5	36	36
Townbush	5	57.6	54.4	49	51.9
Blackborough	6	64.8	37.3	42.4	37.8
Baynespruit	7	16.3	16	15.7	16.2
Baynespruit	8	24.6	18.1	18.6	18.3
Mpushini	9	55	53.1	54	54.5
Mpushini	10	52	48.3	50.6	51.3
Mpushini	11	63.6	63.2	56.8	57
uMsunduzi	12	57	56	54.2	57.8
uMsunduzi	13	28	19	18.3	18.4
uMsunduzi	14	48	46.3	51.8	50.6
uMsunduzi	15	18.7	18.3	17.8	17.5
uMsunduzi	16	N/A	18.3	22.3	26.4
uMsunduzi	17	55.8	52	66.1	57.3

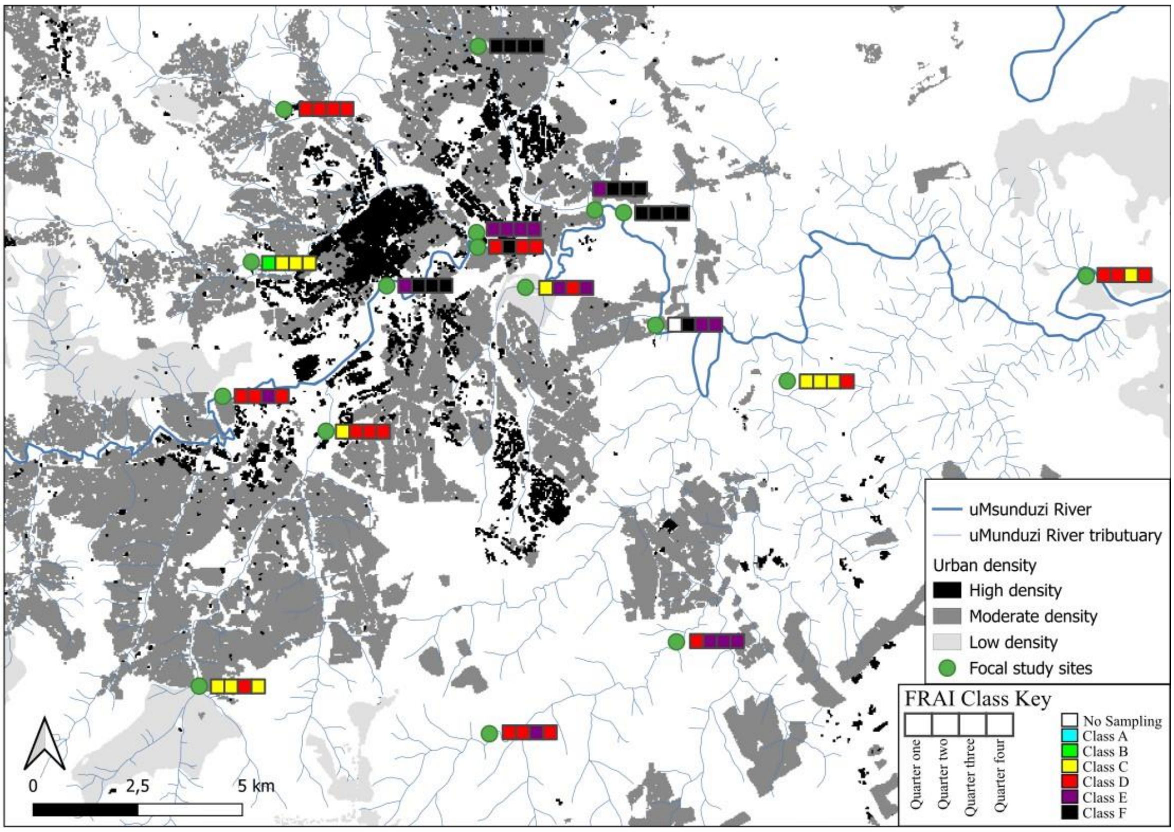

Figure 4.8: The adjusted FRAI classes for the main study sites for four surveys conducted seasonally in the uMsunduzi catchment in Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, South Africa.

Most of our sampling sites had a declining trend using the FRAI scores (Table 4.3, Figure 4.8). Our FRAI scores suggest that seasonal changes put increased pressure on the system (Table 4.3, Figure 4.8). Most sites in the mainstem were either “Largely Modified”, "Seriously Modified", or "Extremely modified" throughout the study period (Table 4.3, Figure 4.8). We did not get scores that suggest that any site was in its natural or pristine state (Table 4.3, Figure 4.8). We did, however, have one site (site three, Dorpspruit upstream) that was “Mostly natural but with light modification”; this was for one season, and the site was in a “moderately modified” state after that (Tables 4.1 and 4.3).

4.5 Discussion

In our study of the uMsunduzi catchment in Pietermaritzburg, uMgungundlovu District, KwaZulu-Natal, we found that the overall fish diversity consisted of nine species, 50% of the 18 expected species. This was relatively poor compared with the 64% of KwaZulu-Natal indigenous species that were found in KwaZulu-Natal major rivers in 2016 (Evans et al. 2022). The uMsunduzi mainstem showed no significant differences in diversity when comparing the Shannon-Weiner and Pielou diversity indices. As we predicted, there was relatively high diversity in the tributaries, with Dorpspruit showing the highest species diversity. The sites with the highest diversity and evenness also had the highest fish abundance. However, four out of nine species were found in low abundance, which suggests that these species are also on the verge of disappearing from the system.

The uMsunduzi catchment is a highly polluted stream (per obs, unpublished data), and there have been various major fish kills in the past; this could also have a significant impact on the fish diversity and abundance in the system (Karssing 2008; Evans et al. 2022). Two of the native species, *A. natalensis* and *E. gurneyii* are listed as “Near threatened” by the IUCN Red List (Chakona et al. 2022). We did not catch *E. gurneyii,* and *A. natalensis* was only caught once during the ad-hoc survey, which calls for conservation measures that need to be taken for these species.

We found that most of our sampling sites had a declining trend using the FRAI scores. The results from our FRAI scores suggest that seasonal changes put pressure on the system. Most sites in the mainstem were either “Largely Modified”, "Seriously Modified", or "Extremely modified" throughout the study. Across the study area, we did not get scores suggesting that these streams are in a natural or pristine state. We did, however, have one site that was "Mostly natural but with light modification"; this was for one season only, during a high flow period. Generally, a natural ecological FRAI class would indicate that the ecosystem can support and uphold a cohesive, adaptable community of organisms, and it can exhibit species composition, diversity, and functional diversity comparable to that found in pristine habitats of a particular region (Kwak and Freeman 2010). Despite this score, key species, such as *E. gurneyii* and *Anguillid* spp., were still missing, indicating that this site would fluctuate.

Most of our sites were near urban areas or high-density areas, including the city centre. Urbanisation is one of the factors that have been documented to impact the functioning of freshwater ecosystems (Evans et al. 2022). The FRAI scores indicated there was a seasonal change in fish community assemblages, and the upstream Dorpspruit site decreased from B, “Mostly natural but with light modification” to C “moderately modified” state, which showed that the summer season improved ecological scores for fish and drier seasons reduced ecological scores. Although this site had the highest abundance and diversity per site, it only had four of the 18 expected fish species. The downstream of the same stream was at a “seriously modified” state throughout all seasons; similar results were seen in Vaal River, Gauteng, South Africa (Wepener et al. 2011). The ecological scores indicated that high urban density areas compromised the ecological integrity of the ecosystem; in essence, the upstream was not as impacted as the midstream and downstream sections. Similarly, in the Nakdong River, South Korea, the ecological scores showed that the river was highly impaired from the middle to downstream after the impact of industrial land use and wastewater treatment (Kim and An 2015). Overall, the ecological health of the uMsunduzi is poor and worsening in areas with higher human disturbances. Furthermore, there is a need for immediate management and maintenance actions, such as controlled disposal of waste into the river (Hara et al. 2019).

Our study's most significant habitat features were substrate features, sand, gravel and mud. The two common species we sampled, *C. gariepinus* and *O. mossambicus*, prefer muddy substrates (Sourced from FishBase), and support the significance of muddy substrates on the catch per unit effort. *Oreochromis mossambicus* has been previously noted to be tolerant of a wide range of physico-chemical pollution, for example, ammonium nitrogen in human effluents, acidic and alkaline environments, high altitude impoundments and high turbidities (Russell et al. 2012). The significance of gravel can be explained by the relatively high abundance of *L. natalensis*. Females of this species prefer gravel beds for spawning, and the offspring are associated with gravel before they can move freely between habitats (Karssing 2007; Dlamini 2019). This species also tends to occur in shoals, and it would be expected to catch them in higher abundance when present (Karssing 2007; Burnett et al. 2021). Due to their rheophilic nature, *L. natalensis* occupies both fast and slow-moving waters seasonally (Burnett et al. 2021); hence, the decrease in catch per unit effort when the average velocity increased could be explained by the seasonal movements of *L. natalensis* associated with different habitats in the present study. Furthermore, *O. mossambicus,* which was dominant in the system, prefers quiet open pools with slow-moving waters (Russell et al. 2012). Cichlid species have various substrate preferences, including accumulating shelters in sandy and muddy substrates (Dario et al. 2018). They also breed in sandy beds with minimal flow (Mckaye 1977). For instance, Dlamini (2019) and Evans et al. (2022) found that *P. philander* and *O. mossambicus* were associated with sandy substrates. In our study, we caught three species that belonged to the Cichlidae family: *O. mossambicus*, *P. philander* and *T. sparmanii*, which were both relatively common at certain sites and were usually found in higher abundance, hence the significance of sand and mud on the catch per unit effort (Wasserman et al. 2016). Cichlidae species have also been noted to prefer sandy, rocky substrates, and in this case, it would explain the significance of gravel and sand substrates because all cichlids were found in higher abundance as in other studies (Kinyange and Lamtane 2019).

According to our results, there was an increase in the availability of glide biotopes, resulting in higher catch per unit effort, while the more pools present caused a decrease. During spawning, *L. natalensis* migrate to glides to spawn in the gravel associated with the glides

(Karssing 2007; Dlamini 2019). We had higher abundances of *L. natalensis* than any other species; hence, the significance of the habitat features could be influenced by the species that were found in greater abundance. As mentioned, *O. mossambicus* is usually found in calm, sandy, slow-moving waters with vegetation covers (Jayaratne and Surasinghe 2010; Russell et al. 2012), which was a common characteristic of the upstream Dorpspruit Stream site which had the highest abundance throughout our study.

Fast deep and fast intermediate ecohydraulic types significantly impacted the catch per unit effort in our study. Fast intermediate ecohydraulics resulted in a higher catch per unit effort, while fast deep resulted in a slight decrease. However, the increase in velocity was associated with decreasing catch per unit effort. Some species we found, like *L. natalensis, A. natalensis,* and juveniles of *A. mossambica* and *C. gariepinus,* are semi-rheophilic species, hence the significance of fast-flowing waters and slow-moving waters or glides for differing biological needs (Burnett et al. 2021; Evans et al. 2022). *Tilapia sparmanii* prefers shallow habitats with vegetation (Wasserman et al. 2016; Evans et al. 2022); hence, deep habitat cover decreased the catch per unit effort. *Anguilla mossambica* is known to be a generalist eel species and usually found in freshwater inland rivers with higher altitudes (Hanzen et al. 2021), which was the case for the present study; we found this species in the upstream of Townbush Stream, which has a higher altitude (Chapter 3 Table 3.2; unpublished data). However, between 1985 and 2020, there was a 47% decline in *A. mossambica* (Hanzen et al. 2021), and we only found one individual in the present study.

Within the physico-chemical parameters, electric conductivity was the only significant variable affecting catch per unit effort. As the electrical conductivity increased, there was a slight increase in the catch per unit effort. Similarly, Mueller et al. (2016) found a positive correlation between electrical conductivity and catch per unit effort. In some species, like *C. gariepinus*, water parameters do not play a significant role, possibly because this species is tolerant to a wide range of environmental conditions (Karssing 2007; Evans et al. 2022). The significance of the high barrier density can be explained by the fact that species cannot move between fragments; in essence, the Dorpspruit and Wilgerfontein had the highest barrier density (Chapter 3, unpublished data), and they also had the highest fish species abundance. In previous studies, fish populations have modified their life-history strategy to enhance residency if they fail to migrate across the barriers (Branco et al. 2017). This could be particularly true for potamodromous species that can still access their required habitats within the newly fragmented river reach; however, this may reduce genetic resilience in the long term (Burnett et al. 2021).

4.5. Conclusions

Generally, our study showed a decline in native fish species in the uMsunduzi catchment. Species like *A. natalensis* are rare in the system, and the declines are supported by the deterioration in the ecological integrity of the streams (Evans et al. 2022). The IUCN "near threatened" listed *E. gurneyii* species was not found in the uMsunduzi catchment despite the effort of the ad-hoc surveys; this species can no longer be reliably found in the system and possibly is locally extinct (Evans et al. 2022). The poor ecological state of the uMsunduzi mainstem possibly jeopardises the ecological integrity of its tributaries, with the less degraded tributaries potentially being refugia for species less tolerant to pollutants, for example, the Mvubukazi Stream with *A. natalensis*. Hence, it is important that care be taken of these tributaries and efforts made to mitigate and restore the uMsunduzi River freshwater vertebrate species. This can be done by mitigating factors driving the decline of fish species and other freshwater taxa, like industrial and domestic pollution, wastewater treatment, and effluents.

4.6 Acknowledgements

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CHAPTER 5

A case study: Monitoring seasonal changes in water quality in the uMsunduzi catchment, KwaZulu-Natal Province, South Africa

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Running header: Seasonal changes in water quality in the uMsunduzi catchment

5.1 Abstract

Open freshwater bodies are facing growing pollution threats from different anthropogenic factors that arise with changes in land use cover. Urban freshwater aquatic ecosystems are even more susceptible to various contamination, such as microbial and chemical waste contamination. The uMsunduzi catchment, KwaZulu-Natal Province, South Africa, is one urban river facing these continuous threats. We conducted this study from January 2022 to January 2023, sampling periodically at 28 sites in the uMsunduzi catchment to determine the concentrations of microbial contamination using *Escherichia coli* as an indicator and chemical waste analysis for different heavy metals and chemical waste. The heavy metals included Cadmium (Cd), lead (Pb), manganese (Mn), and zinc (Zn), and the chemical analysis included sulphates (SO_4), calcium (Ca), volatile fatty acids, polyethersulfone and hydrocarbons. We had 28 sites for four different objectives. Our results indicated that *E. coli* levels are very high in the uMsunduzi catchment, with an average of over 90% increase in *E. coli* concentrations between 2010 and 2022. Most streams, except for the Dorpspruit and Mpushini, showed no significant difference in the *E. coli* concentrations between the upstream and downstream sites. Magnesium, calcium and fatty acids were the only parameters with significant concentrations in the system between periods and sites. We recommend a prolonged assessment of microbial and chemical waste concentrations in the uMsunduzi catchment system and management intervention to ensure the sustainability of this important river and its associated ecosystem services.

Keywords: *E. coli*, Chemical waste, urban aquatic ecosystems.

5.2 Introduction

Water is one of the fundamental needs for all living organisms, from macroinvertebrates to vertebrates, including humans (Dwivedi, 2017; Ngubane et al., 2022). However, the increase in urbanisation and growing industrial and agricultural land use pose a pollution threat to open water bodies such as rivers and streams (Odume et al., 2012; Amoatey and Baawain, 2019; Chetty and Pillay, 2019; Nkosi et al., 2021; Chen et al., 2022). Anthropogenic land use and land cover changes impact freshwater systems' water quality and compromise their ecological integrity (Namugize et al., 2018). Land use change is the primary factor affecting the nutrient concentration in rivers and streams (Mokarram et al., 2020; Van Deventer et al., 2022).

Rivers are facing heavy pressure from the different pollutants affecting river health. For instance, agricultural activities bring about pollutants different from industrial activities, domestic activities, and wastewater treatments (Osibanjo et al., 2011; Chetty and Pillay, 2019). Copper, iron, nitrates, phosphates and sulphates ions are typical pollutants from agricultural activities, and these ions negatively impact the river health by reducing oxygen concentrations, causing excessive eutrophication and algal blooms (Chetty and Pillay, 2019). In contrast, the decline of some chemical ions in freshwater systems may be detrimental; calcium, for instance, is an essential nutrient in freshwater biota (Reid et al., 2019). Hence, the decline in calcium ions would result in a decline in some freshwater organisms, both flora and fauna (Weyhenmeyer et al., 2019).

Copper (Cu), lead (Pb), cobalt (Co), arsenic (As), zinc (Zn), cadmium (Cd), iron (Fe), chromium (Cr), nickel (Ni) and mercury (Hg) are common elements that persist from industrial activities (Chetty and Pillay, 2019; Afzaal et al., 2022). These heavy metals are usually non-degradable contaminants that, even in low concentrations, contaminate both groundwater and water surface, which in turn increases the demand for clean water (Jaiswal et al., 2018; Mokarram et al., 2020; Zaynab et al., 2022). Some of these heavy metals (e.g. Zn, Ni and Fe) are essential for living organisms, plants and animals (including humans), while some (e.g. Cd, Pb and Hg) are toxic and form the topmost toxic heavy metals in river health (Afzaal et al., 2022). The increase of these heavy metals in aquatic ecosystems may pose a fatal threat to fish species as they alter metabolic rates, cause tissue damage and consequently reduce immune responses (Jaiswal et al., 2018; Malik et al., 2020). Industries, such as farming, drug, paper, chlorine and sodium hydroxide manufacturers, release mercury to neighbouring watersheds (Zaynab et al., 2022). Cadmium is usually from coal and mineral fertilisers (Zaynab et al., 2022). Mining industries have been observed to increase the levels of manganese in rivers and streams, which is also a public health risk (Matveeva et al., 2022). Oil, grease and hydrocarbon pollutants are generally common in river sites near petroleum or crude oil and lubricating oil production companies (Kuppusamy et al., 2020; Sarkhel and Ganguly, 2022). There is a consensus that urban streams and rivers are more susceptible to increased concentrations of heavy metal and chemical waste (Das et al., 2009).

Over 82% of South African river ecosystems are threatened, and the ecosystem status is continuously declining; worrisome is that only 13% of the rivers in the country are protected (van Deventer et al., 2022). Deteriorating water quality because of agricultural, mining, and industrial land use has been observed in different parts of the country, such as the Crocodile River and Olifants River in Mpumalanga Province (Nkosi et al., 2021). In KwaZulu-Natal Province, there is a great deal of ecological disturbance and river water quality deterioration, including the uMngeni catchment (Namugize et al., 2018; Van Deventer et al., 2022). The deteriorating water quality has increased as the population of the uMngeni catchment increased by 22% between 1996 and 2009 (Namugize et al., 2018). The uMsunduzi is a sub-catchment to the greater uMngeni catchment, and this sub-catchment is no exception in the degradation of water quality caused by anthropogenic activities (Ngubane et al., 2022).

For decades, the presence of pathogenic microorganisms such as *Escherichia coli* (*E. coli*) in freshwater has been a common discussion as a matter of public health (Pachepsky et al., 2014; Cho et al., 2022). The presence of *E. coli* in aquatic ecosystems is usually associated with faecal contamination or wastewater effluents (Abia et al., 2017; Jang et al., 2017). Hospitals are one of the major contributors of lethal pathogens into freshwater systems, and the effluent from hospitals is considered to be more dangerous because of the drug residues, has resulted in the increase of antibiotic-resistance in multiple variants of *E. coli* (Lorenzo et al., 2018). The increase in ambient temperatures associated with global warming favours the growth of *E. coli* and its long-term survival (Blaustein et al., 2013; Pachepsky et al., 2014; Jang et al., 2017; Cho et al., 2022). Some variants of *E. coli* have developed a resistance to acidic environments in aquatic environments; hence, if ingested by humans, they can invade the human stomach and colon because of their low pH levels (≤ 2.5) (Van Elsas et al., 2011). In Nahoon Beach and reservoirs, Eastern Cape Province, many *E. coli* strains were found to be resistant to eight different antibiotics, which was declared a public health risk (Ebomah et al., 2018).

Our study aimed to assess the levels of various heavy metals, chemical waste and *E. coli* in freshwater samples collected in the uMsunduzi catchment, including river sites near high urban density areas. We also determined the relationship between ambient temperatures and levels of *E. coli*. Lastly, we determined if there was a significant difference in the concentrations of *E. coli* and chemical contamination between sites before and after heavy rains, during industrial shutdown periods, and during high flows. We predicted that there would be a significant level of heavy metals in the downstream sites of the industrial activities compared with upstream and control sites. We also predicted that *E. coli* concentrations would be higher during the spring and summer months when the ambient temperatures were higher, and there would be higher *E. coli* concentrations in the downstream sites of each stream than in most upstream sites.

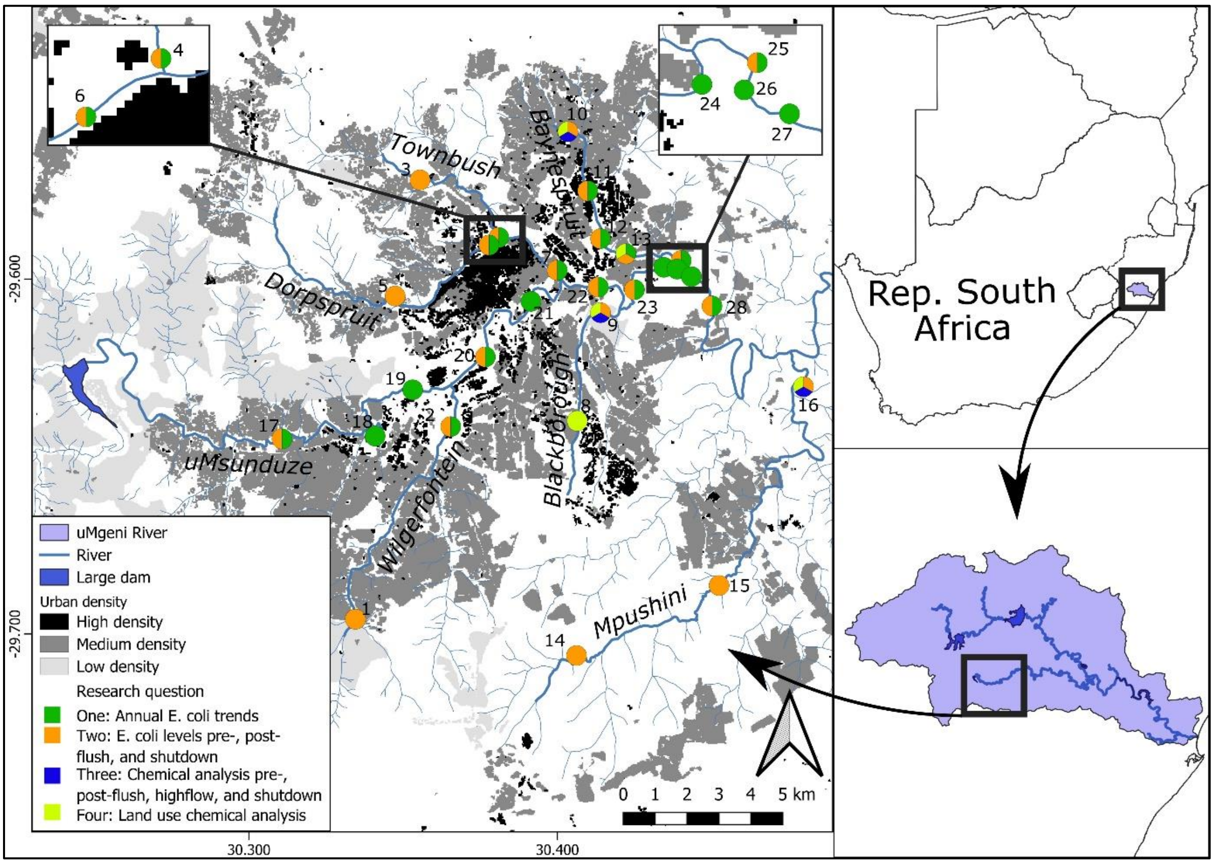

Figure 5.1: Map showing the 28 study sampling sites in the uMsunduzi catchment, KwaZulu-Natal Province, South Africa, their associated level of urban density and associated study objectives.

5.3 Methods

5.3.1 Study sites and data collection

Our study area was in the uMsunduzi catchment in KwaZulu-Natal, South Africa. We had a total of 28 study sites in seven rivers (Figure 5.1, Supplementary information Table S5.1). Our study sites were in mainstem uMsunduzi River, and five tributaries: Wilgerfontein, Dorpspruit, Blackborough, Baynespruit, Mpushini, and one sub-tributary; Townbush Stream, which is a

Dorpspruit tributary. Our study sites were associated with either medium or high urban density (Figure 5.1).

We determined the relationship between the average monthly temperature from January 2022 to January 2023 with the monthly average trends of *E. coli* concentrations sampled and analysed by Umgeni Water, Pietermaritzburg, from 19 sites (Site numbers: 2, 4, 6 to 7, 11 to 13 and 17 to 28; Figure 5.1, Supplementary information Table S5.1 Objective 1). We had 20 (Site numbers: 1 to 7, 9 - 17, 20, 22, 23, 25 and 28, Supplementary information Table S5.1 Objective 2) sites where we collected *E. coli* samples using 250 ml bactro-bottles provided by Umgeni Water to quantify the changes in *E. coli* levels between the periods of pre-flush rains in September 2022, post-flush rains in October 2022 and industrial shutdown during end of year holidays in December 2022. In three of the 20 sites (Site 9, 10, and 16, Supplementary information Table S5.1 Objective 3), we also collected water samples using 2-litre bottles for chemical analyses during four different periods (1. September 2022 before heavy rains, 2. October 2022 after the heavy rains, 3. December 2022 during the holiday closure of industrial companies, and 4. March 2023 during the high flow season). The intended chemical analyses was for sulphuric acid, calcium, manganese, cadmium, oil & grease, lead, hydrocarbons, zinc and volatile fatty acids. In addition, during the high-flow season, we collected samples for chemical analyses only from five sites (8, 9, 10, 13 and 16) for high-flow spatial detection of chemicals in four sites that were in proximity to the industrial areas and in one control site (Site 16; Figure 5.1, Supplementary information Table S5.1 Objective 4). We then sent water samples for *E. coli* and chemical laboratory analyses to Umgeni Water, Pietermaritzburg, and Aquatico Laboratories (Pty). Ltd, Johannesburg, respectively. We requested the Pietermaritzburg ambient temperatures from South African Weather Services. Our control site was the downstream Mpushini site (Site 16) because there was relatively minimal urban density compared with other sites (Figure 5.1)

5.3.2 Statistical analyses

We performed all the statistical analyses using SPSS version 29 (IBM, 2023). Firstly, we conducted a two-way analysis of variance (ANOVA) to determine if there was a significant difference between monthly average *E. coli* levels between sites and months. We assessed the assumptions associated with the two-way ANOVA. We tested if the data were normally distributed using the One-Sample Kolmogorov-Smirnov test. Using Levene's test, we tested if there was equal variance between the residuals assumption. For variables with a significant difference, we used Fisher's least significant difference (LSD) multiple comparison test to determine which groups were different. When the assumption for normal distribution for *E. coli* was not satisfied across sites and seasons, we then conducted a non-parametric Kruskal-Wallis test.

As our sample sizes were small for objectives 2, 3 and 4, so to determine if there was a significant difference in *E. coli* levels between the 21 sites in three periods and chemical contamination levels between the three sites for four periods, we performed a non-parametric MANOVA using the Kruskal-Wallis test. Similarly, we conducted a Kruskal-Wallis test between five sites for a high-flow spatial detection between sites for chemical contamination. We then performed Levene’s test for all the dependent variables using log-transformed data residuals.

5.4 Results

5.4.1 The *E-coli* concentrations

Our results indicated high *E. coli* levels in the uMsunduzi catchment throughout the year, with a significant difference in the average monthly *E. coli* levels between sites (ANOVA, F = 23.821, P = 0.001), and between months (MANOVA, F = 2.745, P = 0.001). Multiple comparison results showed that average *E. coli* levels in each site significantly differed from at least one other site. Between the months, a significant difference in average *E. coli* levels was observed between January and October 2022 (P = 0.009) and between January 2022 and January 2023 (P = 0.012) (Figure 5.2). The assumption that the residuals had equal variance across the independent variables (sites and periods) was satisfied (P = 1.00), which showed that *E. coli*'s variance around the mean was the same for both variables. The assumption of the normality of residuals was also satisfied (P = 0.001). However, there was no correlation between average ambient temperature and average *E. coli* levels (r^2 = 0.156). Although the temperatures were high in January 2022 and January 2023, the *E. coli* means varied distinctively (Figure 5.2).

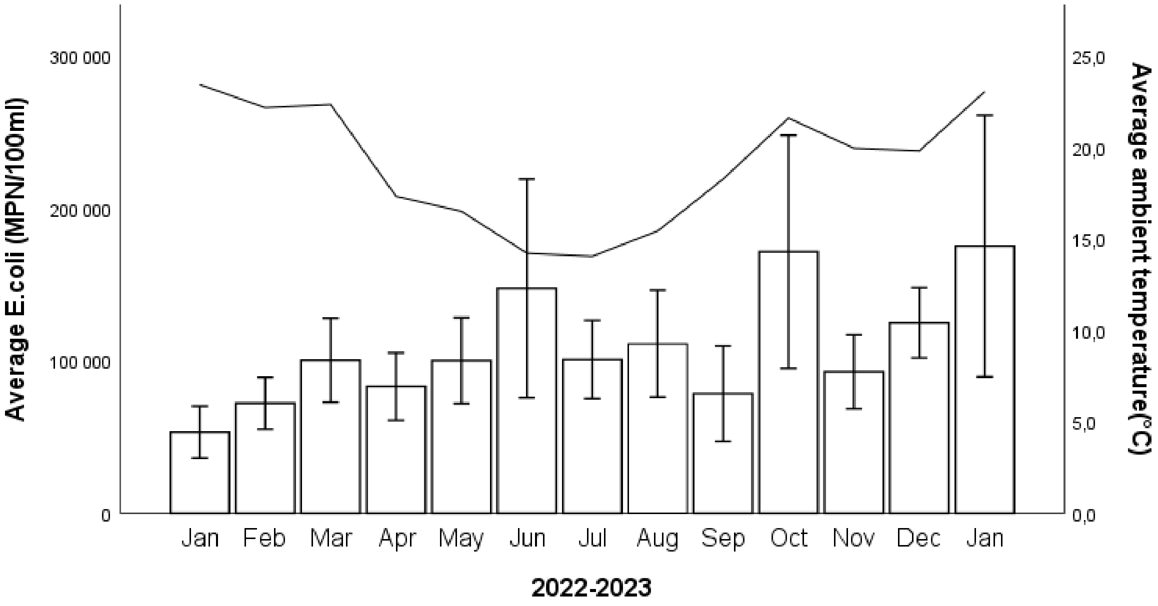

Figure 5.2: The variability of average *E. coli* levels from January 2022 to January 2023 (Bars represent ±2SE of mean), incorporated with the line graph representing the average monthly temperature of Pietermaritzburg.

There was no significant difference in average *E. coli* between pre-rain, post-rain and shutdown periods in the Wilgerfontein (Kruskal-Wallis test, P = 0.106), Blackborough (Kruskal-Wallis test, P = 0.100), Baynespruit (Kruskal-Wallis test, P = 0.124), Mpushini and uMsunduzi (Kruskal-Wallis test, P = 0.051) sites. However, the Dorpspruit (Kruskal-Wallis test, P = 0.0120) and Mpushini (control, Kruskal-Wallis test, 0.047) sites significantly differed between periods. Between sites, there was no significant difference in *E. coli* levels for all the streams. However, in the Dorpspruit stream, the *E. coli* levels were significantly lower during the post-flush rains period than pre-flush rains and shutdown periods (Figure 5.3a). Similarly, in the Mpushini stream, the levels of *E. coli* in post-flush rain period were significantly lower (Figure 5.3b).

5.4.2 Chemical concentrations

There was a significant difference in the amount of fatty acids (Kruskal-Wallis test, df = 3, P = 0.044, Figure 5.4a) and manganese (Kruskal-Wallis test, df = 3, P = 0.013, Figure 5.4b) between pre-rains, post-rain, shut down and high flows. There was a significant difference in the average concentrations of calcium between the four periods (Kruskal-Wallis test, df = 7, P = 0.018, Figure 5.5). The assumption for equality of variance in residuals across all three sites was satisfied (P = 1.000), and across the four periods (pre-rain, post-rain, shutdown and high flows) for fatty acids concentrations (P = 1.000). Comparison of fatty acids between seasons showed that there was a significant difference between the pre-rain season and all the other three seasons; post rain (LSD multiple comparison test, P = 0.003), shut-down (LSD multiple comparison test, P = 0.001) and high flows (LSD multiple comparison test, P = 0.016). The mean volatile fatty acid concentrations were significantly lower during the pre-flush season (Figure 5.4a). Surprisingly, the manganese levels were significantly higher during the shutdown period (Figure 5.4b). Furthermore, there were significant differences in calcium concentrations between the upstream Baynespruit site and the other two sites: downstream Blackborough (P = 0.002) and downstream Mpushini (P = 0.015), and with the Baynespruit site having a relatively low average of calcium (Figure 5.5). The spatial study for high flows showed no significant differences in the chemical concentrations for all the parameters.

Differences in the chemical content of hydrocarbons (C10-C40, C10-C16, C16-C22, C22-C30 and C30-C40) were insignificant in all the sites and between sampling periods (>-12mg/L). Similarly, there were insignificant amounts of zinc, cadmium and lead in water samples (≤-0.004 mg/L), and the polyethersulfone levels were very low (≤3.5 mg/L). Heavy metals were insignificant in the industrial areas' downstream sites except for manganese. There was also no significance in the March spatial detection for all the chemical contamination analyses.

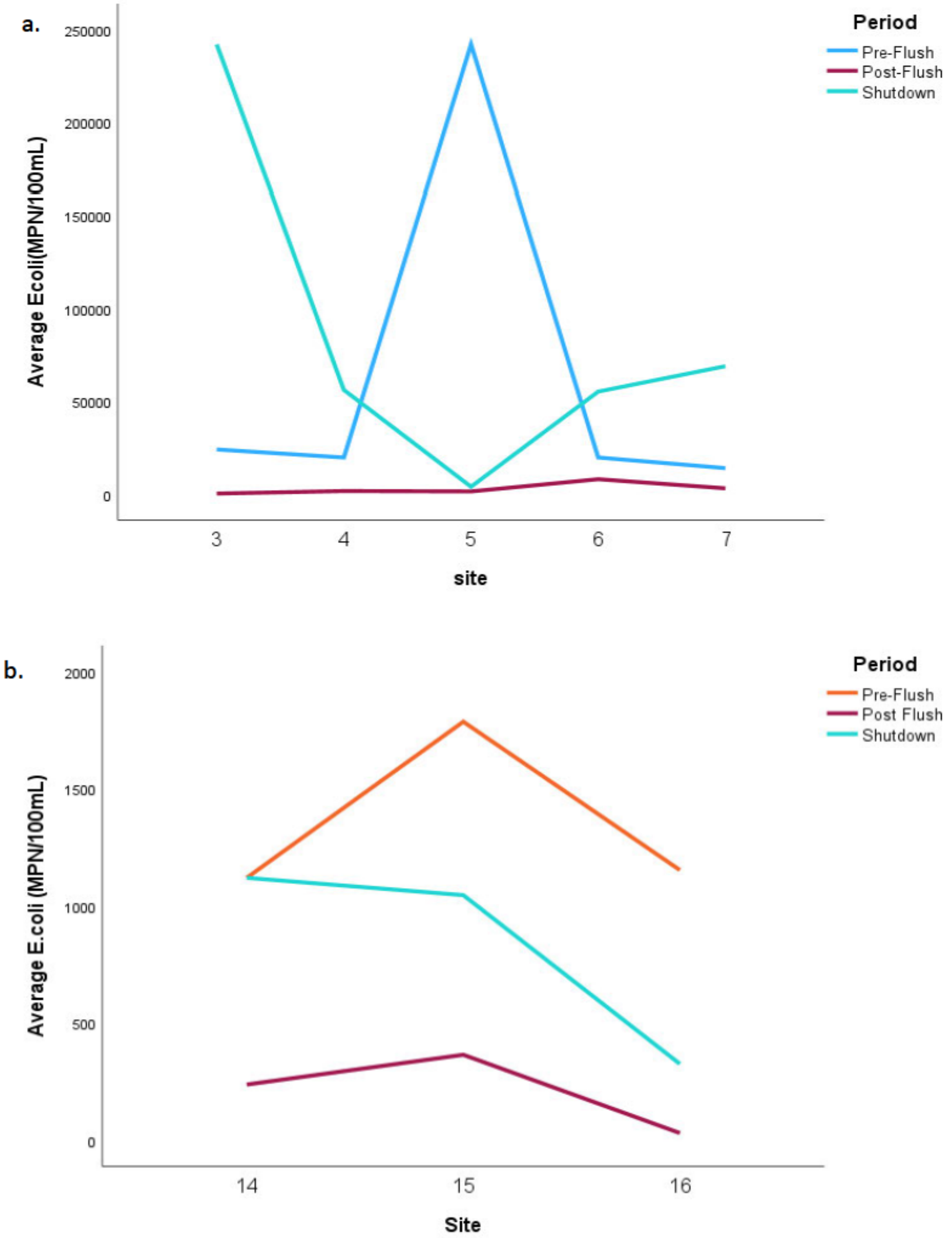

Figure 5.3: Multiple line graphs showing the trends in *E. coli* levels during pre, post flush rains and shutdown seasons for a.) the Dorpspruit (sites 5,6 and 7) and Townbush sites (sites 3 and 4) and b.) the control Mpushini sites from upstream to downstream in the present study.

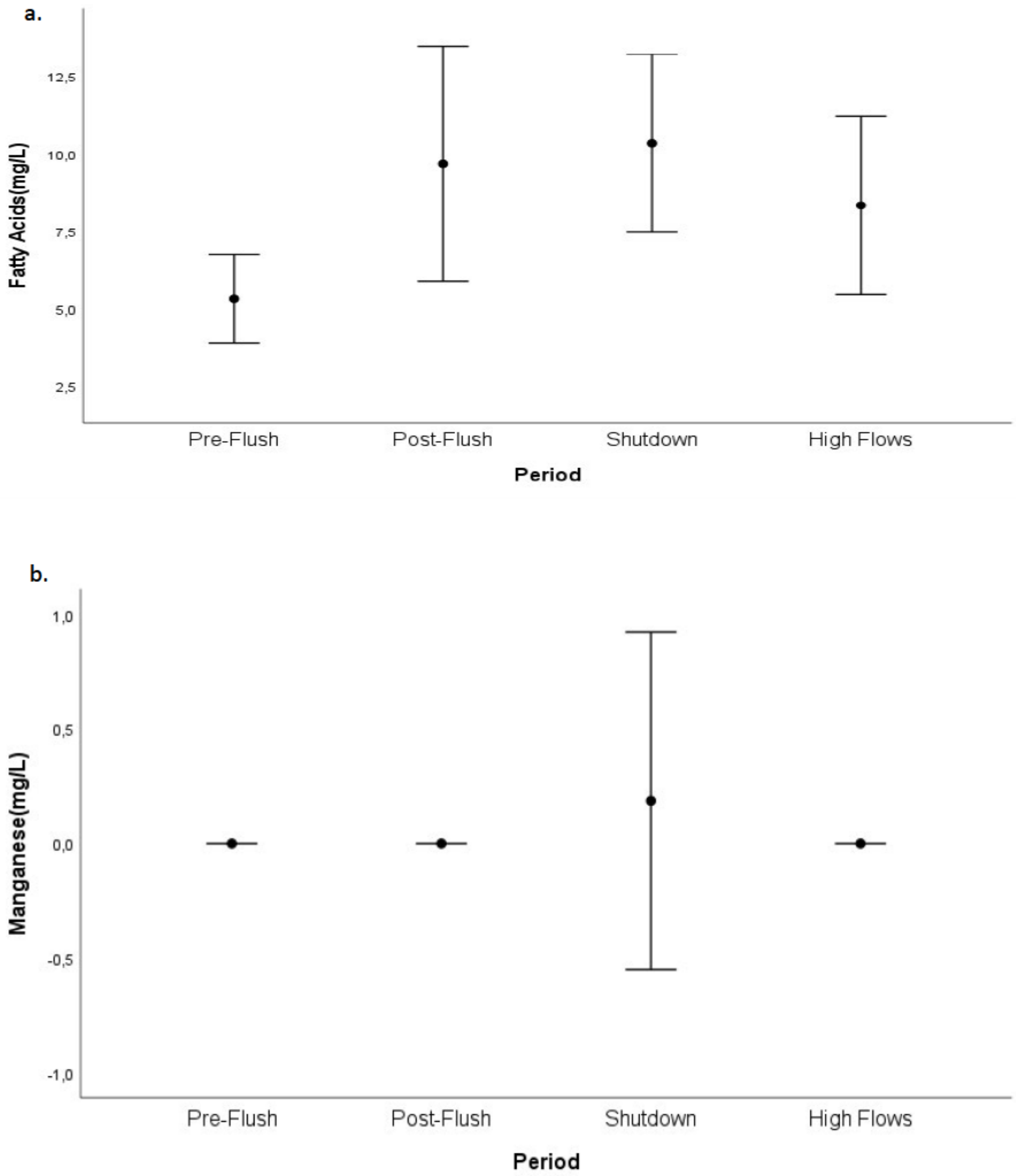

Figure 5.4: Graphical representation of the variability (mean ± 2SE) of a. fatty acids and b. magnesium between pre-rains, post-rain, shut-down and high-flow seasons.

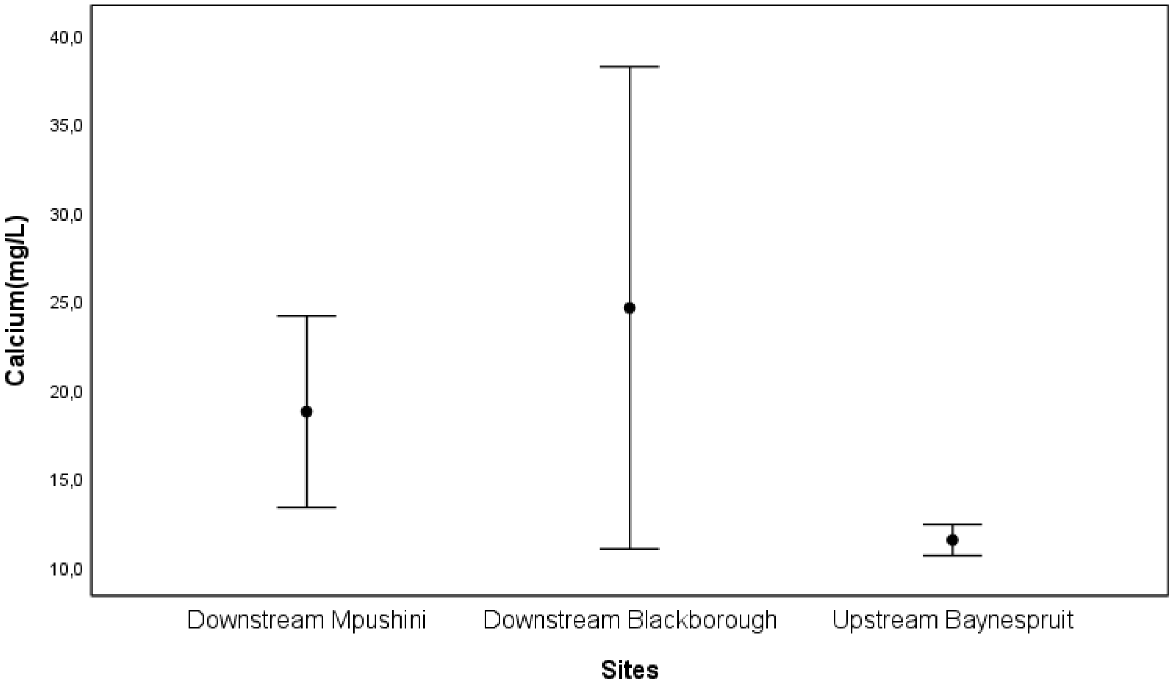

Figure 5.5: Mean (±2 SE) calcium concentrations between the three sampling sites in the present study.

5.5 Discussion

Although our results showed that the ambient temperature does not drive the levels of *E. coli* in the uMsunduzi system, this was likely a masked effect of the high levels of *E. coli* coliforms found throughout the year in this system. According to the World Health Organisation (WHO), the recommendations for environmentally safe drinking water are as follows: 0MPN/100mL is safe for drinking water, followed by low risk of 1 to 10MPN/100mL counts of *E. coli*, 11 to 100MPN/100mL is considered medium risk and any count ≥100MPN/100mL Is high risk (WHO, 2017). In the uMsunduzi catchment, the lowest monthly average was 108614.9MPN/100Ml, over 1000 times higher than the environmentally safe count of *E. coli* coliforms in water. The South African Department of Water Affairs (DWAF, 1996) recommendation for irrigation water is 130MPN/100mL (Gemmel and Schmidt, 2013). Therefore, we found that the water in the uMsunduzi catchment is considered a high environmental health risk for domestic and irrigation use (Odonkor and Mahami, 2020). Ngubane et al. (2022) did a quantitative microbial risk assessment, which calculated the probability of infection when exposed to *E. coli* in the uMsunduzi River, and the results concluded that the system is unsuitable for domestic drinking water and recreational activities, similar to our study.

A similar study of *E. coli* levels was conducted in the uMsunduzi River from January 2010 to January 2011; the average *E. coli* levels were 7900MPN/100mL (Gemmell and Schmidt, 2013). Consequently, our study showed there was a 92% increase in *E. coli* levels in the uMsunduzi in 12 years. Just like the uMsunduzi catchment, most water bodies or sources, such as dams, do not meet the WHO standards for drinking and potable water (Sila et al., 2019). The high levels of *E. coli* in the uMsunduzi system can be partially explained by the high density in the urban areas, including the high density of human settlements (Romanelli et al., 2020).

Our results showed that heavy rains could contribute to the decrease in *E. coli* levels in the system. Contrary to our results, some studies have found that there is an increase in *E. coli* concentrations during wet seasons (Abia et al., 2015), while flooding plays a role in flushing the coliforms from industrial and agricultural areas to the streams and rivers (Kiaghadi and Rifai, 2019). However, dry and wet seasons have been recorded to have an influx of *E. coli* concentrations, with dry seasons associated with farming and minimal episodic rains (Rochelle-Newall et al., 2018). This was contrary to our prediction and further highlights the influx of *E. coli* into the uMsunduzi River.

With a significant concentration of volatile fatty acids during post-flush, shutdown and high flow periods, it shows that there is a source of fatty acid pollution that feeds into the uMsunduzi catchment. We cannot conclusively say which industry contributes to the high concentrations of fatty acids, but it could be anywhere from agricultural land use, oil production companies and domestic waste (Snapp and Lu, 2013), all prevalent land use practices in our study. Manganese concentrations were also significantly high during the shutdown period. Although the industries were not functioning at that time, other factors could contribute to the high manganese concentration; like effluent discharges that have been previously shown to have high concentrations of manganese (Alho et al., 2022). In Sand River, Limpopo, South Africa, manganese was found to have the second highest concentration in sewage effluents among five other heavy metals (Moyo and Rapatsa, 2019). Calcium was significantly higher in downstream Blackborough than downstream Mpushini and upstream Baynespruit, which are associated with minimal industrial land use works. Calcium is not considered a health hazard risk (WHO, 2004). Instead, it considered to be an essential element for the freshwater biota (Weyhenmeyer et al., 2019), which means the low levels of calcium in these sites may not be good for some freshwater biota (Rapant et al., 2017).

5.6 Conclusions

Our results showed that the *E. coli* levels were very high in the uMsunduzi catchment, which calls for better management approaches for the system to avoid health risks in humans and animals. We found that *E. coli* concentrations were not correlated with temperature. This may be because *E. coli* levels were way beyond the recommended limit by the World Health Organisation. Hydrocarbons, zinc, lead, cadmium and polyethersulfone were insignificant in our surveyed sites. We found that heavy metals were not higher in downstream sites of high-density urban land use cover as we predicted. However, we recommend long-term and larger sample-size studies to monitor the chemical influx through different seasons. Manganese levels were high during shutdown periods, which may indicate another source of manganese contamination, like sewage effluents. Fatty acids need to be studied further to determine which industries are contributing to the contamination of fatty acids in the rivers. Overall, we recommend examining the uMsunduzi catchment for potential threats that *E. coli* and chemical wastes may pose. We recommend prolonged monitoring of microbial and chemical waste concentrations in the uMsunduzi catchment system and management intervention to ensure the sustainability of this important river and its associated ecosystem services.

5.7 Acknowledgements

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5.9 Supplementary information

Supplementary information Table S5.1: The sampled site numbers and their associated study objectives.

Site number	**Geographical co-ordinates**		**Objective 1**	**Objective 2**	**Objective 3**	**Objective 4**
	Latitude	**Longitude**				
1	-29.695846	30.3345162	X	X		
2	-29.641555	30.365416		X		
3	-29.5720098	30.3554543		X		
4	-29.588246	30.381	X	X		
5	-29.6047678	30.3473999		X		
6	-29.590395	30.377831	X	X		
7	-29.597505	30.399977	X	X		
8	-29.6094678	30.4139788				X
9	-29.6399695	30.406459		X	X	X
10	-29.5584188	30.4034275		X	X	X
11	-29.5751156	30.4098564	X	X		
12	-29.5885732	30.4139885	X	X		
13	-29.59285	30.422222	X	X		X
14	-29.7060673	30.4062023		X		
15	-29.6863502	30.4524168		X		
16	-29.6303386	30.479795		X	X	X
17	-29.6450414	30.310717	X	X		
18	-29.6442487	30.340915	X			
19	-29.6312	30.353087	X			
20	-29.621926	30.376646	X	X		
21	-29.606281	30.391435	X			
22	-29.602258	30.413293	X	X		
23	-29.60298	30.424991	X	X		
24	-29.596668	30.434497	X			
25	-29.5947355	30.4401464	X	X		
26	-29.597165	30.438802	X			
27	-29.599283	30.443437	X			
28	-29.607553	30.45013	X	X		

CHAPTER 6

Conclusions and recommendations

6.1 Background

Freshwater ecosystems are becoming increasingly threatened, with known stressors and continuously emerging threats (Chakona et al., 2022). Urbanisation and changes in natural vegetation for industrial or agricultural practices disrupt the natural composition of the river, which in turn compromises the balance of freshwater ecosystems (Cerqueira et al., 2020). South African rivers are susceptible to multiple threats that arise because of land use changes, urbanisation, flow modification, habitat disturbance and water pollution (O'Brien et al., 2019). With the high density of barriers, decline in fish communities and poor water quality, the uMsunduzi catchment biodiversity is threatened. The mainstem was more affected by the different stressors compared with the tributaries, and fish abundance and diversity was higher in the tributaries than in the mainstem (Chapter 3; Chapter 4 and Chapter 5).

There is a paucity of literature on the effect of land use change, river connectivity, fish assemblages and water quality in KwaZulu-Natal, particularly in Pietermaritzburg. Hence, the overall aim of this study was to evaluate the various stressors that are degrading the ecological integrity and water quality of the uMsunduzi catchment. Consequently, a literature review was conducted on the effect of anthropogenic impoundments on river longitudinal connectivity and restoration measures. The presence of barriers that affect the river connectivity in the uMsunduzi River and its tributaries was evaluated. Drivers of fish communities in the uMsunduzi River and tributaries were assessed to evaluate the state of water quality at selected sites in the uMsunduzi catchment.

6.2. River connectivity from a global point of view to the uMsunduzi catchment

The extensive systematic review provided evidence that river connectivity and freshwater ecosystems' health are paramount to the biodiversity and ecological integrity of aquatic habitats (Duda and Bellmore, 2022; Chapter 2). This comprehensive analysis has illustrated the complex interplay between anthropogenic activities and the natural functioning of river systems, highlighting the importance of barrier removal and retrofitting of fishways as critical measures for restoring river connectivity (Birnie-Gauvin. 2018; Chapter 2). The extensive literature search and subsequent filtering of publications have indicated the geographical biases towards North American and European studies in river connectivity restoration measures, with publications focusing more on barrier removal than on the retrofitting of fishways. Although North America and Europe have led the publishing of peer-reviewed articles and the implementation of river connectivity restoration projects, there remains a significant need for increased efforts in other developing regions, including Africa, particularly southern Africa (Chapter 3).

The analysis of barrier removal has underscored its complexity, dictated by the unique characteristics of individual barriers, necessitating a case-by-case approach (Duda and Bellmore, 2022). Strategies for barrier prioritisation have evolved, using various models based on barrier types, species movement, and hydrological connectivity, effectively advancing the science of barrier management (Nunn and Cowx, 2012; Lin et al., 2019). These advances have led to more sophisticated decision-support tools that integrate economic, ecological, and social considerations (Marsden et al., 2023). However, unintended consequences can follow barrier removal, such as habitat alteration because of excessive mud silt and the potential spread of invasive species, highlighting that barrier removal is not without its ecological risks (Panagiotou et al., 2022). Research has begun to clarify the need for a multi-faceted approach in barrier removal and retrofitting of fishways that accounts for species life histories and aims to improve the overall ecological integrity of the rivers (Chapter 2; Chapter 3). This has demonstrated the utmost importance of comprehensive biomonitoring pre- and post-barrier removal, which remains a notable gap in current research. While it is clear that fishways serve as an alternative to barrier removal, there is a significant variance in the effectiveness of these structures (Mesinger et al., 2021), challenging stakeholders to implement design systems that cater to the diverse needs of freshwater species.

The uMsunduzi catchment is no exception in disrupted river connectivity, and it is recommended that immediate and sustained interventions are made to restore the disconnected longitudinal pathway of the uMsunduzi catchment. As the uMsunduzi and its tributaries have a high density of barriers, there is a need to balance developmental goals with environmental stewardship. The overall implications of the literature review (Chapter 2) and barrier assessment (Chapter 3) studies highlighted the urgency of joint efforts across scientific, policy-making, and implementation domains. There must be a proactive, strategic approach to managing river ecosystems that promotes resiliency against ecological degradation while maintaining the services provided by these ecosystems to human populations, such as clean water (Chapter 2, Chapter 3 and Chapter 5).

6.3 Ecological health of the uMsunduzi catchment

The fish communities assessment study in the uMsunduzi catchment concluded by discovering the poor state of freshwater ecosystems within high-density urban environments (Chapter 4). The findings were conclusive, displaying various issues in aquatic environments caused by the presence of physical anthropogenic barriers along the longitudinal pathway of the river, changes in habitat structures, increase in land-use changes for socio-economic development and deteriorating water quality (Chapter 4, Chapter 5). There was a reduction in native fish abundance and diversity, as noted through the FRAI scores, Shannon and Pielou diversity indices and evenness. Notably, two near-threatened KwaZulu-Natal native species, *Amphilius natalensis* and *Enteromius gurneyii*, were extremely rare and absent (Chapter 4), indicating a worrying decline in species richness and abundance. The overall fish diversity consisted of nine species, a relatively poor number compared with the expected number of species (Evans et al., 2022). Furthermore, the findings highlighted the serious degradation of the streams' ecological integrity, adversely impacting the fish communities (Chapter 4). Hence, efforts to address the challenges linked to urbanisation, pollution, and anthropogenic alterations to habitat structures are needed throughout the uMsunduzi catchment, perhaps even the uMngeni catchment (Namugize et al., 2022).

6.4 Water quality status in the uMsunduzi catchment

The microbial water quality analyses showed evidence of the substantial presence of *Escherichia coli* throughout the study area, affirming that the uMsunduzi River and tributaries had a degrading water quality (Chapter 5). The *E. coli* contamination levels were far higher than the recommendations of the World Health Organisation for water quality, such that the results illustrated an alarming 92% increase in *E. coli* concentration over a span of 12 years, a figure that indicated the aggravation of microbial pollution in the catchment which is most likely related to faecal contamination (Chapter 5; Gemmell and Schmidt, 2013). It was revealed that even during seasons of high rainfall, which could have presumably diluted microbial levels, the *E. coli* concentrations remained notably high, negating the prediction that rainfall could decrease microbial contamination (Chapter 5). Manganese concentrations spiked during periods of industrial closure, while volatile fatty acids surged post-rain and during high flows. These unexpected results indicated the complexity of pollution dynamics and the influence of unidentified yet persistent sources of contamination in the uMsunduzi catchment (Chapter 5).

6.5 Conclusion

This thesis serves as a call to national stakeholders in South Africa for action towards improving river connectivity, habitat restoration, species conservation and management of water quality. There is a clear imperative to broaden scientific inquiries, strengthen international collaborations, and, most importantly, translate the growing knowledge into tangible, sustainable actions to preserve and revive the freshwater ecosystems in South Africa, especially in KwaZulu-Natal.

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APPENDIX

Supplementary information Table S2.1. Summary of publications used in the systematic review of longitudinal river connectivity and restoration strategies.

No.	Authors	Title	Year	Country	Continent	Duplicates	Inclusion
1	A Albright	Aspects of the conservation biology of an exploited population of migratory European river lamprey (Lampetra fluviatilis)	2021		Europe		Excluded after abstract reading
2	M Brummer, B Rodríguez-Labajos…	" They have kidnapped our river": Dam removal conflicts in catalonia and their relation to ecosystem services perceptions	2017	Portugal	Europe	Duplicate	Excluded after abstract reading
3	A Bok, P Kotze, RGM Heath, J Rossouw	Guidelines for the planning, design and operation of fishways in South Africa	2004	South Africa	Africa		Excluded after abstract reading
4	A Bylak, J Szmuc, K Kukuła	Assessment of the viable effects of structural reconstruction of habitats in a mountain stream: A long-term study	2023	Poland	Europe		Excluded after abstract reading
5	Á Cabezas, E González, B Gallardo, M García…	Effects of hydrological connectivity on the substrate and understory structure of riparian wetlands in the Middle Ebro River (NE Spain): implications for restoration and …	2008	Spain	Europe		Excluded after abstract reading
6	A Cabezas, FA Comín	Carbon and nitrogen accretion in the topsoil of the Middle Ebro River Floodplains (NE Spain): Implications for their ecological restoration	2010	Spain	Europe		Excluded after abstract reading
7	M Brummer, B Rodríguez-Labajos…	" They have kidnapped our river": Dam removal conflicts in catalonia and their relation to ecosystem services perceptions	2017	Portugal	Europe	Duplicate	Excluded after abstract reading
8	A Funk, D Baldan, E Bondar-Kunze, SR Brizuela…	Connectivity as a driver of river-floodplain functioning: A dynamic, graph theoretic approach	2023	Austria	Europe		Excluded after abstract reading
9	A Kaus, S Michalski, B Hänfling, D Karthe…	Fish conservation in the land of steppe and sky: Evolutionarily significant units of threatened	2019	Russia	Europe		Included

		salmonid species in Mongolia mirror major river basins					
10	A Keene, R Bush, W Erskine	Connectivity of stream water and alluvial groundwater around restoration works in an incised sand-bed stream	2007	Australia	Oceania		Excluded after abstract reading
11	Å Kestrup	Remibar: The Impact of Migration Barrier Removal on Connectivity: Evaluation of Remibar	2017		Europe		No access
12	A Meyer, I Combroux, M Trémolières	Dynamics of nutrient contents (phosphorus, nitrogen) in water, sediment and plants after restoration of connectivity in side-channels of the River Rhine	2013	Switzerland	Europe		Excluded after abstract reading
13	A Moldenhauer-Roth, D Lambert, M Müller…	Improving fish protection and downstream movement at the Maigrauge Dam (Switzerland) using an electric barrier	2023	Switzerland	Europe		Excluded after abstract reading
14	A Moldoveanu, D Popescu	Restoring River Connectivity in Line with European Legislation	2022		Europe		Excluded after abstract reading
15	A Paillex, E Castella, G Carron	Aquatic macroinvertebrate response along a gradient of lateral connectivity in river floodplain channels	2007	France	Europe		Excluded after abstract reading
16	A Paillex, S Dolédec, E Castella…	Large river floodplain restoration: predicting species richness and trait responses to the restoration of hydrological connectivity	2009	France	Europe		Excluded after abstract reading
17	A Panagiotou, S Zogaris, E Dimitriou…	Anthropogenic barriers to longitudinal river connectivity in Greece: A review	2022	Greece	Europe	Duplicate	Included
18	A Panagiotou, S Zogaris, E Dimitriou…	Anthropogenic barriers to longitudinal river connectivity in Greece: A review	2022	Greece	Europe	Duplicate	Included
19	K Fryirs	(Dis) Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem	2013	Australia	Oceania	Duplicate	Excluded after abstract reading
20	K Fryirs	(Dis) Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem	2013	Australia	Oceania	Duplicate	Excluded after abstract reading

21	S Beatty, M Allen, A Lymbery, T Storer, G White…	… against climate change in southern Australia: Evaluating small barrier removal to improve refuge connectivity-a global review of barrier decommissioning and a …	2013		Unknown	Duplicate	No access
22	S Beatty, M Allen, A Lymbery, T Storer, G White…	… against climate change in southern Australia: Evaluating small barrier removal to improve refuge connectivity-a global review of barrier decommissioning and a …	2013	Australia	Oceania		Excluded after abstract reading
23	AA Rodeles, D Galicia, R Miranda	A new method to include fish biodiversity in river connectivity indices with applications in dam impact assessments	2020	Peninsula	Europe	Duplicate	Included
24	AA Rodeles, D Galicia, R Miranda	A new method to include fish biodiversity in river connectivity indices with applications in dam impact assessments	2020	Peninsula	Europe	Duplicate	Included
25	AA Rodeles, D Galicia, R Miranda	A simple method to assess the fragmentation of freshwater fish meta-populations: Implications for river management and conservation	2021	Peninsula	Europe		Excluded after abstract reading
26	AA Rodeles, D Galicia, R Miranda	Barriers to longitudinal river connectivity: review of impacts, study methods and management for Iberian fish conservation	2020	Peninsula	Europe	Duplicate	Included
27	AA Rodeles, D Galicia, R Miranda	Barriers to longitudinal river connectivity: review of impacts, study methods and management for Iberian fish conservation	2020	Peninsula	Europe	Duplicate	Included
28	CM Bourne, DG Kehler, YF Wiersma, D Cote	… and barriers to fish passage assessments: the impact of assessment methods and assumptions on barrier identification and quantification of watershed connectivity	2011	Canada	North America	Duplicate	Excluded after abstract reading
29	AC Erwin	Evaluating fish habitat compensation in the Canadian Arctic: stream habitat attributes and macroinvertebrate assemblages	2014	Canada	North America		Excluded after abstract reading

30	AD Buijse, H Coops, M Staras, LH Jans…	Restoration strategies for river floodplains along large lowland rivers in Europe	2002		Europe		Excluded after abstract reading
31	AD Nunn, IG Cowx	Restoring river connectivity: prioritizing passage improvements for diadromous fishes and lampreys	2012	England	Europe		Included
32	AF Isaacman, BS Isaacman	Dams, displacement, and the delusion of development: Cahora Bassa and its legacies in Mozambique, 1965–2007	2013	Mozambique	Africa		Excluded after abstract reading
33	AH Arthington, BJ Pusey	Flow restoration and protection in Australian rivers	2003	Australia	Oceania		No access
34	CM Bourne, DG Kehler, YF Wiersma, D Cote	… and barriers to fish passage assessments: the impact of assessment methods and assumptions on barrier identification and quantification of watershed connectivity	2011	Canada	North America	Duplicate	Excluded after abstract reading
35	DD Hart, TE Johnson, KL Bushaw-Newton…	… for ecological research and river restoration: we develop a risk assessment framework for understanding how potential responses to dam removal vary with dam and …	2002	United States of America	North America	Duplicate	Excluded after abstract reading
36	AJ Gold, K Addy, A Morrison, M Simpson	Will dam removal increase nitrogen flux to estuaries?	2016	United States of America	North America		Excluded after abstract reading
37	AJ Jensen, ML Jones	Forecasting the response of Great Lakes sea lamprey (Petromyzon marinus) to barrier removals	2018		Unknown		No access
38	AJ Lothian, JS Tummers, AJ Albright…	River connectivity restoration for upstream-migrating European river lamprey: The efficacy of two horizontally-mounted studded tile designs	2020	England	Europe		Included
39	AJ Lothian, M Schwinn, AH Anton, CE Adams…	Are we designing fishways for diversity? Potential selection on alternative phenotypes resulting from differential passage in brown trout	2020	England	Europe		Included
40	AJP Harwood, MR Perrow, CD Sayer…	Catchment-scale distribution, abundance, habitat use, and movements of European eel (Anguilla anguilla L.) in a small UK river: Implications for conservation …	2022		Europe		Excluded after abstract reading

41	AL Meerkerk, B van Wesemael…	Application of connectivity theory to model the impact of terrace failure on runoff in semi-arid catchments	2009	Spain	Europe		Excluded after abstract reading
42	DD Hart, TE Johnson, KL Bushaw-Newton…	… for ecological research and river restoration: we develop a risk assessment framework for understanding how potential responses to dam removal vary with dam and …	2002	United States of America	North America	Duplicate	Excluded after abstract reading
43	DD Hart, TE Johnson, KL Bushaw-Newton…	… for ecological research and river restoration: we develop a risk assessment framework for understanding how potential responses to dam removal vary with dam and …	2022	United States of America	North America	Duplicate	Excluded after abstract reading
44	YC Ditya, N Dahlia, D Atminarso, L Baumgartner	… of fisheries and aquaculture of the Southeast Asian Region: Inland fishery resources: Impact and mitigation of impacts of water barrier construction on inland …	2022		Unknown	Duplicate	No access
45	YC Ditya, N Dahlia, D Atminarso, L Baumgartner	… of fisheries and aquaculture of the Southeast Asian Region: Inland fishery resources: Impact and mitigation of impacts of water barrier construction on inland …	2022		Unknown	Duplicate	No access
46	AM Strauch, RW Tingley III, J Hsiao…	Population response to connectivity restoration of high elevation tropical stream reaches in Hawai'i	2022	United States of America	North America		Excluded after abstract reading
47	AT Bednarek	Undamming rivers: a review of the ecological impacts of dam removal	2001	United States of America	North America	Duplicate	Included
48	AT Bednarek	Undamming rivers: a review of the ecological impacts of dam removal	2001	United States of America	North America	Duplicate	Included
49	AT Moody, TM Neeson, S Wangen, J Dischler…	Pet project or best project? Online decision support tools for prioritizing barrier removals in the Great Lakes and beyond	2017	Canada	North America		Excluded after abstract reading
50	M van der Most, PF Hudson	… of floodplain geomorphology and hydrologic connectivity on alligator gar (Atractosteus spatula)	2018	United States of America	North America	Duplicate	Excluded after abstract reading

		habitat along the embanked floodplain of the Lower Mississippi River					
51	AT Silva, MC Lucas, T Castro-Santos…	The future of fish passage science, engineering, and practice	2018		Global	Duplicate	Included
52	AT Silva, MC Lucas, T Castro-Santos…	The future of fish passage science, engineering, and practice	2018		Global	Duplicate	Included
53	AW Lorenz, P Haase, K Januschke…	Revisiting restored river reaches–Assessing change of aquatic and riparian communities after five years	2018	Germany	Europe		Excluded after abstract reading
54	B Klauer, J Schiller, F Bathe	Concept for cost effective improvement of river morphology in the context of the European Water Framework Directive	2015		Europe		No access
55	M van der Most, PF Hudson	… of floodplain geomorphology and hydrologic connectivity on alligator gar (Atractosteus spatula) habitat along the embanked floodplain of the Lower Mississippi River	2018	United States of America	North America	Duplicate	Excluded after abstract reading
56	X Bi, Y Wu, L Meng, J Wu, Y Li, S Zhou…	… two landscape connectivity models to quantify the priorities of wetland conservation and reclamation restoration at multiple scales: A case study in the Yellow River …	2022	China	Asia	Duplicate	Excluded after abstract reading
57	B Morandi, J Kail, A Toedter, C Wolter…	Diverse approaches to implement and monitor river restoration: A comparative perspective in France and Germany	2017	France and Germany	Europe		Excluded after abstract reading
58	B Negreiros, S Schwindt, F Scolari, R Barros…	A database application framework toward data-driven vertical connectivity analysis of rivers	2023	Germany	Europe		Excluded after abstract reading
59	B Smith, NJ Clifford, J Mant	Analysis of UK river restoration using broad-scale data sets	2014	UK	Europe		Excluded after abstract reading
60	X Bi, Y Wu, L Meng, J Wu, Y Li, S Zhou…	… two landscape connectivity models to quantify the priorities of wetland conservation and reclamation restoration at multiple scales: A case study in the Yellow River …	2022	China	Asia	Duplicate	Excluded after abstract reading

61	X Bi, Y Wu, L Meng, J Wu, Y Li, S Zhou…	… two landscape connectivity models to quantify the priorities of wetland conservation and reclamation restoration at multiple scales: A case study in the Yellow River …	2022	China	Asia	Duplicate	Excluded after abstract reading
62	B Tesfa	Benefit of grand Ethiopian renaissance dam project (GERDP) for Sudan and Egypt	2013	Sudan and EGEYPT	Africa		Excluded after abstract reading
63	B van der Waal, K Rowntree	Landscape connectivity in the upper Mzimvubu river catchment: an assessment of anthropogenic influences on sediment connectivity	2018	South Africa	Africa		No access
64	B Vercoutere, O Honnay…	Vegetation response after restoring the connectivity between a river channel and its floodplain	2007		Unknown		No access
65	BA Burroughs, DB Hayes, KD Klomp…	The effects of the Stronach Dam removal on fish in the Pine River, Manistee County, Michigan	2010	United States of America	North America		No access
66	BG Laub, GP Thiede, WW Macfarlane, P Budy	Evaluating the conservation potential of tributaries for native fishes in the upper Colorado River basin	2018	United States of America	North America		Excluded after abstract reading
67	BJ Robson, BD Mitchell, ET Chester	An outcome-based model for predicting recovery pathways in restored ecosystems: The Recovery Cascade Model	2011	Australia	Oceania		Excluded after abstract reading
68	BM Renöfält, R Jansson, C Nilsson	Effects of hydropower generation and opportunities for environmental flow management in Swedish riverine ecosystems	2010	Sweden	Europe		Excluded after abstract reading
69	BN Abbott, J Wallace, DM Nicholas, F Karim…	Bund removal to re-establish tidal flow, remove aquatic weeds and restore coastal wetland services—North Queensland, Australia	2020	Australia	Oceania		Excluded after abstract reading
70	BP Buchanan, SA Sethi, S Cuppett, M Lung…	A machine learning approach to identify barriers in stream networks demonstrates high prevalence of unmapped riverine dams	2022	United States of America	Europe		Excluded after abstract reading
71	BR Paxton	… and habitat utilisation of freshwater fish in rivers: implications for dam location, design and operation: a review and methods development for South Africa	2004	South Africa	Africa		Excluded after abstract reading

72	C Ade, EL Hestir, CM Lee	Assessing fish habitat and the effects of an emergency drought barrier on estuarine turbidity using satellite remote sensing	2021	United States of America	North America		Excluded after abstract reading
73	C Amoros, G Bornette	Connectivity and biocomplexity in waterbodies of riverine floodplains	2002		Unknown		No access
74	SK McKay, EH Martin, PB McIntyre…	A comparison of approaches for prioritizing removal and repair of barriers to stream connectivity	2020	United States of America	North America	Duplicate	Excluded after abstract reading
75	SK McKay, EH Martin, PB McIntyre…	A comparison of approaches for prioritizing removal and repair of barriers to stream connectivity	2020	United States of America	North America	Duplicate	Excluded after abstract reading
76	C Boys, T Glasby, F Kroon, L Baumgartner, K Wilkinson…	Case studies in restoring connectivity of coastal aquatic habitats: floodgates, box culvert and rock-ramp fishway	2011	Australia	Oceania		Excluded after abstract reading
77	C Ding, X Jiang, L Wang, H Fan, L Chen, J Hu…	Fish assemblage responses to a low-head dam removal in the Lancang River	2019	China	Asia	Duplicate	Included
78	C Ding, X Jiang, L Wang, H Fan, L Chen, J Hu…	Fish assemblage responses to a low-head dam removal in the Lancang River	2019	China	Asia	Duplicate	Included
79	M King, M van Zyll de Jong, IG Cowx	A dynamic dendritic connectivity assessment tool for the planning and design of barrier mitigation strategies in river networks	2023	UK	Europe	Duplicate	Excluded after abstract reading
80	C Garcia de Leaniz, KM Wantzen, C Wolter…	Challenges and benefits of restoring river connectivity	2023		Europe		Excluded after abstract reading
81	C Gardner, SM Coghlan Jr, J Zydlewski…	Distribution and abundance of stream fishes in relation to barriers: implications for monitoring stream recovery after barrier removal	2013	United States of America	North America		Included
82	C Katopodis, LP Aadland	Effective dam removal and river channel restoration approaches	2006		Unknown		No access
83	C Mitchell, K Graham, G Ringwood	Concurrent Sessions A: Co-Benefits of Barrier Removal: Fish Passage and Public Safety-Loudoun	2013	United States of America	North America		Excluded after abstract reading

		Weir, The Fishway That Never Ends: Maintaining Ongoing …					
84	M King, M van Zyll de Jong, IG Cowx	A dynamic dendritic connectivity assessment tool for the planning and design of barrier mitigation strategies in river networks	2023	UK	Europe	Duplicate	Excluded after abstract reading
85	JA Stanford, JV Ward, WJ Liss…	A general protocol for restoration of regulated rivers	1996		Europe	Duplicate	Excluded after abstract reading
86	JA Stanford, JV Ward, WJ Liss…	A general protocol for restoration of regulated rivers	1996		Europe	Duplicate	Excluded after abstract reading
87	C Ang, WU Miao, Z Xiao-guo, Z Zhou-wen…	A holistic method of riverine connectivity assessment	2020		Asia	Duplicate	Excluded after abstract reading
88	C Solà, M Ordeix, Q Pou-Rovira, N Sellarès, A Queralt…	Longitudinal connectivity in hydromorphological quality assessments of rivers. The ICF index: A river connectivity index and its application to Catalan rivers	2011	Spain	Europe		Excluded after abstract reading
89	C Ang, WU Miao, Z Xiao-guo, Z Zhou-wen…	A holistic method of riverine connectivity assessment	2020		Asia	Duplicate	Excluded after abstract reading
90	D Sear, M Newson, C Hill, J Old…	A method for applying fluvial geomorphology in support of catchment-scale river restoration planning	2009	UK	Europe	Duplicate	Excluded after abstract reading
91	C Walmsley	Using Digital River Network Data to Improve Methods for Prioritising the Mitigation of Barriers to Fish Passage	2016		Unknown		No access
92	C Xie, B Cui, Z Ning, S Yu, T Xie	Longitudinal dynamics of hydrological connectivity in the yellow River Delta, China	2022	China	Asia		Excluded after abstract reading
93	CA Fox, FJ Magilligan, CS Sneddon	"You kill the dam, you are killing a part of me": Dam removal and the environmental politics of river restoration	2016	United States of America	North America		Excluded after abstract reading

94	CA Murphy, G Taylor, T Pierce, I Arismendi…	Short-term reservoir draining to streambed for juvenile salmon passage and non-native fish removal	2019	United States of America	North America		Excluded after abstract reading
95	D Sear, M Newson, C Hill, J Old…	A method for applying fluvial geomorphology in support of catchment-scale river restoration planning	2009	UK	Europe	Duplicate	Excluded after abstract reading
96	H Mader, C Maier	A method for prioritizing the reestablishment of river continuity in Austrian rivers	2008	Australia	Oceania	Duplicate	Excluded after abstract reading
97	CC Schmidt, BB Fokkens	A European National River Continuity Restoration Policies	2023		Europe		Excluded after abstract reading
98	CD Baker, KE Polito, GN Peterson Jr, T Purinton…	Economic &Community Benefits from Stream Barrier Removal Projects in Massachusetts	2015	United States of America	North America		Excluded after abstract reading
99	H Mader, C Maier	A method for prioritizing the reestablishment of river continuity in Austrian rivers	2008	Australia	Oceania	Duplicate	Excluded after abstract reading
100	X Shao, Y Fang, B Cui	A model to evaluate spatiotemporal variations of hydrological connectivity on a basin-scale complex river network with intensive human activity	2020	China	Asia	Duplicate	Excluded after abstract reading
101	X Shao, Y Fang, B Cui	A model to evaluate spatiotemporal variations of hydrological connectivity on a basin-scale complex river network with intensive human activity	2020	China	Asia	Duplicate	Excluded after abstract reading
102	PA Franklin, J Sykes, J Robbins, DJ Booker…	A national fish passage barrier inventory to support fish passage policy implementation and estimate river connectivity in New Zealand	2022	New Zealand	Oceania	Duplicate	Excluded after abstract reading
103	PA Franklin, J Sykes, J Robbins, DJ Booker…	A national fish passage barrier inventory to support fish passage policy implementation and estimate river connectivity in New Zealand	2022	New Zealand	Oceania	Duplicate	Excluded after abstract reading
104	D Cote, DG Kehler, C Bourne, YF Wiersma	A new measure of longitudinal connectivity for stream networks	2009	Canada	North America	Duplicate	Excluded after abstract reading
105	D Cote, DG Kehler, C Bourne, YF Wiersma	A new measure of longitudinal connectivity for stream networks	2009	Canada	North America	Duplicate	Excluded after abstract reading

106	CM Tonra, K Sager-Fradkin, SA Morley, JJ Duda…	The rapid return of marine-derived nutrients to a freshwater food web following dam removal	2015	United States of America	North America		Included
107	CN Dahm, KW Cummins, HM Valett…	An ecosystem view of the restoration of the Kissimmee River	1995	United States of America	North America		Excluded after abstract reading
108	CP Henry, C Amoros, Y Giuliani	Restoration ecology of riverine wetlands: II. An example in a former channel of the Rhône River	1995	France and Switzerland	Europe		Excluded after abstract reading
109	CP Mainstone, NTH Holmes	Embedding a strategic approach to river restoration in operational management processes—experiences in England	2010	England	Europe		Excluded after abstract reading
110	SL White, EM Hanks, T Wagner	A novel quantitative framework for riverscape genetics	2020	United States of America	North America	Duplicate	Excluded after abstract reading
111	SL White, EM Hanks, T Wagner	A novel quantitative framework for riverscape genetics	2020	United States of America	North America	Duplicate	Excluded after abstract reading
112	PD Powers, M Helstab…	A process-based approach to restoring depositional river valleys to Stage 0, an anastomosing channel network	2019	United States of America	North America	Duplicate	Excluded after abstract reading
113	PD Powers, M Helstab…	A process-based approach to restoring depositional river valleys to Stage 0, an anastomosing channel network	2019	United States of America	North America	Duplicate	Excluded after abstract reading
114	D Campana, E Marchese, JI Theule, F Comiti	Channel degradation and restoration of an Alpine river and related morphological changes	2014	Italy	Europe		Excluded after abstract reading
115	M Papazekou, AI Tsavdaridou, V Almpanidou…	A river-based approach in reconstructing connectivity among protected areas: Insights and challenges from the Balkan region	2022		Europe	Duplicate	Excluded after abstract reading
116	M Papazekou, AI Tsavdaridou, V Almpanidou…	A river-based approach in reconstructing connectivity among protected areas: Insights and challenges from the Balkan region	2022		Europe	Duplicate	Excluded after abstract reading
117	D Grimardias, C Chasserieau, M Beaufils…	Ecological connectivity of the upper Rhône River: Upstream fish passage at two successive large hydroelectric dams for partially migratory species	2022	France	Europe	Duplicate	Included

118	D Grimardias, C Chasserieau, M Beaufils…	Ecological connectivity of the upper Rhône River: Upstream fish passage at two successive large hydroelectric dams for partially migratory species	2022	France	Europe	Duplicate	Included
119	S King, JR O'Hanley, LR Newbold…	A toolkit for optimizing fish passage barrier mitigation actions	2017		North America	Duplicate	Excluded after abstract reading
120	S King, JR O'Hanley, LR Newbold…	A toolkit for optimizing fish passage barrier mitigation actions	2017		North America	Duplicate	Excluded after abstract reading
121	JW Koebel Jr	An historical perspective on the Kissimmee River restoration project	1995	United States of America	North America	Duplicate	Excluded after abstract reading
122	JW Koebel Jr	An historical perspective on the Kissimmee River restoration project	1995	United States of America	North America	Duplicate	Excluded after abstract reading
123	D Teschlade, A Niemann	Analysis of contributions and uncertainties of fish population models for the development of river continuity concepts in the river basin Ruhr, Germany	2016	Germany	Europe		Excluded after abstract reading
124	D Tickner, JJ Opperman, R Abell, M Acreman…	Bending the curve of global freshwater biodiversity loss: an emergency recovery plan	2020		Global		Excluded after abstract reading
125	D Wang, X Wang, Y Huang, X Zhang, W Zhang…	Impact analysis of small hydropower construction on river connectivity on the upper reaches of the great rivers in the Tibetan Plateau	2021	China	Asia		Excluded after abstract reading
126	D Wang, Z Li, Z Li, B Pan, S Tian, X Nie	Environmental gradient relative to oxbow lake-meandering river connectivity in Zoige Basin of the Tibetan Plateau	2020	China	Asia		Excluded after abstract reading
127	DA Boughton, A East, L Hampson, JD Kiernan…	Removing a dam and re-routing a river: will expected benefits for steelhead be realized in Carmel River, California	2016	United States of America	North America		Excluded after abstract reading
128	DA Saunders, RJ Hobbs, CR Margules	Biological consequences of ecosystem fragmentation: a review	1991		Unknown	Duplicate	Included
129	DA Saunders, RJ Hobbs, CR Margules	Biological consequences of ecosystem fragmentation: a review	1991		Unknown	Duplicate	Included

130	DA Sear, A Briggs, A Brookes	A preliminary analysis of the morphological adjustment within and downstream of a lowland river subject to river restoration	1998	UK	Europe		Excluded after abstract reading
131	JS Perkin, MR Acre, J Graham, K Hoenke	An integrative conservation planning framework for aquatic landscapes fragmented by road-stream crossings	2020	United States of America	North America	Duplicate	Excluded after abstract reading
132	JS Perkin, MR Acre, J Graham, K Hoenke	An integrative conservation planning framework for aquatic landscapes fragmented by road-stream crossings	2020	United States of America	North America	Duplicate	Excluded after abstract reading
133	A Zitek, S Schmutz, M Jungwirth	Assessing the efficiency of connectivity measures with regard to the EU-Water Framework Directive in a Danube-tributary system	2008		Europe	Duplicate	Excluded after abstract reading
134	DP Zielinski, C Freiburger	Advances in fish passage in the Great Lakes basin	2021	United States of America	North America		Included
135	DPS Terêncio, RMV Cortes, FAL Pacheco, JP Moura…	A method for estimating the risk of dam reservoir silting in fire-prone watersheds: a study in Douro River, Portugal	2020	Portugal	Europe		Excluded after abstract reading
136	DS Baldwin, MJ Colloff, SM Mitrovic…	Restoring dissolved organic carbon subsidies from floodplains to lowland river food webs: a role for environmental flows?	2016	United States of America	North America		Excluded after abstract reading
137	DW Llewellyn, GP Shaffer, NJ Craig…	A decision-support system for prioritizing restoration sites on the Mississippi River Alluvial Plain	1996	United States of America	North America		Excluded after abstract reading
138	DW Schultz, JE Garvey…	Backwater immigration by fishes through a water control structure: implications for connectivity and restoration	2007	United States of America	North America		Excluded after abstract reading
139	E Castella, O Béguin…	Realised and predicted changes in the invertebrate benthos after restoration of connectivity to the floodplain of a large river	2015	France and Switzerland	North America		Excluded after abstract reading
140	E Howe, CA Simenstad	Using isotopic measures of connectivity and ecosystem capacity to compare restoring and	2015	United States of America	North America		Excluded after abstract reading

		natural marshes in the Skokomish River Estuary, WA, USA					
141	E Kampa	Why is nature restoration critical for river connectivity?	2022		Europe		Excluded after abstract reading
142	E Pini Prato, C Comoglio…	A simple management tool for planning the restoration of river longitudinal connectivity at watershed level: priority indices for fish passes	2011	Italy	Europe		Excluded after abstract reading
143	E Quaranta, MD Bejarano, C Comoglio…	Digitalization and real-time control to mitigate environmental impacts along rivers: Focus on artificial barriers, hydropower systems and European priorities	2023		Europe		Excluded after abstract reading
144	A Zitek, S Schmutz, M Jungwirth	Assessing the efficiency of connectivity measures with regard to the EU-Water Framework Directive in a Danube-tributary system	2008		Europe	Duplicate	Excluded after abstract reading
145	SK McKay, JR Schramski, JN Conyngham…	Assessing upstream fish passage connectivity with network analysis	2013		Unknown		Excluded after abstract reading
146	E Wohl, G Brierley, D Cadol…	Connectivity as an emergent property of geomorphic systems	2019		Unknown		No access
147	E Wohl, J Castro, B Cluer, D Merritts…	Rediscovering, reevaluating, and restoring lost river-wetland corridors	2021	UK	Europe		Excluded after abstract reading
148	E Wohl, PL Angermeier, B Bledsoe…	River restoration	2005	United States of America	North America		Excluded after abstract reading
149	EA Kristensen, B Kronvang, P Wiberg-Larsen…	10 years after the largest river restoration project in Northern Europe: Hydromorphological changes on multiple scales in River Skjern	2014	Denmark	Europe		No access
150	EC Enders, C Charles, DA Watkinson, C Kovachik…	Analysing habitat connectivity and home ranges of bigmouth buffalo and channel catfish using a large-scale acoustic receiver network	2019	Canada	North America		Excluded after abstract reading
151	ED Dascher	Modeling river connectivity using the barrier assessment tool and available data on registered	2019	United States of America	North America		Excluded after abstract reading

		dams in the Guadalupe–San Antonio River System, Texas					
152	EH Martin	Assessing and prioritizing barriers to aquatic connectivity in the Eastern United States	2019	United States of America	North America		No access
153	SK McKay, JR Schramski, JN Conyngham…	Assessing upstream fish passage connectivity with network analysis	2013	United States of America	North America	Duplicate	No access
154	H Li, D Zhou, S Hu, J Zhang, Y Jiang, Y Zhang	Barrier-based longitudinal connectivity index for managing urban rivers	2018	China	Asia	Duplicate	Excluded after abstract reading
155	EJ Andersen	A Bayesian network for prioritizing restoration of aquatic connectivity	2010	United States of America	North America		Excluded after abstract reading
156	ER Collins	Evaluating connectivity in three watersheds in the southeastern United States	2016	United States of America	North America		Excluded after abstract reading
157	F Amtstaetter, J O'Connor, D Borg…	Fishways provide catchment-scale improvements to common galaxias (Galaxias maculatus) upstream of a barrier in south-eastern Australia	2023	Australia	Oceania		No access
158	F Costa, A Vieira	Stream Barrier Removal: Are New Approaches Possible in Small Rivers? The Case of the Selho River (Northwestern Portugal)	2023	Portugal	Europe		Excluded after abstract reading
159	F Lee, KS Simon, GLW Perry	Network topology mediates freshwater fish metacommunity response to loss of connectivity	2022		Unknown		Included
160	F Schiemer, C Baumgartner…	Restoration of floodplain rivers: The 'Danube restoration project'	1999	Germany	Europe		Excluded after abstract reading
161	FD Shields Jr, SS Knight, R Lizotte Jr…	Connectivity and variability: Metrics for riverine floodplain backwater rehabilitation	2011		Unknown		No access
162	H Li, D Zhou, S Hu, J Zhang, Y Jiang, Y Zhang	Barrier-based longitudinal connectivity index for managing urban rivers	2018	China	Asia	Duplicate	Excluded after abstract reading
163	A Angulo-Rodeles, D Galicia-Paredes…	Barriers to longitudinal river connectivity: review of impacts, study methods and management for Iberian fish conservation	2020	Peninsula	Europe		Excluded after abstract reading

164	C Garcia de Leaniz, J O'Hanley	Best practices for selecting barriers within European catchments	2021		Europe	Duplicate	Excluded after abstract reading
165	CG de Leaniz, J O'Hanley	Best practices for selecting barriers within European catchments	2021		Europe	Duplicate	Excluded after abstract reading
166	G Cozzi, F Broekhuis, JW McNutt…	Comparison of the effects of artificial and natural barriers on large African carnivores: implications for interspecific relationships and connectivity	2013	Botswana	Africa		Excluded after abstract reading
167	G Duarte, P Segurado, G Haidvogl, D Pont…	Damn those damn dams: Fluvial longitudinal connectivity impairment for European diadromous fish throughout the 20th century	2021		Europe		Included
168	G Fielding	Barriers to Fish Passage in Nova Scotia: The Evolution of Water Control Barriers in Nova Scotia's Watershed	2011	Canada	North America		Excluded after abstract reading
169	G Grill, B Lehner, AE Lumsdon…	An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales	2015		Global		Excluded after abstract reading
170	G Merriam	Connectivity: a fundamental ecological characteristic of landscape pattern	1984	Denmark	Europe		Included
171	FJ Rahel	Biogeographic barriers, connectivity and homogenization of freshwater faunas: it's a small world after all	2007		Unknown	Duplicate	No access
172	FJ Rahel	Biogeographic barriers, connectivity and homogenization of freshwater faunas: it's a small world after all	2007		Unknown	Duplicate	No access
173	GC O'Brien, M Ross, C Hanzen…	River connectivity and fish migration considerations in the management of multiple stressors in South Africa	2019	South Africa	Africa	Duplicate	Included
174	GC O'Brien, M Ross, C Hanzen…	River connectivity and fish migration considerations in the management of multiple stressors in South Africa	2019	South Africa	Africa	Duplicate	Included

175	GM Kondolf	Lessons learned from river restoration projects in California	1998	United States of America	North America		No access
176	GM Kondolf	River restoration and meanders	2006	United States of America	North America		Excluded after abstract reading
177	CT Ioannidou, TM Neeson, JR O'Hanley	Boosting large-scale river connectivity restoration by planning for the presence of unrecorded barriers	2023	United States of America	North America	Duplicate	Excluded after abstract reading
178	CT Ioannidou, TM Neeson, JR O'Hanley	Boosting large-scale river connectivity restoration by planning for the presence of unrecorded barriers	2023	United States of America	North America	Duplicate	Excluded after abstract reading
179	GR Pess, TJ Beechie, JE Williams, DR Whitall…	Watershed assessment techniques and the success of aquatic restoration activities	2003	United States of America	North America		Excluded after abstract reading
180	CT Ioannidou, TM Neeson…	Boosting large-scale river connectivity restoration by planning for the presence of unrecorded barriers	2023	United States of America	North America	Duplicate	Excluded after abstract reading
181	CT Ioannidou, TM Neeson…	Boosting large-scale river connectivity restoration by planning for the presence of unrecorded barriers	2023	United States of America	North America	Duplicate	Excluded after abstract reading
182	H Habersack, H Piégay	27 River restoration in the Alps and their surroundings: past experience and future challenges	2007		Europe		Excluded after abstract reading
183	H Hajdukiewicz, B Wyżga, J Zawiejska, A Amirowicz…	Assessment of river hydromorphological quality for restoration purposes: an example of the application of RHQ method to a Polish Carpathian river	2017	Poland	Europe		Excluded after abstract reading
184	MR Fuller, MW Doyle, DL Strayer	Causes and consequences of habitat fragmentation in river networks	2015		Unknown	Duplicate	No access
185	MR Fuller, MW Doyle, DL Strayer	Causes and consequences of habitat fragmentation in river networks	2015		Unknown	Duplicate	No access
186	L Marchi, F Comiti, S Crema, M Cavalli	Channel control works and sediment connectivity in the European Alps	2019		Europe	Duplicate	Excluded after abstract reading
187	L Marchi, F Comiti, S Crema, M Cavalli	Channel control works and sediment connectivity in the European Alps	2019		Europe	Duplicate	Excluded after abstract reading

188	H Marques, JHP Dias, IP Ramos	Can fishways restore river connectivity? A case study using β diversity as a method of assessment	2018	Brazil	South America	Duplicate	Included
189	H Marques, JHP Dias, IP Ramos	Can fishways restore river connectivity? A case study using β diversity as a method of assessment	2018	Brazil	South America	Duplicate	Included
190	JA Falke, RL Flitcroft, JB Dunham…	Climate change and vulnerability of bull trout (Salvelinus confluentus) in a fire-prone landscape	2015	United States of America	North America	Duplicate	Excluded after abstract reading
191	JA Falke, RL Flitcroft, JB Dunham…	Climate change and vulnerability of bull trout (Salvelinus confluentus) in a fire-prone landscape	2016	United States of America	North America	Duplicate	Excluded after abstract reading
192	HH Hansen, M Schneider…	A habitat connectivity reality check for fish physical habitat model results and decision-making for river restoration	2023	Germany	Europe		Excluded after abstract reading
193	HI Jager, JA Chandler, KB Lepla…	A theoretical study of river fragmentation by dams and its effects on white sturgeon populations	2001	United States of America	North America	Duplicate	Included
194	HI Jager, JA Chandler, KB Lepla…	A theoretical study of river fragmentation by dams and its effects on white sturgeon populations	2001	United States of America	North America	Duplicate	Included
195	HL Diefenderfer, GE Johnson, NK Sather, JR Skalski…	… of life history diversity, habitat connectivity, and survival benefits associated with habitat restoration actions in the Lower Columbia River and Estuary, annual report …	2011	United States of America	North America		Excluded after abstract reading
196	HM Bothwell, SA Cushman, SA Woolbright…	Conserving threatened riparian ecosystems in the American West: Precipitation gradients and river networks drive genetic connectivity and diversity in a foundation …	2017	United States of America	North America		Excluded after abstract reading
197	HM Poulos, KE Miller, ML Kraczkowski…	Fish assemblage response to a small dam removal in the Eightmile River system, Connecticut, USA	2014	United States of America	North America		Included
198	HS SÜTÜNÇ	Detecting Barriers Between Protected Areas to Restore Ecological Connectivity	2021	Turkey	Asia		Excluded after abstract reading
199	HY Lin, A Bush, S Linke…	Climate change decouples marine and freshwater habitats of a threatened migratory fish	2017	Australia	Oceania		Excluded after abstract reading

200	HY Lin, K Robinson, A Milt, L Walter	The application of decision support tools and the influence of local data in prioritizing barrier removal in lower Michigan, USA	2019	United States of America	North America		Included
201	HY Lin, KF Robinson	How do migratory fish populations respond to barrier removal in spawning and nursery grounds?	2019		Unknown		Included
202	I Poudevigne, D Alard, R Leuven…	A systems approach to river restoration: a case study in the lower Seine valley, France	2002	France	Europe		Excluded after abstract reading
203	IG Stuart, LJ Baumgartner…	Lock gates improve passage of small-bodied fish and crustaceans in a low gradient vertical-slot fishway	2008	Australia	Oceania		Included
204	J Boardman, I Foster	Are 'free-flowing rivers'a good idea? The challenge of removing barriers from our rivers	2023	UK	Europe		No access
205	J England, MA Wilkes	Does river restoration work? Taxonomic and functional trajectories at two restoration schemes	2018	UK	Europe		Excluded after abstract reading
206	J Feng, J Liang, Q Li, X Zhang, Y Yue, J Gao	Effect of hydrological connectivity on soil carbon storage in the Yellow River delta wetlands of China	2021	China	Asia		Excluded after abstract reading
207	J Gessner, S Zahn, I Jaric…	Estimating the potential for habitat restoration and connectivity effects on European sturgeon (Acipenser sturio L. 1758) population rehabilitation in a lowland river …	2014		Europe		Excluded after abstract reading
208	CH Chen	Climate warming and the effectiveness of restoring longitudinal river connectivity for endangered non-anadromous Taiwan salmon (*Oncorhynchus formosanus*)	2020	Taiwan	Asia	Duplicate	Excluded after abstract reading
209	CH Chen	Climate warming and the effectiveness of restoring longitudinal river connectivity for endangered non-anadromous Taiwan salmon (*Oncorhynchus formosanus*)	2020		Asia	Duplicate	Excluded after abstract reading
210	J Harvey, J Gomez-Velez, N Schmadel…	How hydrologic connectivity regulates water quality in river corridors	2019		Unknown	Duplicate	Included

211	J Harvey, J Gomez-Velez, N Schmadel…	How hydrologic connectivity regulates water quality in river corridors	2019		Unknown	Duplicate	Included
212	J Kail, C Wolter	Analysis and evaluation of large-scale river restoration planning in Germany to better link river research and management	2011	Germany	Europe		Excluded after abstract reading
213	C Tamario, O Calles, J Watz, PA Nilsson…	Coastal river connectivity and the distribution of ascending juvenile European eel (Anguilla anguilla L.): Implications for conservation strategies regarding fish …	2019		Europe	Duplicate	Excluded after abstract reading
214	C Tamario, O Calles, J Watz, PA Nilsson…	Coastal river connectivity and the distribution of ascending juvenile European eel (Anguilla anguilla L.): Implications for conservation strategies regarding fish …	2019		Europe	Duplicate	Excluded after abstract reading
215	J Matanzima, T Mosuoe-Tsietsi	A complex balance: assessing perspectives on decommissioning large dams to restore river ecosystems	2023	Australia	Oceania		No access
216	J O'Connor, F Amtstaetter, M Jones…	Prioritising the rehabilitation of fish passage in a regulated river system based on fish movement	2015	Australia	Oceania		No access
217	J Sendzimir, P Magnuszewski, Z Flachner, P Balogh…	Assessing the resilience of a river management regime: informal learning in a shadow network in the Tisza River Basin	2008		Unknown		Excluded after abstract reading
218	RA McManamay, JS Perkin, HI Jager	Commonalities in stream connectivity restoration alternatives: an attempt to simplify barrier removal optimization	2019	United States of America	North America	Duplicate	Excluded after abstract reading
219	RA McManamay, JS Perkin, HI Jager	Commonalities in stream connectivity restoration alternatives: an attempt to simplify barrier removal optimization	2019	United States of America	North America	Duplicate	Excluded after abstract reading
220	B Ma, Z Chen, X Wei, X Li, L Zhang	Comparative ecological network pattern analysis: a case of Nanchang	2022	China	Asia	Duplicate	Excluded after abstract reading
221	B Ma, Z Chen, X Wei, X Li, L Zhang	Comparative ecological network pattern analysis: a case of Nanchang	2022	China	Asia	Duplicate	Excluded after abstract reading

222	J Sun, SM Galib, MC Lucas	Are national barrier inventories fit for stream connectivity restoration needs? A test of two catchments	2020	England	Europe		No access
223	J Sun, SM Galib, MC Lucas	Rapid response of fish and aquatic habitat to removal of a tidal barrier	2021	England	Europe		Included
224	J Watson	Effects of Dam Removal on Assemblage Composition and the Interactions of Fishes in the Penobscot River, Maine	2017	United States of America	North America		No access
225	JA Benítez-Torres, A Roé-Sosa…	Enhancing Environmental Services in Candelaria River by Restoring Ecological Connectivity	2019	Spain	Europe		No access
226	A Singler, A Bowden	Concurrent Sessions A: Co-Benefits of Barrier Removal: Fish Passage and Public Safety-Improving Fish Habitat to Reduce Flood Damage: The Multiple Benefits of …	2013	UNited States of America	North America	Duplicate	Excluded after abstract reading
227	A Singler, A Bowden	Concurrent Sessions A: Co-Benefits of Barrier Removal: Fish Passage and Public Safety-Improving Fish Habitat to Reduce Flood Damage: The Multiple Benefits of …	2013	UNited States of America	North America	Duplicate	Excluded after abstract reading
228	JA Hare, DL Borggaard, MA Alexander…	A Review of River Herring science in support of species conservation and ecosystem restoration	2021		North America		Excluded after abstract reading
229	E Wohl	Connectivity in rivers	2017		Unknown	Duplicate	Included
230	E Wohl	Connectivity in rivers	2017		Unknown	Duplicate	No access
231	JAM Raeymaekers, D Raeymaekers…	Guidelines for restoring connectivity around water mills: a population genetic approach to the management of riverine fish	2009	Belgium	Europe		Excluded after abstract reading
232	JC Zweifel	… landscape-scale watershed assessment method to support fish passage restoration in Puget Sound, Washington State: An analysis for the Fish Barrier Removal …	2016	United States of America	North America		Excluded after abstract reading

233	JD Olden	Challenges and opportunities for fish conservation in dam-impacted waters	2016		Unknown		No access
234	JF Kocik, SA Hayes, SM Carlson…	A Resist-Accept-Direct (RAD) future for Salmon in Maine and California: Salmon at the southern edge	2022	United States of America	North America		Excluded after abstract reading
235	JH Harris, RT Kingsford, W Peirson…	Mitigating the effects of barriers to freshwater fish migrations: The Australian experience	2016	Australia	Oceania		No access
236	JJ Cancel Villamil, SA Locke	Fish assemblage response to removal of a low-head dam in the lower reach of a tropical island river	2022	Germany	Europe		No access
237	JJ Duda, CE Torgersen, SJ Brenkman…	Reconnecting the Elwha River: spatial patterns of fish response to dam removal	2021	United States of America	North America		Included
238	JJ Duda, JR Bellmore	Dam removal and river restoration	2022	United States of America	North America		Included
239	JJ Duda, S Jumani, DJ Wieferich…	Patterns, drivers, and a predictive model of dam removal cost in the United States	2023	United States of America	North America		Excluded after abstract reading
240	JK Raabe, JE Hightower	Assessing distribution of migratory fishes and connectivity following complete and partial dam removals in a North Carolina river	2014	United States of America	North America	Duplicate	Included
241	JK Raabe, JE Hightower	Assessing distribution of migratory fishes and connectivity following complete and partial dam removals in a North Carolina river	2014	United States of America	North America	Duplicate	Included
242	J Sun	Connectivity restoration for fishes in post-industrial rivers of north east England	2021	England	Europe	Duplicate	Excluded after abstract reading
243	J Sun	Connectivity restoration for fishes in post-industrial rivers of north east England	2021	England	Europe	Duplicate	Excluded after abstract reading
244	JL Florsheim, JF Mount…	A geomorphic monitoring and adaptive assessment framework to assess the effect of lowland floodplain river restoration on channel–floodplain sediment continuity	2006	United States of America	North America		Excluded after abstract reading

245	JL Florsheim, MD Dettinger	Promoting atmospheric-river and snowmelt-fueled biogeomorphic processes by restoring river-floodplain connectivity in California's Central Valley	2015	United States of America	North America		Excluded after abstract reading
246	JM Farrell, BL Brown	Restoring connectivity in coastal wetland habitats via channel creation in a large regulated river	2012	Canada	North America		Excluded after abstract reading
247	JP Benitez, A Dierckx, BN Matondo, X Rollin…	Movement behaviours of potamodromous fish within a large anthropised river after the reestablishment of the longitudinal connectivity	2018	Belgium	Europe		Included
248	JR Bellmore, GR Pess, JJ Duda, JE O'Connor…	Conceptualizing ecological responses to dam removal: If you remove it, what's to come?	2019	United States of America	North America		Included
249	JR O'hanley, D Tomberlin	Optimizing the removal of small fish passage barriers	2005	united States of America	North America		Included
250	B Sullivan	Dam removal as a tool for restoring fish connectivity–a literature review and field study	2017		Unknown	Duplicate	No access
251	B Sullivan	Dam removal as a tool for restoring fish connectivity–a literature review and field study	2017		Unknown	Duplicate	No access
252	SK Mantel, DA Hughes, NWJ Muller	Ecological impacts of small dams on South African rivers Part 1: Drivers of change–water quantity and quality	2010	South Africa	Africa	Duplicate	Excluded after abstract reading
253	SK Mantel, DA Hughes, NWJ Muller	Ecological impacts of small dams on South African rivers Part 1: Drivers of change–water quantity and quality	2010	South Africa	Africa	Duplicate	Excluded after abstract reading
254	JV Ward, K Tockner, F Schiemer	Biodiversity of floodplain river ecosystems: ecotones and connectivity1	1999	Austria	Europe		Excluded after abstract reading
255	J Stoller, D Hayes, B Murry	Effects of a rock-ramp fishway on summer fish assemblage in a Lake Huron tributary	2016	Canada	North America	Duplicate	No access
256	J Stoller, D Hayes, B Murry	Effects of a rock-ramp fishway on summer fish assemblage in a Lake Huron tributary	2016	Canada	North America	Duplicate	No access

257	JW Lee, SH Chun, KH Kim, CW Kim	Flow analysis based on the recovery of lateral connectivity in the River	2014	Korea	Asia		Excluded after abstract reading
258	JY Park, JW Lee	A Study on River Management for the Restoration of Aquatic Ecosystem Connectivity	2023	Korea	Asia		Language Barrier
259	K Birnie-Gauvin, J Nielsen, SB Frandsen…	Catchment-scale effects of river fragmentation: A case study on restoring connectivity	2020	Denmark	Europe	Duplicate	Included
260	K Birnie-Gauvin, J Nielsen, SB Frandsen…	Catchment-scale effects of river fragmentation: A case study on restoring connectivity	2020	Denmark	Europe	Duplicate	Included
261	K Birnie-Gauvin, MH Larsen, J Nielsen…	30 years of data reveal dramatic increase in abundance of brown trout following the removal of a small hydrodam	2017	Denmark	Europe		Excluded after abstract reading
262	K Birnie-Gauvin, MM Candee, H Baktoft…	River connectivity reestablished: E ffects and implications of six weir removals on brown trout smolt migration	2018	Denmark	Europe	Duplicate	Included
263	K Birnie-Gauvin, MM Candee, H Baktoft…	River connectivity reestablished: E ffects and implications of six weir removals on brown trout smolt migration	2018	Denmark	Europe	Duplicate	Included
264	K Birnie-Gauvin, MM Candee, H Baktoft…	River connectivity reestablished: E ffects and implications of six weir removals on brown trout smolt migration	2018	Denmark	Europe	Duplicate	Included
265	K Birnie-Gauvin, P Franklin, M Wilkes…	Moving beyond fitting fish into equations: Progressing the fish passage debate in the Anthropocene	2019		Global	Duplicate	Included
266	K Birnie-Gauvin, P Franklin, M Wilkes…	Moving beyond fitting fish into equations: Progressing the fish passage debate in the Anthropocene	2019		Global	Duplicate	Included
267	AM González-Ferreras, E Bertuzzo…	Effects of altered river network connectivity on the distribution of Salmo trutta: Insights from a metapopulation model	2019		Unknown	Duplicate	No access

268	AM González-Ferreras, E Bertuzzo…	Effects of altered river network connectivity on the distribution of Salmo trutta: Insights from a metapopulation model	2019		Unknown	Duplicate	No access
269	K Guetz	Dam removal prioritization in the west: An optimization approach for river restoration and conservation	2020	United States of America	North America		No access
270	K Guetz, T Joyal, B Dickson, D Perry	Prioritizing dams for removal to advance restoration and conservation efforts in the western United States	2022	United States of America	North America		No access
271	K Jensen, M Trepel, D Merritt, G Rosenthal	Restoration ecology of river valleys	2006		Europe		No access
272	K Kukuła, A Bylak	Barrier removal and dynamics of intermittent stream habitat regulate persistence and structure of fish community	2022	Poland	Europe		Included
273	K Lambeets, F Hendrickx, S Vanacker…	Assemblage structure and conservation value of spiders and carabid beetles from restored lowland river banks	2008	Belgium	Europe		Excluded after abstract reading
274	K O'Mara, M Venarsky, B Stewart-Koster…	Connectivity of fish communities in a tropical floodplain river system and predicted impacts of potential new dams	2021	Australia	Oceania		Excluded after abstract reading
275	K Tockner, F Malard, JV Ward	An extension of the flood pulse concept	2000	France	Europe	Duplicate	Included
276	K Tockner, F Malard, JV Ward	An extension of the flood pulse concept	2000	France	Europe	Duplicate	Included
277	K Tockner, F Schiemer	Ecological aspects of the restoration strategy for a river-floodplain system on the Danube River in Austria	1997	Ausria	Europe		Excluded after abstract reading
278	K Tockner, F Schiemer, JV Ward	Conservation by restoration: the management concept for a river-floodplain system on the Danube River in Austria	1998	Austria	Europe		Excluded after abstract reading
279	K Unami, M Yangyuoru, AHMB Alam	Rationalization of building micro-dams equipped with fish passages in West African savannas	2012	West Africa	Africa		Excluded after abstract reading

280	K Van Looy, T Tormos, Y Souchon	Disentangling dam impacts in river networks	2014	France	Europe		Excluded after abstract reading
281	KA Fryirs, GJ Brierley, NJ Preston, M Kasai	Buffers, barriers and blankets: The (dis) connectivity of catchment-scale sediment cascades	2007	New Zealand	Europe		Excluded after abstract reading
282	KA Young, P Gaskell, T Jacklin…	Brown trout management for the 21st century	2017		Unknown		No access
283	KB Fitzpatrick, AT Moody, A Milt, ME Herbert…	Can indicator species guide conservation investments to restore connectivity in Great Lakes tributaries?	2021	Canada	North America		Excluded after abstract reading
284	KB Fitzpatrick, TM Neeson	Aligning dam removals and road culvert upgrades boosts conservation return-on-investment	2018	United States of America	North America		Included
285	KL Bouska, BD Healy, MJ Moore, CG Dunn…	Diverse portfolios: Investing in tributaries for restoration of large river fishes in the Anthropocene	2023	United States of America	North America		Excluded after abstract reading
286	KM Hoenke, M Kumar, L Batt	A GIS based approach for prioritizing dams for potential removal	2014	United States of America	North America		Excluded after abstract reading
287	KPT Atta, JP Maree, MS Onyango…	Chemical phosphate removal from Hartbeespoort Dam water, South Africa	2020	South Africa	Africa		Excluded after abstract reading
288	L Greenberg, O Calles	Restoring Ecological Connectivity in Rivers to Improve Conditions for Anadromous Brown Trout (Salmo trutta)	2010	United States of America	North America		No access
289	L Hommes	The ageing of infrastructure and ideologies: Contestations around dam removal in Spain	2022	Spain	Europe		Excluded after abstract reading
290	CH Chen	Effects of dam removal on resident fish movement in Cijiawan River, Taiwan	2012	Taiwan	Asia	Duplicate	No access
291	CH Chen	Effects of dam removal on resident fish movement in Cijiawan River, Taiwan	2012	Taiwan	Asia	Duplicate	No access
292	LA James	Bed waves at the basin scale: implications for river management and restoration	2006		Unknown		No access

293	LC Garcia, JS Santos, M Matsumoto…	Restoration challenges and opportunities for increasing landscape connectivity under the new Brazilian Forest Act	2013	Brazil	South America		Excluded after abstract reading
294	LM Walter, JM Dettmers, JT Tyson	Considering aquatic connectivity trade-offs in Great Lakes barrier removal decisions	2021	United States of America	North America	Duplicate	Included
295	LM Walter, JM Dettmers, JT Tyson	Considering aquatic connectivity trade-offs in Great Lakes barrier removal decisions	2021	uNited States of America	North America	Duplicate	Included
296	LR Klein, SR Clayton, JR Alldredge…	Long-term monitoring and evaluation of the lower red river meadow restoration project, Idaho, USA	2007	United States of America	North America		No access
297	JR Shuman	Environmental considerations for assessing dam removal alternatives for river restoration	1995	United States of America	North America	Duplicate	No access
298	JR Shuman	Environmental considerations for assessing dam removal alternatives for river restoration	1995	United States of America	North America	Duplicate	No access
299	M Allen	Barriers to fish migration in drying climates: contributions from south-western Australia	2016	Australia	Oceania		Excluded after abstract reading
300	G Thomas, AW Lorenz, A Sundermann…	Fish community responses and the temporal dynamics of recovery following river habitat restorations in Europe	2015	Liechtenstein, Germany and Switzerland	Europe	Duplicate	No access
301	G Thomas, AW Lorenz, A Sundermann…	Fish community responses and the temporal dynamics of recovery following river habitat restorations in Europe	2015	Liechtenstein, Germany and Switzerland	Europe	Duplicate	No access
302	M Choy, D Lawrie, CB Edge	Measuring 30 years of improvements to aquatic connectivity in the Greater Toronto Area	2018	United States of America	North America		No access
303	M González del Tánago, D García de Jalón…	River restoration in Spain: theoretical and practical approach in the context of the European Water Framework Directive	2012	Spain	Europe		Excluded after abstract reading
304	M Gordos, S Nichols, C Lay, A Townsend…	Audit and remediation of fish passage barriers in coastal NSW	2007	Australia	Oceania		Excluded after abstract reading

305	M Habel, K Mechkin, K Podgorska, M Saunes…	Dam and reservoir removal projects: a mix of social-ecological trends and cost-cutting attitudes	2020	United States of America	North America		Included
306	M Kelly-Quinn, M Bruen, JN Turner, J O'Sullivan…	Assessment of the Extent and Impact of Barriers on Freshwater Hydromorphology and Connectivity in Ireland (Reconnect)	2015	Ireland	Europe		Excluded after abstract reading
307	M King, M van Zyll de Jong, D Piercey…	An integrated decision driven design framework to support the ecological restoration of rivers	2022	UK	Europe		Excluded after abstract reading
308	C Nilsson, CA Reidy, M Dynesius, C Revenga	Fragmentation and flow regulation of the world's large river systems	2005		Unknown	Duplicate	No access
309	C Nilsson, CA Reidy, M Dynesius, C Revenga	Fragmentation and flow regulation of the world's large river systems	2005		Unknown	Duplicate	No access
310	M Kraft, DE Rosenberg, SE Null	Prioritizing stream barrier removal to maximize connected aquatic habitat and minimize water scarcity	2019	United States of America	North America		No access
311	M Kraft, S Null	Optimizing Barrier Removal in Utah's Weber Basin	2018	United States of America	North America		Excluded after abstract reading
312	M Mallen-Cooper, DA Brand	Non-salmonids in a salmonid fishway: what do 50 years of data tell us about past and future fish passage?	2007	Australia	Oceania		No access
313	M Moore	Hilliards Creek Rock Ramp Fishway Monitoring Report	2017	Australia	Oceania		Included
314	M Ordeix, Q Pou-Rovira, N Sellares, M Bardina…	Fish pass assessment in the rivers of Catalonia (NE Iberian Peninsula). A case study of weirs associated with hydropower plants and gauging stations	2011	Peninsula	Europe		Excluded after abstract reading
315	M Ovidio, D Sonny, Q Watthez, D Goffaux…	Evaluation of the performance of successive multispecies improved fishways to reconnect a rehabilitated river	2020	Belgium	Europe		Included
316	M Palmer, A Ruhi	Linkages between flow regime, biota, and ecosystem processes: Implications for river restoration	2019		Unknown		No access

317	C Nilsson, CA Reidy, M Dynesius, C Revenga	Fragmentation and flow regulation of the world's large river systems. Science308 (5720): 405-408	2005		Unknown	Duplicate	No access
318	C Nilsson, CA Reidy, M Dynesius, C Revenga	Fragmentation and flow regulation of the world's large river systems. Science308 (5720): 405-408	2005		Unknown	Duplicate	No access
319	M Rinaldi, AM Gurnell, MG Del Tánago, M Bussettini…	Classification of river morphology and hydrology to support management and restoration	2016		Europe		Excluded after abstract reading
320	M Słowik	Is history of rivers important in restoration projects? The example of human impact on a lowland river valley (the Obra River, Poland)	2015	Poland	Europe		Excluded after abstract reading
321	M Søndergaard, E Jeppesen	Anthropogenic impacts on lake and stream ecosystems, and approaches to restoration	2007		Europe		Excluded after abstract reading
322	AJ Boulton	Hyporheic rehabilitation in rivers: restoring vertical connectivity	2007		Unknown	Duplicate	Excluded after abstract reading
323	AJ Boulton	Hyporheic rehabilitation in rivers: restoring vertical connectivity	2007		Unknown	Duplicate	Excluded after abstract reading
324	M Walls	Aligning dam removal and dam safety: Comparing policies and institutions across states	2020	United States of America	North America		Excluded after abstract reading
325	MA Ginders, KJ Collier, IC Duggan…	Influence of hydrological connectivity on plankton communities in natural and reconstructed side-arms of a large New Zealand river	2016	New Zealand	Europe		Excluded after abstract reading
326	MA Mensinger, AM Brehm, A Mortelliti…	American eel personality and body length influence passage success in an experimental fishway	2021	United States of America	North America		Excluded after abstract reading
327	MA Wilkes, M Mckenzie, JA Webb	Fish passage design for sustainable hydropower in the temperate Southern Hemisphere: an evidence review	2018	Australia	Oceania	Duplicate	Included
328	MA Wilkes, M Mckenzie, JA Webb	Fish passage design for sustainable hydropower in the temperate Southern Hemisphere: an evidence review	2018	Australia	Oceania	Duplicate	Included

329	ME Borsuk, P Reichert, A Peter, E Schager…	Assessing the decline of brown trout (*Salmo trutta*) in Swiss rivers using a Bayesian probability network	2006	Switzerland	Europe		Excluded after abstract reading
330	AM Merenlender, MK Matella	Maintaining and restoring hydrologic habitat connectivity in Mediterranean streams: an integrated modeling framework	2013	United States of America	North America	Duplicate	Excluded after abstract reading
331	AM Merenlender, MK Matella	Maintaining and restoring hydrologic habitat connectivity in mediterranean streams: an integrated modeling framework	2013	United States of America	North America	Duplicate	Excluded after abstract reading
332	MF Adame, AH Arthington, N Waltham…	Managing threats and restoring wetlands within catchments of the Great Barrier Reef, Australia	2019	Australia	Oceania		Excluded after abstract reading
333	MF Johnson, CR Thorne, JM Castro…	Biomic river restoration: A new focus for river management	2020	United States of America	North America		Excluded after abstract reading
334	MG Bennett, JH Howell, BR Kuhajda…	New upstream records for fishes following dam removal in the Cahaba River, Alabama	2015	United States of America	North America		Included
335	MH Bond, TG Nodine, TJ Beechie…	Estimating the benefits of widespread floodplain reconnection for Columbia River Chinook salmon	2019	Colombia	South America		Excluded after abstract reading
336	MJ Burnett, B Van Zyl, CT Downs	The migration of aquatic macrocrustaceans over an artificial barrier in the uThukela river, South Africa	2023	South Africa	Africa		Included
337	MJ Catalano, MA Bozek, TD Pellett	Effects of dam removal on fish assemblage structure and spatial distributions in the Baraboo River, Wisconsin	2007	United States of America	North America		No access
338	MJ Kuby, WF Fagan, CS ReVelle, WL Graf	A multiobjective optimization model for dam removal: an example trading off salmon passage with hydropower and water storage in the Willamette basin	2005	United States of America	North America		Included
339	MK Matella, AM Merenlender	Scenarios for restoring floodplain ecology given changes to river flows under climate change: case from the San Joaquin River, California	2015	United States of America	North America		Excluded after abstract reading

340	ML Pedersen, JM Andersen, K Nielsen…	Restoration of Skjern River and its valley: project description and general ecological changes in the project area	2007	Denmark	Europe		Excluded after abstract reading
341	T Ysebaert, DJ van der Hoek, R Wortelboer…	Management options for restoring estuarine dynamics and implications for ecosystems: A quantitative approach for the Southwest Delta in the Netherlands	2016	Netherlands	Europe	Duplicate	Excluded after abstract reading
342	T Ysebaert, DJ van der Hoek, R Wortelboer…	Management options for restoring estuarine dynamics and implications for ecosystems: A quantitative approach for the Southwest Delta in the Netherlands	2016	Netherlands	Europe	Duplicate	Excluded after abstract reading
343	MR Masnavi, H Tasa, M Ghobadi…	Restoration and reclamation of the river valleys' landscape structure for urban sustainability using FAHP process, the case of Northern Tehran-Iran	2016	Iran	Asia		Excluded after abstract reading
344	N Teichert, A Lizé, H Tabouret, C Gerard, G Bareille…	A multi-approach study to reveal eel life-history traits in an obstructed catchment before dam removal	2022	Switzerland	Europe		Excluded after abstract reading
345	NA Mazany-Wright, J Noseworthy, S Sra…	Breaking Down Barriers	2021	Canada	North America		Excluded after abstract reading
346	NJ Mantua, CL Raymond	Climate change, fish, and fish habitat in the North Cascade Range	2014	United States of America	North America		Excluded after abstract reading
347	NJ Waltham, D Burrows, C Wegscheidl…	Lost floodplain wetland environments and efforts to restore connectivity, habitat, and water quality settings on the Great Barrier Reef	2019	Australia	Oceania		Excluded after abstract reading
348	NP Hitt, S Eyler, JEB Wofford	Dam removal increases American eel abundance in distant headwater streams	2012	United States of America	North America		No access
349	P Bednarek, L Mołoniewicz	River fragmentation in the northern Sandomierz Basin (SE Poland)	2023	Poland	Europe		Excluded after abstract reading
350	P Branco, I Boavida, JM Santos, A Pinheiro…	Boulders as building blocks: improving habitat and river connectivity for stream fish	2013		Unknown		No access

351	P Branco, P Segurado, JM Santos, P Pinheiro…	Does longitudinal connectivity loss affect the distribution of freshwater fish?	2012	Peninsula	Europe		Included
352	P Hu, Q Zeng, J Wang, J Hou, H Wang, Z Yang…	Identification of hotspots of threatened inland fish species and regions for restoration based on longitudinal river connectivity	2021	China	Asia		Excluded after abstract reading
353	P McIntyre	Using optimization models to support barrier removal decisions for native migratory fishes in Great Lakes tributaries	2014	Canada	North America		Excluded after abstract reading
354	P Roni	Does river restoration increase fish abundance and survival or concentrate fish? The effects of project scale, location, and fish life history	2019		Unknown		Excluded after abstract reading
355	P Roni, TJ Beechie, RE Bilby, FE Leonetti…	A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds	2002	United States of America	North America		Excluded after abstract reading
356	Z Yu, M Lu, Y Xu, Q Wang, Z Lin, S Luo	Network structure and stability of the river connectivity in a rapidly urbanizing region	2023	China	Asia	Duplicate	Excluded after abstract reading
357	Z Yu, M Lu, Y Xu, Q Wang, Z Lin, S Luo	Network structure and stability of the river connectivity in a rapidly urbanizing region	2023	China	Asia	Duplicate	Excluded after abstract reading
358	SE Null, J Medellín-Azuara, A Escriva-Bou…	Optimizing the dammed: Water supply losses and fish habitat gains from dam removal in California	2014	United States of America	North America	Duplicate	Excluded after abstract reading
359	SE Null, J Medellín-Azuara, A Escriva-Bou…	Optimizing the dammed: Water supply losses and fish habitat gains from dam removal in California	2014	United States of America	North America	Duplicate	Excluded after abstract reading
360	AT Silva, M Bermúdez, JM Santos, JR Rabuñal…	Pool-type fishway design for a potamodromous cyprinid in the Iberian Peninsula: the Iberian barbel—synthesis and future directions	2020	Peninsula	Europe		Excluded after abstract reading
361	PS Kemp, JR O'hanley	Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis	2010		Unknown	Duplicate	Excluded after abstract reading
362	PE Hirsch, M Thorlacius, T Brodin…	An approach to incorporate individual personality in modeling fish dispersal across in-stream barriers	2017	Switzerland	Europe		Excluded after abstract reading

363	PJ Boon	River restoration in five dimensions	1998		Unknown		No access
364	PJ Whalen, LA Toth, JW Koebel…	Kissimmee River restoration: a case study	2002	United States of America	North America		No access
365	PK Brewitt	Do the fish return? A qualitative assessment of anadromous Pacific salmonids' upstream movement after dam removal	2016	United States of America	North America		Included
366	PM Davies	Climate change implications for river restoration in global biodiversity hotspots	2010	Australia	Oceania		Excluded after abstract reading
367	PM Rodríguez-González, C García, A Albuquerque…	A spatial stream-network approach assists in managing the remnant genetic diversity of riparian forests	2019	Peninsula	Europe		Excluded after abstract reading
368	PS Kemp	Impoundments, barriers and abstractions: impact on fishes and fisheries, mitigation and future directions	2015		Unknown		No access
369	PS Kemp, JR O'hanley	Procedures for evaluating and prioritising the removal of fish passage barriers: a synthesis	2010		Unknown	Duplicate	Excluded after abstract reading
370	TJ Beechie, DA Sear, JD Olden, GR Pess…	Process-based principles for restoring river ecosystems	2010	United States of America	North America	Duplicate	Excluded after abstract reading
371	PS Lake, NR Bond	Australian futures: freshwater ecosystems and human water usage	2007	Australia	Oceania		Excluded after abstract reading
372	PSO Fouché, RG Heath	Functionality evaluation of the xikundu fishway, luvuvhu river, south africa	2013	South Africa	Africa		Included
373	R Finn	Defining an historical baseline and charting a path to restoring habitat connectivity for salmonids in a highly urbanized landscape	2021	United States of America	North America		Excluded after abstract reading
374	R Hogg, SM Coghlan Jr, J Zydlewski	Anadromous sea lampreys recolonize a Maine coastal river tributary after dam removal	2013	United States of America	North America		Included
375	TJ Beechie, DA Sear, JD Olden, GR Pess…	Process-based principles for restoring river ecosystems	2010	United States of America	North America	Duplicate	Excluded after abstract reading

376	R Voicu, E Luca	Proposals for the restoration of longitudinal connectivity of the Jiu River and ensuring fish migration upstream/downstream of Isalnita dam	2012	Romania	Europe	Duplicate	Excluded after abstract reading
377	R Manenti, D Ghia, G Fea, GF Ficetola…	Causes and consequences of crayfish extinction: Stream connectivity, habitat changes, alien species and ecosystem services	2019		Unknown		No access
378	R May	“Connectivity” in urban rivers: Conflict and convergence between ecology and design	2006	United States of America	North America		Excluded after abstract reading
379	R Schumann, M Kende	Lifting barriers to Internet development in Africa: suggestions for improving connectivity	2013		Unknown		Excluded after abstract reading
380	R Voicu, K Miles, R Sotir, AC Bănăduc…	Proposing a Technical Solution for Restoring Longitudinal Connectivity in the Brădeni/Retiş Accumulation Area on Hârtibaciu River	2016	Romania	Europe	Duplicate	Excluded after abstract reading
381	ME Qureshi, T Shi, SE Qureshi, W Proctor	Removing barriers to facilitate efficient water markets in the Murray-Darling Basin of Australia	2009	Australia	Oceania	Duplicate	Excluded after abstract reading
382	ME Qureshi, T Shi, SE Qureshi, W Proctor	Removing barriers to facilitate efficient water markets in the Murray-Darling Basin of Australia	2009	Australia	Oceania	Duplicate	Excluded after abstract reading
383	RL McLaughlin, A Hallett, TC Pratt, LM O'Connor…	Research to guide use of barriers, traps, and fishways to control sea lamprey	2007	United States of America	North America	Duplicate	Excluded after abstract reading
384	RL McLaughlin, A Hallett, TC Pratt, LM O'Connor…	Research to guide use of barriers, traps, and fishways to control sea lamprey	2007	United States of America	North America	Duplicate	Excluded after abstract reading
385	RA Coleman, B Gauffre, A Pavlova, LB Beheregaray…	Artificial barriers prevent genetic recovery of small isolated populations of a low-mobility freshwater fish	2018		Unknown		No access
386	RA Francis, SPG Hoggart, AM Gurnell, C Coode	Meeting the challenges of urban river habitat restoration: developing a methodology for the River Thames through central London	2008	England	North America		Excluded after abstract reading
387	RA Tabor, FT Waterstrat, JD Olden	Response of migratory sculpin populations to barrier removal in four small lowland urban streams in the Lake Washington basin	2020	United States of America	North America	Duplicate	No access

388	RA Tabor, FT Waterstrat, JD Olden	Response of migratory sculpin populations to barrier removal in four small lowland urban streams in the Lake Washington basin	2020	United States of America	North America	Duplicate	No access
389	JL Florsheim, JF Mount	Restoration of floodplain topography by sand-splay complex formation in response to intentional levee breaches, Lower Cosumnes River, California	2002	United States of America	North America	Duplicate	Excluded after abstract reading
390	JL Florsheim, JF Mount	Restoration of floodplain topography by sand-splay complex formation in response to intentional levee breaches, Lower Cosumnes River, California	2002	United States of America	North America	Duplicate	Excluded after abstract reading
391	RB Jacobson, DW Blevins…	Sediment regime constraints on river restoration—An example from the Lower Missouri River	2009	United States of America	North America		Excluded after abstract reading
392	RC Grabowski, N Surian…	Characterizing geomorphological change to support sustainable river restoration and management	2014		Unknown		No access
393	RC Rooney, C Carli, SE Bayley	River connectivity affects submerged and floating aquatic vegetation in floodplain wetlands	2013	Colombia	South America		Excluded after abstract reading
394	RGM Heath, A Bok, PSO Fouche, WK Mastenbroek…	Development of criteria for the design of fishways for South African rivers and estuaries	2005	South Africa	Africa		Included
395	RJ Chou	Achieving successful river restoration in dense urban areas: Lessons from Taiwan	2016	Taiwan	Asia		Excluded after abstract reading
396	RJ Naiman, JR Alldredge…	Developing a broader scientific foundation for river restoration: Columbia River food webs	2012	Columbia	South America		Excluded after abstract reading
397	RJ Wasserman, OLF Weyl, NA Strydom	The effects of instream barriers on the distribution of migratory marine-spawned fishes in the lower reaches of the Sundays River, South Africa	2011	South Africa	Africa		Included
398	RL Flitcroft, I Arismendi…	A review of habitat connectivity research for pacific salmon in marine, estuary, and freshwater environments	2019	United States of America	North America		No access
399	J Mant, AB Gill, M Janes…	Restoration of rivers and floodplains	2012	United States of America	North America	Duplicate	Excluded after abstract reading

400	J Mant, AB Gill, M Janes…	Restoration of rivers and floodplains	2012	United States of America	North America	Duplicate	Excluded after abstract reading
401	RL McLaughlin, ERB Smyth, T Castro-Santos…	Unintended consequences and trade-offs of fish passage	2013		Unknown		No access
402	RM Quinones, TE Grantham, BN Harvey…	Dam removal and anadromous salmonid (Oncorhynchus spp.) conservation in California	2015	United States of America	North America	Duplicate	Included
403	RM Quinones, TE Grantham, BN Harvey…	Dam removal and anadromous salmonid (Oncorhynchus spp.) conservation in California	2015	United States of America	North America	Duplicate	Included
404	RMV Cortes, A Peredo, DPS Terêncio…	Undamming the Douro River catchment: A stepwise approach for prioritizing dam removal	2019	Spain	Europe		Excluded after abstract reading
405	RS Hogg	Fish Community Response to Small-stream Dam Removal in a Coastal Maine Tributary	2012	United States of America	North America		Included
406	RS Hogg, SM Coghlan Jr, J Zydlewski…	Fish community response to a small-stream dam removal in a maine coastal river tributary	2015	United States of America	North America	Duplicate	Included
407	RS Hogg, SM Coghlan Jr, J Zydlewski…	Fish community response to a small-stream dam removal in a maine coastal river tributary	2015	United States of America	North America	Duplicate	Included
408	S Atkinson, M Bruen, JJ O'Sullivan, JN Turner…	An inspection-based assessment of obstacles to salmon, trout, eel and lamprey migration and river channel connectivity in Ireland	2020	Ireland	Europe		Excluded after abstract reading
409	V Lüderitz, T Speierl, U Langheinrich, W Völkl…	Restoration of the Upper Main and Rodach rivers–The success and its measurement	2011	Germany	Europe	Duplicate	Excluded after abstract reading
410	V Lüderitz, T Speierl, U Langheinrich, W Völkl…	Restoration of the Upper Main and Rodach rivers–The success and its measurement	2011	Germany	Europe	Duplicate	Excluded after abstract reading
411	S Beatty, M Allen, J Keleher	Assessment of the Rushy Creek fishway system, south-western Australia.	2012	Australia	Oceania	Duplicate	Included
412	S Beatty, M Allen, J Keleher	Assessment of the Rushy Creek fishway system, south-western Australia.	2012	Australia	Oceania	Duplicate	Included

413	S Bowie, E Bocker	National Fish Passage Management Symposium	2013	New Zealand	Europe		Excluded after abstract reading
414	S Dufour, AJ Rollet, M Chapuis, M Provansal…	On the Political Roles of Freshwater Science in Studying Dam and Weir Removal Policies: A Critical Physical Geography Approach.	2017		Unknown		No access
415	S Fischer, J Greet, CJ Walsh, JA Catford	Restored river-floodplain connectivity promotes woody plant establishment	2021		Unknown	Irrelevant	Excluded after abstract reading
416	S Gregory, H Li, J Li	… basis for ecological responses to dam removal: resource managers face enormous challenges in assessing the consequences of removing large dams from rivers …	2002		North America	Duplicate	Included
417	S Gregory, H Li, J Li	… basis for ecological responses to dam removal: resource managers face enormous challenges in assessing the consequences of removing large dams from rivers …	2002		North America	Duplicate	Included
418	S Höckendorff, JD Tonkin, P Haase…	Characterizing fish responses to a river restoration over 21 years based on species' traits	2017	Germany	Europe		Excluded after abstract reading
419	S Hohensinner, C Hauer, S Muhar	River morphology, channelization, and habitat restoration	2018	Netherlands	Europe		Excluded after abstract reading
420	S Jumani, MJ Deitch, D Valle, S Machado, V Lecours…	A new index to quantify longitudinal river fragmentation: Conservation and management implications	2022	United States of America	North America		Excluded after abstract reading
421	S King	Economic Valuation and Optimisation of River Barrier Mitigation Actions	2015	UK	Europe		Included
422	S King, JR O'Hanley	Optimal fish passage barrier removal—revisited	2016		Unknown	Duplicate	Included
423	S King, JR O'Hanley	Optimal fish passage barrier removal—revisited	2016		Unknown	Duplicate	Included
424	J Greet, S Fischer, CJ Walsh, MJ Sammonds…	Restored river-floodplain connectivity promotes riparian tree maintenance and recruitment	2022	Australia	Oceania	Duplicate	Excluded after abstract reading

425	J Greet, S Fischer, CJ Walsh, MJ Sammonds…	Restored river-floodplain connectivity promotes riparian tree maintenance and recruitment	2022	Australia	Oceania	Duplicate	Excluded after abstract reading
426	S Laureys, ME Faymonville, A Luxen, M Lamy…	Restoration of thalamocortical connectivity after recovery from persistent vegetative state	2000		Unknown		No access
427	S Muhar, M Jungwirth, G Unfer, C Wiesner…	30 Restoring riverine landscapes at the Drau River: successes and deficits in the context of ecological integrity	2007		Europe		Excluded after abstract reading
428	S Santoro, I Pluchinotta, A Pagano, P Pengal…	Assessing stakeholders' risk perception to promote Nature Based Solutions as flood protection strategies: The case of the Glinščica river (Slovenia)	2019	Slovenia	Europe		Excluded after abstract reading
429	S Schmutz, M Jungwirth	Fish as indicators of large river connectivity: the Danube and its tributaries	1999		Europe		Excluded after abstract reading
430	S Schmutz, O Moog	Dams: ecological impacts and management	2018	Austria	Europe		Excluded after abstract reading
431	S Woolsey, F Capelli, TOM Gonser, E Hoehn…	A strategy to assess river restoration success	2007	Switzerland	Europe		Excluded after abstract reading
432	SD Arruda	Dam Removal II: No Longer Caught Up in that Old Race: Successful Velocity Barrier Elimination for Anadromous Fish	2016	United States of America	North America		N/A
433	SD Langhans, M Pagter, S Domisch, V Hermoso…	… for barrier removals to benefit longitudinal and lateral connectivity according to the EU Biodiversity Strategy 2030? A proposal for a new barrier removal …	2023		Europe		Excluded after abstract reading
434	PA Franklin, B Bartels	Restoring connectivity for migratory native fish in a New Zealand stream: effectiveness of retrofitting a pipe culvert	2012	New Zealand	Europe	Duplicate	No access
435	PA Franklin, B Bartels	Restoring connectivity for migratory native fish in a New Zealand stream: effectiveness of retrofitting a pipe culvert	2012	New Zealand	Europe	Duplicate	No access

436	SG Roy, E Uchida, SP de Souza…	A multiscale approach to balance trade-offs among dam infrastructure, river restoration, and cost	2018	United States of America	North America	Duplicate	Included
437	SG Roy, E Uchida, SP de Souza…	A multiscale approach to balance trade-offs among dam infrastructure, river restoration, and cost	2018	United States of America	North America	Duplicate	Included
438	SH Kim, D Kim, KH Cho	Evaluation of habitat improvement using two-dimensional fish habitat modeling after the connectivity restoration in an isolated former channel	2015		Asia	Irrelevant	Language Barrier
439	SJ Beatty, DL Morgan, A Torre	Restoring ecological connectivity in the Margaret River: Western Australia's first rock-ramp fishways	2007	Australia	Oceania		No access
440	SJ Brenkman, RJ Peters, RA Tabor…	Rapid recolonization and life history responses of Bull Trout following dam removal in Washington's Elwha River	2019	United States of America	North America		No access
441	SJ Cooke, HL Auld, K Birnie-Gauvin…	On the relevance of animal behavior to the management and conservation of fishes and fisheries	2023	Canada	North America		Excluded after abstract reading
442	SJ Ormerod	A golden age of river restoration science?	2004	UK	Europe		Excluded after abstract reading
443	R Jansson, C Nilsson, B Malmqvist	Restoring freshwater ecosystems in riverine landscapes: the roles of connectivity and recovery processes	2007	Sweden	North America	Duplicate	No access
444	R Jansson, C Nilsson, B Malmqvist	Restoring freshwater ecosystems in riverine landscapes: the roles of connectivity and recovery processes	2007	Sweden	North America	Duplicate	No access
445	R Voicu, D Bănăduc	Restoring longitudinal connectivity of the Someşul Mic River near the dam in Mănăstirea Village (Transylvania, Romania).	2014	Romania	Europe	Duplicate	Excluded after abstract reading
446	R Voicu, L Voicu, A Curtean-Bănăduc…	Restoring the fish fauna connectivity of the Hârtibaciu River–Retiş Dam study case (Transylvania, Romania)	2017	Romania	Europe	Duplicate	Excluded after abstract reading

447	R Voicu, L Voicu, A Curtean-Bănăduc…	Restoring the fish fauna connectivity of the Hârtibaciu River–Retiş Dam study case (Transylvania, Romania)	2017	Romania	Europe	Duplicate	Excluded after abstract reading
448	H Drouineau, C Carter, M Rambonilaza…	River continuity restoration and diadromous fishes: much more than an ecological issue	2018	France	Europe	Duplicate	Excluded after abstract reading
449	SK McKay, L Batt, RB Bringolf, S Davie…	Fish passage in Georgia: planning for the future	2013	United States of America	North America	Duplicate	Included
450	SK McKay, L Batt, RB Bringolf, S Davie…	Fish passage in Georgia: planning for the future	2013	United States of America	North America	Duplicate	Included
451	SK McKay, MK Reif, J Conyngham, DM Kohtio	Barrier prioritization in the tributaries of the Hudson-Raritan Estuary	2017	United States of America	North America		Excluded after abstract reading
452	SK McMillan, GB Noe	Increasing floodplain connectivity through urban stream restoration increases nutrient and sediment retention	2017	United States of America	North America		Excluded after abstract reading
453	SL Ecohidráulica…	An Analysis of River Fragmentation in the Spanish River Basins	2016	Spain	Europe		Excluded after abstract reading
454	H Drouineau, C Carter, M Rambonilaza…	River continuity restoration and diadromous fishes: much more than an ecological issue	2018	France	Europe	Duplicate	Excluded after abstract reading
455	FR Hauer, MS Lorang	River regulation, decline of ecological resources, and potential for restoration in a semi-arid lands river in the western USA	2004	United States of America	North America	Duplicate	Excluded after abstract reading
456	SM Baker, EA Reyier, BJ Ahr, GS Cook	Assessing the Effects of Physical Barriers and Hypoxia on Red Drum Movement Patterns to Develop More Effective Management Strategies	2023	United States of America	North America		Excluded after abstract reading
457	T Bölscher, E Van Slobbe, MTH Van Vliet, SE Werners	Adaptation turning points in river restoration? The Rhine salmon case	2013	Sweden	Europe		Excluded after abstract reading
458	T Copeland, D Blythe, W Schoby…	Population effect of a large-scale stream restoration effort on Chinook salmon in the Pahsimeroi River, Idaho	2021	United States of America	North America		Included

459	T Erős, JR O'Hanley, I Czeglédi	A unified model for optimizing riverscape conservation	2018	Hungary	Europe		Excluded after abstract reading
460	T Hein, C Baranyi, GJ Herndl, W Wanek…	Allochthonous and autochthonous particulate organic matter in floodplains of the River Danube: the importance of hydrological connectivity	2003		Europe		No access
461	T Marsden, LJ Baumgartner, D Duffy, A Horta…	Evaluation of a new practical low-cost method for prioritising the remediation of fish passage barriers in resource-deficient settings	2023	Australia	Oceania		Included
462	T Yang, S Wang, X Li, T Wu, L Li, J Chen	River habitat assessment for ecological restoration of Wei River Basin, China	2018	China	Asia		Excluded after abstract reading
463	FR Hauer, MS Lorang	River regulation, decline of ecological resources, and potential for restoration in a semi-arid lands river in the western USA	2004	United States of America	North America	Duplicate	Excluded after abstract reading
464	A Dorobek, SMP Sullivan, A Kautza	Short-term consequences of lowhead dam removal for fish assemblages in an urban river system	2015	United States of America	North America	Duplicate	No access
465	TJ Beechie, C Fogel, C Nicol, B Timpane-Padgham	A process-based assessment of landscape change and salmon habitat losses in the Chehalis River basin, USA	2021	United States of America	North America		Excluded after abstract reading
466	AC Dorobek	Short-term consequences of lowhead dam removal for fish community dynamics in an urban river system	2016	United States of America	North America	Duplicate	No access
467	D Perera, T North	The socio-economic impacts of aged-dam removal: a review	2021	Canada	North America	Duplicate	Excluded after abstract reading
468	TJ Beechie, GR Pess, H Imaki, A Martin…	Comparison of potential increases in juvenile salmonid rearing habitat capacity among alternative restoration scenarios, Trinity River, California	2015	United States of America	North America		Excluded after abstract reading
469	TM Neeson, AT Moody, JR O'Hanley…	Aging infrastructure creates opportunities for cost-efficient restoration of aquatic ecosystem connectivity	2018	United States of America	North America		Included

470	TP Muha, D Rodriguez-Barreto, R O'Rorke…	Using eDNA metabarcoding to monitor changes in fish community composition after barrier removal	2021	England	Europe	Duplicate	Included
471	TP Muha, D Rodriguez-Barreto, R O'Rorke…	Using eDNA metabarcoding to monitor changes in fish community composition after barrier removal	2022	England	Europe	Duplicate	Included
472	V Hermoso, M Clavero, AF Filipe	An accessible optimisation method for barrier removal planning in stream networks	2021	Peninsula	Europe	Duplicate	Included
473	V Hermoso, M Clavero, AF Filipe	An accessible optimisation method for barrier removal planning in stream networks	2021	Peninsula	Europe	Duplicate	Included
474	D Perera, T North	The socio-economic impacts of aged-dam removal: a review	2021	Canada	North America	Duplicate	Excluded after abstract reading
475	HBN Hynes	The stream and its valley: With 4 figures and 2 tables in the text	1975		Unknown	Duplicate	No access
476	W Hou, L Zhai, S Feng, U Walz	Restoration priority assessment of coal mining brownfields from the perspective of enhancing the connectivity of green infrastructure networks	2021		Unknown	Irrelevant	Excluded after abstract reading
477	WM Twardek, IG Cowx, NWR Lapointe…	Bright spots for inland fish and fisheries to guide future hydropower development	2022		Global		Excluded after abstract reading
478	WW Li, JH Bao, CS Zhang, LW Wang, HT LI…	A review of international fishways adaptive management systems and management prospects for China	2018	China	Asia		Excluded after abstract reading
479	HBN Hynes	The stream and its valley: With 4 figures and 2 tables in the text	1975		Unknown	Duplicate	No access
480	EH Stanley, MW Doyle	Trading off: the ecological effects of dam removal	2003	United States of America	North America	Duplicate	No access
481	EH Stanley, MW Doyle	Trading off: the ecological effects of dam removal	2003	United States of America	North America	Duplicate	No access
482	X Hu, Y Zhang, F Yang, K Zhang, Y He	An efficiency analysis of the low-head gate Dam Fishway for freshwater fish ascending Liuxi River in South China	2020	China	Asia		Included

483	GM Kondolf, S Anderson, R Lave, L Pagano…	Two decades of river restoration in California: what can we learn?	2007	United States of America	North America	Duplicate	Excluded after abstract reading
484	GM Kondolf, S Anderson, R Lave, L Pagano…	Two decades of river restoration in California: what can we learn?	2007	United States of America	North America	Duplicate	Excluded after abstract reading
485	XK Volk, JP Gattringer, A Otte, S Harvolk-Schöning	Connectivity analysis as a tool for assessing restoration success	2018	Germany	Europe		Excluded after abstract reading
486	Y Cai, J Liang, P Zhang, Q Wang, Y Wu, Y Ding…	Review on strategies of close-to-natural wetland restoration and a brief case plan for a typical wetland in northern China	2021	China	Asia		Excluded after abstract reading
487	Y Liu, B Cui, J Du, Q Wang, S Yu…	A method for evaluating the longitudinal functional connectivity of a river–lake–marsh system and its application in China	2020	China	Asia		Excluded after abstract reading
488	Y Lu, WY Zhu, QY Liu, Y Li, HW Tian…	Impact of Low-Head Dam Removal on River Morphology and Habitat Suitability in Mountainous Rivers	2022	China	Asia		Included
489	Y Reyjol, C Argillier, W Bonne, A Borja…	Assessing the ecological status in the context of the European Water Framework Directive: where do we go now?	2014		Europe		Excluded after abstract reading
490	Y Zhao, L Zeng, Y Wei, J Liu, J Deng, Q Deng…	An indicator system for assessing the impact of human activities on river structure	2020	China	Asia		Excluded after abstract reading
491	LR Oliver, WC Gendron	Upper Narragansett Bay fish passage: Case studies in connectivity restoration	2018		Unknown	Duplicate	No access
492	LR Oliver, WC Gendron	Upper Narragansett Bay fish passage: Case studies in connectivity restoration	2018		Unknown	Duplicate	No access
493	Z Bian, L Liu, S Ding	Analysis of forest landscape restoration based on landscape connectivity: a case study in the Yi River Basin, China, during 2015–2020	2021	China	Asia		Excluded after abstract reading
494	CA Tomsic, TC Granata, RP Murphy, CJ Livchak	Using a coupled eco-hydrodynamic model to predict habitat for target species following dam removal	2007	United States of America	North America	Duplicate	Excluded after abstract reading

495	CA Tomsic, TC Granata, RP Murphy, CJ Livchak	Using a coupled eco-hydrodynamic model to predict habitat for target species following dam removal	2007	United States of America	North America	Duplicate	Excluded after abstract reading
496	Baldan, D., Cunillera-Montcusí, D., Funk, A. and Hein, T	Introducing ‘riverconn’: an R package to assess river connectivity indices	2022	Peninsula	Europe		Included
497	Branco, P., Segurado, P., Santos, J.M., Ferreira, M.T., 2014	Prioritizing barrier removal to improve functional connectivity of rivers.	2014	Portugal and Spain	Europe		Included
498	Kondolf, G.M., Boulton, A.J., O'Daniel, S., Poole, G.C., Rahel, F.J., Stanley, E.H., Wohl, E., Bång, A., Carlstrom, J., Cristoni, C. and Huber, H	Process-based ecological river restoration: visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages	2006		Unknown		Included
499	Kukuła, K. and Bylak, A	Barrier removal and dynamics of intermittent stream habitat regulate persistence and structure of fish community	2022	Poland	Europe		Included
500	Magilligan, F.J., Graber, B.E., Nislow, K.H., Chipman, J.W., Sneddon, C.S. and Fox, C.A	River restoration by dam removal: Enhancing connectivity at watershed scales.	2016	United States of America	North America		Included
501	O’Hanley, J.R	Open rivers: barrier removal planning and the restoration of free-flowing rivers.	2011	United States of America	North America		Included
502	Rincón, G., Solana-Gutiérrez, J., Alonso, C., Saura, S. and García de Jalón, D	Longitudinal connectivity loss in a riverine network: accounting for the likelihood of upstream and downstream movement across dams	2017	Peninsula	Europe		Included
503	Segurado, P., Branco, P. and Ferreira, M.T	Prioritizing restoration of structural connectivity in rivers: a graph based approach.	2013	Portugal	Europe		Included
504	Thieme, M., Birnie-Gauvin, K., Opperman, J.J., Franklin, P.A., Richter, H., Baumgartner, L., Ning, N., Vu, A.V., Brink, K., Sakala, M. and O’Brien, G.C	Measures to safeguard and restore river connectivity	2023		Unknown		Included

505	Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. and Cushing, C.E	The river continuum concept	1980		Unknown		Included
506	Williams, J.G., Armstrong, G., Katopodis, C., Larinier, M. and Travade, F.	Thinking like a fish: a key ingredient for development of effective fish passage facilities at river obstructions.	2012		Unknown		Included