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Environmental monitoring of freshwater ecosystems using telemetered behavioural indicators from free-swimming fish in southern Africa

Matthew James Burnett

Submitted in fulfilment of the academic requirements for the degree of

Doctor of Philosophy

in the Discipline of Ecological Sciences

School of Life Sciences

College of Agriculture, Engineering and Science

University of KwaZulu-Natal

Pietermaritzburg Campus

2019

UNIVERSITY OF
KWAZULU-NATAL
INYUVESI
YAKWAZULU-NATALI

ABSTRACT

The anthropogenic stressors associated with the increased demand for water have degraded aquatic ecosystems in both southern Africa and globally. The behavioural ecology of fishes as a line of evidence can be used to assess the impacts of anthropogenic stressors. Fish telemetry methods are available to monitor fish behaviour and the response of tagged fish to altered water quality, flow and instream habitat variability. Fish telemetry methods are well established and used widely to describe the behaviour of fishes in aquatic environments. The goals set out in this thesis were to evaluate and implement the FISHTRAC programme in southern African, to achieve this objectives were set out to apply the activity sensors on fish, recording water quality and quantity variables, implement data analyses methods and improve on the remote capabilities of the programme.

This study included a review highlighting the development of fish telemetry methods within African freshwater environments to assess their application across various disciplines as a method to contribute to knowledge gaps on the continent. We found 52 studies using fish telemetry on inland African waters across eight countries. Radio telemetry (82%) was favoured over acoustic telemetry (11%), while the remaining studies included reviews and tagging procedures non-specific to a telemetry method. Telemetry was used on 23 native fish species in Africa across various families, as well as for two invasive species. Tigerfish *Hydrocynus vittatus* (n = 16) and the Yellowfish *Labeobarbus* spp. (n = 15) being the most studied species. The review highlights the benefits derived from fish telemetry methods and how the approach can provide evidence-based data for decisions that can affect human livelihoods across Africa. Various studies were found that applied fish telemetry methods to suit local conditions and contribute to the understanding of fish behavioural data needed for management decisions in southern Africa. The southern African inland fish tracking (FISHTRAC) programme was then developed to grow the

use of fish telemetry in the region and extend its use for collecting fish behaviour and environmental data in real-time and remotely. Eight case studies that contributed to its development were conducted over the last decade and are reviewed here. The approach was applied on five socio-economically important freshwater ecosystems across southern Africa and eight indicator fish species and included a four-phase guideline to implement radio telemetry techniques within the region successfully.

To understand the biological response to anthropogenic stressors; data from *Hydrocynus vittatus* (n = 10) and *Labeobarbus marequensis* (n = 7) tagged in the Crocodile River, Mpumalanga, was revisited to evaluate the use of activity sensors. To implement the FISHTRAC programme *Labeobarbus natalensis* (n = 43) were studied on the uMngeni River, KwaZulu-Natal. Radio telemetry was used to record linear movement and activity rates of fish where data were obtained through an established remote network. On the Crocodile River, activity sensors could detect different behavioural patterns between two ecologically different fusiform shaped species, *H. vittatus* and *L. marequensis*. Discharge and temperature had significant effects on both species. On the uMngeni River, *L. natalensis* were facultative migrators and showed individual plasticity, with only 11 individuals (25.6%) moving over a reach scale. Refuge habitat played an important role in maintaining temperatures above 9 °C during winter.

The response of *L. natalensis* to a planned management flow release was evaluated using the FISHTRAC programme downstream of Midmar Dam in the uMngeni River. Activity sensors from ten tagged *L. natalensis* were used to record spatial and non-spatial movements during the experiment and included an assessment of the fish community and water quality. Three behavioural type responses were identified using the activity sensor consisting of the following: Type 1, peaked activity and changes in diurnal behaviour. Type 2, no peak activity and changes in

diurnal behaviour. Type 3, mortality (LNAT37). These Type responses showed the responsiveness of ecological indicators and can be used to evaluate the measure of change and impact of anthropogenic stressors on the aquatic ecosystem. There was no observed movement of tagged fish into the Karkloof River and no change in community structure substantiated this, while water quality results showed to increase in concentration at the front of the release.

The large data sets that are acquired through the FISHTRAC programme in real-time needs interpretation as it is obtained to alert managers of changes in fish behaviour. In order to detect behavioural changes based on the preceding behaviour, an algorithm was developed and successfully tested on 15 *L. natalensis* individuals. Alerts were set to when changes in behaviour occurred and could be linked to biological functions such as reach-scale movement or changes in water temperature. Causal effects for behavioural changes were examined using generalised mixed effect models and showed that water temperature was the primary driver for fish behavioural change.

The fish species responding to anthropogenic stressors evaluated in this study highlighted the need to manage these stressors with a better understanding of the biological component. The FISHTRAC programme reviewed and implemented in this study has successfully demonstrated a method to do this in real-time and remotely, allowing water resource managers to be responsive through an alert system. This methodology will greatly assist in gathering much need behavioural data of African fish species, assisting with improving the assessment and management of ecosystem well-being as demand for water resource increase.

Keywords: fish behaviour, freshwater ecosystems, smart technology, electronic tags, activity sensors, real-time, remote monitoring, ecological indicators.

PREFACE

The data described in this thesis were collected in the Republic of South Africa from September 2011 to January 2012 and June 2018 to August 2019. Experimental work was carried out while registered at the School of Life Sciences, University of KwaZulu-Natal, Pietermaritzburg campus, under the supervision of Dr Gordon C. O'Brien, Professor Colleen T. Downs and Professor Graham Jewitt.

This thesis, submitted for the degree of Doctor of Philosophy in Ecological Sciences 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.

………………………….

Matthew Burnett

December 2019

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

…………………………..

Professor Colleen T. Downs

Supervisor

December 2019

COLLEGE OF AGRICULTURE, ENGINEERING AND SCIENCE

DECLARATION 1 - PLAGIARISM

I, Matthew Burnett, 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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Matthew J. Burnett

December 2019

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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

MJ Burnett, GC O'Brien, FJ Jacobs, G Jewitt and & CT Downs

African inland fish telemetry methods for water resource and fisheries management: A review

Author contributions:

MJB conceived paper with input from GOB, FJJ, GJ and CTD. MJB collected and analysed data and wrote the paper. CTD, GJ, GCOB and FJJ contributed valuable comments to the manuscript.

Publication 2

MJ Burnett, GC O'Brien, FJ Jacobs, F Botha, G Jewitt and & CT Downs

The southern African inland fish tracking programme (FISHTRAC): An evaluation of the approach for monitoring ecological consequences of multiple water resource stressors, remotely and in real-time

Author contributions:

MJB conceived paper with GCOB, FJJ, FB, GJ and CTD. MJB collected and analysed data and wrote the paper. CTD, GJ, GCOB, FJJ and FB contributed valuable comments to the manuscript.

Publication 3

MJ Burnett, GC O'Brien, V Wepener, G Jewitt, & CT Downs

Locomotive activity of free-swimming fish as an indicator of environmental factors in the Crocodile River, Kruger National Park, South Africa

Author contributions:

MJB conceived paper with GOB, VW, GJ and CTD. MJB collected and analysed data and wrote the paper. CTD, GJ, GCOB and VP contributed valuable comments to the manuscript.

Publication 4

MJ Burnett, GC O'Brien, G Jewitt & CT Downs

The behavioural ecology of *Labeobarbus natalensis* and its contribution to the sustainable management of the uMngeni River, KwaZulu-Natal, South Africa

Author contributions:

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

Publication 5

MJ Burnett, GC O'Brien, T Rowe, G Jewitt & CT Downs

Evaluating the behavioural response of fishes towards management flows in a regulated river using fish telemetry methods

Author contributions:

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

Publication 6

MJ Burnett, GC O'Brien, G Jewitt & CT Downs

Detecting changes in fish behaviour in real-time to alert managers to thresholds of potential concern within an urban river

Author contributions:

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

Signed: ………………………………………………………

Matthew James Burnett

December 2019

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"Therefore the land mourns, and all who dwell in it languish; together with wild animals and the birds of the air, even the fish of the sea are perishing." Hosea 4:3

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The many staff members, students and assistants that contributed in small and great ways are a true testimony of strength in community. These people that came to my aid during the study were Celine Hanzen, Dr. Mahomed Desai, Tobias von Seydlitz, Sanele Ngubane, Dr. Allistair Clulow, Cormac Price, Hazel Govender, Melissa Wade, Camille Fritsch, Wesley Evans, Pumla Dlamini, Bayanda Sonamzi, Cormac Price. Thank you.

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Last but most certainly not least, my heartfelt gratitude to my parents, James and Lyn Burnett. Without their steadfast prayers, unwavering support, encouragement and advice I would not have accomplished what I have today. Their example of humility, love and kindness, not only to each other but to all of those around them, has made me who I am today and inspired me to go furtherer than I have ever dreamed. This one is for them.

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CHAPTER 1

Introduction

The quality of freshwater on a global scale and locally in South Africa is decreasing from the impact that anthropogenic stressors have on aquatic ecosystems (Dugdeon 2014; Nel 2017; Rodell et al. 2018; Du Plessis 2019). These stressors are mostly as a result of the need to meet the growing demand for water resources as human populations increase (Du Plessis 2019; Sabater et al. 2019). The importance of aquatic ecosystems to provide clean water and remedial action for used water is increasingly becoming relevant in the management of water resources, provision of ecosystem services and the ability to reach sustainable development goals (Hughes et al. 2018a,b; Dickens et al. 2019). Protecting the ecosystem services provided by these aquatic ecosystems involves the management of environmental flows, reducing poor water quality stressors and ensuring the presence of biodiversity within the biological component (King and Brown 2006; O'Brien et al. 2018; Dickens et al. 2018).

The understanding and monitoring of the impacts from anthropogenic stressors are important to achieve the sustainability of water resource use within freshwater aquatic ecosystems (O'Brien et al. 2018; Dickens et al. 2018; Dickens et al. 2019). Using the biological component as indicators is one way to evaluate the impact of anthropogenic stressors and their response to exposure of stressors monitored through various bioassays and biomonitoring (Scherer 1992; Baumgartner et al. 2014; Dickens et al. 2018). Fish are one such biological taxon that has been established as ecological indicators for aquatic ecosystem well-being (Harris 1995; McDowall and Taylor 2000; Schiemer 2000; Depledge and Galloway 2005; Kleynhans and Louw 2008; O'Brien et al. 2009; Arthington and Balcombe 2011). Fish are generally charismatic to people, long-lived organisms, have different niche guilds or habitat dependencies and are relatively easily monitored, these traits make them relatively good ecological indicators (Depledge and Galloway 2005; Impson et al. 2008; Baumgartner et al. 2014; O'Brien et al. 2018). Various biological organisation levels of assessment have been identified to monitor fish as ecological indicators; with fish behaviour regarded as 10 to 100 times more sensitive than any other levels of biological organisation (Beitinger 1990; Beitinger and McCauley 1990; Wepener et al. 2008; Sharma 2019). Collecting behavioural data from wild fish *in situ* can be problematic as fish are often out of sight and highly mobile making terrestrial observation cumbersome and limited to absence-presence data (Cowley and Naesje, 2004; Cooke et al. 2004; Cooke et al. 2012). Fish behavioural monitoring methods have incorporated telemetry techniques addressing these limitations and have advanced over the decades to become a reliable method to obtain data from wild fishes (Cowley and Naesje 2004, Cooke et al. 2013; Thorstad et al. 2013; Hussey et al. 2015; Lennox et al. 2017). Fish telemetry methods are traditionally used to determine spatial movements of fishes (Lucas and Baras 2000, Thorstad et al. 2013; Hussey et al. 2015). Recent advancements in tag development through the use of activity sensors has contributed to the understanding of energy budgets, evaluating abnormal behaviour and fish activities, and determining stressors associated with wild fish (Wong et al. 2012; Broell et al. 2013; Wright et al. 2014; Broell et al. 2016; Cooke et al. 2016a; Beltramino et al. 2019; Fuchs and Caudill 2019).

Fish telemetry methods have resulted in the formation of large collaborative research programmes within freshwater environments to maximise the use of underwater receivers, detect large-scale movement of tagged fish, reduce costs and shown to be a valuable approach to managing fisheries internationally (Landsman et al., 2011; Lennox et al., 2017; Taylor et al., 2017; Krueger et al., 2017; Abecacis et al., 2018). The first African fish telemetry study was conducted in 1988 with irregular use of the methods since (Hocutt et al. 1988; Baras and Lagard 1995; Baras et al. 2002a; Burnett et al. 2019a). The adaptation of fish telemetry methods within the African continent has steadily increased in popularity since mid-2000's with southern

Africa leading in the field (Baras et al. 2002; Økland et al. 2003; Økland et al. 2005; Mlewa et al. 2003, 2007; O'Brien et al. 2012,2013; Jacobs et al. 2016; Burnett et al. 2018; Jacobs et al. 2019).

The application of fish telemetry within southern Africa (South Africa, Lesotho, Eswatini, Mozambique, Namibia, Zimbabwe and Botswana) has contributed considerably to the understanding of two fish taxa, primarily *Hydrocynus* spp. and *Labeobarbus* spp. (Økland et al. 2005; O'Brien et al. 2013; Burnett et al. 2018). These fish species are regarded as important ecological indicators to varying water quality and quantity states and have high socio-economic importance in southern Africa (Brand et al. 2009). Fish telemetry methods can assist in addressing the challenges faced from anthropogenic stress by monitoring the behaviour of wild fishes exposed to these stressors (Cooper et al. 2014; Cooke et al. 2016b; Cooke et al. 2017; Burnett et al. 2019b).

1.1 Problem statement

The increase in anthropogenic stressors affecting the well-being of aquatic ecosystems and the need to broaden the knowledge of fish behaviour for southern Africa (and the rest of Africa) has highlighted the need to develop methods that describe the behaviour of fishes and their responses to anthropogenic stresses (Impson et al. 2008; Thorstad et al. 2013; Du Plessis 2019). Fish telemetry methods can assess both fish behaviour and their response to changes in the environment (Lucas and Baras 2000; Cooper et al. 2014; Cooke et al. 2016a). With the advancement in fish telemetry technologies and understanding its limitations, a compact methodology that integrates these telemetry methods to evaluate the behaviour of fish and their response to anthropogenic and environmental stressors remotely and in real-time with the aim to assist with managing the aquatic ecosystem in the region was developed (O'Brien et al. 2013; Jacobs et al. 2016; Burnett et al. 2018; Burnett et al. 2020). This thesis examines the use of telemetry methods in Africa, the development of such methods, the implementation of the method for key indicator fish species and contributions towards management within southern Africa.

Several reviews on aquatic telemetry methods used globally exist (Cooke et al. 2013; Thorstad et al. 2013; Hussey et al. 2015; Lennox et al. 2017). Despite these extensive reviews, Africa inland freshwater systems were lacking and a primary focus on marine and estuarine environments were found (Hussey et al. 2015; Lennox et al. 2017). To understand the use of fish telemetry methods within Africa, and how these methods contribute to the management of water resources, a thorough review of fish telemetry methods used globally and within Africa was conducted (Chapter 2). This review highlighted the use of fish telemetry methods in the management of water resource management and included the many techniques available in acquiring fish behavioural information of fishes. The review attempted to address some of the problems associated with the use of fish telemetry methods in developing countries, as highlighted by Hocutt et al. (1994) and Lennox et al. (2017).

The review on fish telemetry methods in freshwater ecosystems of Africa found that its use was limited in comparison to developed countries, as was seen by Hussey et al. (2015) and Lennox et al. (2017). The successful implementation of fish telemetry studies were found in marine environments or large socio-economically important freshwater environments such the Laurentian Lakes (North America), The Murray-Darling River (Australia) and numerous European Rivers (Landsman et al. 2011; Lennox et al. 2017; Taylor et al. 2017; Krueger et al. 2017; Abecacis et al. 2018). These fish telemetry studies saw the development of fish telemetry networks to improve on the behavioural ecology information on fishes through collaborations between, management authorities, countries and research groups (Lennox et al. 2017). An African freshwater fish telemetry network has been developed, called the FISHTRAC programme (O'Brien et al. 2013; Jacobs et al. 2016; Burnett et al. 2018). This fish telemetry programme had not yet been implemented, and a review of its development was conducted to describe its approach to monitoring fish behaviour in this study (Chapter 3). The FISHTRAC programme uses radio-telemetry techniques and can detect fish behaviour remotely and in real-time, broadening the application of the fish telemetry method.

The FISHTRAC programme uses activity counts as a proxy to understand the movements of fish (Burnett et al. 2020). These activity sensors make use of an omni-directional tilt vibration sensor and present fish movement in a one-dimensional count reading (activity). Since the development of the FISHTRAC programme little work has been done to understand and enhance the use of these activity sensors in the region despite similar application as early as the 1990's globally using accelerometers (Baras and Lagard 1995; Wong et al. 2012; Broell et al. 2013; Wright et al. 2014; Cooke et al. 2016a; Beltramino et al. 2019; Fuchs and Caudill 2019). The use of accelerometer data is popular within developed countries as it provides a three-dimensional activity reading associated with the tagged fish (Cooke et al. 2016; Fuchs and Caudill 2019). The one-dimensional activity reading used in the FISHTRAC programme had not yet been fully understood as a behavioural variable to assess anthropogenic stressors in the region. Activity sensor data from a study in the Crocodile River, Mpumalanga, South Africa, used to develop the FISHTRAC programme was revisited. This study (Chapter 4) evaluated the use of activity sensors to detect the differences in the behaviour of two fish species and evaluate their response to environmental stressors.

Understanding the development of the FISHTRAC programme highlighted the need to fully implement the programme within a socio-economically important river, demonstrating its value towards the management of water resources (Burnett et al. 2020). The uMngeni River, KwaZulu-Natal, South Africa, was selected because of the high anthropogenic stressors, urban and agriculture, associated with the catchment included the increased demand for water (Hughes et al. 2018a,b; Namugezi et al. 2018). For the study, 43 *Labeobarbus natalensis* were tagged with activity sensors then released back into the river, and their behaviour monitored remotely and in real-time. *Labeobarbus natalensis* are considered ecological indicators; however, little is known about how they respond to anthropogenic stress (Crass 1964; Karssing et al. 2008). The species has been poorly studied with limited behavioural ecological information available (Crass 1964; Karssing et al. 2008). These factors make a good case study to implement the FISHTRAC programme, as behavioural information could be acquired and the responses of the species to anthropogenic stressors evaluated.

Labeobarbus natalensis are endemic to the province of KwaZulu-Natal, South Africa and are abundant in the rivers where they occur (Crass 1964; Karssing et al. 2008). In recent years, however, the population on the uMngeni River has experienced large fish kills negatively impacting their abundance and resilience (Karssing et al. 2008). Wright and Coke (1974a,b) conducted two studies to characterise the breeding ecology of the species. These studies along with Crass (1964) and Karssing (2008) have been the only peer-reviewed articles that focus on the behavioural ecology of the species, highlighting the need to revisit and add to the behavioural ecology of the species and their response to these stressors. This is especially important as anthropogenic stressors are predicted to increase for the uMngeni River as it is an ecologically and socio-economically important river (Riversmoore and Goodman 2010; Hughes et al. 2018a,b; Kusangaya et al. 2019; Namugize et al. 2018).

The impacts of managed flow releases in regulated rivers to water quality are well documented globally (Yarnell et al. 2015; McGrane 2016; Zuraini et al. 2018). Understanding the impact these changes in water quality and how they affect the freshwater ecosystems biological component can contribute to meeting required environmental flow (King and Brown 2008; Dickens et al. 2018; Mehdi et al. 2018; O’Brien et al. 2018). The behavioural responses by fishes to these altered flow regimes have been extensively studied, however, vary from species to species (Flitcroft et al. 2016; Mehdi et al. 2018; McCallum et al. 2019). The

Labeobarbus spp. within southern Africa are used as indicator species for changes in flow (Fouché and Health 2013; Burnett et al. 2018), however the knowledge on *L. natalensis* is limited (Impson et al. 2008). This study (Chapter 5) used the FISHTRAC programme to evaluate the response by *L. natalensis* to a management flow release on the uMngeni River. Using the activity sensor on tags, the water probes and remote monitoring network developed in the FISHTRAC programme and established on the uMngeni River to assess the response by *L. natalensis*. The use of activity sensors on tagged fish has been used previously to determine the effects of flow on fish behaviour (Metcalfe et al. 2016; Burnett et al. 2018; Thiem et al. 2018). This study contributed to the understanding of management flow releases on *L. natalensis* movement and highlighted the ability to detect behavioural changes of wild fishes in real-time to environmental changes.

The activity sensor measured as an activity count over time allowed the movement of free-swimming fish to be measured and recorded as a numeric value known as the activity rate (or activity) (Burnett et al. 2018; Burnett et al. 2019b). The ability to obtain this information in real-time and remotely provides large data sets that can be accessed on-demand (Greene et al. 2014; Cooke et al. 2016a; Lv et al. 2017; Thum et al., 2018). The large datasets created by activity sensor recording in real-time need to be interpreted in near real-time for managers to make an active decision and with the improvement of software development this can be done through modelling and machine learning (Callebaut 2012; Greene et al. 2014; Chimienti et al. 2016). Models require algorithms to query datasets and produce real results that assist in the processing of data acquired in the field (Callebaut 2012; Leonelli 2014). Using data from activity sensors from fish in real-time has, through the development of the FISHTRAC programme, giving researchers and water resource managers the ability to do develop such an algorithm (Burnett et al. 2019b). This study (Chapter 7) developed an algorithm that could serve the purpose of interpreting these data in real-time. The study went further to evaluate and understand the environmental variables that affected the changes in fish behaviour to understand the potential drivers behind behavioural changes.

The use of environmental flows to mitigate the anthropogenic stressors for freshwater ecosystems has gained interest in recent years as a tool to achieve the sustainable development of freshwater aquatic ecosystems globally (King and Brown 2006; O'Brien et al. 2018; Dickens et al. 2019). Monitoring indicators species and understanding their responses to anthropogenic stressors is important when achieving sustainability (Dickens et al. 2019). Developing fish telemetry methods and implementing them to answer questions around the impact of anthropogenic stress can assist managers in mitigating these impacts and work towards achieving sustainability (Rivers-Moore and Goodman 2010; Dickens et al. 2019). The implementation of the FISHTRAC programme through this study set out to address some of the issues around monitoring the biological responses to understand the impact of anthropogenic stress and showcased the ability to do this remotely and in real-time.

1.2 Aims and objectives

The overall aim of this study was to use recent fish telemetry advancements to develop and implement a real-time and remote fish tracking approach that water resource managers could use to understand freshwater ecosystems responses to anthropogenic stressors and mitigate such impacts where possible. The aims of the study were to, through a review of telemetry methods used in African freshwater ecosystems, evaluate the development of the FISHTRAC programme and the use of its behavioural variable, activity counts, to implement it. The implementation of the FISHTRAC programme to determine the behavioural ecology of *Labeobabrus natalensis* on the socio-economical uMngeni River, KwaZulu-Natal, South Africa was demonstrated. The behavioural response of *L. natalensis* through a flow release from Midmar Dam which included monitoring the water quality variables characteristic of the flow release, was evaluated. To feed the behavioural information into management structures and decision-making processes in real-time and remotely, an algorithm was developed. The following objectives were set to achieve these aims:

1. Review fish telemetry techniques within Africa and assess these against global practices and evaluate the contributions fish telemetry methods have made to understanding fish behaviour and freshwater aquatic ecosystems. To make recommendations based on fish telemetry studies and their contribution to fisheries and water resource management for the future use of these methods in the region.
2. To review the FISHTRAC programme based on radio telemetry techniques to adequately determine fish behaviour and environmental stressors in real-time and remotely in freshwater aquatic environments.
3. To assess electronic tags with activity sensors in determining the behaviour of fishes remotely in freshwater aquatic environments.
4. To assess the behaviour of *L. natalensis* in real-time and remotely by determining the linear movements and activity rates, this included habitat use and migration cues within the socio-economically important uMngeni River.
5. To use the real-time fish behavioural data acquired remotely in the assessment of anthropogenic stressors in freshwater aquatic ecosystems. To assess the impact of a management flow release in the highly regulated uMngeni River and evaluate the response of *L. natalensis* to the release.
6. To develop an alert system to changes in fish behaviour, in order to improve management responses to anthropogenic stressors in freshwater aquatic environments. To evaluate the real-time data from *L. natalensis* and develop an

algorithm to interpret real-time behavioural data in near real-time to highlight moments that need further investigation.

In achieving these objectives, it was hoped that the implementation of FISHTRAC would successfully lead to the characterisation of the behavioural ecology of indicator fish species and understanding of their responses to anthropogenic stressors within the socio-economically important rivers of southern Africa.

1.3 Structure of the thesis

This chapter (Chapter 1) is the introduction which provides a brief general background, rationale and concepts covered in the present study. The chapters following this introduction have been structured in order to achieve the aims and objectives set out for the study. The following six chapters (Chapters 2, 3, 4, 5, 6 and 7) include two reviews followed by four experimental data chapters with each one covering a specific objective. These chapters form the main body of this thesis and are formatted as manuscripts for submission to international peer-reviewed journals. Because of this thesis paper format, a certain degree of repetition especially in the methods and referencing sections was unavoidable. The concluding chapter (Chapter 8) summarises the findings from the main body and places them into the broader context highlighting the contributions to science.

The details of the chapters prepared as manuscripts are as follows:

- Chapter 2 is an extensive review of freshwater fish telemetry methods within the African continent, whereby global fish telemetry methods are discussed at length and presented in ways that can be applied within the management of freshwater ecosystems, highlighted in Africa.
- Chapter 3 is an overview and evaluation of the development of the southern African inland fish tracking programme (FISHTRAC). The FISHTRAC programme is a

radio-based technology and uses fish telemetry methods with the addition of monitoring tagged fish and water quality variables in real-time and remotely, a first for the region.

- Chapter 4 tests the application of the activity sensor used within the FISHTRAC programme to monitor the non-spatial movement of two fish species demonstrating the sensitivity of the activity sensor.

- Chapter 5 uses the FISHTRAC programme to determine home ranges and habitat use of *Labeobarbus natalensis*, a first for the species.

- Chapter 6 implements the FISHTRAC programme on the uMngeni River and uses the approach to monitor an environmental flow release.

- Chapter 7 develops and demonstrates the use of an algorithm to determine changes in fish behavioural activity to understand the association of these changes to water quality and quantity.

1.4 References

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CHAPTER 2

African inland fish telemetry methods and use for water resource and fisheries management: A review

Matthew J. Burnett[1,2], Gordon C. O'Brien[1,3], Francois J. Jacobs[1,4], Graham Jewitt[2,5] and Colleen T. Downs[1]

[1]*Centre for Functional Biodiversity, School of Life Sciences, University of KwaZulu-Natal, P/Bag X01, Scottsville, Pietermaritzburg, South Africa, 3209*

[2]*Centre for Water Resource Research, University of KwaZulu-Natal, P/Bag X01, Scottsville, Pietermaritzburg, South Africa, 3209*

[3]*School of Biology and Environmental Sciences, Faculty of Agriculture and Natural Sciences, University of Mpumalanga, Nelspruit, South Africa, 1200*

[4]*Ministry of Fisheries and Marine Resources, Kamutjonga Inland Fisheries Institute, Private Bag 5147, Divundu, Namibia*

[5]*Institute for Water Education, IHE Delft, Westvest, South Holland, Netherlands, 2611*

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* Corresponding Author: Colleen T. Downs

Email: downs@ukzn.ac.za
Tel: +27 (0)33 260 5127
ORCID: http://orcid.org/0000-0001-8334-1510
Other emails: matthewburnett014@gmail.com, ORCID: https://orcid.org/0000-0002-6237-1697; gordon.obrien@ump.ac.za, ORCID: https://orcid.org/0000-0001-6273-1288; francoisjacobs.mfmr@gmail.com ORCID: https://orcid.org/0000-0002-0354-3022; g.jewitt@un-ihe.org, ORCID: https://orcid.org/0000-0002-7444-7855

2.1 Abstract

Fish telemetry is a widely established technique in developed countries. However, in underdeveloped regions, this use is generally lacking. We briefly present common fish telemetry methods used globally and then reviewed the use of these in African inland freshwater ecosystems. This review highlights the progress in telemetry studies regionally and evaluates its potential application in various fields. These include the management of water resources, ecosystem responses, movement of fish, river connectivity, conservation of species, management of fisheries, fish passages efficiency and monitoring freshwater ecosystems in Africa. We found 52 studies using fish telemetry on inland African waters across eight countries. Radio telemetry (82%) was favoured over acoustic telemetry (11%), while the remaining studies included reviews and tagging procedures non-specific to a telemetry method. Telemetry was used on 23 native fish species in Africa across various families, as well as for two invasive species. Also, two African native fish were studied in laboratories in Europe. In Africa, the two most studied genera were *Hydrocynus* spp. (n = 19) and the *Labeobarbus* spp. (n = 19). The paucity of African freshwater telemetry studies in comparison with developed countries is of concern, especially as fish behavioural information is required for water resource management decisions across Africa. Finally, we highlight the benefits derived from telemetry studies as outweighing the costs by providing evidence-based data for the management of Africa's water resources.

Keywords: Freshwater, developing countries, smart technology, electronic tags, fish behaviour, movement, water resource management.

2.2 Introduction

Sustainable development is of growing importance when integrating the management and protection of freshwater ecosystems across the globe, especially as the demands for water resource increase (Dallas and Rivers-Moore 2014; Dudgeon 2014; Lynch et al. 2019a). The recent global effort to achieve sustainable development goals (SDG) is shifting research and management in Africa, translating into efforts to address water resources management and conservation (Dickens et al. 2019; Lynch 2019b). Unfortunately, the region is still performing poorly in environmental management because of a plethora of multiple stressors (including invasive species), changing climate and general lack of political will to achieve a sustainable balance between the use and protection of water resources (Bootsma and Hecky 2003; Emerson et al. 2012; Fouchy et al. 2019). As such, the well-being of freshwater ecosystems is affected by multiple stressors that have altered flow, water quality and the habitats of these ecosystems (O'Brien et al. 2018; Rodell et al. 2018; Du Plessis 2019). These alterations often negatively impact the wellbeing of fish populations threatening sustainability (Siciliano and Urban 2017; Cutler et al. 2020). Fish are established ecological indicators of aquatic ecosystems (Harris 1995; Chovanec et al. 2003; Depledge and Galloway 2005), as they are long-lived, relative to other aquatic animals, and highly mobile (Lucas and Baras 2001; Baumgartner et al. 2014). Their wide range of aquatic habitats, dynamic biology and ecology, and their vulnerability to environmental changes caused by anthropogenic activities make then good indicators of the condition of freshwater ecosystems (Chovanec et al. 2003; Impson et al. 2008; Baumgartner et al. 2014). Fish also have relatively high social and economic values, and contribute to the well-being of many human communities, especially in Africa (Tweddle et al. 2015; Lynch et al. 2016).

The use of fish as ecological indicators requires an understanding of their biology, ecology and their response to changes in ecosystem conditions (O'Brien et al. 2018; Fouchy et al. 2019). In Africa, fish have been used as ecological indicators of water resource well-being since the 1990's primarily through a range of community metric measures or biological indices (Kleynhans 1999; Kleynhans and Louw 2008; Malherbe et al. 2016). These tools have been used to evaluate the integrity of communities and the associated state of environmental variables that drive freshwater ecosystems, for example, water flow and quality (O'Brien et al. 2009; Malherbe et al. 2015).

Unfortunately, of the estimated 3500 species of freshwater fishes in Africa, little is known about the biology and ecology of many species relative to other parts of the world (Skelton and Swartz 2011; FISHBASE 2019; Tagliacollo et al. 2020). These knowledge gaps are concerning, as a there has been notable decline and, in some cases, an almost total disappearance, of many of the native fish species in areas throughout Africa (Ogutu-Ohwayo 1990; Bootsma and Hecky 2003; Rodell et 2018; Fouchy et al. 2019). Fishes in Africa and their use as ecological indicators can make a considerable contribution to water resource management and achieving sustainable development in Africa (Gelcich and O'Keeffe 2016; Jackson et al. 2016a). It is, therefore, paramount to improve our biological and ecological knowledge of fishes across the continent and then to use this information to manage fish communities and their ecosystems, so improving the sustainable use of Africa's water resources (Wilby et al. 2010; Capon et al. 2015; O'Brien et al. 2018).

African inland freshwater ecosystems are generally inaccessible and have poorly developed basic infrastructure (Paarlberg 2009; Emerson et al. 2012; Dube et al. 2015). Sampling in these systems is often associated with dangerous animals, diseases and human conflict (O' Keeffe and Rogers 2003; Awoke et al. 2016; Sokolow et al. 2017). Rivers in Africa can be unpredictable and turbid which limits the use of underwater visual monitoring methods, such as snorkelling and camera traps, as lines of evidence when assessing fish behaviour (Lucas and Baras 2000; Cowley and Naesje 2004; Thorstad et al. 2013). These limitations have resulted in many African freshwater ecosystems inhabitants being “out of sight, and out of mind” (Cooke et al. 2013; Darwall and Freyhof 2016). Globally, fish telemetry methods are used to characterise, understand and quantify aspects of the biology and ecology of fish in all aquatic ecosystems, not only where visual observations are limited (Pine et al. 2003; Cooke et al. 2013; Thorstad et al. 2013). This information has enabled evidence-based decisions in water resource and fisheries management (Cooke et al. 2017; Brooks et al. 2017; 2018). These methods assist in characterising; fish behaviour, migration pathways, understanding fishery capacities, invasive species, habitat use and biological responses to the changes in environmental variables (Melnychuk 2009; Trancart et al. 2018; Block et al. 2019), and can be used to validate traditional fish assessment methods used to inform managers (Cooke et al. 2016a; Koster and Crook 2017).

The use of fish telemetry on the African continent continues to lag behind the developed world, despite the cost-benefit it has to inland African water resource management (Hocutt et al. 1994; Baras et al. 2002a). Since the promotion of fish telemetry in the management of African fisheries by Baras et al. (2002a), no one has revisited the adoption of the methods for the region, and so doing this will contribute to its continued use in the management of African inland waters in present times.

For the present study, we reviewed fish telemetry in Africa by (1) describing commonly used methods, (2) assessing their application in inland waters, and (3) using the data obtained to recommend their future application to the management of water resources and fisheries. To achieve this, we sourced and assessed grey and peer-reviewed literature using various search engines (Web of Science and Google Scholar). We used the following keywords: ‘fish telemetry’, ‘Africa’ and ‘inland freshwater’ and combinations of such keywords using “And” to narrow down findings relevant to our study. We then mined articles found further for possible additional publications. We then gleaned information from these search results for relevance to African inland freshwaters, African fish species and telemetry techniques used on the continent, and we recorded these for later evaluation.

2.3 Overview of African inland fish telemetry

The opportunities to use fish telemetry methods in Africa inland waters have been demonstrated and are further discussed in this review (Nyboer and Chapman 2013; Jacobs et al. 2019; Burnett et al. 2020). The renewed demand for the biology and ecology evidence of fish and the growing use of fish telemetry methods in Africa makes it an ideal approach for its application in African inland waters (Lennox et al. 2017). A review of the methods, opportunities and constraints of the approach can contribute to the continued development of fish telemetry in African inland waters assisting decision-makers with obtaining the evidence they need for sustainable water management.

We found 52 articles documenting fish telemetry methods used in Africa which comprised of acoustic (n = 6, 11%) and radio telemetry (n = 43, 82%) including two reviews. This included five preliminary outputs from current projects by authors and known collaborations, highlighting the potential increase in the use of these methods. The total number of studies (n = 52) were relatively low in comparison with developed parts of the globe, where fish telemetry studies include over ~200 per sub-region in comparison (Godfrey and Bryant 2003; Landsman et al. 2011; Abecasis et al. 2018). Despite the size of Africa, we found there was a paucity of studies across the region (Figure 2.1). Fish telemetry research has extended from developed countries into developing countries through the connectivity and global interest around marine environments and estuaries (Hussey et al. 2015; Maggs and Cowley 2016; Cowley et al. 2017). In Africa, fish telemetry began in the late 2000s for marine and estuarine environments (Maggs and Cowley 2016; Cowley et al. 2017). Despite fish telemetry application in inland waters being earlier than this (late 1980's), it has been mostly neglected in application (Hocutt et al. 1994). Relatively few studies have been conducted in freshwater ecosystems, and usually through collaborative international fishery projects (Hocutt et al. 1994; Baras et al. 2002a; Dlodlo 2012; Nkhata et al. 2012).

The cost of the methods, lack of skills and misperceptions on their benefits have limited the implementation of fish telemetry for Africa, despite effective collaboration (Hocutt et al. 1994; Ngunyen et al. 2018). The improvement in technology, the changes in perceptions and the importance of fish behaviour in managing multiple stressors on water resources are being realised in the region making telemetry a cost-effective method in managing water resources (Cooper et al. 2014; Cooke et al. 2016b; O'Brien et al. 2018; Burnett et al. 2020). This interest is evident with the incremental increase over the last three decades with 57% of African fish telemetry studies across eight countries (out of 54) conducted in the previous decade (Figures 2.1 and 2.2). A pilot telemetry workshop held in West Africa to specifically address the use of fish telemetry in Africa has been influential in this (Baras et al. 2002a).

Hocutt et al. (1994) and Baras et al. (2002a) primarily showcased radio telemetry methods in Africa, not excluding the use of other methods, such as acoustic, archival tags (DST) and passive integrated transponders (PIT). The latter two methods did not feature in any of the African inland freshwater fish telemetry studies we reviewed. The lack of fish telemetry focused skills, and paucity of studies in Africa highlighted the importance in understanding the potential use and limitations of each telemetry method when applying them in African inland waters (Baras et al. 2002a; Nguyen et al. 2018). The diversity of African freshwater ecosystems across the continent varies extensively highlighting the need to understand the context in which each method is suited for such as perennial and non-perennial, lentic and lotic, deep and shallow, brackish and freshwater environments as examples. These environments pose their challenges when applying particular fish telemetry methods (Tables 2.1 and 2.2; Cooke et al. 2013; Cooke et al. 2016b; Lennox et al. 2017). A significant influence in the choice of application is the suitability of the fish species for telemetry, as their form and size play an essential role in the application of the respective methods (Broadhurst et al. 2009).

As a consequence, we found certain methods have dominated in certain field study areas, generally based on best practice and what has worked to answer research questions in specific parts of Africa. An example of this being the marine and estuarine use of acoustic telemetry (Maggs and Cowley 2016; Cowley et al. 2017). We found that despite the rapid expansion (from 2000) in the use of fish telemetry in marine and estuaries, it was not evident in African inland freshwater ecosystems despite the ability of telemetry methods to address research questions here (Hocutt et al. 1994; Landsman et al. 2011; Thomas et al. 2012; Lennox et al. 2017).

2.4 Fish telemetry methods

We found fish telemetry methods available showed relatively little application and implementation in freshwater ecosystems in Africa. This was partially because of the few cases studies here, but primarily as a consequence of the plethora of applications in regions where they are applied extensively, for example, the Laurentian Great Lakes, Australia and Europe (Bridger and Booth 2003; Abecasis et al. 2018; Godfrey and Bryant 2003; Landsman et al. 2012; Taylor et al. 2017; Lennox et al. 2017). These applications and technology are suited for Africa and highlighted in Table 2.1 (Hocutt et al. 1994; Koehn 2000; Thomas et al. 2012; Cooke et al. 2012, 2013; Thorstad et al. 2013). All methods have limitations and are continually being developed, emphasising the need for local researchers and technology developers to work together to improve applications and research outputs (Cooke et al. 2013; Lennox et al. 2017; Burnett et al. 2020). Fish telemetry methods consist of an electronic (telemeter) tag that is attached to the fish and a receiver/transponder/transceiver where communication between the two occurs over short distances (< 2 km) (Thorstad et al. 2013). The four main fish telemetry methods highlighted here included; radio, acoustic, passive integrated transponders (PIT) and data storage tags (DST) (Cooke et al. 2012; Thorstad et al. 2013; Whoriskey et al. 2019).

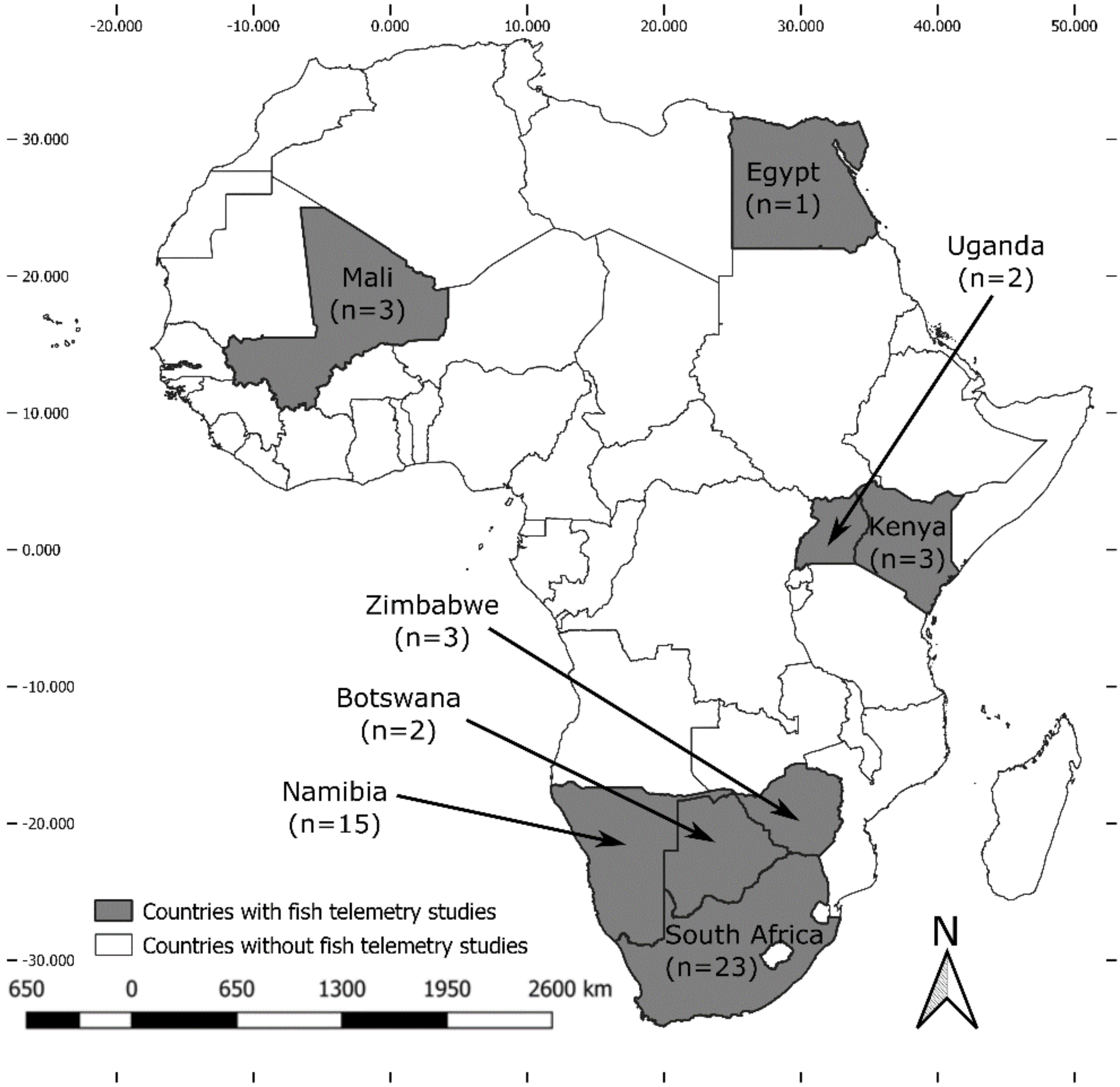

Figure 2.1: Geographical representation of fish telemetry studies that have included ecosystems in various African countries identified in the present study.

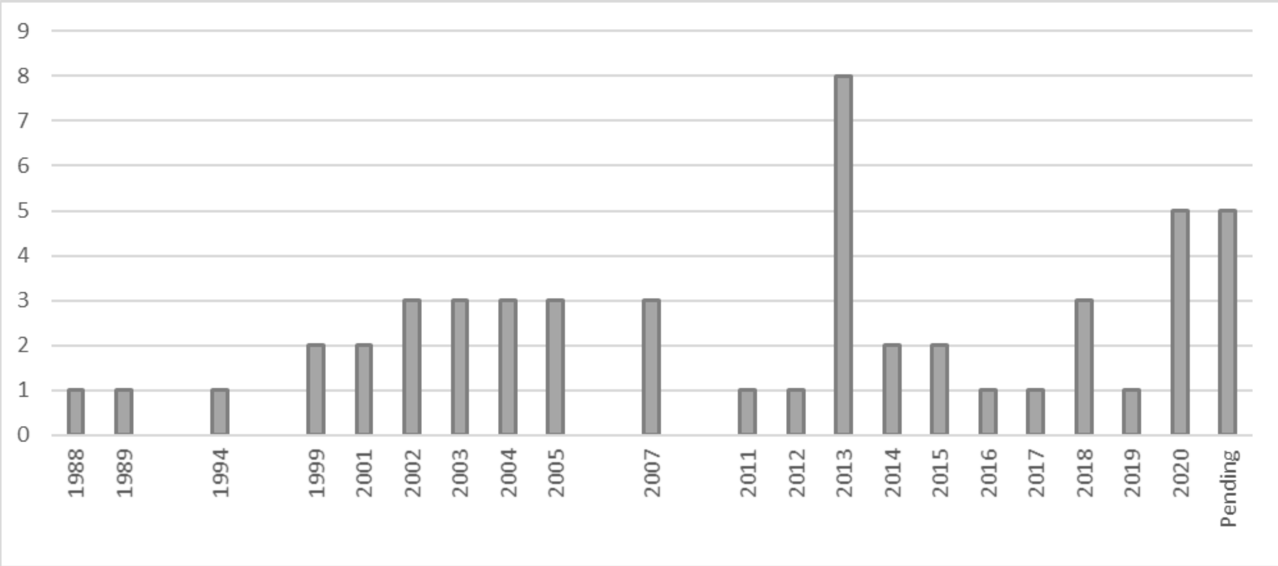

Figure 2.2: A timeline of the number of fish telemetry studies in African inland freshwater ecosystems from the first study in 1988 to 2020, included are current projects with preliminary article outputs (pending).

Both acoustic and radio telemetry methods have similar applications, yet function using different technologies (Table 2.2; Cooke et al. 2013). These two methods can make use of manual and remote monitoring techniques to acquire data from the telemeter tag (Cooke et al. 2012; Burnett et al. 2020). In addition, data storage capacity for these more recent smart tags allow for peripheral and associated variables to be monitored (for example, fish activity and water temperature). These features highlighted the versatility of these methods to meet various needs, such as remote access, detection of smart tags in diverse habitats and acquiring data when not in range of a receiver (Thorstad et al. 2013; Burnett et al. 2020). Furthermore, smart tags allowed for changes in the frequency of data collection or pulse rates per minute, allowing stored data to be downloaded to a receiver when in range. This improves the smart tag life span and data retrieval limitations associated with fish telemetry. The battery life (tag life span) still plays a significant role in determining the size and weight of a tag, and often affects the design of the project and selected targeted species (Thorstad et al. 2013; Jepsen et al. 2015). Recent real-time applications allow field data to be stored off-site through a network of remote receivers linked to a data management system (DMS) (Burnett et al. 2020). The remote access to data is particularly useful in obtaining information from isolated hard to access locations. In addition, PIT and DST methods operate differently and so can be used for specific applications.

2.4.1 Radio telemetry

We found that radio telemetry methods were the most widely used in inland water ecosystems in Africa, primarily as rivers are erratic and turbid typically limiting the application of acoustic telemetry (Koehn 2000; Cooke et al. 2013; Thorstad et al. 2013; Burnett et al. 2020). Water quality (salinity gradients and electrical conductivity), habitat structure and depth can alter the effectiveness of the radio signal used to detect radio-tagged fish (Peters et al. 2008; Thorstad et al. 2013). The radio tags submersion depth limits radio frequency signals, and they operate best in shallow water (< 10 m) or near the water surface (Peters et al. 2008; Cooke et al. 2013). Despite this, five studies used radio telemetry in impoundments, despite acoustic telemetry generally being a preferred method for this habitat type. Mlewa et al. (2007) used this limitation to determine whether mottled lungfish *Protopterus aethiopicus* were obligatory breathers by monitoring signal strength in proximation to the water surface. Similarly, Burnett et al. (2020), showed *Laboebarbus* spp. rest near the surface in impoundments on a water storage facility in the Vaal River Catchment, South Africa, foraging in deeper waters during the day.

Table 2.1: General evaluation and summary of four popular telemetry methods used in freshwater environments (Hocutt et al. 1994, Koehn 2000, Bridger et al. 2001, Thomas et al. 2011, Cooke et al. 2012, 2013; Thorstad et al. 2013).

Category	**Function**	**Radio**	**Acoustic**	**PIT**	**DST/Archival tags**
Technical operation	Transceiver (smart tag)	Yes	No	No	No
	Power Usage	Moderate	Moderate	Good	Moderate
	Range	Good	Good	Poor	-
	Data sotrage capacity	Good	Poor	Poor	Good
	Remote monitoring	Good	Good	Moderate	-
	Recapture required	No	No	No	Yes
	Ease of use	Moderate	Moderate	Easy	-
Cost	Infrastructure	Low	High	High	Low
	Tag	Moderate	Low	Low	High
	Longevity	Moderate	Moderate	high	Low
	Data analasys	Moderate	High	Low	Low
Environment	Deep water (>5m)	Poor	Good	-	-
	Turbulent water (inc. water obstructions)	Good	Poor	-	-
	Low conductivity	Yes	Yes	Yes	Yes
	High conductivity	No	Yes	Yes	Yes
	Noisy environments (rapids, engine noise)	Good	Poor	Moderate	-
	Fine-scale movement	Yes	Yes	No	-
	Thermocline	Good	Good	-	Good
	Out of water	Yes	No	Yes	-
Acquiring data	Manual tracking	Good	Poor	-	-
	Remote Tracking	Good	Good	Moderate	-
	Continual data	Good	Moderate	Moderate	Good
	Sample size	10 to > 1000	10 to > 100	100 to > 100 000	10 to > 1000
Tagging technique	External	Good	Moderate	poor	Good
	Internal	Good	Good	Good	Moderate
	Gastric	Poor	Poor	Not recommended	Not recommended
Fish/species suitability	Fish size	Moderate	Moderate	Good	Low
	Migratory species	Good	Good (array dependent)	Good	Poor
	Long term study (> 1year)	Moderate	Moderate	Good	Moderate
Application	Migration studies	Yes	Yes	Yes	No
	Fisheries	Yes	Yes	Yes	No
	Environmental flow	Yes	Yes	Yes	Yes
	Energy Conservation	Yes	Yes	-	Yes
	Real-time monitoring	Yes	-	-	-
	Fish passages	Yes	Yes	Yes	Yes

2.4.2 Acoustic telemetry

We found there were few studies (n = 6) that made use of acoustic telemetry techniques in African inland water ecosystems, despite its suitability for large deep lakes such as the African Great Lake Complex. All these studies were conducted in impoundments with no applications in river systems. Acoustic telemetry generally works best in environments where underwater noises (boat engine, turbidity, wave action and turbulent water) are minimal allowing transducers (receivers) to detect acoustic tags (Cooke et al. 2013). This limitation has seen acoustic telemetry develop rapidly for use in large calm bodies of water such as lakes, estuaries and oceans making up a large proportion of fish telemetry studies globally (Cooke et al. 2013; Hussey et al. 2015). This does not limit its application in rivers if they are slow, stable and/or interspaced with pools (Taylor et al. 2017; Thiem et al. 2018). Generally, data are stored on the receiver and then downloaded manually, unless it is connected by cable or modem to a remote network that transfers the data to a central DMS (Cooke et al. 2012). For manually tracking, a hydrophone receiver positioned underwater attached to a boat to triangulate for acoustically tagged fish.

2.4.3 Combined, PIT and DST telemetry methods

Typically combined acoustic and radio telemetry (CART) systems are used to study diadromous fish species that move between highly saline or brackish water and freshwater such as in estuaries and rivers (Cooke et al. 2012). These CART tags widen the application of telemetry methods and improve detection of telemeter tagged fish that actively move between different aquatic environments (Thorstad et al. 2013). However, we found these methods are yet to be applied in African inland waters. A potential application for these telemeter tags is on fish such as the African anguillids species that migrate back into the ocean, and nondiadromous species that migrate between lentic and lotic environments, such as *Labeobarbus* spp. (Anteneh et al. 2012; Hanzen et al. 2019). The CART tags optimise the benefits of both radio and acoustic telemetry (Cooke et al. 2012).

Passive integrated transponders (PIT) generally use radio frequencies ranging between 125 – 400 kHz to energise a PIT tag by radiating energy using the tuned antenna of a reader (transceiver) which then sends its unique identity code (Bridger et al. 2001; Cooke et al. 2012). The detection range is generally limited to the size of the tuned antenna circuit and is typically limited to within 5 m of the antennas. We found this method was mostly used to assess the effectiveness of fish passage design where fish were forced to move through a narrow gate section, ensuring the detection of fish. This method has been used extensively in highly regulated rivers where the movement of fish up and downstream of weirs is essential to the well-being of fish communities (Enders et al. 2007; Murchie et al. 2008; Davies et al. 2010; Verhelst et al. 2018). An instream set-up outside of impoundment infrastructure for antennas arrays are best suited for small streams, as large fast-flowing and erratic rivers hinder the durability and effectiveness of the antenna. A significant benefit of the PIT methods is that no battery is required to maintain the PIT tag, thus reducing its cost and size, and extending its life span for years. This generally allows for larger sample sizes and smaller fish to be used in studies, and are often applied in capture-mark-recapture (CMR) studies for identification of individuals.

Archival tags or DST tags work similarly to other telemeter tags attached to fish; however, communication to a receiver or transceiver is limited or non-existent. These tags store peripheral or internal data, such as activity, temperature and depth when attached to a fish. Data can then be accessed on retrieval of the DST tag through the recapture of the fish (Cooke et al. 2013; Thorstad et al. 2013; Hussey et al. 2015; Jepsen et al. 2015). The application of this method can also be used with CMR methods; however, DST tags are costly and data retrieval uncertain because of low re-capture rates and the extended-time period between attachment and subsequent retrieval (Cooke et al. 2012). The data storage capacity is seldom applied in solidarity and often incorporated into the acoustic and radio tags to make use of data transfer to receivers, and these are referred to as smart tags (Cooke et al. 2012; Burnett et al. 2020).

2.5 Applications of telemetry in African inland freshwater ecosystems

We found the many challenges when applying fish telemetry methods in Africa vary from accessibility to research sites, poor infrastructure, political instability, hidden costs, lack of expertise and few local examples to draw on (Hocutt et al. 1994; Paarlberg 2009; Dube et al. 2015; Lennox et al. 2017). The first two fish telemetry studies both by Hocutt (1988; 1989) in Zimbabwe were both novel and experimental in developing the method for application in the region. He studied red-breasted tilapia *Coptodon rendalii* (n = 1) and sharp-tooth catfish *Clarius* g*ariepinus* (n = 6) using radio telemetry methods. The low sample size and difficulties found by Hocutt (1988; 1989) saw little expansion and use of telemetry in freshwater ecosystems until the late 1990s and early 2000s, despite being assisted by international collaborations such as the Norwegian Institute for Nature Research (NINA) in southern Africa (Figure 2.1) (Hocutt et al. 1994; Paxton 2004; Økland et al. 2005).

2.5.1 Early expansion of fish telemetry

A pilot workshop was held in 2001 in Mali to demonstrate fish telemetry methods and their applications (Baras et al. 2002a). This attempted to address challenges in the skills gap specifically when implementing fish telemetry in African inland water systems and demonstrated how the methods could be used in fishery management (Marulla and Benech 2000; Baras et al. 2002b). These studies highlighted the need for collaborative work and a fish telemetry network to improve the understanding of fish behaviour and aid in the effective management of fisheries. Despite these efforts, no further studies have come from West Africa since.

We found that it was in southern Africa that fish telemetry contributed most to the management of fisheries in Africa through an initiative in the late 1990s by NINA. These studies included documenting the movements and habitat utilisation of fish species important to the fisheries in the Namibian section of the upper Zambezi River, such as tigerfish *Hydrocynus vittatus* and three-spot tilapia *Oreochromis andersonii* as examples. These studies were initiated by the Namibian Ministry of Fisheries and Marine Resources in collaboration with NINA (Thorstad et al. 2001; Økland et al. 2003; Thorstad et al. 2003; 2004, Økland et al. 2005). All these fish species are popular recreational angling species and are important in the floodplain subsistence and commercial fisheries (Økland et al. 2005). During the same period, the Clan William yellowfish *Labeobarbus capensis* in the Olifants River system in the Western Cape (Paxton 2004) and *H. vittatus* in the Incomati River system (Roux et al. 2018) were studied in South Africa. Recently in the Namibian section of the Kavango River system, NINA has revisited *H. vittatus* to evaluate the conservation and fisheries potential for the species (Jacobs 2018). The drive produced various reports and scientific outputs, accelerating the use of freshwater fish telemetry in the region and enhancing the protection of freshwater fisheries (Jacobs et al. 2019). The initial implementation was not without difficulties, and the region could not sustain the development primarily because of the high costs of equipment and lack of resources (Paxton 2004; Økland et al. 2005). The information obtained from these studies were, however, valuable in understanding previously unknown movements of fish species and initiated the use of fish telemetry in the region (Thorstad et al. 2001; Økland et al. 2005). Challenges found in this era of African freshwater fish telemetry saw little uptake of the methods by researchers and managers, and we found there were relatively few outputs until 2011 (Figure 2.2).

2.5.2 The development of FISHTRAC

We found an initiative from 2010 by local researchers in southern Africa to use fish telemetry in understanding the behaviour of charismatic indicator fish species such as yellowfish *Labeobarbus* spp. and *H. vittatus.* This resulted in the development of a locally produced, radio telemetry based, robust programme called FISHTRAC (Burnett et al. 2020). This saw the previous use of predominantly manual radio telemetry methods (O'Brien et al. 2013; 2014) conversion to use of smart tags with sensors to detect fish movement remotely and in real-time (Jacobs et al. 2016; Burnett et al. 2018). Furthermore, these studies saw the first application of activity sensors for African inland freshwater systems (Burnett et al. 2018). Importantly, fish telemetry methods were applied in several socio-economically important freshwater ecosystems to answer various objectives such as understanding the behavioural ecology of *Labeobarbus* spp. and their response to changes in the environment (O'Brien et al. 2013; Burnett et al. 2018; Ramesh et al., 2018). The FISHTRAC programme increased local support during implementation, and generally reduced costs of tags and receivers, allowing for increased sample sizes and application of remote detection methods (Burnett et al. 2020). Remote access to field data through a DMS increased the applications of these telemetry methods for informing water resource managers that needed the behavioural data presented and processed for decision-making (Burnett et al. 2020). This programme addressed some of the challenges that were identified by Hocutt et al. (1994), such as cost, local support and site accessibility. The FISHTRAC programme saw the development of a versatile fish telemetry method to assist water resource managers in the region (Burnett et al. 2020).

Apart from these initiatives by Baras et al. (2002a) and Burnett et al. (2020), we found smaller independent fish telemetry studies from 2000 onwards. These studies primarily used acoustic telemetry methods to conducted fish behavioural research on impoundments across the African continent (Mlewa et al. 2005; 2007; Huchzermeyer et al. 2013; Kadye and Booth 2013; Howell et al. 2015). Although studies using acoustic telemetry are still mostly lacking for the continent (11 % of inland fish telemetry studies in Africa), it is an established method applied readily in the Laurentian Great Lakes, similar in challenges to the African Great Lakes Complex (Bootsma and Hecky 2003; Landsman et al. 2011). Radio telemetry studies have continued to expand outside of southern Africa with recent studies from Egypt and Uganda conducted to determine the spatial ecology of Nile perch *Lates niloticus* and important alien invasive fish (Nyboer and Chapman 2013; Vaccaro et al. 2013; Grubich and Odenkirk 2014). These studies highlighted previously unknown restricted movement of *L. niloticus* and were important to understand the impact such species have on the fisheries in the region (Vaccaro et al. 2013). This upward trend in the use of telemetry is growing, particularly in southern Africa, where other studies are currently being conducted (various pers. comm.).

2.5.3 Telemetry on freshwater fishes in Africa

We found fish telemetry studies reviewed have significantly contributed to knowledge around the biology and ecology of certain fishes in Africa. In terms of countries, we found South Africa had the most fish telemetry studies in Africa, and that they focused on a range of species. Telemetry studies, the suitability of the methods and their application on certain fish is much debated in the literature (Økland et al. 2003; Jepsen et al. 2015; Hanzen et al. 2020). The high socio-economical value of fish species in supporting livelihoods across the African continent, both through recreational angling and fisheries, highlights the importance of species focus when applying telemetry (Brand et al., 2009; De Graaf and Garibaldi, 2015; Cooke et al. 2016a). In Africa, subsistence fishing methods used are often non-selective and are typical of impoverished communities (Tweddle et al. 2015).

Consequently, these factors may hinder the use of fish telemetry (Hocutt et al. 1994; Tweddle et al. 2015; Lennox et al. 2017). These issues became less orientated around the ability of the method and directed towards an awareness of the advantages of fish telemetry methods in assisting locals with better management of iconic fish species (Dube et al. 2015; Cooke et al. 2016a; Lennox et al. 2017). Communities that have acknowledged this have used fish telemetry methods successfully, showing the dominance of fish telemetry studies in certain regions (e.g., South Africa and Namibia). In these regions, the foci have been mostly on a particular indicator species, for example, *Hydrocynus* spp. because of their iconic status (Baras et al. 2002b; Thorstad et al. 2003; Økland et al. 2005; Smit et al. 2009; O'Brien et al. 2012; 2014; Roux et al. 2018). *Hydrocynus vittatus* has a high conservation status in South Africa (Smit et al. 2013). We found that per species *H. vittatus* has been the focus of the highest number of fish telemetry studies in Africa.

Species focus is not uncommon in fish telemetry study design and often as a result of the ecological and socio-economical value that large growing fish species have (Jepsen et al. 2002; Thorstad et al. 2013; Abecasis et al. 2018). We found this was evident in most African fish telemetry studies (Table 2.2). Understanding the biology and ecology of these fish species often relates to (but is not limited to) targeting those that are long-lived and relatively large growing, so ideal for telemeter tag attachment. Apart from *Hydrocynus* spp., other such fish species have been the yellowfish family (*Labeobarbus* spp.) which is widely distributed throughout the continent and is regarded as an indicator species for water quality and flow (Impson et al. 2008; Fouché and Heath 2013; Mingist and Gebremedhin 2016). Several fish telemetry studies have been conducted on this taxon to gather base-line biological and ecological information for the conservation and management of the *Labeobarbus* spp. in South Africa (Paxton 2004; O'Brien et al. 2013; Jacobs et al. 2016; Burnett et al. 2018). These studies have shown the species to be facultative by nature, only making use of migrations depending on the availability of habitat required at different life stages (O'Brien et al. 2013; Burnett et al. 2018).

Other angling species used in fish telemetry have been *Micropterus salmoides*, further expanding research to understanding this species and other *Centrarchidae* spp. invasive potential and the subsequent impact on native fish species in southern Africa (Huchzermeyer et al. 2013; Howell et al. 2015). The introduction of invasive species has been assessed in other studies using fish telemetry, for example with *L. niloticus* in Lake Nabugabo, Uganda and *Clarius gariepinus* in Glen Melville Reservoir, South Africa (Kadye and Booth 2013; NyBoer and Chapman 2013). These studies add to the diverse applications of fish telemetry that can assist with the conservation of native species and the impact of invasive species on the aquatic ecosystem. Both *H. vittatus* and *L. niloticus* telemetry studies have contributed to understanding the extent these fish move around in protected and unprotected fisheries. We found this information is valuable for setting fish quotas, establishing protected areas and minimising impacts of invasive alien fish (Kadye and Booth 2013; Nyboer and Chapman 2013; Roux et al. 2018; Jacobs et al. 2019).

The retention of a telemeter tag by a fish species varies between tag type; attachment techniques and body form (Cooke et al. 2013; Thorstad et al. 2013). One of the most critical assumptions fish telemetry methods surmise is that the physiological stress of catching, handling and tagging procedures causes minimal behavioural alterations on the tagged individual (Jepsen et al. 2004). We found six tag retention studies that addressed telemeter tag retention in Africa. Two focused on invasive species in African impoundments (Økland et al. 2003; Huchzermeyer et al. 2013). Two were field studies on *H. vittatus* in the Kuvango River, Namibia (Jacobs 2018), and another one was a field study on *Anguillid* spp. in the Thukela River, South Africa (Hanzen et al. 2020). While two were on African species in a European laboratory (Baras and Westloppe 1999; Baras 1999; Table 2.2). Two internal telemeter tag retention studies, one on common carp *Cyprinus carpio* and one on African catfish (other common names vundu or sampa) *Heterbranchus longifilis.* These studies showed that internal radio tags were not a preferred method in tropical waters because of the relatively high mortality and tag expulsion rates seen in these species (Baras and Westloppe 1999; Økland et al. 2003). These studies paved the way for the use of external telemeter tags as the preferred technique in the region when applying radio-telemetry methods. They shifted the focus of studies to species suitable for external telemeter tags. To date, the effect of radio tags in the African context is not well known. However, Jacobs (2018) studied the possible immediate effects of tagging by investigating the daily movements of *H. vittatus* for three consecutive days following external radio-tagging in the Kavango River, Namibia. They found that radio-tagging and/or the associated handling may affect *H. vittatus* behaviour the first days after tagging, this needs to be taken into consideration in the design of telemetry experiments.

Internal tagging of Cichlids has been successful, although these studies generally had low sample sizes (Hocutt 1989; Thorstad et al. 2001). A laboratory study on *Oreochromis niloticus* showed the species to be well suited for internal tags relating to PIT telemetry methods (Baras et al. 1999). Although laboratory experiments are important to identify tagging effects, they do not consider factors such as snagging, increased predation risks and environmental variables linked to *in situ* experiments, which may influence the behaviour of fish after tagging (Ross and McCormick 1981; Jepsen et al. 2015). Recognising the behavioural effects from the telemeter tag attachment is complicated by other associated potential stress factors such as capture, handling, tagging, holding, and reviving concurred during the tagging process (Jepsen et al. 2015). When implementing external telemeter tags, it is important to explore the internal tagging options for African freshwater species. One such recent study has documented the successful internal implantation of telemeter tags in freshwater eels (Anguillids) in the Thukela River, South Africa (Hanzen et al. 2020). This study showed that telemeter tagged eels recovered well from internal tagging procedures with low expulsion rates (n = 1 out of 20). In other studies, the effects of surgical implantation of two different-sized telemeter tags were assessed for *Argyrosomus japonicus* in South Africa, a well-known estuarine species, in a 256-day experiment (Childs et al. 2011). In this study, no adverse effects in growth were observed, nor any long-term tag-related mortality, tag expulsion or internal damage were reported. They suggested that the general 2% tag-to-body mass rule should be regarded only as a broad guide (Childs et al. 2011). For inland freshwater ecosystems, and their increased associated stressors (Fouchy et al. 2019), it is important going forward to address the telemeter tag retention question in freshwater environments, particularly in the abundant and widespread families such as Characidae, Cyprinidae, Cichlidae and Claridae. This will complement the application of fish telemetry methods enabling with more confidence its future use in the region.

Table 2.2: Summary of telemetry studies associated with freshwater fish species in Africa. In addition, whether they are native African species, the tag attachment type and telemetry technique used are also presented (FISHBASE, 2019).

	Species	Common name	Studies	Obtained age (years)	Max size (kg)	Internal tag	External tag	Acoustic	Radio
1	*Hydrocynus vittatus* (Castelnau, 1861)	African Tigerfish	18	8	28		✓		✓
2	*Labeobarbus aeneus* (Burchell, 1822)	Small-Mouth Yellowfish	6	12	7,8		✓		✓
3	*Labeobarbus kimberleyensis* (Gillchrist and Thompson, 1913)	Large-Mouth Yellowfish	5	unknown	22,2		✓		✓
4	*Oreochromis andersonii* (Castelnau, 1861)	Three-Spotted Tilapia	5	13	4,7	✓	✓		✓
5	*Labeobarbus marequensis* (Smith, 1841)	Lowveld Large-scale Yellowfish	5	unknown	6		✓		✓
6	*Lates niloticus* (Linnaeus, 1758)	Nile Perch	3	unknown	200	✓	✓	✓	✓
7	*Protopterus aethiopicus* (Heckel, 1851)	Mottled Lungfish	3	unknown	17	✓		✓	✓
8	*Serranochromis robustus* (Gunther, 1864)	Nembwe	3	unknown	6,1	✓	✓		✓
9	**Micropterus salmoides* (Lacepede, 1802)	Largemouth Bass	3	23	10,1	✓	✓	✓	
10	*Clarius gariepinus* (Burchell, 1822)	Sharptooth Catfish	2	15	60	✓		✓	✓
11	**Cyprinus carpio* (Linnaeus, 1758)	Common Carp	2	38	40,1	✓	✓		✓
12	*Labeobarbus capensis* (Smith, 1841)	Clanwilliam Yellowfish	2	unknown	10,7		✓		✓
13	*Oreochromis mossambicus* (Peters, 1852)	Mozambique Tilapia	2	11	1,1	✓	✓		✓
14	*†Anguilla marmorata* (Quoy and Gaimard, 1824)	Giant Mottled Eel	2	25,5	40		✓‡		
15	*Coptodon rendalii* (Boulenger, 1897)	Red-Breasted Tilapia	1	7	2,5	✓			✓
16	*Hydrocynus brevis* (Gunther, 1864)	West Africa Tigerfish	1	unknown	8,3		✓		✓
17	*Labeo congoro* (Peters, 1852)	Purple Labeo	1	unknown	4,3		✓		✓
18	†*Oreochromis macrochir* (Boulenger, 1897)	Longfin Tilapia	1	unknown	1,8		✓		✓
19	*Sargochromis giardi* (Pellegrin, 1903)	Pink Happy	1	7	2,9	✓	✓		✓
20	*Serranochromis altus* (Castelnau, 1861)	Humpback Largemouth	1	unknown	3,9	✓	✓		✓
21	*Labeobarbus natalensis* (Smith, 1841)	KwaZulu-Natal Yellowfish	1	unknown	4,6		✓		✓
22	*Anguilla mossambica* (Peters, 1852)	African Longfin Eel	1	20	3,3		✓		
23	*Anguilla bengalensis (Gray, 1831*)	Indian Mottled Eel	1	unknown	6				
24	*†Anguilla anguilla* (Linnaeus, 1758)	European Eel	>180	6,6	88	✓	✓	✓	✓
25	*†Heterobranchus longifilis* (Valenciennes, 1840)	African Catfish (Sampa/Vundu)	1	unknown	55	✓			

*Species non-native to Africa
†Native species studied outside the continent of Africa using telemetry
‡Used Pop-up Satellite Tags (PSAT) in marine environments

2.6 The future of fish telemetry in Africa

We found that the potential for fish telemetry to become a preferred method for managing water resources in Africa is high, especially as the cost-benefit has improved and continues to be demonstrated in the region since its initial use. The highly diverse *Labeobarbus* taxon occurs throughout Africa and focusing on these species will likely contribute significantly to the widespread use of telemetry on the continent. It can contribute to assessing flow regimes, ecosystem well-being and anthropogenic stressors. The continual use of the *Hydrocynus vittatus* is encouraged as they are regarded as ecological indicators throughout their distribution range, although expansion on other *Hydrocynus* spp. is also important.

Furthermore, studies on invasive species could greatly benefit from using fish telemetry techniques to assess their movements as seen with *L. niloticus* (Nyboer and Chapman 2013), *C. gariepinus* (Kadye and Booth 2013), *M. salmoides* (Howell et al. 2015), *C. carpio* (Økland et al. 2003) and *O. niloticus* (Baras et al. 1999). We found that each of these species studied using telemetry in African inland waters contributed in various ways to the associated socioeconomics (recreational angling, fisheries or environmental degradation). Consequently, assessing their impacts through telemetry can significantly improve the way we manage freshwater ecosystems going forward.

The paucity of fish telemetry studies in Africa that we found highlighted the limited emphasis on the behavioural ecology of African fish that is needed to make informed management decisions (Skelton and Swartz 2011; O'Brien et al. 2018). These included but are not limited to the Anguillidae (*Anguilla marmorata*, *A. mossambicus*, *A. bengalensis* and *A. bicolor*) and Hepsetidae (*Hepsetus odoe*). Both have similar bodied species that have had telemetry used extensively on them to determine their behavioural ecology and migratory requirements (Baktoft et al. 2013; Arai 2016; Hanzen et al. 2019). *Anguilla anguilla* range distribution in Africa is limited to rivers along the Mediterranean Sea, and it is mostly unknown from the interior of these rivers, such as the Nile River (Dekker 2003; IUCN 2019). Fish telemetry studies on *A. anguilla* have primarily occurred in Europe, with none found for the species in Africa despite its socio-economic importance for Africa (Deriouche et al. 2016; Abecasis et al. 2018). Lastly, the Cichlid family (arguable the most diverse family in Africa) could include telemetry to understand movement, particularly for large specimens and the invasive *O. niloticus*.

We found that the African inland water fish telemetry studies reviewed here have demonstrated the successful application of telemetry in these waters. Furthermore, these studies showed that local developments and international collaborations could aid with fine-tuning technology for specific applications and bring down costs (Burnett et al. 2020; Lennox et al. 2017). Adaptations and applications for telemetry in Africa are essential considering future developments in the water sector for Africa and results from telemetered studies can contribute to meeting SDG objectives (Cooke et al. 2016b; Tilman et al. 2017; Dickens et al. 2019). The opportune time is now is to orientate research around acquiring behavioural ecology to assess the impacts of future developments on the freshwater ecosystems (Tilman et al. 2017; O'Brien et al. 2018). Fish telemetry studies around the world have been used to evaluate, determine and assess impacts that can be transferred for use in the African context (Donaldson et al. 2014; Dudgeon et al. 2015; Lennox et al. 2017; Roberts et al. 2017; Taylor et al. 2017). This includes some parallels from application and collaborations with marine research institutions and organisations already operating on the fringes of African inland water (Cowley et al. 2017). The increase in construction of large impoundments for hydropower and water security, where the use of fish telemetry has not featured as a method to assess the ecological impacts is concerning (Jackson et al. 2016b; O'Brien et al. 2019). This may see the continued decline of fish abundance and species as decisions are based typically on low confidence data. Fish telemetry methods do exist to monitor and determine these factors effectively and can be used as a method to evaluate and monitor changes in the environment and mitigate against known destructive impacts (Cooke et al. 2013; Lennox et al., 2017; Burnett et al., 2020). Generally, Africa has yet to capitalise on implementing these methods to do this.

As the equipment becomes affordable, technology advances and behavioural ecology becomes a requirement, opportunities for fish telemetry studies are becoming worth the cost (Thomas et al., 2012; Dickens et al. 2019). We found many of the issues highlighted by Hocutt et al. (1994) have been addressed with recent studies and are becoming more accessible through collaborations, technology and applications in ecological field studies (Dube et al., 2015; Lennox et al., 2017; Burnett et al. 2020). The involvement of communities surrounding research sites can significantly assist in the implementation of fish telemetry methods through the security of remote stations, acquiring fish to tag and retrieving tagged fish, thus meeting the field requirements needed (Hocutt et al., 1994; Thorstad et al., 2001; Mlewa et al., 2005). Community involvement can incorporate both local and government authorities and form collaborative initiatives between different disciplines, countries and people groups facilitating interest in important African freshwater ecosystems (Nkhata et al. 2012; Belhabib et al., 2016; Nguyen et al. 2018). In addition to traditional descriptive and ecological studies, fish telemetry methods have also been used to assess effects of migration barriers, protected areas, fishing regulations, catch-and-release angling, hatchery-rearing, fish aggregating devices (FADs), water pollution and aquaculture (Lucas and Baras 2000; Baxter et al. 2003; Kuklina et al. 2017; Bower et al. 2019; Jacobs et al. 2019). There has been, in the turn of the century, interest through local and international collaborations to improve the management of African inland waters using fish telemetry methods in the Zambezi and Nile Rivers, and in lakes such as Baringa, Kenya, Nagugabo, Uganda, and Lake Nasser, Egypt (Melwa et al., 2007; Vaccaro et al., 2013; Grubich and Odenkirk, 2014). This hopefully will pave the way for the use of fish telemetry across Africa.

We found developing fish telemetry networks is a growing field as it can increase collaborative work both regionally and internationally increase outputs and understanding of freshwater fish and the ecosystems they inhabit (Marmulla and Benech 2000; Lennox et al. 2017). Several fish telemetry networks exist for inland waters such as the Laurentian Great Lakes in North America (Landsman et al. 2011; Krueger et al. 2017), Murray-Darling Basin in Australia (Taylor et al. 2017) and several European rivers (Abecasis et al. 2018). The FISHTRAC programme is one such network in Africa; however, it is still in its infant stages but has the potential to provide the same resources and data than their international equivalents (Burnett et al. 2020). The potential to create other networks can become fundamental in managing large inland waters with high fisheries potential such as the African Great Lakes complex. To achieve this, there need to be collaborations among concerned stakeholders, locally and internationally, to improve evidence-based decisions around inland water management (Cooke et al. 2017).

2.6.1 Fisheries

The initial promotion of fish telemetry methods for use in Africa was leveraged using the contribution it can make to the management of African fisheries (Marmulla and Benech 2000; Baras et al. 2002a). Fisheries in Africa as a whole (marine, inland fisheries and aquaculture) contributed U$ 24 billion to the GDP of all African countries (1.26 %) with inland fisheries contributing an estimated 26 % (6.3 U$ billion) to this (De Graaf and Garibaldi 2015; Chan et al. 2019). It is also estimated that the fisheries sector employs about 12.3 million, 2% of the African population (De Graaf and Garibaldi 2015). Furthermore, it is estimated that for every African fisher there are approximately five people who are linked to the fisheries value chain (e.g. via processing, preservation, transport, marketing, production and maintenance of boats and gear) (Tveldten et al. 1996; Welcomme 2011; Youn et al. 2014). Many of these fisheries go un-noticed despite the role they play in alleviating poverty and achieving the SDGs (Lynch et al. 2017; 2019b). Unfortunately reports from various fisheries in Africa are seeing a decline in abundances and the potential permanent loss of fisheries in some regions (Tweddle et al. 2015). This is concerning as for the sustainability of these livelihoods, an in-depth understanding of fish migrations, their refugia habitats and seasonal patterns are needed to protect and better manage fisheries. Telemetry can acquire these data, especially in floodplain fisheries or with migratory species (Lucas and Baras 2000). Fish telemetry has been used extensively in the management of North American fisheries for acquiring fish behavioural data, where for example in the Laurentian Great Lakes system over 112 articles using fish telemetry exist (Landsman et al. 2011).

In contrast in the African Great Lakes System, only five studies on two fish species have been conducted using fish telemetry to understand their movements, namely: *L. niloticus,* and *P. aethiopicus* (Mlewa et al. 2005; 2007; Nyboer and Chapman 2013). These studies are examining means to understand the fisheries potential better and are working alongside communities to manage these important fisheries better and improve their resilience (Vaccaro et al. 2013; Nguyen et al. 2018). Impoundments in southern Africa, a water-scarce region of Africa, have created artificial water bodies supposedly boosting fishery potential in the region (Barkhuizen et al. 2016). However, low yields have caused the failure of many inland fisheries and instead fragmented rivers, further reducing the abundance of species that rely heavily on river connectivity (McCafferty et al. 2012; O'Brien et al. 2019). Fish telemetry using PIT tags can serve as CMR techniques to estimate potential yields, movement of fish and population trends of fisheries. The use of PIT instead of other tradition CMR methods allows, likewise with acoustic and radio telemetry, to assess movement without needing to recapture fish (Pine et al. 2003; Cooke et al. 2013; Taylor et al. 2015). These benefits, when applied, could potentially see a shift in the way Africa manages their fisheries.

2.6.2 Fish passage

River connectivity is a growing concern globally (Brink et al. 2018). In Africa, large water storage schemes are planned, further disrupting river connectivity (O'Brien et al. 2019). Effective fishways (a functional fish passage for the passing of fish) to ensure river connectivity is unavoidable, where impoundment/dam development supersedes ecological importance (O'Brien et al. 2019). Although regulations are slowly improving to accommodate fish passages, this may be too late for many rivers in the region that have experienced the decline or total disappearance of species, a case being anguillids in the uMngeni, Olifants and Sabie catchments in South Africa (Arthington and Balcombe 2011; Mantel et al. 2017; Hanzen 2020). Fish passage design is essential and often fail when built for the incorrect species or insufficient information on fish navigation exists (Silva et al. 2018). Using fish telemetry methods can determine the effectiveness of fish passage design but also the extent to which a river needs to be connected to maintain healthy fish stocks (Roux et al. 2018). The PIT telemetry method is well suited for measuring fish passage efficiency, and an antennae array can be fitted to fish passage structures. The tags are affordable for large sample sizes and can easily be applied to fish sized > 10 g. Telemetry studies provide evidence to evaluate the restoration progress of rivers where instream barriers have been removed, showing the improvement of fish stocks and habitat use (Brooks et al. 2017). This has highlighted the importance of setting aside fish-reserve that are largely free-flowing with low anthropogenic impacts to protect fisheries and conserve endangered fish species (Nel et al. 2007; Jacobs et al. 2019). Telemetry can assess the potential impacts of river fragmentation determining the cost-benefit of an impoundment before its construction mitigating environmental degradation and maintaining the livelihoods of millions of people (Morand et al. 2012; Sokolow et al. 2017; O'Brien et al. 2019). The importance of telemetry to understand the fine-scale movement of fish is becoming increasingly important as rivers continue to fragment altering flows and reducing water availability to fish for survival (Mantel et al. 2017; O'Brien et al. 2019). The growth in water storage facilities is inescapable however mitigating these impacts through the understanding and adjustment of developments to meet fish requirements is important to meet the sustainable development goals by 2050 (Dickens et al. 2019; O'Brien et al. 2019). Fish telemetry methods are extremely effective at assessing home ranges of fish and habitat use, therefore, feeding into mitigation measures to reduce the impacts that river fragmentation will have and the potentially contribute to understanding the need to restore river connectivity.

2.6.3 Water resource protection

With the increased demand for water resources, the role of protected areas in river health and the need to adequately protect Africa's water resources are becoming more evident (Nel et al. 2007; Cooke 2008; Du Plessis 2019). Knowing fishes home ranges, habitat requirements, spawning sites and behavioural response to changes in flow and water quality is important when demarcating and determining fish protection and the effectiveness of current conservation areas. In South Africa, many rivers in conservation areas occur downstream from highly impacted reaches. This allows for remedial processes to take place to meet water quality goals and standards, however, may not allow fish to thrive given the multiple stressors originating upstream (Nel et al. 2017; Roux et al. 2018). Additionally, many of these conservation areas have traditionally been demarcated for the protection of terrestrial biodiversity and seldom take into consideration the movement and use of the river by fish, this is evident with the many fish barriers in South African rivers (O'Brien et al. 2019). Understanding the biology and ecology of fish is crucial to improving their protection; ensuring that the management of fisheries and water resource use is adequately considered. This behavioural ecology can adequately be determined using fish telemetry methods, examples of this are with *H. vittatus* in demarcating fisheries protection areas (Jacobs et al. 2019; Roux et al. 2018) and evaluating adequate flow and water quality received in protected areas for *Labeobarbus* spp. (Burnett et al. 2018; Ramesh et al. 2018). These findings have successfully contributed to the conservation and protection of these species creating an awareness of potential threats to their health (O'Brien et al. 2013; Ramesh et al. 2018; Jacobs et al. 2019).

Water resource development and the associated alteration in water flow and water quality involves balancing consumer use and ecosystem requirements; this includes the maintenance of ecosystem processes and services (Jewitt 2002; Lui et al. 2016; Brisman et al. 2019). The understanding of environmental flow required to sustain freshwater ecosystem is a necessity, as rivers are increasingly running dry to keep up with the demand for water (King et al. 2016; Pearce 2018). The environmental water requirements (EWR) determine the correct allocation of water needed to maintain its basic function and is determined by meeting the needs of ecological indicators (Hughes 2001; King and Brown 2006; Seaman et al. 2016). Fish telemetry can determine the environmental requirements for fish to maintain their biological processes, feeding into the management to ensure environmental flows are adequately met (Saraiva Okello et al. 2015; O'Brien et al. 2018).

Fish telemetry studies globally and recently in Africa are using these methods to monitor impacts such as flow, habitat and water quality changes in the environment and the effects they have on fish biological processes outside of protected areas (Flitcroft et al. 2016; O'Brien et al. 2013; Ramesh et al. 2018). Telemetry methods can determine when, where and what drives fish movement, this information greatly assists water stakeholders in setting EWR and mitigating against poor water quality impacts (Burnett et al. 2020). Ecological risk assessment on freshwater ecosystems takes into consideration the behavioural response by fish to mitigate against stressors in the environment to achieve desired endpoints (O'Brien et al. 2018; Opperman et al. 2018). These assessments depend heavily on the known biology and ecology of fishes as indicators for ecosystem well-being in the freshwater system. The lack of telemetry studies indicates relatively poor knowledge of the behaviour of these ecological indicators. The low confidence decisions can have management implications and negatively affect fish stocks in fisheries that millions of people are dependent on (Morand et al. 2012; Closs et al. 2016; Chan et al. 2018). Increasing telemetry outputs on the continent in ecologically important river systems can increase the confidence of water resource management decisions, positively impacting these ecosystems.

2.7 Conclusions

We found that over the last three decades fish telemetry in inland waters of Africa has seen a steady increase in the use of the method; however, outputs for the region are still considerably lower in comparison with developed countries (Landsman et al. 2011; Abecacis et al. 2018). The potential to increase behavioural ecology outputs using fish telemetry for African studies is high, considering the application of methods still constitutes as novel or baseline research. Continuing to build on baseline data where fish telemetry studies have been implemented by improving the monitoring of fish behaviour in freshwater ecosystems is important. Future fish telemetry studies for Africa in the next 20 years have the potential to more than double the total current outputs, and with current trends and projections, this is likely. The need for behavioural studies to understand impacts in developing water infrastructure can be provided for by using fish telemetry methods. These planned impoundment developments across the continent need to evaluate fish behavioural movement making provision for this where necessary, and once constructed monitored for efficiency (Zarfl et al. 2014; Siciliano and Urban 2017; O'Brien et al. 2019). This provides scope to use telemetry methods not only to determine the adequate fish passage structures catered for migratory species but also monitoring of these passages post-construction using PIT telemetry. Altered flow regime caused by impoundment releases and water extractions can also use telemetry to determine fish movement in response to these changes assessing whether biological processes are maintained (Flitcroft et al. 2016; O'Brien et al. 2018; Burnett et al. 2020). The cost-benefit of infrastructure development across Africa can be adequately assessed with evidence-based behavioural ecology of fishes obtained using telemetry methods (Cutler et al. 2019). Furthermore, costs can be reduced through the establishment of shared telemetry networks across important socio-economical ecosystems such as the great lakes of Africa, facilitating research and improving management strategies for fisheries and proposed future developments.

With the combination of the various telemetry methods available, improved cost-benefit and the ability to acquire behavioural ecology of fish indicates that telemetry methods across Africa in various inland waters can successfully be applied. Despite this, the uptake of these methods is still relatively low. It suggests that there is still a perceived lack of understanding, market, securing of equipment, expertise, political will or funding availabilities resulting in the low research outputs for the region. Adequately implementing these methods will greatly assist and accelerate the process of acquiring the much-needed biology and ecology of fishes for the region. The importance of having this information is paramount to making evidence-based management decisions that affect the way we manage our water resource and fisheries, both locally and internationally across the continent. This includes the contribution that telemetry studies can make to; managing environmental flows, ecosystem responses to environmental stressors, assessing river connectivity, the protection and understanding of fisheries, the conservation of ecosystems with high diversity, the effects of existing and proposed impoundments, assessing ecosystem services, monitoring freshwater ecosystems, evaluating the effect of hydropower infrastructure and restoring ecological processes in a freshwater ecosystem. All these are growing concerns for the African continent faced with increasing human population and demand for water (Rodell et al. 2018; Du Plessis 2019). However, with suitable collaborations between water resource managers, local and national governance, researchers, technology developers, and support from local communities, fish telemetry methods can expand throughout Africa. Fish telemetry can provide an evidence-based understanding of the biology and ecology of fish required in regulatory trade-off discussions to determine objectives and or targets for managing water resources needed to achieve the SDG's (Cooke et al. 2016a; 2017; Dickens et al. 2019). Fish telemetry will increase knowledge outputs gaining much-needed information on the biology and ecology of African freshwater fish species. The international collaborations and development initiatives have been evident, showcasing the valuable contribution that these methods can make to managing water resources in Africa.

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CHAPTER 3

The southern African inland fish tracking programme (FISHTRAC): An evaluation of the approach for monitoring ecological consequences of multiple water resource stressors, remotely and in real time

Matthew J. Burnett[1,2], Gordon C. O'Brien[1,3], Francois J. Jacobs[1,4], Francois Botha[5], Graham Jewitt[2,6], Colleen T. Downs[1*]

[1]Centre for Functional Biodiversity, School of Life Sciences, P/Bag X01, Scottsville, Pietermaritzburg, 3209, South Africa

[2]Centre for Water Resource and Research, School of Engineering, P/Bag X01, Scottsville, Pietermaritzburg, 3209, South Africa

[3]School of Biology and Environmental Sciences, Faculty of Agriculture and Natural Sciences, University of Mpumalanga, Nelspruit, South Africa, 1200

[4]Ministry of Fisheries and Marine Resources, Kamutjonga Inland Fisheries Institute, Private Bag 5147, Divundu, Namibia

[5] Wireless Wildlife cc, Potchefstroom, North West, South Africa

[6] Institute for Water Education, IHE Delft, Westvest, South Holland, Netherlands, 2611

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* Corresponding Author: Colleen T. Downs
Email: downs@ukzn.ac.za
Tel: +27 (0)33 260 5127
ORCID: http://orcid.org/0000-0001-8334-1510
Other emails: matthewburnett014@gmail.com, ORCID: https://orcid.org/0000-0002-6237-1697; gordon.obrien@ump.ac.za, ORCID: https://orcid.org/0000-0001-6273-1288; francoisjacobs.mfmr@gmail.com ORCID: https://orcid.org/0000-0002-0354-3022; francois@agri-alert.co.za; g.jewitt@un-ihe.org, ORCID: https://orcid.org/0000-0002-7444-7855

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Review

The southern African inland fish tracking programme (FISHTRAC): An evaluation of the approach for monitoring ecological consequences of multiple water resource stressors, remotely and in real-time

Matthew J. Burnett[a,b], Gordon C. O'Brien[a,c], Francois J. Jacobs[a,d], Francois Botha[e], Graham Jewitt[b,f], Colleen T. Downs[a,*]

[a] Centre for Functional Biodiversity, School of Life Sciences, P/Bag X01, Scottsville, Pietermaritzburg 3209, South Africa
[b] Centre for Water Resources Research, School of Agricultural, Earth and Environmental Sciences, P/Bag X01, Scottsville, Pietermaritzburg 3209, South Africa
[c] School of Biology and Environmental Sciences, Faculty of Agriculture and Natural Sciences, University of Mpumalanga, Nelspruit 1200, South Africa
[d] Ministry of Fisheries and Marine Resources, Kamutjonga Inland Fisheries Institute, Private Bag 5147, Divundu, Namibia
[e] Wireless Wildlife cc, Potchefstroom, North West, South Africa
[f] IHE Delft Institute for Water Education, Delft, The Netherlands

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ABSTRACT

Fishes are indicators of aquatic ecosystem wellbeing globally and used when understanding impacts from water resources. The behavioural ecology of fishes as a Line of Evidence (LoE) is between 10 and 100 times more responsive to changes in environmental variables, compared with traditional LoEs including standard mortality bioassay LoEs. Fish telemetry methods are available to monitor fish behaviour and the response of tagged fish to altered water quality, flow and instream habitat variability exist globally. Developing regions have relatively poor use of fish telemetry as a methodology to gather behavioural information, compared with developed regions for various reasons. Fish telemetry methods can assist in answering water resource management questions faced in developing regions. For this purpose, we describe the development of the southern African inland fish tracking (FISHTRAC) programme and its use for collecting fish behaviour, and water quality and quantity data in real-time and remotely. We also detail eight case studies that contributed to FISHTRAC over the past decade. The FISHTRAC programme was initially based on internationally recognised radio telemetry methods that were then adapted for application in southern Africa. Developments within the FISHTRAC programme have seen radio telemetry methods expand beyond manual monitoring techniques to incorporate a real-time and remote monitoring feature. The case studies demonstrated the development of FISHTRAC's functionality; data management systems, real-time communications and data evaluations. This included its implementation in five economically important freshwater ecosystems across southern Africa and using eight large charismatic fish species. Following the description of the FISHTRAC programme, we provide a four-phase guideline to successfully implement radio telemetry methods to obtain behavioural information of fishes and contribute to the essential management and monitoring of fisheries and water resources within the southern Africa context, applicable globally with continued anthropogenic stressors.

1. Introduction

Fish are used as indicators of aquatic ecosystem wellbeing, health or status globally and are used in a range of environmental monitoring, conservation and research programmes (Harris, 1995; Kleynhans, 1999; McDowall and Taylor, 2000; Schiemer, 2000; Depledge and Galloway, 2005; O'Brien et al., 2009; Arthington and Balcombe, 2011). Attributes of the various levels of biological organisation for fish have been used to evaluate the effect of physico-chemical, toxicological and ecological lines of evidence (LoE) (Fairbrother, 2003; Wepener, 2008; O'Brien et al., 2018). These LoE's have their foundation on the biological and ecological understanding of fish and their preferences or dependence on the ecosystems they live in (Wepener et al., 2011; Capon et al., 2015; Cooke et al., 2017a). The continued development in understanding the

* Corresponding author.
E-mail addresses: matthew@riversoflife.co.za (M.J. Burnett), gordon.obrien@ump.ac.za (G.C. O'Brien), francoisjacobs.mfmr@gmail.com (F.J. Jacobs), francois@agri-alert.co.za (F. Botha), g.jewitt@un-ihe.org (G. Jewitt), downs@ukzn.ac.za (C.T. Downs).

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responses of fish to environmental variability is important in improving our knowledge of the effects of multiple stressors and associated changes in ecosystem wellbeing, and the resilience of these ecosystems to change (Lucas and Baras, 2008; Burnett et al., 2018; O'Brien et al., 2018).

Changes in water resources because of multiple water quality, flow and habitat stressors are negatively affecting socio-ecological systems and the biology and ecology of species that abide in these systems (Dallas and Rivers-Moore, 2014; Dudgeon, 2014; Rodell et al., 2018; Du Plessis, 2019). The biological organisational level of the behaviour of fishes and their responses to stressors are known to be 10–100 times more sensitive than other established LoE and are ecologically relevant for the monitoring of aquatic environments (Beitinger, 1990; Beitinger and McCauley, 1990; Wepener, 2008). The behaviour of fishes is known to respond to natural changes in the environment such as; daily, lunar and seasonal cycles, water quality, water quantity and habitat variability and biological events such as migrations (Jacobs et al., 2016; Burnett et al., 2018; Ramesh et al., 2018). These behavioural changes can be subtle, such as seeking refugia habitat, or total disruption by vacating areas to avoid external stimuli (O'Brien et al., 2013). Fish behavioural studies using telemetry techniques have been used extensively to characterise the biological, ecological and associated habitat requirements of fishes within their natural environment (Cooke et al., 2013; Thorstad et al., 2013; Hussey et al., 2015; Lennox et al., 2017; Flitcroft et al., 2016). These telemetry techniques have been used globally to measure behavioural biology and ecology of fishes *in situ* and are recognised as effective tools in acquiring information on wild fish (Winter, 1996; Lucas and Baras, 2000; Rogers and White, 2007; Cooke et al., 2013; Thorstad et al., 2013; Hussey et al., 2015; Lennox et al., 2017).

A wide range of fish telemetry methods exist such as hydro-acoustic, radio, passive integrated transponders (PIT) and data storage tags (DST), and are available for fish behavioural studies within freshwater ecosystems (Koehn, 2000; Cooke and Schreer, 2003; Cooke et al., 2013; Lennox et al., 2017). The type of fish telemetry method used largely depends on the research objectives, functionality of techniques, the targeted species and habitat availability (Koehn, 2000; Cooke et al., 2004; Cooke et al., 2013). The application of these fish telemetry methods, in some cases, has seen the establishment of large networks. These networks can detect fish across a wide range of regions using the behaviour and movement of fish both locally and internationally to drive fisheries management (Landsman et al., 2011; Lennox et al., 2017; Taylor et al., 2017; Krueger et al., 2017; Abecasis et al., 2018). Application of fish telemetry methods in southern Africa has contributed to the knowledge of the behavioural ecology and movement of fish in impoundment planning, construction and operation (Paxton, 2004; Cooke et al., 2017a; O'Brien et al., 2019), environmental flows (Burnett et al., 2018; O'Brien et al., 2018), water quality stressors (O'Brien et al., 2013; Ramesh et al., 2018), fisheries and alien invasive species (Jacobs et al., 2019; Kadye and Booth, 2013; Roux et al., 2018; Thorstad et al., 2003).

Fish telemetry methods have been used in southern Africa for the past 30 years, contributing to fish behavioural information in the region and assisting with the management of fisheries and water resources particularly in southern Africa (Hocutt, 1988; Burnett et al., in review). Radio telemetry methods are the preferred method to conduct fish behavioural studies within freshwater ecosystem in southern Africa, with recent studies in the Limpopo, Vaal and Crocodile Rivers using the behaviour of fishes to manage multiple stressors within the aquatic ecosystem (O'Brien et al., 2012, 2013; Jacobs et al., 2016; Burnett et al., 2018; Burnett et al., in review). These studies have formed the basis of developing the southern Africa inland fish tracking programme (FISHTRAC) and have used both local and international equipment to monitor fish behaviour. Due to limited resources within southern Africa, perceived lack of market and high variability within aquatic ecosystems, the use of fish telemetry methods have been restricted in the region (Hocutt et al., 1994; Cooke et al., 2013; Lennox et al., 2017; Burnett et al., in review). Hence, a local telemetry manufacturer invested in the research to overcome these challenges, establishing a cost-effective alternative remote fish telemetry method for the region (Cooke et al., 2013; Jacobs et al., 2016; Burnett et al., 2018). This remote telemetry monitoring approach makes use of digital radio telemetry communication systems and "smart" tags with sensory capabilities to monitor and store fish energetics, depth and water physico-chemical variable data transferring this information to a remote data management system in real-time.

In this study, we describe the development of the southern African inland fish tracking programme (FISHTRAC) along with its feature to use *in situ* fish behavioural responses to evaluate the ecological consequences of altered flows and water quality, remotely and in real-time. Furthermore, we discuss and present clear guidelines for best application when using FISHTRAC, as with any fish telemetry study the planning and suitability of the method needs to be adequately researched before implementation. This study serves to provide a concise overview of the FISHTRAC programme's combination of fish telemetry methods, and measuring of environmental variables into a holistic ecosystem monitoring programme for water resource management and ecological research. We highlight the opportunities the FISHTRAC programme has for monitoring fisheries, water quality stressors, regulating rivers and fish behavioural research. These in turn will contribute to the local and international management of water resources.

2. Methods

To demonstrate the development of FISHTRAC, we detail eight radio telemetry case studies conducted over the past decade in southern Africa and present guidelines for further use. These case studies have contributed to the development of the FISHTRAC programme and the implementation of radio telemetry methods using various techniques (Table 1, Fig. 1). These case studies use radio telemetry methods on generally large and charismatic fishes (Table 1), contributing to developing both manual and remote monitoring techniques (Table 1). Tags with sensors were used to monitor water quality and quantity as well as fish behaviour, and the remote networks were used to gather and evaluate data (Kuklina et al., 2013; Burnett et al., 2018). It is through these case studies and their outcomes that guidelines were developed for FISHTRAC (Table 1).

2.1. Fish capture and tagging

Suitable fish, large enough to carry tags (Jepsen et al., 2015), were caught using various angling, netting (gill, fyke and seine nets) and electro fishing techniques (Table 1; O'Brien et al., 2012, 2013; Jacobs et al., 2016; Burnett et al., 2018). Prior to the capture and tagging procedures ethical clearance for sampling, and experimental permits were obtained from relevant authorities for the attachment of tags (Bennett et al., 2016; Cooke et al., 2017b; Table 1).

Two commonly used tag attachment methods, external and internal, are used in fish radio telemetry studies, and are applied based on the morphology of species (Bridger and Booth, 2003; Thorstad et al., 2013). A general guideline when tagging fish is a tag to body mass ratio of 2% (Jepsen et al., 2002; 2004; Childs et al., 2011; Jepsen et al., 2015). When using internal tagging techniques further limitations must be considered such as abdomen cavity size in relation to tag size (Broadhurst et al., 2009). External tags do not work well on species that do not have a suitable body shape and habits to attach the tag, such as *Anguillid* spp. and *Clariidae* spp. (Broadhurst et al., 2009; Cooke et al., 2011; Thorstad et al., 2013). Internal tagging of fish was experimented in the field (unpublished data), however limited success and impractical field surgical procedures showed external tagging methods to be the favourable method and they were used in all case studies subsequently (Økland et al., 2003; O'Brien et al., 2013; Table 1).

Table 1
A summary of the case studies used within the FISHTRAC programme development, including the river system, fish species, technology used and period of study for each case.

Case study	Title	Freshwater system	Contribution	Focal species	Smart tag	Time period	Reference/s (outcomes)
1	*Labeobarbus kimberleyensis* and *L. aeneus* behavioural ecology on the Vaal River, southern Africa	Vaal River, ZA	Successful use of beacon tags to characterise behavioural ecological of *Labeobarbus kimberleyensis* and *L. aeneus* and their response to water quality variables	*Labeobarbus kimberleyensis* (n = 22) *Labeobarbus aeneus* *(n = 13)*	No No	2006–2008	O'Brien et al., 2013; Ramesh et al., 2018
2	*Hydrocynus vittatus* relocation, recruitment and predation strategies, Schoda and Letsibogo Impoundment, southern Africa	Limpopo River, ZA and BW	Successful use of beacon tags within shallow (<10 m) lentic system to determine behavioural ecology of two populations of *H. vittatus*.	*Hydrocynus vittatus* *(n = 11 and n = 14)*	No	2009–2010	O'Brien et al., 2012,2014
3	*Labeobarbus marequensis* and *Hydrocynus vittatus* behavioural ecology in the Crocodile River, Kruger National Park, southern Africa	Crocodile River, ZA	Comparison between beacon tags and smart tags in acquiring manual and remote monitoring fish behaviour. The compatibility of activity (integer counts) as a movement variable.	*Hydrocynus vittatus* *(n = 13)* *Labeobarbus marequensis* *(n = 16)*	Both Both	2011–2013	Burnett et al., 2018
4	The behavioural ecology of *Labeobarbus aeneus* a comparison between Boskop Impoundment and the Vaal River, southern Africa	Vaal River, ZA	The successful use of smart tags to manually track fish and the use of the Remote network to determine spatial movements and area use.	*Labeobarbus aeneus* *(n = 18)*	Yes	2011–2013	Jacobs et al., 2016
5	Suitability of a rehabilitated impoundment for *Labeobarbus aeneus*, Vaal River, southern Africa.	Vaal River, ZA	Describing data storage tags (DST) and their application in FISHTRAC.	*Labeobarbus aeneus* *(n = 5)*	Yes	2012	Series of Reports 2012
6	Assessing the use of Albert Falls Impoundment as refugia habitat for fish in the uMngeni River, southern Africa	uMngeni River, ZA	Successfully implementing data storage tags and using stations as 'gates' to determine spatial movement of fish. Understanding the limitations of different fish behaviour on the working out of techniques.	*Labeobarbus natalensis* *(n = 52)* *Micropterus salmoides* *(n = 2)* *Oroechromis mossambicus* *(n = 2)*	Yes Yes Yes	2014–2019	This study 2014 – 2019
7	Incorporating water quality and quantity monitoring into the FISHTRAC programme, the Senqu River, southern Africa.	Senqu (Orange) River, LS	Successful development of water quality and quantity probes linked to the remote network and recorded in real-time	*NA*	Yes	2014	O'Brien et al., 2018
8	The effect of capture stress on tagged, Okavango Delta, Crocodile and Vaal Rivers, southern Africa	Okavango Delta, BW Vaal and Crocodile River, ZA	Understanding recovery post tagging procedure and the influence of predation, namely; crocodiles, otters and fish-eagles on tagged fish. Describing internal tagging on fish in southern Africa.	*Hydrocynus vittatus* *(n = 17)* *Labeobarbus* spp. *(n = 51)*	Both	2010	Smit et al., 2009; O'Brien et al., 2013; Burnett et al., 2018

Countries: ZA = South Africa, BW = Botswana, LS = Lesotho.

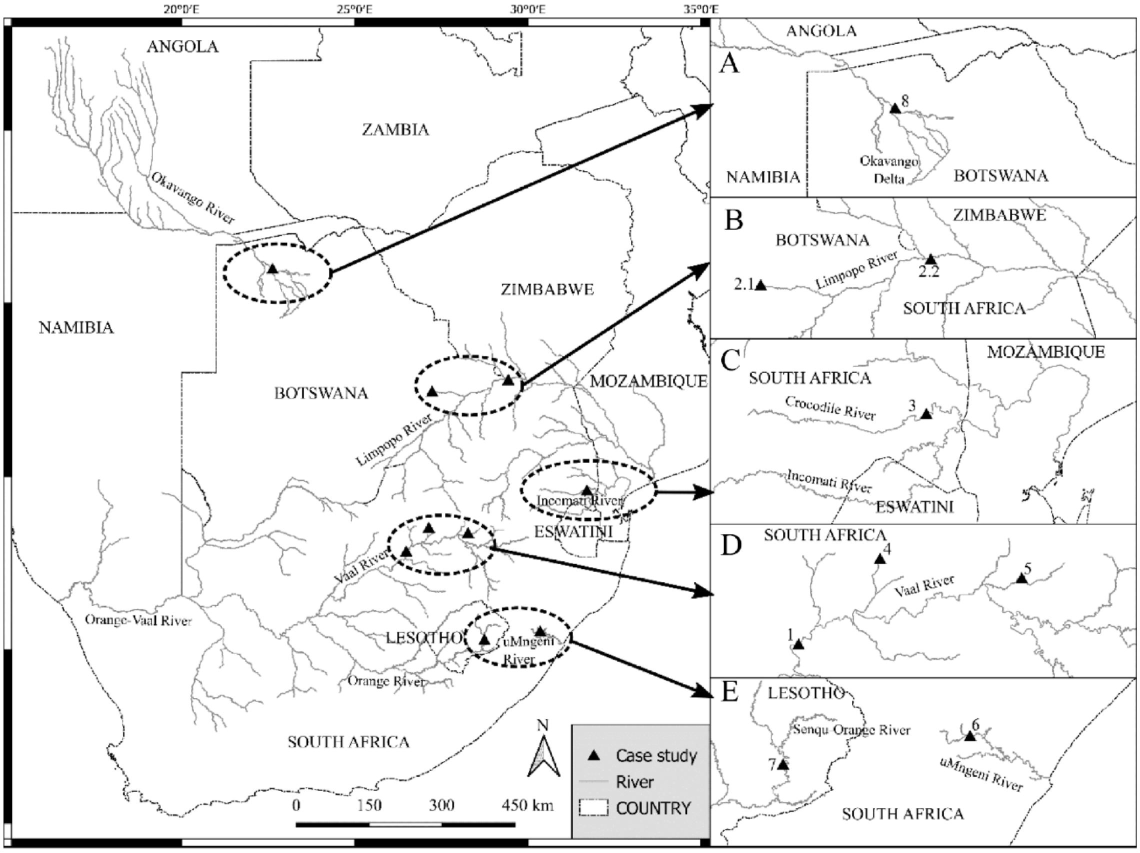

Fig. 1. Locations of the eight study sites across southern Africa where inset A. shows case study 8 in the Okavango Catchment; B. shows case studies 2.1 on the Letsibogo and 2.2 Shroda Impoundments in the Limpopo Catchment; C. shows case study 3 in the Inkomati Catchment; D. shows case studies 1, 4 and 5 in the Orange-Vaal Catchment; and E. shows case studies 6 and 7 in the uMngeni and Orange-Vaal Catchments respectively.

2.1.1. External tagging procedures

Once fish were captured, they were weighed to determine suitability for external tag attachment (Table 1). Fishes suitable for tagging were moved to a covered container with water supplied directly from the source of capture, ideally using a submersible pump (Table 1; O'Brien et al., 2012, 2013; Jacobs et al., 2016; Burnett et al., 2018). During the tagging process, water temperature was kept constant and air exposure kept to a minimum. A separate aerated container was used as an anaesthetic bath with 2-phenoxy ethanol (0.5 ml l^{-1}) or clove oil (0.1 ml l^{-1}) (Munday and Wilson, 1997; Neiffer and Stamper, 2009; Fernandes et al., 2017). Anaesthetised fish were then tagged externally or internally as shown in Fig. 2 and described elsewhere in detail (Bridger and Booth, 2003; O'Brien et al., 2013; Jacobs et al., 2016; Burnett et al., 2018). An antibiotic (Terramycin® containing oxytetracycline; Zoetis, Johannesburg, South Africa) was then injected into the muscle (1 ml/kg) and fish wound care gel applied around the wound (Aqua Vet, Veterinary hospital, Lydenburg, South Africa) (Schardt et al., 1982; Thorstad et al., 2013). After the operation, a picture and morphological measurements (total, fork and standard lengths) were recorded. Tagged fish were left in a container with circulating water until each had fully recovered before being released near their capture points (Table 1; Fig. 3; O'Brien et al., 2012, 2013; Jacobs et al., 2016; Burnett et al., 2018).

2.2. Radio telemetry, incorporating smart tag technology

There are various types of radio telemetry tags available and commonly developed for the use within freshwater environments (Cooke et al., 2013; Thorstad et al., 2013). Most of these techniques work within a wide range of frequencies to maximise the detection of beacon and coded tags within freshwater systems (Sisak and Lotimer, 1998; Koehn, 2000; Peters et al., 2008). The selection of a frequency range depends largely on the type of information needed and the best fit technology available for the study. These variables can alter based on water quality (salinity gradients and electrical conductivity (EC) as examples), technique and application of use (Thorstad et al., 2013; Burnett et al., in review). Due to this, developers and researchers need to work closely with each other to find the best fit combinations of these variables (Cooke et al., 2013). This has led to recent developments, such as FISHTRAC, to meet local requirements including site accessibility, reduced costs and increase technical support (Table 1; Hocutt et al., 1994). In the FISHTRAC programme, the use of ultra-high frequency (UHF) was shown to be the best trade-off to support the sending and receiving of peripheral data acquired by sensors and was incorporated into a tag (Sisak and Lotimer, 1998; Enders et al., 2007; Jiang and Georgakopoulos, 2011). It must be noted that the data storage and transmission function on these tags (Table 1; Jacobs et al., 2016; Burnett et al., 2018) is different to data storage (DST) or archival tags used in various other telemetry studies where the tag has to be retrieved to access the data (Thorstad et al., 2013; Jepsen et al., 2015). The application of these smart technology features into the tag using radio frequency to transmit information has broadened the application of radio telemetry techniques not yet documented (Lennox et al., 2017). These tags, hereafter referred to as "smart tags", can detect information from sensors, record and store this information at set intervals and send this information (when in range) to a receiver (Table 1; Jacobs et al., 2016; Burnett et al., 2018). Another benefit of using smart tags is that the tag and receiver can communicate back and forth, thus allowing

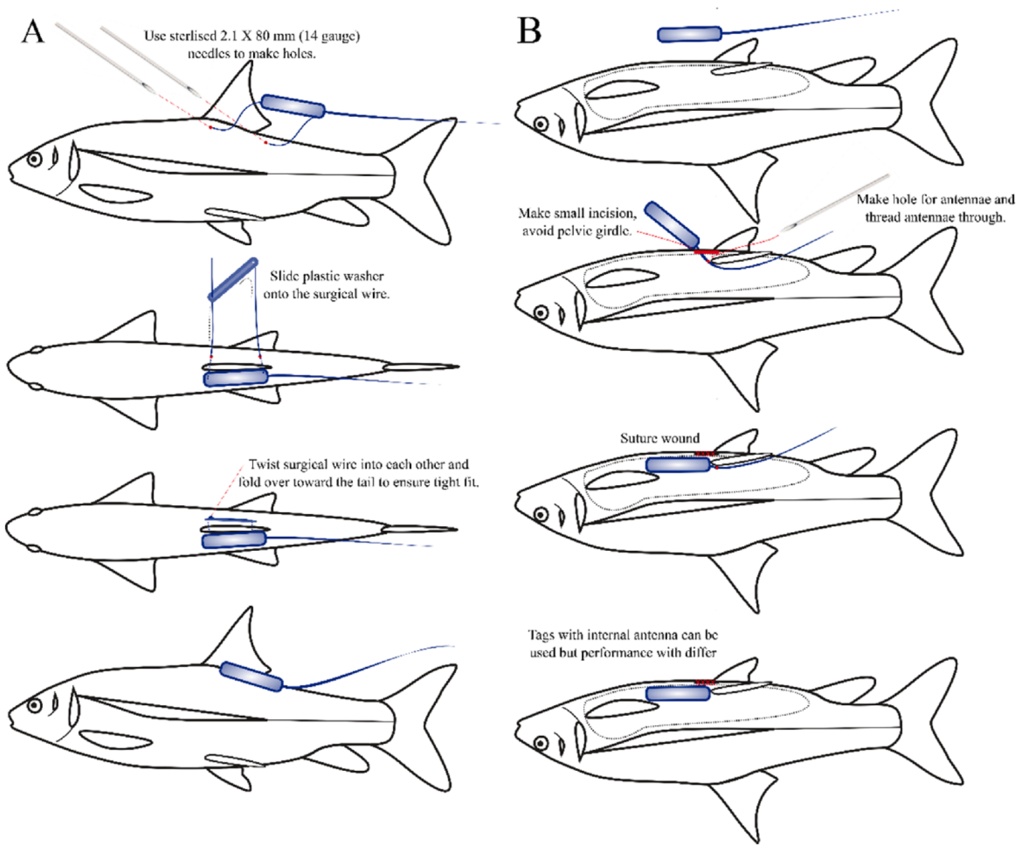

Fig. 2. A graphical representation of the two commonly used tagging procedures A) external and B) internal tagging (Modified from Bridger and Booth, 2003).

pulse rate and data schedule changes to suit different applications according to seasons or events. This additional feature does not hinder the ability to manually track a tagged fish but instead expands on the functions of the radio tag adapting FISHTRAC to multiple applications (Table 1; Jacobs et al., 2016; Burnett et al., 2018).

The FISHTRAC programme tested several sensors and their applications including motion (activity), water temperature and pressure (depth) (Table 1; Jacobs et al., 2016; Burnett et al., 2018). The motion sensor (SQ-SEN-200, SignalQuest, Inc, Lebanon, NH) used consisted of an omnidirectional tilt and a vibration sensor that detected the movement of the fish in the form of integer counts per time interval and described the behavioural variable as activity (counts of movement that can be related to behaviour). Temperature sensors were used to measure the water temperature around a tag. Pressure sensors permitted the measurement of the depth (below the surface) of the tag, as the water pressure is directly proportional to the atmospheric pressure and calibrated accordingly (Thompson and Taylor, 2008; O'Brien et al., 2018). A smart tag can have any of these sensors based on the projects requirements and with technological advancements can have other sensors added. For example, water quality probes incorporated as additional sensors allowing for the assessment of fish behavioural and environmental variables concurrently.

2.2.1. Water probes

For FISHTRAC results to be of value, an understanding of the multiple stressors affecting fish behaviour is required. For this purpose, a robust water probe to monitor abiotic factors was developed using the same smart technology and radio telemetry techniques as for fish tags (Fig. 3; O'Brien et al., 2018). This allowed for water quality and flow (based on depth and hydraulic cross-sections of the river) to be detected in real-time and near tagged fish, especially in areas where these variables are not monitored nationally nor routinely (Table 1; O'Brien et al., 2018). These probes need to be fully submerged at depths of 0.2–3 m to avoid signal loss, and remain submerged through variable flows (Jiang and Georgakopoulos, 2011). Additional snap-shot or grab sampling, hydraulic analyses (habitat modelling) and remote sensing (unmanned aerial vehicle's (UAV) and satellite imagery) were used to characterise environmental variable conditions around the probe (Table 1; Consi et al., 2015; O'Brien et al., 2018). Water quality variables can be readily measured within this framework and include EC, water temperature (°C), depth (mBar) and dissolved oxygen (DO). Further developments include the addition of variables such as metals, organics and nutrients (O'Brien et al. unpublished data) and new sensors can be fitted to the probes for real-time monitoring (Mercante et al., 2017; Belikova et al., 2019).

2.3. Manual monitoring

Manual monitoring by foot or boat included the use of a Yagi antenna and rapid pulse per minute (ppm) (15–48 ppm) schedule from tags to triangulate signals from a tagged fish (Table 1; O'Brien et al., 2012, 2013; Jacobs et al., 2016; Burnett et al., 2018) to identify its geographical location (Cooke et al., 2012). The manual monitoring exercises were based off a systematic tracking methodology designed to align efforts and approaches in the development of FISHTRAC, this ensured consistency and reliability of the data and validated the tags functional status (Fig. 4; Table 1; O'Brien et al., 2012, 2013; Jacobs et al., 2016; Burnett et al., 2018). Once tagged fish were found frequenting preferred habitats within the ecosystem, the remote system was established with greater certainty in detecting tagged fish (Table 1; O'Brien et al., 2012, 2013; Jacobs et al., 2016; Burnett et al., 2018).

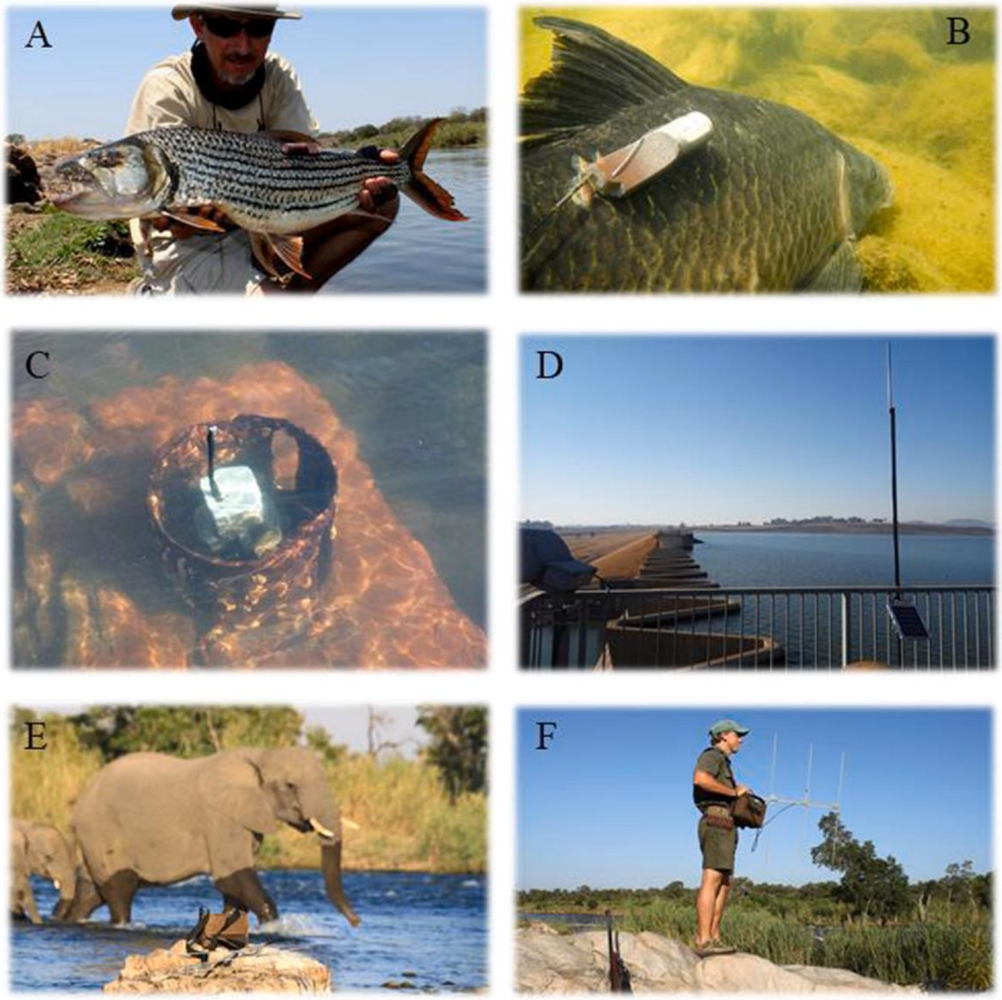

Fig. 3. Photographs to detail various aspects of the study where the positioning of external tags on A. tigerfish (*Hydrocynus vittatus*) and B. purple labeo (*Labeo congoro*) during the recovery from the anesthetic are shown; C. depicts the water probes used; D. the remote stations used within the FISHTRAC programme; E. is an example of a disturbance to tagged fishes recorded as anecdotal evidence (the receiver can be seen in the foreground, the tagged fish moved out of the rapids and into a pool downstream in this case) and F. is an example of a researcher manually using triangulation to find tagged fish.

2.4. Remote monitoring

Remote monitoring systems include the establishment of a network coverage using base and relay receiver stations that detect signals from tagged fish *in situ*. Once detected, the tag identification (ID), signal strength of the transmission and any sensory data were transmitted directly to a Data Management System (DMS) as real-time and stored data (Fig. 5; Table 1; Jacobs et al., 2016; Burnett et al., 2018). Real-time data recorded the time of detection and the station the tag was in range of, while stored data recorded the sensory data over the stipulated schedule. Stations were equipped with a global positioning system (GPS) unit, to prevent theft and were erected near important fish habitat types and water quality and quantity monitoring sites (Table 1; Jacobs et al., 2016; Burnett et al., 2018). Additional water quality, flow and habitat variable data were generated using water probes, by collecting additional samples and or using a range of hydrological, water quality and hydraulic modelling tools (Case study 7) (Table 1; O'Brien et al., 2018). The DMS can be used to change ppm for real-time and storage data when in range of a station, furthermore commands can be left pending and alerts set for when a tag comes into range. This has been successful in changing the ppm when needing to conduct manual monitoring or searches for tagged fish (unpublished data). Mobile stations as used in manual monitoring can also be used as temporary remote stations to search for missing tagged fish and retrieve data from outside the network coverage. In addition, relay receiver stations were often set up as "gates" to define study areas and movement of tagged fish outside of this area. These receivers reduced resource costs by finding tags outside the study area, and assisted in determining home ranges remotely (Table 1; Jacobs et al., 2016; Burnett et al., 2018).

The data collected from remote and manual tracking are used to characterise the biology and ecology of tagged species (Thorstad et al., 2013; Lennox et al., 2017). The water probes provide the abiotic variables that affect the behaviour of fish species. The continual monitoring of the species, water quality, flow and habitat through the remote system validates the effect and adds to the understanding of the species and ecosystem through new findings. To achieve this, the potential correlations between the behavioural data of the tagged fish and multiple water quality, flow and habitat variables are tested using a range of statistical methods (Littell et al., 1996; Burnham and Anderson, 2003; Rogers and White, 2007; Ramesh et al., 2018). Basic data analyses can be derived from the real-time data to present managers with thresholds of potential concern to be responsive and mitigate possible pollution events. The data that are then stored can be used for further analyses allowing a better understanding of the aquatic ecosystem and

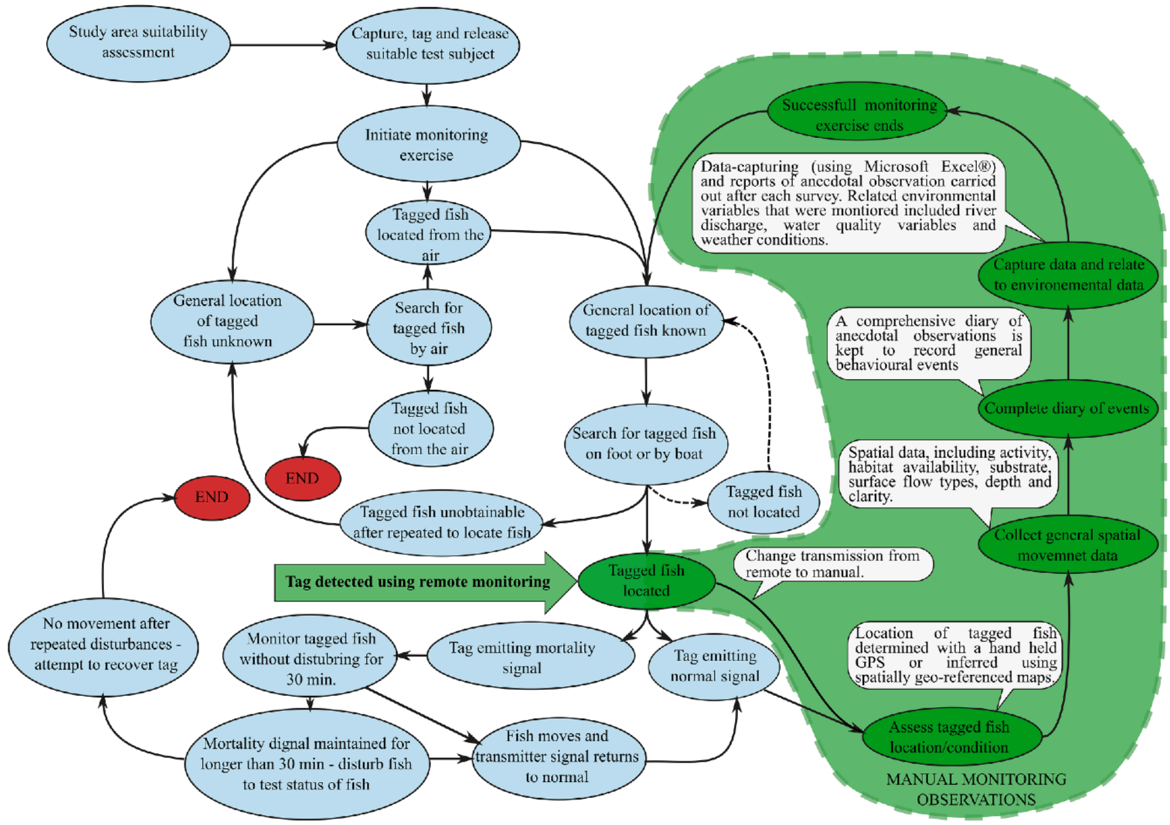

Fig. 4. A schematic diagram depicting the route taken to find tags during manual monitoring surveys. The shaded area shows the manual monitoring exercise followed by the researcher once fish were located. The arrow indicating the contribution of remote monitoring techniques by downloading stored data and providing real-time data from tagged fish is also shown.

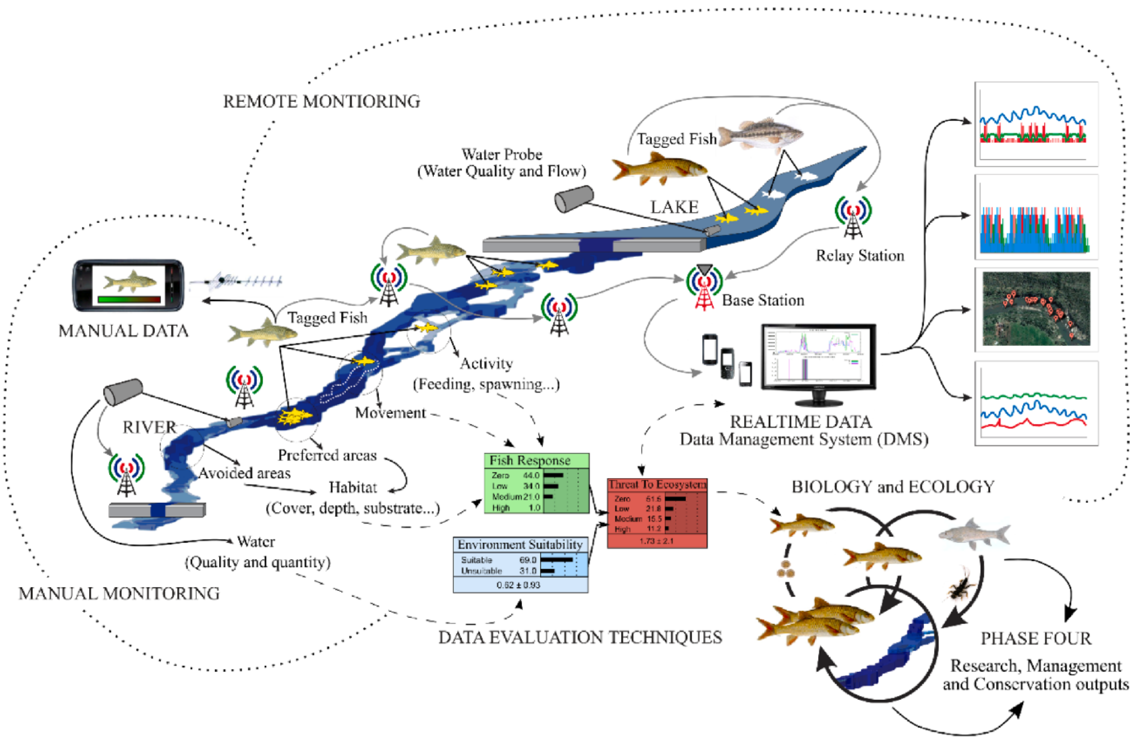

Fig. 5. A schematic diagram showing the communication pathways of data obtained using remote and manual monitoring through to the data presented on the data management system (DMS) and to water resource managers as developed in the present study.

its response to changes over time (Table 1; O'Brien et al., 2012, 2013; Jacobs et al., 2016; Burnett et al., 2018).

3. Case study findings

Case studies one to seven progressed from using beacon tags to using smart tags (Table 1). The two techniques were applied both within lotic and lentic systems (Table 1). Using beacon and smart tags to develop the FISHTRAC programme showed similar application for manual monitoring. However, smart tags had better application for remote monitoring techniques. Case study one and two implemented beacon tags to assess the use of radio telemetry in southern Africa in lotic and lentic systems, and these were successful (Table 1). Case study three made use of both beacon and smart tags demonstrating the compatibility of both tag types (Table 1). This case study showed similarities between maximum displacement per minute (MDPM) and activity (integer counts) which was used as a behavioural variable in manual and remote monitoring respectively. Case studies three and four showed that the new activity variable measured in integer counts was compatible with manual monitoring in detecting rhythmic behavioural patterns (daily and seasonal) (Table 1). With remote monitoring techniques, spatial movement could be accounted for using a series of stations to detect longitudinal movement of tagged fish, showing site-fidelity or migration patterns if the stations are adequately set up as in case study three and six. Case studies four to six used smart tags and helped address some of the limitations in developing FISHTRAC into a robust programme (Table 1). The addition of a water probe in case study seven, demonstrated the ability to monitor aquatic environmental variables in real-time, such as habitat and water quality (Table 1). This allowed for an inclusive programme that monitored both *in situ* water variables and the fish behaviour. This feature makes FISHTRAC unique in that it can use these variables and incorporate them into a holistic ecosystem monitoring programme (Table 1). Finally, case study eight considered other important applications of fish telemetry and includes similar results obtained through other case studies worth noting, such as tagging procedure, recovery period and predator influences that were experienced during developing the FISHTRAC programme (Table 1).

3.1. *Case study one: Labeobarbus kimberleyensis and Labeobarbus aeneus behavioural ecology on the Vaal River, southern Africa*

In this case study the behaviour of yellowfish, *Labeobarbus kimberleyensis* (n = 22) and *L. aeneus* (n = 13) was successfully described, and included the use of beacon tags on the Vaal River, southern Africa (O'Brien et al., 2013). This case study was the first fish telemetry study conducted on these two species and in the largest catchment of South Africa. From this study, the response of yellowfish to environmental variables including water quality, flow, habitat and disturbance to wildlife threats were determined (O'Brien et al., 2013; Ramesh et al., 2018). Manual monitoring was the main means of data collection with additional 24 h surveys conducted (n = 2640; n = 78 observations respectively) over 36 months from July 2007 to August 2010. The behavioural variable selected in this study to represent the behaviour of the tagged fish was MDPM (O'Brien et al., 2013). The data were statistically correlated to a range of environmental variables including instream biotope variability, discharge (m^3/s), water quality (temperatures (°C), conductivity (mS/m), oxygen levels (mg/l) and turbidity (ntu) and atmospheric pressure) (O'Brien et al., 2013; Ramesh et al., 2018). Outcomes included significant differences in movement of these species at different times of the day and between seasons as well as in association with different biotopes. Results also included significant behavioural responses of the yellowfish to rapid changes in discharge, reductions in water temperatures and oxygen levels, and increases in conductivity. Outcomes from this study included new behavioural ecology information of these socio-ecologically important species, a better understanding of the effect of multiple stressors to the Vaal River ecosystem and showed that radio telemetry methods can be successfully implemented in South Africa on *Labeobarbus spp.*

3.2. *Case study two: Hydrocynus vittatus relocation, recruitment and predation strategies, Schoda and Letsibogo Impoundment, southern Africa*

In this case study, an experimental population of *H. vittatus* (n = 14) were captured in the Schroda Impoundment in South Africa and relocated to the Lestsibogo Impoundment in Botswana. The aim was to evaluate the suitability of the impoundment for a *H. vittatus* population and the potential for the population to control local alien invasive fishes (O'Brien et al., 2012). A sample population of *H. vittatus* in Schoda Impoundment (n = 11) was also tagged and tracked for comparison purposes. Both lakes are in the middle reaches of the Limpopo Catchment in southern Africa where the *H. vittatus* population is relatively rare and now locally protected (Smit et al., 2013). Using beacon tags, the behavioural ecology of *H. vittatus* on the relocated population and the source population were manually tracked successfully in the two impoundments (O'Brien et al., 2012). Outcomes of the study showed the compatibility of using radio telemetry within a lentic environment for *H. vittatus*. The outcomes showed that Letsibogo Impoundment is suitable for *H. vittatus*, and showed the successful recruitment of the experimental populations in the impoundment by *H. vittatus* predating on available fishes, including alien fishes (O'Brien et al., 2014a). Movement of the recruited population was within 200 m of their release point for the duration of the study. Although Letsibogo Impoundment (1740 ha) was noticeably larger than Schoda Impoundment (50 ha), home ranges were generally smaller in the Letsibogo Impoundment with less activity possibly because of the high abundance of food (O'Brien et al., 2014a). With Schoda Impoundment being the smaller of the two available food resources were limited and populations highly stressed which showed the *H. vittatus* population adapted to apivorous predation behaviour taking swallows *Hirundo* spp. drinking off the surface of the water (O'Brien et al., 2012,2014).

3.3. *Case study three: Labeobarbus marequensis and Hydrocynus vittatus behavioural ecology in the Crocodile River, Kruger National Park, southern Africa*

Here the habitat preferences of adult *L. marequensis* (n = 16) and *H. vittatus* (n = 13) were evaluated in the Crocodile River, Kruger National Park. This study made use of beacon tags (*L. marequensis* n = 9; *H. vittatus* n = 3) and smart tags (*L. marequensis* n = 7; *H. vittatus* n = 9) and fish were tracked for 33 months from September 2009 to June 2012. Manual monitoring using both tags techniques successfully determined habitat preference, spatial ecology and MDPM similarly to case study one. Results for this study showed that adult *L. marequensis* did not partake in longitudinal migrations (>2 km) instead were more facultative by nature (Burnett et al., 2018). Known migrations of smaller *L. marequensis* through fish passages showed adult fish to exhibit different behaviours highlighting size class limitation when understanding the spatial ecology and life history of species using telemetry techniques (Meyer, 1974). *Hydrocynus vittatus* made extensive (>10 km) use of the river moving in and out of the study area. Activity data from smart tags replicated the MDPM result showing that *L. marequensis* had similar diurnal patterns to other yellowfish species (case study one and three). *Hydrocynus vittatus* results showed similar trends, and this showed the similarities determined through manual monitoring of the behavioural variable MDPM and the smart tag activity sensor. Application of the use of activity sensors determined in detail the effects of flows on the population of *L. marequensis* (Burnett et al., 2018). Comparatively, both tag techniques could determine species variation. However, these could be more accurately determined using the smart tags depth and activity sensors (Fig. 6). Depth profiles determined using the smart tags were definitive in compariosn to the beacon tags estimates, showing in detail distinct differences in depth use profiles for the two species (Fig. 6).

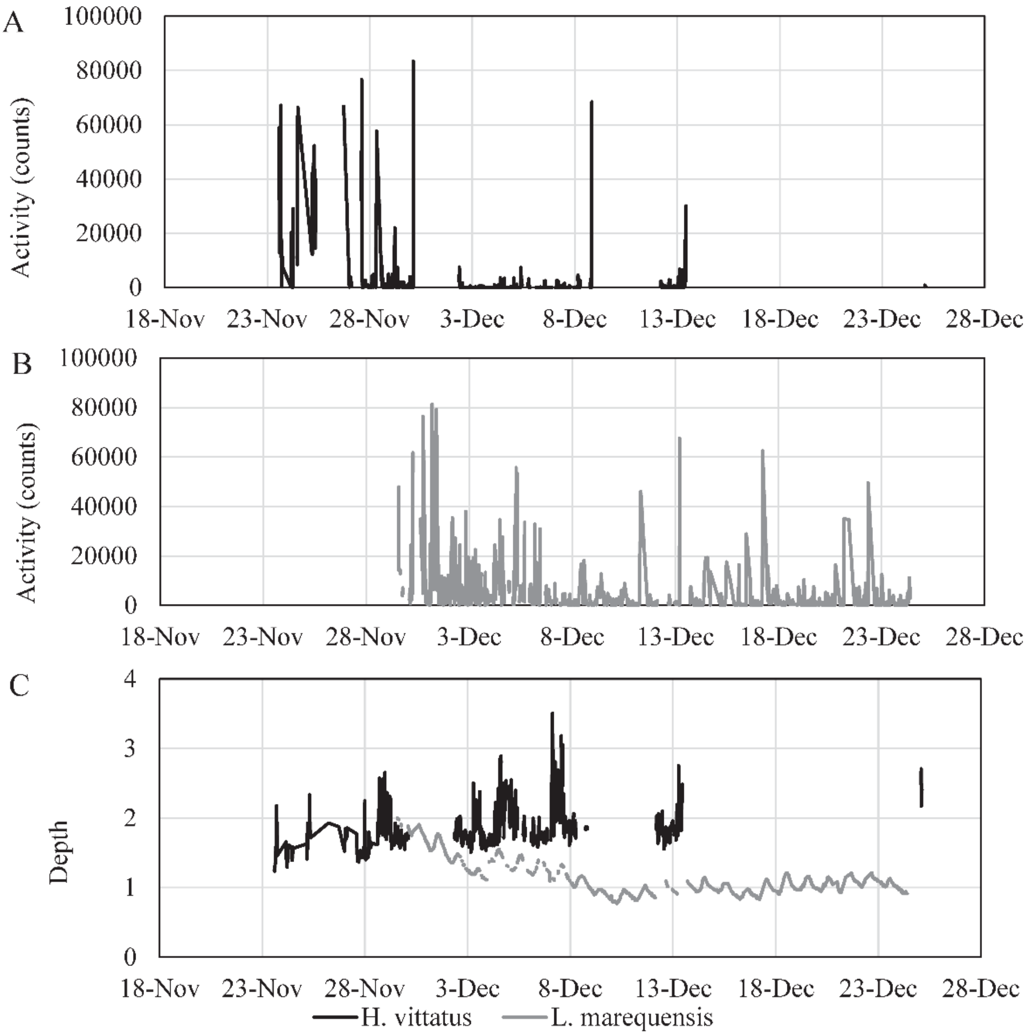

Fig. 6. Real-time (remote) data depicting the activity integer counts of (A) *Hydrocynus vittatus* and (B) *Labeobarbus marequensis*. The depth (m) profiles (C) of *H. vittatus* (Black) and *L. marequensis* (Grey) showed different usage of the depth of the river. The gaps in the data show when the smart tags were out of range, and this highlighted that *L. marequensis* were residential where *H. vittatus* made more extensive use of the river (Source: Data from Burnett, 2013).

Using remote stations to obtain real-time data, the spatial use could be determined on a reach scale, with stations situated as gates in the reach to determine longitudinal use of the reach. This was valuable, as the remote feature and smart tags assisted in overcoming the difficulties found in accessing the site regularly to manually track fish in a protected area containing dangerous wildlife.

Additionally, during this case study, semi-aquatic organisms were experimented on using smart tags that included GPS devices. Two Nile crocodiles *Crocodylus niloticus* were tagged and successfully tracked through the study using the same remote stations used to collect the fish telemetry data. Activity, temperature and spatial movement data showed preferred basking areas and habitat use for *C. niloticus* (Burnett, 2013). Importantly, this showed that the FISHTRAC programme is not limited to fish and could be applied to other semi-aquatic and aquatic (freshwater crustaceans) organism, as technology improves, incorporating an ecosystem approach to freshwater management.

3.4. Case study four: The behavioural ecology of Labeobarbus aeneus a comparison between Boskop Impoundment and the Vaal River, in southern Africa

To characterise the behavioural ecology of the yellowfish *L. aeneus* in lentic and lotic ecosystems, 18 *L. aeneus* were fitted with smart tags in Boskop Impoundment (n = 4) and the Vaal River (n = 14) (Jacobs et al., 2016). *Labeobarbus aeneus* were successfully monitored for 11 months from March to May 2012 using the movement variable, MDPM for manual tracking. Similarly, to case study two, various sensors were tested on tags such as water temperature, activity and depth. These sensors, when tested with the manual monitoring techniques, showed similar results when examining the movement variable, MDPM for manual and activity (integer counts) for the remote system. Results from this study and case study three demonstrated that the smart tag technique could be reliably applied. Again, the use of remote stations as gates along the Vaal River were used to establish focal area use by *L. aeneus* and were found to be more successful as *L. aeneus* were shown to move between stations (Fig. 7). These stations determined at what time and where fish were moving over the duration of the study. Outcomes from activity and MDPM data showed that the *L. aeneus* established distinct daily behavioural patterns, with some individual variations. In Boskop Impoundment *L. aeneus* exhibited higher movement (MDPM) that were associated with deeper water during daylight hours (04:00–16:00). During nighttime (20:00–04:00) *L. aeneus* showed a decrease in movement activity and preferred shallower water compared with daytime (Jacobs et al., 2016). However, *L. aeneus* in the Vaal River appeared to be less influenced by bright daylight, and this might be because of the turbidity of the river water. Moon phases did affect

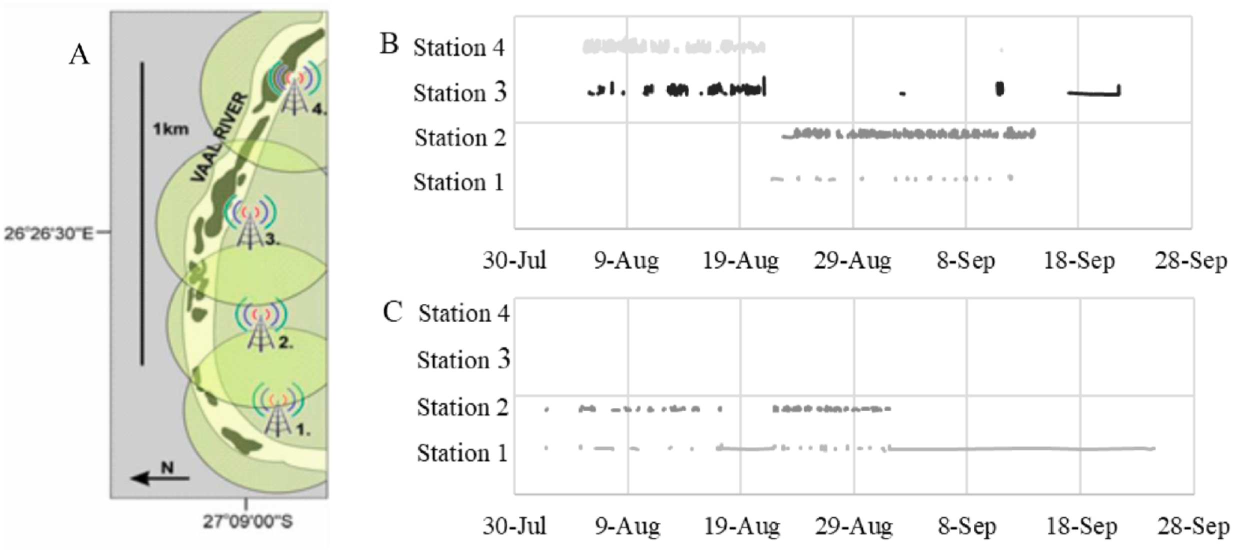

Fig. 7. The spatial use of the river by two individuals of *Labeobarbus aeneus* (Tags 20 and 52) in the Vaal River, South Africa, in case study 4 (A) detected by remote stations situated along the River, (B) the location of tag 20, and (C) tag 52 at the established stations showing the spatial movement of fish in the study area. (Source: Data from Jacobs, 2013).

movement of *L. aeneus* both in the Vaal River and Boskop Impoundment. Movements were significantly higher with increased temperatures and shallower water in summer whereas movements significantly decreased with a decrease in temperature and increased depth in autumn and winter (Jacobs et al., 2016). Seasonal movement data were, however, limited (Jacobs et al., 2016).

Outcomes also included significant behavioural responses of the fish to the availability of different habitats and temperature levels and the establishment of home ranges. High use areas by the *L. aeneus*, drivers of migration and preferred area avoidance were also identified (Jacobs et al., 2016). *Labeobarbus aeneus* showed similar diurnal habitats both within lentic and lotic environments. Sensors were successfully used to evaluate the behavioural responses of the tagged fish to water temperature changes and were validated using the activity sensor on the smart tag and MDPM (Jacobs et al., 2016). The flexible application of using smart tags and smart telemetry technologies together in both a lotic and lentic system in this case study were shown to be valuable and achievable.

3.5. Case study five: Suitability of a rehabilitated impoundment for Labeobarbus aeneus, Vaal River, southern Africa

Building on the known biology and ecology, from case studies one and four, *L. aeneus* (n = 5) were tagged with smart tags to assess whether a rehabilitated small offset impoundment used in a mining operation was suitable for the species (Table 1; O'Brien et al., unpublished data). *Labeobarbus aeneus* were relocated, tagged, released and monitored in real-time for 3 months from October 2012 to December 2012. Signal losses in combination with real-time data indicated that *L. aeneus* moved into deep (>10 m) water during the day. The loss in signal is a limitation when working within a lake environment using radio telemetry methods, as in this case study and case study four, storage tags were developed to record sensory data from fish that were out of range of the remote network. Storing data allows for the continued measurement of variables, which are then stored on the tag to be downloaded once the tag is retrieved, this is commonly known as data storage (DST) or archival tags within telemetry studies (Cooke et al., 2013; Jepsen et al., 2015). The depth of the impoundment exceeded 10 m and the depth use by *L. aeneus* was observed to exceed the radio detection limit. The data storage feature on the smart tags could capture data when a tag was not in range of a remote station because of depth but could be applied for lateral and longitudinal movements too. Preliminary results showed tagged fish to rest near the surface at night, but when feeding during the day the tagged fish were out of range moving into deeper water. Storage capacity on the tag successfully collected movement, depth and temperature data during periods when tagged fish were out of range and downloaded the data when they returned. The stored data along with the real-time data provided a continuous data set for the duration of a study despite the spatial movements of fish. These technical outcomes contributed to understanding the data storage technique developed within the smart tags, however, because of small sample sizes only reports to the funders were presented (Table 1; O'Brien et al., unpublished data).

3.6. Case study six: Assessing the use of Albert Falls Impoundment as refugia habitat for fish in the uMngeni River, southern Africa

In this case study *L. natalensis* (n = 52) were tagged in Albert Falls Impoundment, Cramond, South Africa, over 3 years from December 2015 to June 2019 to test the ability of smart tags to store data when out of range of a relay station (Table 1; Burnett et al., unpublished data). *Labeobarbus natalensis* use Albert Falls Impoundment as refugia habitats occasionally moving into the river, primarily during the summer months (Crass, 1964; Impson et al., 2008). The data storage feature of smart tags used allowed the download of data without the need to retrieve the tag and linked the fish to where it was detected, and could determine when and where *L. natalensis* left the refugia habitats. This study showed how the application of DST could be incorporated into FISHTRAC, while accumulating data in real-time to understand activity (Fig. 8) and movement, whether it was on a vertical, longitudinal and latitudinal scale. In this study, relay stations were set-up to cover the impoundment and the uMngeni River inlet. As *L. natalensis* moved in and out of Albert Falls Impoundment and into the river stored data were obtained. Further assessments could be conducted to determine activity movement within lentic and lotic environments based on data acquired through the storage tags. In addition, two other species not known to migrate upstream were tagged, *Micropterus salmoides* (n = 2) and *Oreochromis mossambicus* (n = 2), to preliminarily assess their movements within the impoundment and use of the river: These tagged individuals remained in the impoundment with no movement upstream. A limitation was experienced in that large impoundments did not allow for the remote network to cover the central area of the

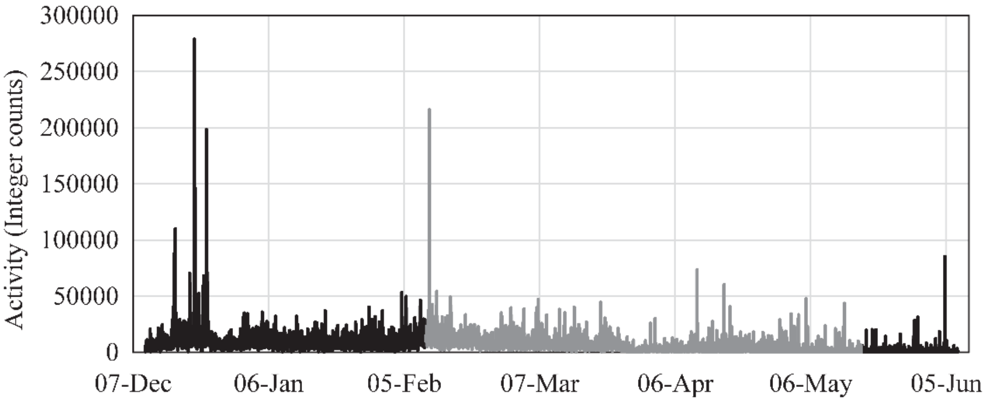

Fig. 8. Example of remote monitoring activity (integer counts) data from a *Labeobarbus natalensis* tagged in Albert Falls, KwaZulu-Natal, South Africa. Real-time data (black) obtain from the fish when in range of the remote network on the lake and stored data (grey) recorded while out of range and downloaded on return into range of the remote network. (Source: Burnett et al., unpublished data).

impoundment adequately. Only when fish moved within 500 m of the remote station, and close to the surface, could signal be detected and stored data downloaded. This limitation was found to be an important consideration when capturing and tagging fish as the latter should be done within range of an established remote network. Remote stations set-up around important habitats can show affiliation to these habitats (lotic versus lentic environments) especially if these habitats are only used during certain periods of the year (Table 1; Burnett et al., unpublished data).

3.7. Case study seven: Incorporating water quality and quantity monitoring into the FISHTRAC programme, the Senqu River, southern Africa

In this study the functionality of the water probe was tested, and hydraulic modelling techniques were used to determine habitat variability of two sites in the Senqu River in Lesotho (Table 1; Merwade et al., 2008; O'Brien et al., 2018). The water probes were deployed onto hydraulic transects in the river for which flow-duration curves were established using the depth (a function of the atmospheric pressure subtracted from water pressure and thereafter 0.9807 mBar = 1 cm depth of water) to calculate the discharge at the site (Thompson and Taylor, 2008). This information was of great value in linking the discharge modelling outputs to probe depth allowing the evaluation of various flows on habitat availability (Fig. 9). In addition to the depth data, EC and temperature information associated with the site were available. The outcomes of this study showed that habitat availability and water quality linked to discharge, as determined through the hydraulic cross-sections, and depth could be determined successfully remotely using the water probe (O'Brien et al., 2018). This demonstrated the functionality of the probes to generate environmental data, with the possibility to relate the biological variable in real-time and remotely. The successful use of the water probes to measure and communicate environmental variables on the same time intervals, and through the same radio telemetry system as the smart tags, showed the potential to integrate water probes and fish tags into one study. This will greatly aid data collection along similar temporal scales to determine the ecological responses of fish to multiply stressors and the associated changes within the aquatic environment (Table 1; O'Brien et al., 2018).

3.8. Case study eight: The effect of capture stress on tagged fish, Okavango Delta, Vaal and Crocodile Rivers, southern Africa.

A telemetry study was conducted on *H. vittatus* (n = 4) in the Okavango River to assess angling stress and tag attachment procedures (Table 1; O'Brien et al. unpublished data). This study formed part of a greater study to evaluate the effect of angling on *H. vittatus* in the Okavango River and demonstrated the use of radio telemetry methods within a tropical river system (Smit et al., 2009). *Hydrocynus vittatus* were caught using standard angling techniques, they were then tagged with external tags and had blood drawn for analyses before being release and monitored for two weeks to assess their recovery. Outcomes from this study showed the successful recovery of the fish after tagging and drawing blood. This showed that fish, given the time, can recover from the angling capture techniques and tagging procedure, and often seek out temporary refuge areas to do so (Smit et al. 2009; O'Brien et al., 2013). These results were validated in other case studies in the Vaal River (O'Brien et al., 2013) and in the Crocodile River (Burnett et al., 2018) developing the concept around response behaviour to external stimuli or environmental variables.

In developing the FISHTRAC programme, external tags were chosen as the primary means to attaching tags to fish. External tagging, where possible, is the preferred field tagging procedure as it is easy to learn and apply in the field (Thorstad et al., 2013). This tagging technique showed to be true when developing FISHTRAC and fits its application in southern Africa where field site access is often limited, field laboratories not always accessible to site and expertise lacking (Hocutt et al., 1994). During preliminary tagging procedure tests, it was found that tag size had a greater effect for internal tags than weight, when using the 2% body mass rule and further studies would be required to understand the tag body mass ratio particularly for *Labeobarbus* spp. (Jepsen et al., 2004; Childs et al., 2011; Cooke et al., 2011). Tag development techniques for the FISHTRAC programme still require large fish to be tagged because of battery trade-offs, making internal tags difficult to administer on fish with small abdominal cavities, this could change with advancements in technology.

Tagged fish need a recovery period post-tagging procedure before any data analyses can be carried out as normal behaviour, as shown in previous studies (Bridger and Booth, 2003; Thorstad et al., 2004). This period is when fish are most vulnerable to predation as they inhibit normal predatory response mechanisms (Thorstad et al., 2004; Burnett et al., 2018). This needs to be considered when working in African aquatic ecosystems because of the high presence of natural predators such as African fish-eagles (*Haliaeetus vocifer*), *C. niloticus* and otters (*Aonyx* spp.) that can have an influence on fish telemetry project as seen in case study one and three (O'Brien et al., 2013; Burnett et al., 2018). This does highlight the importance of understanding the predator avoidance strategies or impacts on fish telemetry studies. In some instances, the presence of field researchers during manual monitoring surveys was shown to cause disturbance to tagged fish when approaching too close to the fish, so care should be taken to minimise disturbance of tagged fish that could bias results (O'Brien et al., 2013). This disturbance is one of the drawbacks of using manual techniques and is overcome when using remote monitoring.

4. FISHTRAC an ecological and environmental monitoring programme

Following these case studies, the telemetry approach, using radio

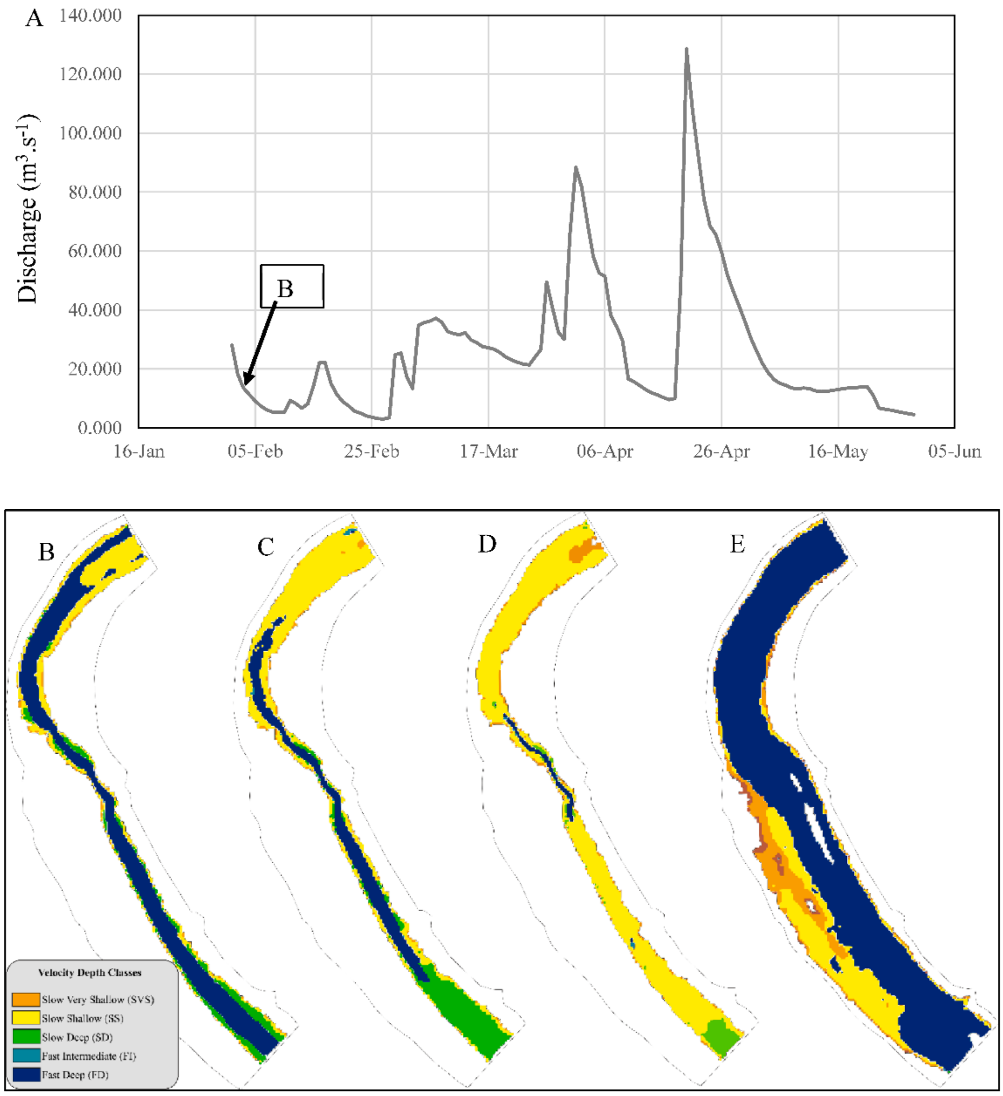

Fig. 9. The hydrograph (discharge) determined using the depth (mm) data from water probes (A) and then used to model the velocity depth classes on the Senqu (Orange) River, Lesotho, (B) at 16.54 $m^3.s^{-1}$ using River 2D hydraulic/hydrology modelling techniques. Velocity depth class models C, D and E are modelled flows for 10, 5 and 400 $m^3.s^{-1}$ respectively (Source: Data from O'Brien et al., 2018).

and smart technologies into fish tags and water probes, established a monitoring programme to understand the ecological consequences of multiple water quality and quantity variables in real-time and remotely. This application of incorporating smart tags and manual and remote monitoring techniques has contributed to the FISHTRAC programme's success.

The smart tags can receive and transmit information, so transferring digital coded messages (data) from sensors on the tag. Tag size currently limits the size of fish used (>500 g); smaller fish can be used in short term applications and as technology advances to create smaller smart tags. The stored data on tags can be obtained without the retrieval of the tag, if the tagged fish returns into range of an established remote network. This feature allows for continued data retrievals over the study period. Water probes can last up to three years, while fish tags will last up to a year dependent on the variables needed and time frame of the study. The ability to add a range of sensory components to tags that can measure different variables directly associated with the fish's geographical location in the aquatic ecosystem is a valuable feature and can grow as technologies improve. Tagged fish can then be tracked using these techniques so that their movement, activity and habitat associations (as examples) can be linked to water quality variables recorded by probes.

The manual monitoring feature operates similarly to that of traditional radio techniques. The conservation of battery life through scheduled changes allows for the use of both manual and remote tracking when needed. Changes to schedules requires more tag management but can be beneficial in the long run. For example, changing from remote to manual tracking allows retrieval of expelled tags or tagged fish that have been predated. In addition, switching to manual monitoring following an event detected using the remote systems, allows the researcher to investigate the event further. Manual monitoring is important to ground-truth data from the established remote monitoring system.

The remote monitoring systems are a relatively new concept within fish telemetry that has been implemented in at least three case studies (Table 1; Case study 6; Burnett et al., 2018; Jacobs et al., 2016) and shown to be effective on various levels namely: to acquire data remotely from tags in real-time and provide information for reach-scale spatial movements of individuals determined when field researchers are absent. The remote monitoring stations are robust, self-sustaining with solar panels, cost effective (twice the cost of fish tags) and small (30 × 30 cm in size). They can easily be mounted on poles/trees and structures adjacent to rivers or lakes, this can aid their concealment protecting them from theft. Establishing an array of remote stations within an economically important river system could facilitate various studies across water quality, quantity and animal (semi-aquatic and aquatic) behaviour disciplines providing valuable information towards river ecosystem management. An array of receivers will greatly reduce the cost of establishing a network as this can be shared between users and promote long-term research collaborations (Lennox et al., 2017; Reubens et al., 2019). Remote stations transmit data automatically to the DMS that can be accessed through a secure password protected internet portal. The DMS can also be set up to send alert messages to users when data from specific tags are obtained and/or when certain thresholds of water quality and/ or flow variables are exceeded, this is true for activity signatures from tagged fish.

If tagged fish move too deep (>10 m) or out of range of a station, not only can data be stored on the tag, but this movement can be set-up in the DMS as a behavioural response to send alerts to users. The FISHTRAC programme is ideal for rivers, large instream pools or lakes that do not generally exceed >10 m in depth and/or for application of species that are more pelagic by nature. Stored data can be statistically analysed to generate important biological and ecological information for tagged species and can be used to evaluate the effect of water quality, flow and habitat alterations on freshwater ecosystems. Software platforms can be developed to utilise incoming data and set alarms around pre-determined thresholds of potential concerns (TPC) to alert managers to important events or occurrences that exceed these TPC's.

In addition to the understanding these techniques and based on the knowledge and experience gained from the case studies, we advocate four phases to complete a successful FISHTRAC monitoring exercise. These phases consist of an inception phase, planning phase, analysis phase and an outcome phase.

4.1. Phase I – inception

In this phase the objectives, scope, hypotheses and resource requirements of a project are considered. This important step considers the technology trade-offs to determine the cost effectiveness and maximise the benefits of using FISHTRAC where resources and expertise are limited (Dube et al., 2015). The FISHTRAC programme has multi-applications, making it cost-effective and applicable through a range of research, conservation, fisheries and water resource management fields where behavioural information of fish is required to make management decisions.

4.2. II – planning

Once FISHTRAC is chosen, an evaluation of information, experimental design, fish species and area suitability must be considered. Although this can take place in the inception phase, it is considered as part of the planning phase as the study becomes more specific to the area and fish species being studied. The evaluation of past telemetry studies, the design of such studies and this present publication can greatly assist in understanding the best way forward to answer hypotheses, even if these studies have not been implemented within the proposed study area. Thus, part of the experimental design for the study is to contextualise information towards local conditions. Finalising the inception phase can be done here as a work plan and is developed with an adaptive model considered for unseen circumstances, characteristic of behavioural studies, where possible; such as seasonal events, environmental changes and other dynamic ecological processes. Finally, the suitability of the study site (security and access) and fish species (size and abundance) need to be considered. This is especially true for remote monitoring where extensive networks need to be installed to determine fish behavioural movements. It is preferred to use fish species where behavioural information exists to ease the experimental design of the project and set-up of the remote network. If this does not exist, initial manual monitoring surveys should be implemented.

4.3. Phase III – data collection and analyses

Once FISHTRAC is implemented, then the data collection and analyses follow, this is presented in a seven sub-step process to implement the study. These sub-steps include: (1) remote monitoring network set-up, (2) water probe deployment, (3) capture, tagging and release strategies, (4) recovery monitoring considerations, (5) remote and manual tracking/monitoring techniques, (6) data collection and evaluation and (7) uncertainty considerations. These steps, as discussed in the case studies, create a structured, repeatable and robust programme in which to undertake a telemetry project. Uncertainty is minimised through careful planning in phase one and two, preparing for unseen circumstances. These unpredictable changes in movement are important when tracking and monitoring to obtain adequate data and/or valuable outliers that indicate changes. The evaluation of such data is valuable to any hypotheseis testing and can implicate the outcomes of the study. It is important to document such events or lack of response and account for them to adapt the approach where applicable. Statistical testing of data needs to be evaluated to determine significant changes in behaviour that warrant the investigation and determination of TPC's for the aquatic ecosystem.

4.4. Phase IV – outcomes

This is the final and most important phase of FISHTRAC: it sums up the study and evaluates the hypotheses and predictions, considers biological and ecological outcomes for the species studied and communicates findings to managers and other researchers. In all the case studies evaluated, reports, papers and articles surrounding the projects were published or presented in some form (Table 1). Without reporting or publishing, the study cannot conclude adequately even after successful implementation. If outcomes are not achieved successfully, failures and shortcomings should be documented in order to build on and learn from them. The user interface platforms or dashboards such as the DMS can be used to communicate the outcomes alongside the real-time application, through quarterly or annual monitoring reports. Importantly with fish telemetry studies, sufficient sample sizes are necessary to improve research outputs and confidence in data, and must be considered during the planning phase.

These four phases advocated by the FISHTRAC programme do not replace, but instead add value to established radio telemetry methods through a fish behavioural monitoring programme, by using smart tags that allow the use of real-time monitoring for multiple stressor management in southern Africa. The FISHTRAC programme can facilitate much needed fish behavioural data for the region in promoting and supporting the use of fish telemetry studies and monitoring of inland aquatic ecosystems. The FISHTRAC programme has overcome some of the limitations described for fish telemetry method applications in Africa by integrating sensors, data storage and remote techniques. Fish telemetry studies within the region in freshwater ecosystems post the 2010's have been driven primarily through the development of FISHTRAC to showcase the importance of managing inland aquatic ecosystems using fish behaviour (O'Brien et al., 2012, 2013; Jacobs et al., 2016; Burnett et al., 2018). The four phases and clear implementation of the methodology for FISHTRAC are designed to assist researchers in using fish telemetry but these guidelines can also be used by conservation and water resource managers. The application of this methodology through manual and remote monitoring techniques (Fig. 5) is set out relatively simplistically for managers to clearly understand the application of the technologies and how biological and environmental information needed are obtained.

5. Conclusions

The FISHTRAC programme adds to a growing body of work that illustrates remote capabilities of radio telemetry methods to monitor fish behaviour and water quality issues in real-time. This, along with the local support, reduces the costs of using telemetry within the region. The DMS that stores, presents and evaluates data for alerts to breaches in TPC's, allows for remote and rapid access to data, assisting in prompt action to mitigate pollution events or disruptive behavioural changes. The development and implementation of FISHTRAC, following the eight case studies highlighted here have successfully shown how radio telemetry methods can be used to answer critical management questions within southern Africa, for freshwater ecosystems that are under anthropogenic land use and climate change pressures. To adequately evaluate the ecological impact of these multiple stressors, 'normal' behaviours of fish species as a baseline are required and from there 'abnormal' behaviour can be used to determine the stressor. There are several metrics and indices used to measure and monitor the ecological responses of these multiple stressors, however, they can be invasive, time consuming, resource intensive and unable to address the ecological responses in real-time nor remotely (Kleynhans, 1999; Wepener, 2008; O'Brien et al. 2018). Using fish behaviour to alert mangers to TPC's can be coupled by further assessment to use more sensitive and time-consuming methods in order to understand the reason for these behavioural changes. These methods can include biomarkers, fish health and fish community indices. In addition, alternative aquatic organisms such as aquatic macro-invertebrates can be assessed as these are food sources for many fish species and are exposed to similar stressors (O'Brien et al., 2014b; Sabullah et al., 2015; Gerber et al., 2016; Dickens et al., 2018). Changes (sudden or chronic) in fish behaviour can then direct managers to pollutants that otherwise would remain undetected or persist within the aquatic ecosystem undetected because of the inability to test for such variables on a regularly basis (Vieira et al., 2009; Gerber et al., 2016). The FISHTRAC programme uses fish telemetry methods to monitor these behavioural changes and then with continual monitoring of known stressors and fish behaviour can determine the chronic and event-base stressors on further investigation. The FISHTRAC programme can further update baseline and response data, making it an ongoing, in real-time and adaptable approach. Existing real-time water quantity and ecological monitoring programmes, such as Pollard et al. (2012) and Agboola et al. (2019), can incorporate the FISHTRAC programme to better achieve nationally set objectives. Alternatively, the FISHTRAC programme can be used as LoE when setting ecological reserves and can be used in adaptive relative risk models (O'Brien et al., 2018). With the multiple anthropogenic stressors such as flow reductions and augmentation through water schemes, waste water treatment works and the mining sector's discharges affecting freshwater ecosystems in southern Africa, fish are constantly exposed to such stressors and will change their behaviour in response to them (O'Brien, 2013; Rodell et al., 2018; O'Brien et al., 2019). The FISHTRAC programme can detect and evaluate fish movements and responses remotely and in real-time providing managers with evidence-based data to inform the decision-making process and is applicable within freshwater ecosystems across the region and globally.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests nor personal relationships that influenced the work reported in this paper.

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CHAPTER 4

Locomotive activity of free-swimming fish as an indicator of environmental factors in the Crocodile River, Kruger National Park, South Africa

Matthew J. Burnett[1,5], Gordon C. O'Brien[1,2], Victor Wepener[3], Graham Jewitt[4,5], Colleen T. Downs[1]

[1] Centre for Functional Biodiversity, School of Life Sciences, University of KwaZulu-Natal, P/Bag X01, Scottsville, Pietermaritzburg, South Africa, 3209

[2] School of Biology and Environmental Sciences, Faculty of Agriculture and Natural Sciences, University of Mpumalanga, Nelspruit, South Africa,

[3] School of Biology and Environmental Sciences, Faculty of Agriculture and Natural Sciences, University of Mpumalanga, Nelspruit, South Africa, 1200

[4] Centre for Water Resource Research, University of KwaZulu-Natal, P/Bag X01, Scottsville, Pietermaritzburg, South Africa, 3209

[5] *Institute for Water Education, IHE Delft, Westvest, South Holland, Netherlands, 2611*

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* Corresponding Author: Colleen T. Downs
Email: downs@ukzn.ac.za
Tel: +27 (0)33 260 5127
ORCID: http://orcid.org/0000-0001-8334-1510
Other emails: matthewburnett014@gmail.com, ORCID: https://orcid.org/0000-0002-6237-1697; gordon.obrien@ump.ac.za, ORCID: https://orcid.org/0000-0001-6273-1288; victor.wepener@nwu.ac.za, ORCID: https://orcid.org/0000-0002-9374-7191; g.jewitt@un-ihe.org, ORCID: https://orcid.org/0000-0002-7444-7855

Running header: The use of locomotive activity to understand stressors on the behaviour of different fish species.

4.1 Abstract

The increase in anthropogenic stress on river ecosystems is of growing concern globally as demand for water increases and aquatic ecosystem deterioration is observed. Understanding the biological response to these stressors is important to maintain ecosystem functioning, the conservation of species and the ecosystem services they provide. In using radio telemetry to determine the biological response of ten *Hydrocynus vittatus* and seven *Labeobarbus marequensis* to environmental factors evaluated from September 2011 to January 2012 in the Crocodile River, Kruger National Park. Remote sensing techniques were used to collect data from *H. vittatus* (total 18505 data entries) and *L. marequensis* (total = 17468 data entries) and validated with manual monitoring surveys (number of fixes n = 74 from *H. vittatus* and n = 21 from *L. marequensis*). The results showed that *L. marequensis* and *H. vittatus* did have different locomotive activity as expected. Activity from both species showed them to be diurnal, however, their activity patterns differed over the time of day (TOD). *Hydrocynus vittatus* utilised early mornings into midday, while *L. marequensis* showed a peak in activity around midday. Rest periods were identified at night for *L. marequensis* and *H. vittatus* by moving into back water as observed during manual monitoring. Changes in the environment (both water temperature and discharge, with greater response to minimum temperatures) significantly affected behaviour of *H. vittatus* in terms of activity. *Labeobarbus marequensis* behaviour was affected by increased water temperatures and changes in discharge. Full moon periods showed to increase the activity of *L. marequensis* and further supports findings that these species are affiliated with high water clarity where light penetration is good. Both species responded to water temperature highlighting the importance of monitoring temperature

changes in the system using the biological response as an indicator and posits pressure to meet the environmental water reserve (EWR). The relationship both these species had towards changes in flow (including temperature) strengthened the argument to use behavioural ecology of fishes as indicators when monitoring environmental flows that can be conducted in real-time.

Keywords: fish behaviour temperature, discharge, movement, environmental flows, river connectivity, indicator species

4.2 Introduction

Aquatic ecosystem well-being is becoming an important management directive as the stressors for water resources continue to increase globally along with the increase in anthropogenic stressors (Dudgeon 2014; Rodell et al. 2018; Du Plessis 2019; Sabater et al. 2019). Monitoring and understanding the effect of these stressors is important when it comes to setting management goals and objectives to mitigate pollution events and achieve sustainable management for aquatic ecosystems (Pearce 2018; Dickens et al. 2019).

Fish are exposed to these stressors inducing behavioural responses to maintain biological and ecological functioning (Chovanec et al. 2003; Chevin et al. 2010; Tamburello et al. 2015). Fish are, therefore, considered important indicators of aquatic ecosystem well-being as they respond to the environmental variables and stressors within the aquatic ecosystem (Harris 1995; Chovanec et al. 2003; Baumgartner et al. 2014; Tamburello et al. 2015). Fish are adapted to the environments in which they occur, this includes both intra- and inter-species competition for space and resources (Godin 1997; Ward et al. 2006; Pinsky 2019). These relationships often cause species to take up suitable niches to minimise direct competition and will result in use of different trophic levels and habitats resulting in varying tolerances to environmental variables (Leibold and McPeek 2006; Pinsky 2019).

The ability and response of fishes to maintain biological and ecological functioning within a changing environment shows the resilience of a species and its vulnerability towards certain ecosystem stressors (Ramesh et al. 2018; Pinsky 2019). Measuring this resilience can be challenging because of a multi-variable environment and behavioural factors that contribute to the make-up of a species and their niche (Godin 1997; Ward et al. 2006; Pinsky 2019). Understanding these differences is important for water resource managers as the biological response to changes in water quality and quantity variables will vary between species effecting the ecosystem well-being if managed for one indicator species (Kleynhans 1999, 2008; O'Brien et al. 2018). Fish behavioural studies have contributed to determining these behavioural niche differences, especially in reference to understanding their responses to changes in environmental conditions (O'Brien et al. 2013; Cooke et al. 2013, 2017; Burnett et al. 2018). Conventional capture and mark-recapture (CMR) techniques limit the continual monitoring of behaviour of fish and their response, which can be achieved using more responsive techniques such as fish telemetry (Thorstad et al. 2013; Burnett et al. 2020). Fish telemetry studies make use of accelerometers or motion sensors to monitor the locomotive activity of fish to answer various management and research questions around the biology and ecology of fishes (Thiem et al. 2015; Cooke et al. 2016; Burnett et al. 2018; Thiem et al. 2018). These motion sensors are increasing in popularity as they assign fish behaviour with a unit of measurement that has relatively little observer bias and can provide continual information to researchers (Cooke et al. 2016; Thiem et al. 2018; Burnett et al. 2020). Studies conducted within South Africa have used activity sensors to evaluate the response of *Labeobarbus marequensis* to flows (Burnett et al. 2018).

Labeobarbus species along with tigerfish (*Hydrocynus vittatus*) are relatively good indicator fish species within southern Africa as they are long-lived, large growing and found in a range of aquatic ecosystems (Skelton 2000; Impson et al. 2008; Wepener et al. 2011; Smit et al. 2013). These species have been shown to be sensitive to anthropogenic related environmental stressors, occupy similar trophic levels, are charismatic species and they share the same rivers (Pienaar 1978; Skelton 2000; Impson et al. 2008). Further these species hold economical value within the angling and fisheries industry for the region (Brand et al. 2009; Smit et al. 2016; Gerber et al. 2017). Understanding a species tolerance can assist managers in managing the state of the aquatic ecosystems based off a real-time response or no response of tagged fish instead of relying on quarterly changes to the fish community index (Kleynhans 1999; Burnett et al. 2019). The *Labeobarbus* taxon and *Hydrocynus Vittatus* has widely been used in telemetry studies within the region (Roux et al. 2018; Burnett et al. 2018; Burnett et al. 2020). *Labeobarbus marequensis* and *H. vittatus* have relatively different morphic measurements and habits taking up different niches within the systems they occur, and occasionally competing for the same food source (Pienaar 1978; Skelton 2016). *Labeobarbus marequensis* are sensitive to changes in flow but it has been poorly studied in understanding its response to water quality and quantity variables (Fouché 2009; Burnett et al. 2018). *Hydrocynus vittatus* have been extensively studied for its use as an indicator species for changes in water quality and is considered a relatively good indicator of changes in flow (O'Brien et al. 2012; Smit et al. 2013; Gerber et al. 2016; Gerber et al. 2018). Comparing these two species concurrently will contribute to the knowledge of the environmental factors and how they respond, this knowledge can help managers mitigate environmental stressors.

For the present study, we used motion sensors attached to tigerfish (*H. vittatus*) and yellowfish (*L. marequensis*) to determine the sensitivity of the motion sensor in understanding differences in species behaviour. Further we used activity rates to determine the responses of these species to environmental variables. We explored the relationships between *H. vittatus* and *L. marequensis* and their responses to environmental factors present in the study.

4.3 Materials and methods

The Crocodile River in the Incomati River catchment, South Africa, has shown to be impacted directly from anthropogenic stressors (Arthington and Balcombe 2011; Nel et al. 2007; Saraiva Okello et al. 2015). A 12 km reach on the Crocodile River, Kruger National Park (KNP), South Africa (Fig. 4.1) was selected for the study because of an already establish remote radio-telemetry network between Van Graan Dam and Mjejane Bridge (Burnett et al. 2018). Van Graan Dam is a semi-permeable barrier restricting the movement of fish upstream out of the study area. The study area is one of the few ecosystems within South Africa where the two fish species occur together naturally, in high abundances of adult specimens (Pienaar 1978; Skelton 2016) (Fig. 4.1). Furthermore, there is an abundance of diverse habitats suitable for the two species to interact with during the study period (Kleynhans and Louw 2008).

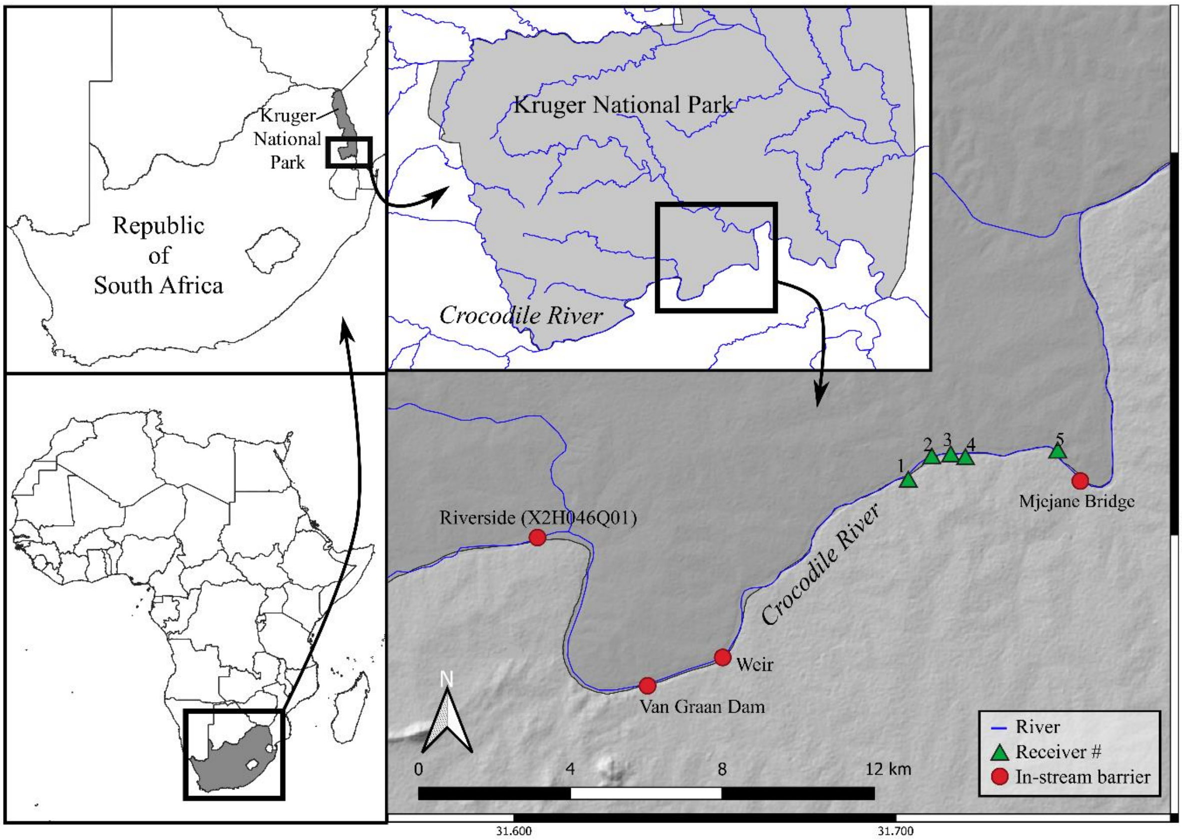

Fig. 4.1 The study area along the Crocodile River, Kruger National Park, South Africa, used in the present study. The location of Van Graan Dam and the Riverside Gauging Station are depicted along with the lower limits of the research area at the Mjejane Bridge.

Hydrocynus vittatus and *L. marequensis* species were caught primarily using angling techniques targeting the two species separately (Table 4.1). *Hydrocynus vittatus* were caught on bait or lures used for targeting *L. marequensis* which composed of earthworms and aquatic invertebrate mimics. *Labeobarbus marequensis* did not take to bait used to target *H. vittatus* (large artificial lures). Fish tagged met the 2 % body mass to tag ratio as recommended by Jepsen et al. (2004, 2015). Both species were tagged using external tagging techniques based from Burnett et al. (2018) and Jacobs et al. (2017). All suitable fish caught were anaesthetised with clove oil (0.4 ml l^{-1}) until signs of narcosis were shown. Two 14-gauge surgical needles were inserted through the muscular tissue below the dorsal fin and then surgical wire threaded through before the needles were removed. The surgical wire was then fastened to secure the tag, with the motion sensor, to the fish. The fish was then moved into a recovery container holding freshwater from the capture location and monitored until full recovery was observed. Once recovered and the fish could swim strongly it was released in the vicinity where it was caught and in range of the remote monitoring network (Burnett et al. 2018).

Table 4.1: The tagged individuals of *Hydrocynus vittatus* and *Labeobarbus marequensis* indicating the tag used, size of fish, tagged location and the number of data samples per individual used in the present study

WW Tag	Tag code	Species	Weight (g)	Capture site		Tag date	End date	Fixes (n)
Series I	*HVIT9	*H. vittatus*	1700	-22.22422	31.43179	19-Sep-11	16-Nov-11	3701
Series I	HVIT13	*H. vittatus*	2100	-22.22422	31.43179	22-Sep-11	17-Jan-12	6740
Series I	HVIT15	*H. vittatus*	4000	-22.22422	31.43179	22-Oct-11	22-Nov-11	1833
Series I	HVIT16	*H. vittatus*	2000	-25.37885	31.71478	4-Nov-11	02-Dec-11	1664
Series I	HVIT19	*H. vittatus*	2500	-25.37871	31.71586	19-Sep-11	22-Oct-11	161
Series I	HVIT21	*H. vittatus*	2200	-25.37864	31.71333	16-Sep-11	04-Oct-11	1550
Series I	HVIT23	*H. vittatus*	1300	-25.22438	31.42529	19-Sep-11	25-Dec-11	49
Series I	HVIT31	*H. vittatus*	2100	-22.22422	31.43179	26-Nov-11	02-Jan-12	236
Series I	HVIT35	*H. vittatus*	2100	-25.2249	31.42282	28-Nov-11	17-Dec-11	224
Series IV	HVIT41	*H. vittatus*	3000	-25.22394	31.44291	23-Nov-11	25-Dec-11	892
Series I	*LMAR6	*L. marequensis*	2500	-25.3784	31.7197	19-Sep-11	17-Jan-12	5049
Series I	*LMAR7	*L. marequensis*	2500	-25.3784	31.7197	19-Sep-11	15-Nov-11	5809
Series I	LMAR12	*L. marequensis*	2200	-25.37885	31.71478	19-Sep-11	20-Nov-11	2997
Series I	LMAR14	*L. marequensis*	2300	-25.3784	31.7197	15-Oct-11	20-Oct-11	479
Series I	LMAR17	*L. marequensis*	2300	-25.3784	31.7197	19-Sep-11	23-Sep-11	312
Series I	*LMAR25	*L. marequensis*	2800	-25.3784	31.7197	19-Sep-11	27-Dec-11	1563
Series IV	LMAR42	*L. marequensis*	3900	-25.3784	31.7197	29-Nov-11	24-Dec-11	1260

*Monitored manually during the study (*Hydrocynus vittatus* n =74; *Labeobarbus marequensis* n =21)

All fish tracked in the present study had Wireless Wildlife (WW, 13 Forsman Street, Potchefstroom, 2531) tags (WW tag series I and IV) attached. These tags included temperature and omnidirectional tilt and vibration (SQ-SEN-200 series) sensors which were used to monitor water temperature and fish activity patterns (behavioural movement variable) respectively as described in Burnett et al. (2020). The activity sensors have been used to evaluate activity patterns of animals when using telemetry techniques and provide a measure of locomotive activity (Horn et al. 2011). Data from the tags were recorded and transmitted at 10 min intervals during the study, as tags did not have data storage options, therefore data acquired was done in real-time through an established network of remote stations (Fig. 4.1). Remote telemetry was the preferred monitoring method for this study as it allowed for data to be gathered continually for extended periods as access to the study area was limited. The core study area (5 km) was covered adequately with remote stations and consisted of 5 stations, including a base station that served as a receiver and could send data to the central data management system (DMS) where data could be accessed (Fig. 4.1; Burnett et al. 2020). Manual monitoring techniques were based on O'Brien et al. (2013) and Burnett et al. (2018), whereby fish were additionally tracked using a Yagi-directional antenna and included repeated 24 h surveys. During surveys the movement and position of individuals in relation to associated habitats and environmental variables were monitored. Manual monitoring primarily served to validate the remote data for both species within the study area and provide habitat and behavioural insight.

4.3.1 Data analyses

Site fidelity was determined by continual monitoring of tags in range of the remote network, tags not detected determined the absence of the fish from the study area indicating home ranges greater than 5 km. Frequency distributions and descriptive statistical analyses included the use of Windows Excel, (©2013, Microsoft Corporation) and R v. 3.6.1using LME4 and Vegan packages (Rstudio Team 2015; Oksanen et al. 2007; Douglas et al. 2015).

Data points were assessed hourly for TOD assessment to determine movement over the diel period. Further analyses on the activity of fish against environmental variables monitored during the study were tested for multicollinearity and selected for based on Pearson's correlation co-efficient test ($r < 0.60$) and then a principal component analysis (PCA) used to test for relationships (Graham 2003). For this study we compared the behavioural component (locomotive activity) for the individuals of each species and the environmental variables such as flow, temperature rainfall and moon phases (Van den Brink et al. 2003; Bengraïne and Marhaba 2003; O'Brien et al. 2009; Nasir et al. 2011). The PCA is the preferred method with large complex databases such as various species (n=2) and individuals (n=16) accounting for n = 35973 data points using a linear response model relating species against environmental variables (Van den Brink et al. 2003; Nasir et al. 2011). To understand the groupings between species response and environmental variables measured, a redundancy analyses (RDA) was assessed on top of the PCA plot to create a bi-plot, that graphically depicted the linear regression relationship between the individuals (for both species) and the directional pull from the environmental variables by plotting the best fit regression linear graphical in the direction of the pull from the environmental variable (O' Brien et al. 2009; Nasir et al. 2011).

Environmental variables were obtained from various sources, with water temperature acquired from the mean, maximum and minimum temperatures recorded using the fish tags in the study from 13 fish. Moon phases were calculated using the date of sampling and the moon intensity (% of phase, 100 % = Full moon) at the time of sampling. Rainfall data were collected at two rainfall stations by the Department of Water and Sanitation (DWS) through the Incomati Catchment Management Agency (IUCMA) at Malelane and Crocodile Bridge rest camps in KNP, upstream and downstream of the study site respectively. River flow ($m^3.s^{-1}$) was determined using the DWS (http://www.dwa.gov.za/Hydrology/) Riverside gauging station in KNP directly upstream of the study site (station no. X2H046Q01) (Fig. 4.1).

4.4 Results

Seven *L. marequensis* and 10 *H. vittatus* were caught for the study (Table 4.1). Remote monitoring fixes acquired during the study and used in analyses was n = 18505 for *H. vittatus* and n = 17468 for *L. marequensis.* Fish were tagged and monitored remotely from 19 September 2011 through to January 2012 (Table 4.1). During this period *L. marequensis* showed high site fidelity contrary to *H. vittatus* (n = 5) that periodically move in and out of the study area, resulting in lower data points from those individuals. While manual monitoring an individual *H. vittatus* (HVIT9), visual observations were obtained of the individual swimming in a patrolling manner around structure and darted out of its patrol route to capture prey. In addition to patrolling the same individual would hold position near a run or a rapid and dart occasional out of position to capture prey into the run/rapid. During periods of inactivity (20h00 to 02h00), the same individual was visually observed resting in backwater close to the surface, only moving when disturbed by the researcher's presence. Manual monitoring of *L. marequensis* (n = 21) revealed the use of runs, strewn with boulders and use of pools within the river, this formed part of a descriptive study for *L. marequensis* (Burnett et al. 2018).

The locomotive activity exhibited between the two species was significant with *L. marequensis* showing larger periods of high activity than *H. vittatus* ($p < 0.001$) (Figs 4.2 and 4.3). Time of day (TOD) for both species showing diurnal patterns, with *H. vittatus* being active earlier in the morning with its activity tapering off from late afternoon into the evening (Fig. 4.4). *Labeobarbus marequensis* activity increased consistently into the day with a peak during midday and then gradually decreased (Fig. 4.4). Both species exhibited less activity periods between 20h00 and 2h00 than those observed during the day (Fig. 4.4).

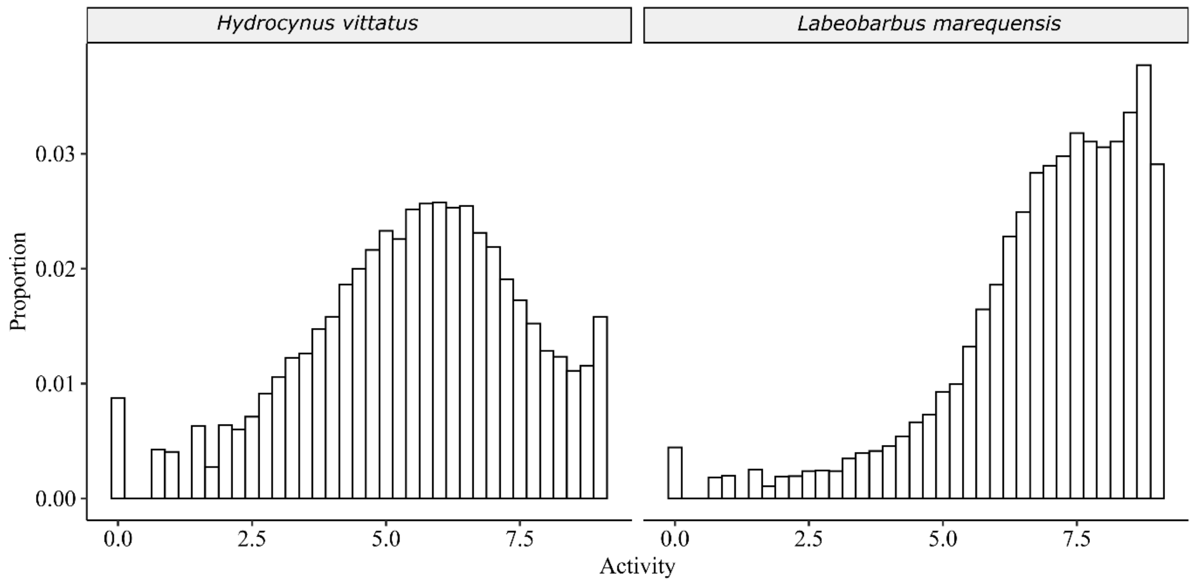

Fig. 4.2 The frequency distribution of log-transformed locomotive activity between *Hydrocynus vittatus* (HVIT) and *Labeobarbus marequensis* (LMAR), graphically presenting the range of locomotive activity associated with each species.

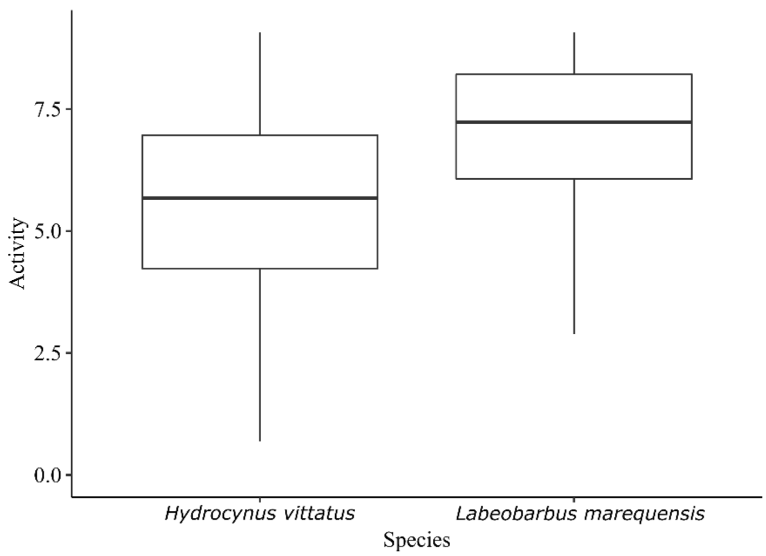

Fig. 4.3 The locomotive activity for *Hydrocynus vittatus* and *Labeobarbus marequensis* during the present study showing the significant differences between the two species ($p < 0.001$).

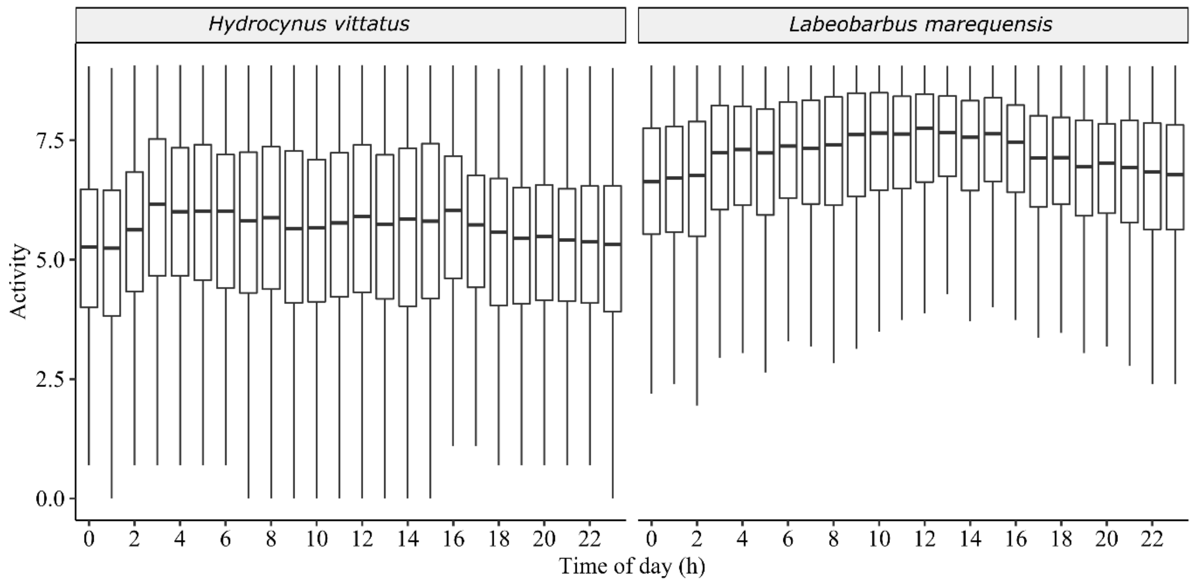

Fig. 4.4 A Whisker-Box plot for the activity of a. *Hydrocynus vittatus* and b. *Labeobarbus marequensis* for the time of day, showing heightened periods of activity from the early mornings through to mid-afternoon for *H. vittatus* and gradual increase in activity until a peak at midday and then gradual decline late afternoon into the evening for *L. marequensis* in the present study.

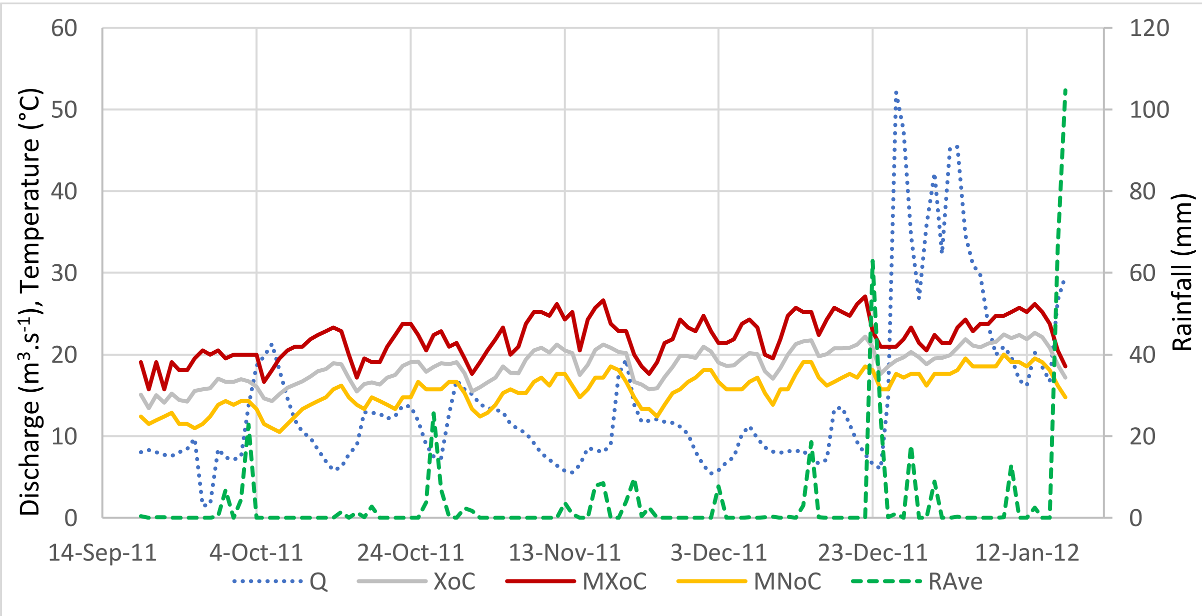

Fig. 4.5 The environmental variables recorded throughout the present study where Q is discharge (flow), XoC is average temperature, MXoC is maximum temperature, MNoC is minimum temperature and RAve is the rainfall average.

The environmental stressors measured showed change throughout the study, with flows increasing from 1.47 $m^3.s^{-1}$ to 52.1 $m^3.s^{-1}$. The mean water temperatures increased from the beginning of the study in September to January as ambient temperatures increased (Fig. 4.5). The flow was shown to correlate with water temperature decreasing when discharge increased with flows greater than 5 $m^3.s^{-1}$ (Fig. 4.5).

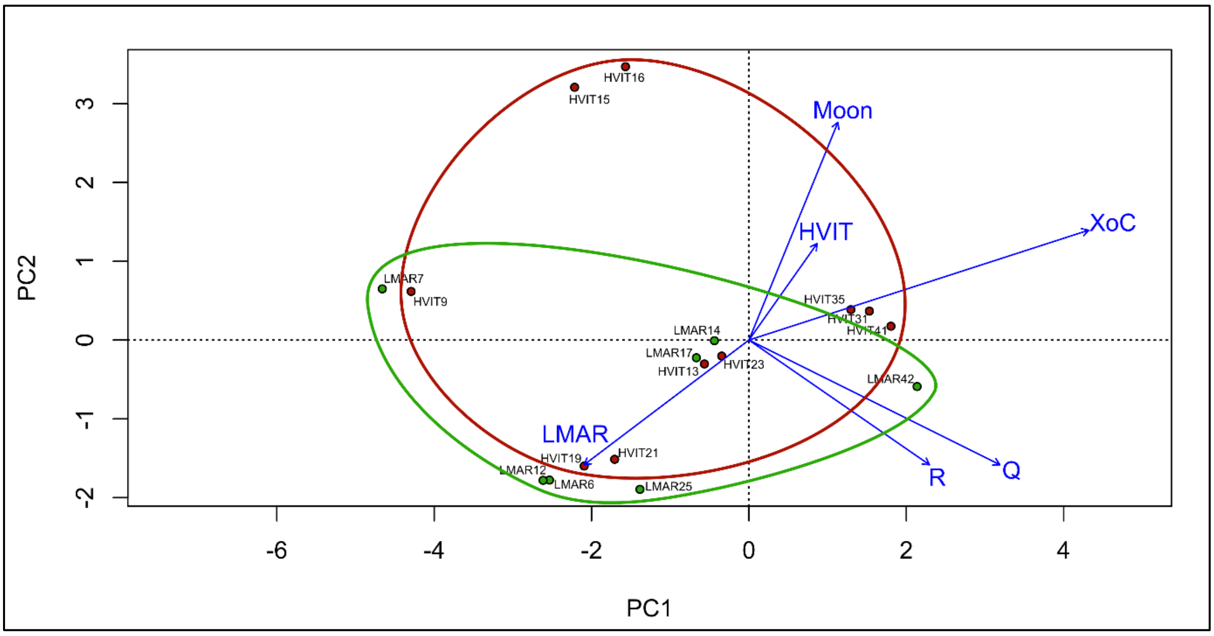

Fig. 4.6 The redundancy analyses (RDA) bi-plot depicting the pull effects of the environmental (Q = discharge, R = rainfall, XoC = water temperature, Moon =moon phase) drivers measured (straight lines in blue) on the behaviour of individuals (labelled according to tag code in Table 4.1) where discharge and water temperature affected behaviour of individuals significantly ($p < 0.01$ and $p < 0.001$ respectively) in the present study. The difference between *Hydrocynus vittatus* (HVIT, in red) and *Labeobarbus marequensis* (LMAR, in green) is depicted using the ellipses and the RDA plot (in blue) to show the differences between the two species.

The response of both fish species to environmental factors assessed using an RDA plot showed locomotive activity significantly affected by discharge and the water temperature (p <

0.01 and $p < 0.001$ respectively, Fig. 4.6). *Hydrocynus vittatus* behaviour differed significantly with changes in discharge and maximum temperatures respectively ($p < 0.01$) and showed a greater significant difference for mean and minimum temperatures respectively ($p < 0.001$). *Labeobarbus marequensis* behaviour was not significantly affected by discharge ($p = 0.11$) but was significantly affected by moon intensity and the mean, maximum and minimum temperatures, respectively ($p < 0.001$). Rainfall at both stations did not significantly affect the behaviour of the species. The analyses showed high individual variability for both species (Fig. 4.6).

4.5 Discussion

The locomotive activity showed the different TOD behaviour between *H. vittatus* and *L. marequensis* supporting the known niche separation between the two species. The differences shown by locomotive activity between the species confirmed the ability of detecting behavioural changes not only within species (between individuals) but between species and supported the use of locomotive activity as a behavioural variable to detect behavioural changes in fish as found in recent studies (Cooke et al. 2016; Thiem et al. 2018; Burnett et al. 2018). These differences also supported the high sensitivity of behaviour to changes in environmental conditions (Beitinger et al. 1990). Locomotive activity could detect individual plasticity which is seen to increase population resilience when adapting to environmental changes in response to climatic and anthropogenic stressors (Chevin et al. 2011; Sabater et al. 2019).

At the time stored data were not available, in going forward it should be considered when collecting behavioural movement, this will improve datasets and create a more holistic understanding of fish activity during a study, as found in this study that the activity of *H. vittatus* was not obtained when out of range of a remote station. The real-time monitoring of flow for the environmental water requirements (EWR) in the catchment has been highlighted and is being implemented (Pollard et al. 2012). The FISHTRAC programme and its behavioural variable (activity) as studied here can feed into this system providing the response behaviour of fishes to managers ensuring that the ecological flow requirements are met (Burnett et al. 2019).

Adult *H. vittatus* are known to be piscivorous by diet (Gaigher 1970), although do feed on aquatic invertebrates as found when catching them for the present study. The higher protein diet allows for longer rest periods between feeding than an omnivorous diet (Welch 1968; Tamburello et al. 2015). The high energy source from its food resource explains the heightened activity from 3h00 to between 15h00 and 18h00. The patrolling behaviour and holding position observed in this study showed relatively little body shifts (affecting locomotive activity) until strikes were made at their prey, this could account for lower activity, despite being a more mobile (spatial use) species than *L. marequensis* that would feed in between boulders and cobble constantly shift body position (Jacobs et al. 2017; Burnett et al. 2018; Roux et al. 2018).

Hydrocynus vittatus are known to be indicators of ecosystem well-being when managing flow and temperature changes (Steyn et al. 1996; Vlok and Engelbrecht 2000; Smit et al. 2013). *Hydrocynus vittatus* has been shown to avoid low temperatures, although it has not been clear as to the exact limits (Steyn et al. 1996; Vlok and Engelbrecht 2000). Generally, winter low water temperatures and low flows reduce the overall condition of *H. vittatus*, with their condition improving with warmer waters and increased flows during spring and summer (Gaigher 1970). In the present study, *H. vittatus* had higher activity during minimum water temperatures than maximum temperatures, showing that temperatures less than 15 °C adversely affect their behaviour. Gaigher (1970) and Steyn et al. (1996) both indicated downstream movement of *H. vittatus* during hailstorms moving into pool or dam environments where temperatures were more stable in winter. The present study found the movement of *H. vittatus* in and out the network of receivers downstream of the study area. This movement is likely to indicate that the spatial response was more to changes in flow and temperature than rainfall.

The development of instream barriers has restricted the upstream movement of *H. vittatus* after moving downstream to avoid temperature inversions eliminated from upper reaches in the Incomati and Crocodile River systems (Steyn et al. 1996; O'Brien et al. 2019). Roux et al. (2018) found *H. vittatus* to have restricted movement upstream because of in-stream barriers, this further highlights the importance of river connectivity for the survival of the species for both up and downstream movement over these barriers. Jacobs et al. (2019) showed *H. vittatus* to move in excessive of 397 km upstream in a river if unrestricted and supports the need for river conservation areas greater than 10 km of the river reach. In the present study upstream movement was restricted by the Van Graan Dam which was detected by the remote stations in this study indicating that movement of *H. vittatus* into and out of the study area was to and from downstream respectively. Only several (n = 5) *H. vittatus* moved out of the study area, occasionally returning. Individual variability found in Roux et al. (2018), Jacobs et al. (2019) and the present study support the role of individual plasticity as a response to environmental changes. No upstream movement in this study was observed, possibly due to Van Graan Dam (an in-stream barrier), indicating longitudinal movement is restricted heightening the impact of changing environmental variables that these species need to adapt for, in turn reducing the species resilience.

Labeobarbus marequensis are omnivorous feeding off both algae and small invertebrates (Fouché 2009; Burnett et al. 2018). Locomotive activity over the day (diel) showed gradual increases in activity that peaked at midday and then gradually decreased, being active for longer periods of the day than *H. vittatus*. Being omnivorous *L. marequensis* have been found feeding on algae and invertebrates around substrates such as cobble and boulders and need to feed longer because of low energy in-take from their food source (Welch 1968;

Burnett et al. 2018). These substrate types are often associated with higher flows (Gretener 1985; Woldegiorgis et al. 2018) and may account for higher locomotive activity for *L. marequensis* to that of *H. vittatus* to maintain their energy balance (Tamburello et al. 2015).

Both fish species were diurnal showing high activity during the photoperiods of the day indicating some preference for light when feeding. The moon intensity measured in this study showed that *L. marequensis* were significantly less active during new moon phases supporting the importance of the photoperiod of the day and water clarity in finding its food source. This type of alteration in diel behaviour due to an environmental factor has been recorded in yellowfin bream A*canthopagrus australis* during rainfall events (Payne et al. 2013). Water temperatures were also shown to significantly influence the behaviour of *L. marequensis* although no difference was shown between maximum or minimum temperatures as seen with *H. vittatus*. *Labeobarbus marequensis* are known to be more tolerable of low temperatures than *H. vittatus* (Fouché 2009). Temperature is showing to be an important role in the response of aquatic invertebrate well-being, this can relate to fish behaviour too as seen with this study for both *L. marequensis* and *H. vittatus* and is known to be a limiting factor in the distribution of fish species such as trout (*Oncorhynchus mykiss* and *Salmo trutta*) (Ross-Gillespie et al. 2018; Rivers-Moore et al. 2019). Flow, despite not being significant, suggested a relationship between discharge and *L. marequensis* behaviour as emphasised in Fouché (2009) and Burnett et al. (2018). Loss of habitat caused by a reduction in flow has been seen to adversely affect other populations of *L. marequensis* primarily because the reduction in flow affects the available habitat for spawning (Vlok and Engelbrecht 2000).

Both fish species studied showed significant behavioural response to an environmental variable. The response is important in understanding the effects of flow regime and temperature changes on fishes, especially as the demand for water resources increases. Importantly, is the need to mitigate the anthropogenic stressors that exasperates the effect on fish behaviour

(Rivers-Moore et al. 2013; Saraiva Okello et al. 2015; Ramulifho et al. 2019). Flow changes showed relatively low base flows during the low flow season, with little changes in the high flows during the high flow season and this resulted in high degrees of change in flows from low (< 0.5 $m^3.s^{-1}$) to flows greater than 50 $m^3.s^{-1}$ as seen in this study (Saraiva Okello et al. 2015). These extreme changes to flows are brought about by increased water use placing pressure the quantity of available water and difficulty in meeting the EWR (Saraiva Okello et al. 2015). These anthropogenic stressors increase fish stress as flow and temperature move into intolerable conditions (Rivers-Moore et al. 2013; Ramulifho et al. 2019). Water temperatures are still largely affected by atmospheric temperatures with an increasing average into summer (present study). The seasonal change was seen to affect the activity of both fish species with increased activity as temperature increased. Fish telemetry methods can detect changes of behaviour in response to these extreme flows and temperature fluctuations and if not mitigated, can negatively affect the populations of fishes in the Crocodile River. The spatial movement observed in this study and by others (Jacobs et al. 2019; Roux et al. 2018) for *H. vittatus* emphasised not only associated movements of *H. vittatus* to environmental factors but also the negative presence of instream barriers exasperated by poor flow releases.

4.6 Conclusions

The use of locomotive activity was successful in understanding the differences between two active fusiform fish species. Further, locomotive activity as a behavioural variable can be used to understand the movement of two species and their relationship to environmental stressors. These findings highlight that free-swimming fish behaviour can be monitored with the use of omni-directional vibration tilt sensors similarly to accelerometers showing responses to temperature and discharge. Temperature plays an equal and if not more important role than discharge when effecting the behavioural responses of fish species in the Crocodile River.

Hydrocynus vittatus were more sensitive to changes in lower water temperatures than higher temperatures while any change in temperature affected the movement of *L. marequensis*. The use of these two species as ecological indicators species is important where they both occur and should be monitored to ensure environmental flows and temperature guidelines for the catchment are met. In upper reaches where *H. vittatus* do not occur, *L. marequensis* can be used as ecological indicators as they can tolerate lower temperatures and will respond to changes.

River connectivity is an important consideration to make in the conservation of both species (O'Brien et al. 2019), considering the conservation status (protected) of *H. vittatus* in South Africa and understanding their responses to flow and temperature changes can assist in meeting the ecological flow reserve and enhancing the protection of the species throughout its range. Incorrect management and continual pressure placed on flows and changes in temperatures could see the same conservation status enlisted for *L. marequensis*.

It is important to note that with the changes in flow regimes as a result of increased water resource demand has exasperated the water temperatures downstream causing sudden changes in temperature during rainfall events or flow releases. These sudden changes can negatively affect the behaviour of fishes. The present study showed the importance of understanding these relationships, and it is proposed that further behavioural monitoring will contribute to the effective management of rivers in South Africa.

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CHAPTER 5

Locomotive activity and spatial ecology of *Labeobarbus natalensis* and its contribution to the sustainable management of the uMngeni River, KwaZulu-Natal, South Africa

Matthew J. Burnett[1,2], Gordon C. O'Brien[3], Graham Jewitt[2,4], Colleen T. Downs[1*]

[1]*Centre for Functional Biodiversity, School of Life Sciences, P/Bag X01, Scottsville, Pietermaritzburg, 3209, South Africa*

[2] *Centre for Water Resource and Research, School of Engineering, P/Bag X01, Scottsville, Pietermaritzburg, 3209, South Africa*

[3] *School of Biology and Environmental Sciences, Faculty of Agriculture and Natural Sciences, University of Mpumalanga, Nelspruit, South Africa, 1200*

[4] *Institute for Water Education, IHE Delft, Westvest, South Holland, Netherlands, 2611*

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* Corresponding Author: Colleen T. Downs
Email: downs@ukzn.ac.za
Tel: +27 (0)33 260 5127
ORCID: http://orcid.org/0000-0001-8334-1510
Other emails: matthewburnett014@gmail.com, ORCID: https://orcid.org/0000-0002-6237-1697; gordon.obrien@ump.ac.za, ORCID: https://orcid.org/0000-0001-6273-1288; g.jewitt@un-ihe.org, ORCID: https://orcid.org/0000-0002-7444-7855

Running header: locomotive and spatial ecology of *Labeobarbus natalensis*.

5.1 Abstract

The anthropogenic stressors placed on aquatic environments is increasing across the globe. Understanding the biological response to these stressors is important to consider within aquatic ecosystems and their associated organisms. Fish are good ecological indicators of the aquatic ecosystem and can be monitored relatively easily. Within the ecologically important uMngeni River, KwaZulu-Natal Province, South Africa, that experience regular fish kills and seen the reduction in abundances of the iconic KwaZulu-Natal yellowfish (*Labeobarbus natalensis*). These events threaten the sustainable management of the ecosystem and in turn, jeopardise the ecosystem services provided to sustain the economy. Understanding *L. natalensis* behaviour can greatly assist water resource users to understand the stressors placed on this environment. We used telemetry to determine reach scale movement, home range and habitat use of *L. natalensis* (n = 43) within sections of this river that included an impoundment from August 2018 to August 2019. We also assessed these in terms of environmental stressors placed on the system. We found *L. natalensis* showed individual variability and facultative movement. Some did undertake seasonal upstream movements during summer. It appeared that this was dependent on the availability of habitats required for refuge during winter, and spawning or body condition during summer. Tagged individuals (n = 11, 25.6%) that made reach scale movements were cued primarily by water temperature during upstream movements as below-average rainfall and flows were experienced during this part of the study. Morton's Drift, a weir within the study area, hindered upstream movement with only one out of the six fish that moved upstream passing the barrier. Habitat use was also found to be significantly different between the uMngeni River and Albert Falls impoundment. Generally, *L. natalensis* showed diel movement and diurnal activity patterns with significant differences between day and night

activity throughout the study. However, pulses of activity were observed periodically throughout the night, indicating the use of rapids and pool habitats in the uMngeni River by *L. natalensis* during both day and night. Maintaining adequate flows during critical periods of movement and spawning is important and will assist in maintaining and providing habitat for *L. natalensi*s. The removal of redundant instream barriers or fitting of adequate fish passages to them will facilitate *L. natalensis* access into required habitats. These mitigation measures will improve ecosystem resilience and reduce impacts of anthropogenic stressors.

Keywords: fish movement, ecological cues, diel behaviour, fish telemetry, activity sensors

5.2 Introduction

Aquatic ecosystems are under severe pressure globally, primarily from anthropogenic induced changes (Saraiva Okello et al. 2015; Rodell et al. 2018; Du Plessis 2019). The impact these changes have on both human livelihoods and the aquatic ecosystems has been excessive (Nel et al. 2017; Sokollow et al. 2017; Du Plessis 2019). The loss of aquatic biodiversity affects ecosystem processes that provide socio-economically important services (Depledge and Galloway 2005; Dudgeon 2014; Dickens et al. 2019). Understanding the relationship between the response of aquatic organisms and aquatic ecosystems well-being is important as they serve as ecological indicators (Harris, 1995; Schiemer, 2000; O'Brien et al. 2009; McLoughlin et al. 2011; Soko and Gyedu Ababio 2015). Fish are good ecological indicators of ecosystem well-being as they are long-lived organisms, have different niche guilds or habitat dependencies, are relatively easily monitored and charismatic (Baumgartner et al. 2014; O'Brien et al. 2018).

There are many ways to measure ecosystem well-being using fish, with fish behaviour being recognised as 10-100 times more sensitive to change than other lines of evidence (Lucas and Baras 2000; Wepener 2008; Sharma 2019). Fish telemetry is a recognised method to describe fish behaviour as it can detect cryptic movements otherwise undetected by traditional survey methods (Cowley and Naesje 2004; Cooke et al. 2013; Hussey et al. 2015). Despite fish telemetry methods established internationally as being one of the main means of collecting locomotive activity and spatial ecology of fishes, it remains under-utilised in Africa (Lennox et al. 2017; Burnett et al. 2019). Spatial movement and habitat use of fish often indicates a response to environmental factors, to meet biological functioning or both (O'Brien et al. 2013a; Burnett et al. 2018). Understanding spatial movements and habitat use and what affects these are important to water resource managers as these generally assist in understanding ecosystem well-being in highly impacted aquatic ecosystems (Cooke et al. 2016; O'Brien et al. 2018; Rodell et al. 2018; Du Plessis 2019). The FISHTRAC programme uses the behavioural ecology of fishes to monitor aquatic ecosystem well-being in real-time and then remotely feeds into water resource management systems (Burnett et al. 2020). Fish behavioural and spatial ecology information as a baseline can, when altered, feed into decision-making processes improving the sustainability of aquatic ecosystem faced with anthropogenic stress (Depledge and Galloway 2005; Cooke et al. 2016; Dickens et al. 2019; Burnett et al. 2019; 2020).

In southern Africa, the well-being of freshwater ecosystems continue to deteriorate at alarming rates (Du Plessis 2019; Van Deventer et al. 2019). The effects of these anthropogenic stressors and the impacts on the ecosystem well-being is largely lacking (Dudgeon 2014; Du Plessis 2019). Understanding the locomotive activity and spatial ecology of some established fish ecological indicators can greatly assist in determining ecosystem well-being (Kleynhans and Louw 2008; Impson et al. 2008). One such taxon includes the *Labeobarbus* spp. which because of their charismatic nature, wide distribution range, generally high abundances, typically large size (> 3 kg), long-lived characteristics, target of fishermen and specific habitat requirements make them ideal ecological indicators (Skelton 2000; Impson et al. 2008; Hoogendoorn 2010; Brand et al. 2013). The use of *Labeobarbus* spp. as a food source has been recorded in hieroglyphics in Egypt and depicted in rock art in South Africa, showing the longstanding relationship this taxon has had contributing towards the livelihoods of people (Hall 1997; Impson et al. 2008). The seasonal movement of *Labeobarbus* spp. has been recognised through indigenous knowledge as well as records through fish ladders in South Africa (Meyer 1974; Impson et al. 2008, Fouché and Heath 2013). However, preliminary fish telemetry studies on *Labeobarbus* spp. have shown them to be facultative by nature and affected by habitat availability during different times of the year for biological needs, such as spawning and winter refugia (O'Brien et al. 2013a; Jacobs et al. 2016; Burnett et al. 2018; Ramesh et al. 2018). The KwaZulu-Natal yellowfish (*Labeobarbus natalensis* (Castelnau 1861)) occurs in the highly stressed and socio-economically important uMngeni River, KwaZulu-Natal Province, however, its behaviour is relatively poorly known (Crass 1964; Karssing 2008; Kusanga et al. 2018). Understanding the movements of *L. natalensis* is important as any changes in fish species behaviour can be assessed and form baseline data going forward when setting thresholds of potential concern especially when changes in behaviour are observed during both long and short term periods (O'Keeffe and Rogers 2003; Chevin et al. 2010; McLoughlin et al. 2011; Pinsky 2019).

In order to understand the behaviour and spatial ecology of *L. natalensis* and establish baseline data, we assessed their movements, home range and habitat use with fish telemetry techniques. We hypothesised that *L. natalensis* change habitats during the year and show different activity within these habitats. We also assessed whether behaviour were affected by environmental stress, including predators, by monitoring water conditions and evaluating predation of *L. natalensis* by natural predators as disturbances to their behaviour.

5.3 Methods

We tagged and monitored *L. natalensis* (n = 43) using radio-telemetry methods in a section of the uMngeni River between and including the Albert Falls and Midmar Dams, in KwaZulu-

Natal Province, South Africa (Fig. 5.1.; Table 5.1). This reach includes the Karkloof River, a tributary of the uMngeni River that was accessible for fish within the study. This tributary generally has better water quality conditions than the main stem which is downstream of Howick's wastewater treatment works (Namugize et al. 2018, Fig. 5.1). Both these river sections have a series of semi-permeable and permeable instream barriers (Fig. 5.1), making it an ideal location to track the spatial movement of fish. Both rivers contain boulder-strewn fast-flowing rapids interlinked with shallow (< 6 m) pools in the river and Albert Falls Dam (here on referred to as Albert Falls) (depth > 10 m) that serves as a refuge area for *L. natalensis* in winter (Crass 1964).

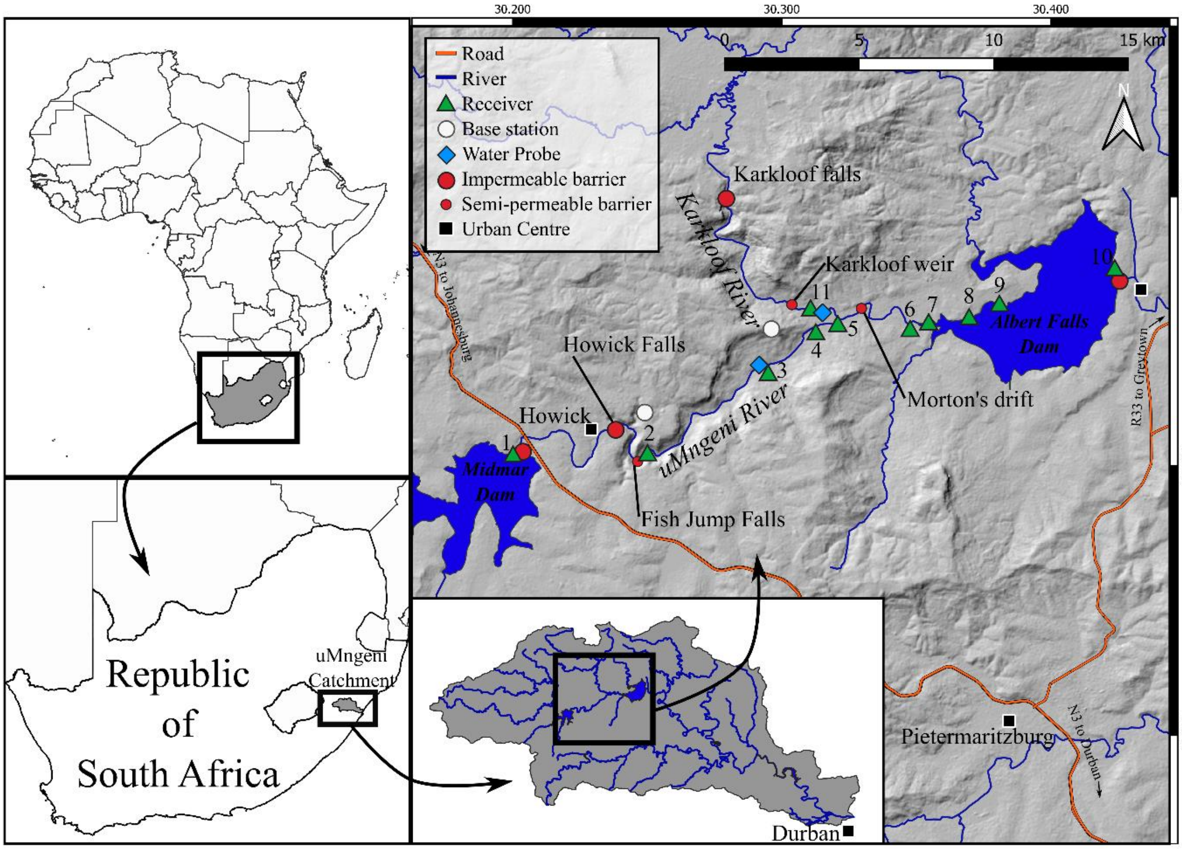

Fig. 5.1 The location of the study area in the present study in KwaZulu-Natal Province, South Africa, showing the positioning of receivers and water probe within the uMngeni River and the Karkloof River. (Note: Instream barriers are also shown).

Table 5.1: Summary of tagged *L. natalensis* morphological and tracking data in a section of the uMngeni River between Midmar Dam and Albert Falls Dam in KwaZulu-Natal Province, South Africa

Tag code	ID	WW Tag	Tag type	SL	Weight	Tagged location (GPS)		Start	End	Days tracked
455:40	LNAT01	Series III	External	460	1980	-29,448404	30,355185	09-Aug-18	17-Sep-18	39
455:41	LNAT02	Series III	External	505	2370	-29,448404	30,355185	09-Aug-18	21-Feb-19	196
455:42	LNAT03	Series III	External	455	1820	-29,448404	30,355185	09-Aug-18	09-Sep-18	31
455:43	LNAT04	Series III	External	460	2150	-29,448404	30,355185	09-Aug-18	20-Oct-18	72
455:44	LNAT05	Series III	External	445	1800	-29,448404	30,355185	09-Aug-18	26-Oct-18	78
455:45	LNAT06	Series III	External	440	1720	-29,448404	30,355185	22-Aug-18	15-Nov-18	85
455:46	LNAT07	Series III	External	460	1650	-29,448404	30,355185	22-Aug-18	03-Mar-19	193
455:47	LNAT08	Series III	External	410	1400	-29,448404	30,355185	22-Aug-18	04-Sep-18	13
455:48	LNAT09	Series III	External	410	1280	-29,448404	30,355185	23-Aug-18	16-Dec-18	115
455:49	LNAT10	Series III	External	410	1320	-29,448404	30,355185	22-Aug-18	01-Sep-18	10
455:50	LNAT11	Series III	External	400	2400	-29,448404	30,355185	22-Aug-18	15-Sep-18	24
455:51	LNAT12	Series III	External	390	2380	-29,448404	30,355185	22-Aug-18	04-Sep-18	13
455:52	LNAT13	Series III	External	420	1450	-29,448404	30,355185	22-Aug-18	11-Sep-18	20
455:53	LNAT14	Series III	External	400	1280	-29,448404	30,355185	22-Aug-18	07-Sep-18	16
455:54	LNAT15	Series III	External	430	1540	-29,448404	30,355185	22-Aug-18	28-Jan-19	159
455:20	LNAT16	Series III	External	420	1760	-29,446287	30,321621	05-Sep-18	14-Sep-18	9
455:21	LNAT17	Series III	External	430	1750	-29,446287	30,321621	05-Sep-18	06-Sep-18	1
455:24	LNAT18	Series III	External	420	1400	-29,446287	30,321621	05-Sep-18	09-Nov-18	65
455:25	LNAT19	Series III	External	440	1840	-29,446287	30,321621	05-Sep-18	08-Oct-18	33
455:55	LNAT20	Series III	External	465	2030	-29,446287	30,321621	05-Sep-18	21-Jan-19	138
455:56	LNAT21	Series III	External	410	1690	-29,446287	30,321621	05-Sep-18	15-Feb-19	163
455:57	LNAT22	Series III	External	415	1750	-29,446287	30,321621	05-Sep-18	30-Apr-19	237
455:58	LNAT23	Series III	External	450	1340	-29,446287	30,321621	05-Sep-18	09-Sep-18	4
455:59	LNAT24	Series III	External	440	1500	-29,446287	30,321621	05-Sep-18	15-Oct-18	40
455:26	LNAT25	Series III	External	425	1630	-29,446287	30,321621	05-Sep-18	17-Oct-18	42
455:49	LNAT26	Series III	External	410	1490	-29,446287	30,321621	30-Nov-18	10-Dec-18	10
455:25	LNAT27	Series III	External	440	1840	-29,446287	30,321621	14-Nov-18	30-Nov-18	16
455:40*	LNAT28	Series III	External	445	1640	-29,446287	30,321621	14-Nov-18	11-Mar-19	117
455:47*	LNAT29	Series III	External	410	1410	-29,446287	30,321621	14-Nov-18	25-Feb-19	103
455:60	LNAT30	Series III	External	540	3010	-29,446287	30,321621	14-Nov-18	09-May-19	176
455:61	LNAT31	Series III	External	420	1580	-29,446287	30,321621	14-Nov-18	16-Nov-18	2
455:53*	LNAT32	Series III	External	430	1680	-29,446287	30,321621	30-Nov-18	26-May-19	177
455:62	LNAT33	Series III	External	420	1570	-29,446287	30,321621	30-Nov-18	24-Jan-19	55
455:63	LNAT34	Series III	External	440	1550	-29,446287	30,321621	30-Nov-18	03-Mar-19	93
455:64	LNAT35	Series III	External	455	1560	-29,446287	30,321621	30-Nov-18	24-Mar-19	114
455:29	LNAT36	Series III	External	440	1760	-29,446287	30,321621	06-Feb-19	14-May-19	97
455:61*	LNAT37	Series III	External	420	1740	-29,446287	30,321621	06-Feb-19	10-Apr-19	63
455:25*	LNAT38	Series III	External	440	1680	-29,446287	30,321621	07-Feb-19	17-Jul-19	160
455:28	LNAT39	Series III	External	445	1340	-29,446287	30,321621	14-Mar-19	07-May-19	54
455:62*	LNAT40	Series III	External	440	1530	-29,446287	30,321621	14-Mar-19	06-May-19	53
455:65	LNAT41	Series III	External	440	1700	-29,446287	30,321621	21-Mar-19	16-Aug-19	148
455:66	LNAT42	Series III	External	450	1620	-29,446287	30,321621	21-Mar-19	27-Aug-19	159
455:67	LNAT43	Series III	External	440	1450	-29,446287	30,321621	21-Mar-19	21-Mar-19	0

* Tags retrieved and re-used.

We captured *L. natalensis* near receivers 5 and 7 (Fig. 5.1), using gill nets mesh sizes of 73 mm, 95 mm and 125 mm (Eigevis group of companies, Cape Town, South Africa) that we monitored for movement to minimise the time fish spent in the net. On capture, fish were placed in +/- 80 *l* holding container with fresh water from the capture site circulating using a submersible pump (Burnett et al. 2018). Fish greater than 1200 g exceeded the body mass to tag ratio (tags weighed 20g) and were selected for tagging (Childs et al. 2011; Jepsen et al. 2015; Table 5.1). Fish tags (series III; Wireless Wildlife (WW), Potchefstroom, South Africa) were attached externally (Burnett et al. 2020). After being placed in the holding container, fish were then transferred to an aerated anaesthetic bath containing clove oil (0.1 ml l^{-1}) as the active drug and monitored for signs of narcosis (Fernandes et al. 2017). Once anaesthetised, the tagging procedure was initiated by inserting two 14-gauge needles through the muscular tissue below and to the back of the dorsal fin, while the fish's gills remained submerged in water (Bridger and Booth, 2003; Jepsen et al. 2015). The surgical wire (0.508 mm diameter), attached to the tag, was inserted through the surgical needles and the needles removed. The surgical wire was threaded through the tags backplate and secured (Thorstad et al. 2013; Burnett et al. 2018, 2019b). Wound care gel (Aqua Vet, Veterinary hospital, Lydenburg, South Africa), a protective antibiotic gel that aids the reformation of skin mucus is applied around the tag. In addition, an antibiotic (Terramycin® containing oxytetracycline) is injected into the muscle (1 ml/kg) around the wound. The tagged fish was then returned to the holding container to recover from the anaesthetic; during this period, morphological measurements and a photograph were taken (Table 5.1). On full recovery, each tagged fish was released back into the river at the site of capture within 1 h after capture, with the surgical procedure taking less than 3 min. per fish.

Tags were equipped with an activity sensor and recorded a count of activity associated with the movement of the individual fish as well as the environmental water temperature directly associated with it. Data from tags were recorded every hour and stored on the tag if out of range of a receiver and downloaded once returned into the range of the network (Burnett et al. 2020). A remote network composing of 11 receivers were used to detect movement of fish up and down the reach and set-up at key locations along the uMngeni River and Karkloof River (Fig. 5.1). The linear distance of the river between receiver was recorded and did not alter during the study (Fig. 5.1; Table 5.2). The receivers were able to detect fish situated in the habitats within range (100 m) and any of their movement past the receivers. Periodic manual monitoring surveys were conducted to find fish out of range, ground-truth findings and to retrieve lost tags. In addition to the monitoring of fish behaviour, two water probes (WW, Series IX) were positioned in the river system (Fig. 5.1). These probes recorded depth, as a function for discharge ($m^3.s^{-1}$) using an associated hydraulic cross-section, and water temperature (°C) within the uMngeni River and Karkloof River and were used to evaluate the drivers of spatial movement of the fish.

Table 5.2: The distance (meters) between the receivers along the uMngeni and Karkloof River, with receiver four and seven as reference points. (See Fig. 5.1 for geographical localities).

Receiver #	Meters	Accumulated distance	Receiver 4	Receiver 7
1-2	9602	0	9602	25188
2-3	6550	9602	6550	15586
3-4	2553	16152	2553	9036
4-5	1253	18705	1253	6483
5-6	4198	19958	5451	5230
6-7	1032	24156	6483	1032
7-8	1345	25188	7828	1345
8-9	1200	26533	9028	2545
9-10	4060	27733	13088	6605
5-11	1739	29472	1739	6969

5.3.1 Data analyses

Data retrieved from the remote network were stored on a central data management system (DMS) and then analysed. The association of tagged fish to receivers situated in the study to determine the spatial use of the river and activity patterns of non-spatial movement of fish were also recorded. Data were transferred to Windows Excel, (©2017, Microsoft Corporation) and analysed and plotted in RStudio (RStudio 2015). Side fidelity for each tagged fish was calculated using the frequencies of location points recorded per receiver, and timing of reach-scale movement used the frequencies of these location points at each receiver during the study. Movement within two main habitat types, namely, Albert Falls Dam and the uMngeni River, and nocturnal and diurnal periods were statistically tested using the Mann-Whitey U-test (U-Mann) for non-parametric distributions.

5.4 Results

A total of 43 *L. natalensis* were tagged and monitored from 9 August 2018 to 28 August 2019. Five (11.6%; LNAT 16, 17, 23, 31 and 43) did not provide enough data (< 10 days monitored) to contribute to the activity section of the study (Table 5.1). Eight tags were tracked manually after mortality signals were detected and their tags recovered. Evidence from activity sensors on the tags suggested that subsistence fishers, tagging procedure mortality, and avian and mammalian predation were the cause for mortalities (Table 5.1). During manual tracking, a relatively high presence of aerial avian predators, *Haliaeetus vocifer* and *Pandion haliaetus* and otter spp. (*Aonyx capensis* and *Hydrictis maculicollis*) were observed. Tags that showed a spike in activity of counts > 100 times per normal count (500 counts per min.) before zero locomotive activity were recorded, indicating some form of predatory attack. Manual tracking surveys found these tags out of the river on the banks as high as 3 m from the river surface.

Home ranges of 38 tagged fish (n = 194602 points) varied for each individual tagged, with a high site fidelity for the area they were tagged in (Fig. 5.2). Side fidelity was evident for fish tagged in both Albert Falls and the uMngeni River sections. Of the fish tagged, only 11 (25.6 %) moved out of the area they were tagged. These movements were either upstream for fish tagged in Albert Falls (n = 6) and downstream for fish tagged at receiver five (n = 5) and correlated with the season (Fig. 5.3). Upstream movement of fish ranged between August 2018 and January 2019, while downstream movement occurred between April and May 2019 (Fig. 5.3). This coincided with the movements of visually observed shoals of fish upstream of Albert Falls (but below Morton's Drift, pers. obs.) shortly after the first tagged fish (LNAT09) moved upstream. However, no tagged individuals were detected in the shoal and may have moved into inaccessible areas. The longest movement by one individual was greater than 10 km by LNAT07, from Albert Falls up past receiver 4. Fish that moved upstream varied in the distance moved ranging between 2000 m and 7000 m (Fig. 5.3).

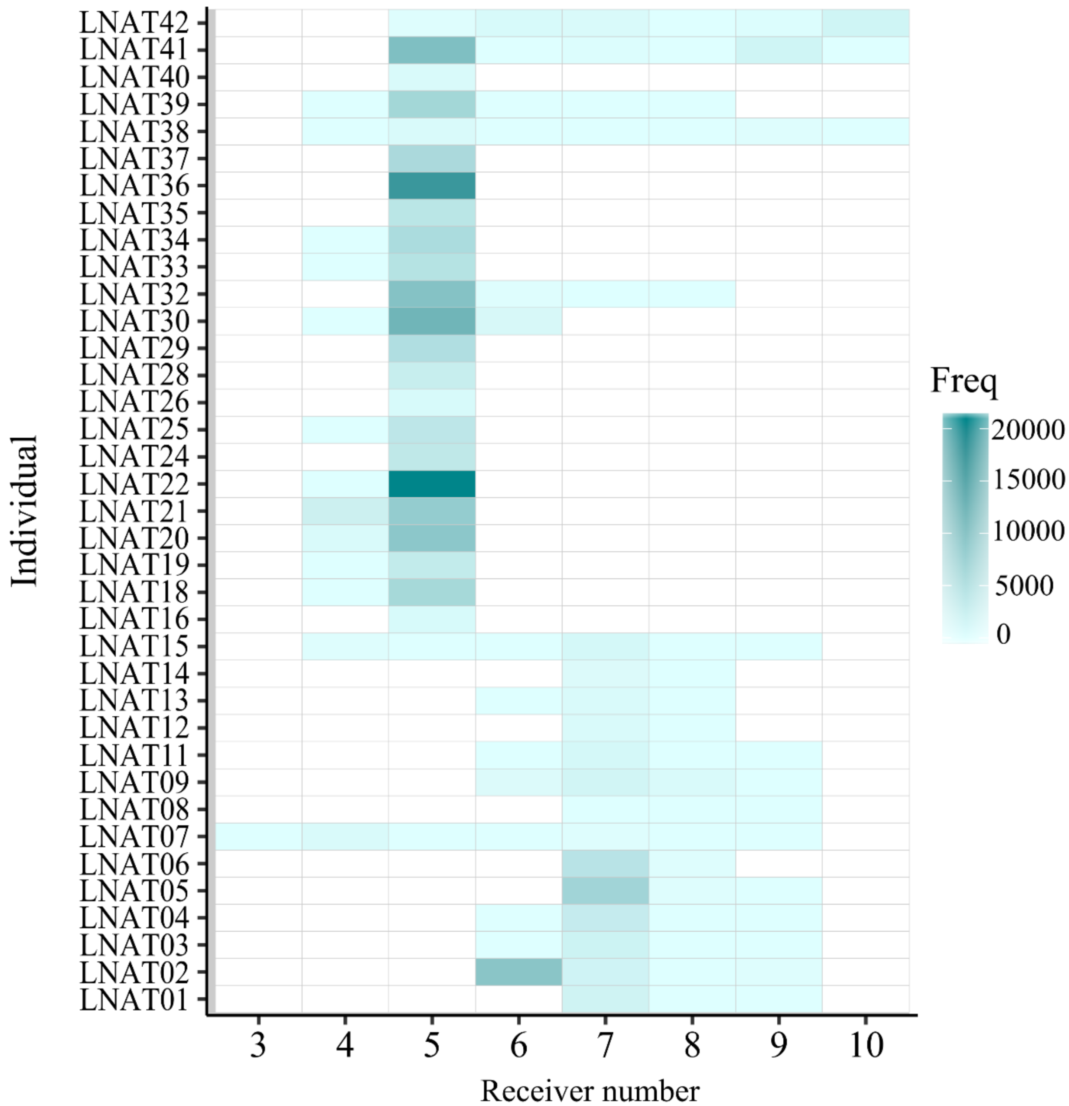

Fig. 5.2 A representation (Receivers not presented on scale, refer to Table 5.2) of tagged individuals and their spatial movement within the study area, where receiver seven is the point where the uMngeni River flows into Albert Falls. The darker the shaded area, the higher the frequencies associated with the receiver. Receivers depicted represent only those that detected fish during the study.

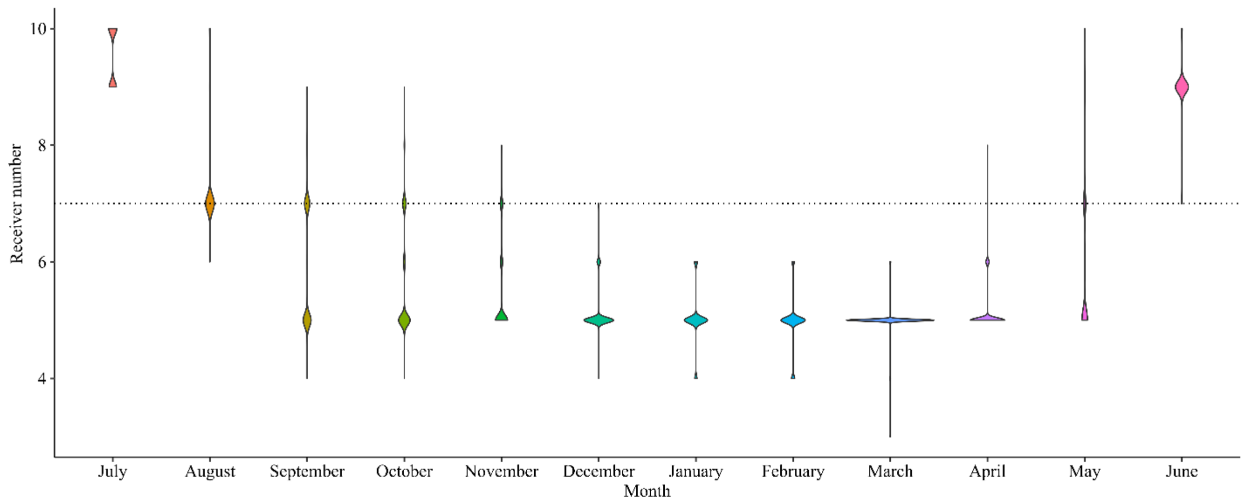

Fig. 5.3 A representation (Receivers not presented on scale, refer to Table 5.2) of the seasonal movement of tagged *Labeobarbus natalensis* (n = 38) during the study in and out of Albert Falls, based off the frequency of occurrence for location points (violin plot) at each receiver (location) during different periods of the year (month). The wider the violin plot, the higher the affiliation at the site (Note: Dotted line separates Albert Falls (above) from the uMngeni River (below)).

Movement cues for upstream and downstream movement were determined by assessing the recorded discharge, water temperature and period of the day at the time fish moved (n = 56) (Fig. 5.4). Baseline flows were maintained at 2 $m^3.s^{-1}$ from Midmar Dam upstream of the study area and monitored with the water probe set-up in the study area (Fig. 5.4). Mean (± SE) water temperature was 16 ± 4.15 °C for the duration of the study (Table 5.3; Fig. 5.4). Water temperatures recorded on fish tags were also evaluated and showed that fish sought out micro-habitats to maintain temperatures above the minimum environmental temperatures especially during winter (Table 5.3). During the study upstream movement was affected more by increasing water temperatures rather than increased flow and occurred largely at night (n = 18) (Table 5.3; Fig. 5.4).

The downstream movement was strongly related to increased flow (mean ± SD upstream movement 6.66 ± 1.91 $m^3.s^{-1}$, mean ± SD downstream movement 11.22 ± 5.31 $m^3.s^{-1}$) and this movement occurred primarily during daytime (n = 21) (Fig. 5.4). Morton's Drift obstructed five out of the six fish that needed to cross the barrier in order to access the upper reaches. All fish that moved downstream were able to navigate Morton's Drift settling in Albert Falls. Unexpectedly, the Karkloof River was not used by tagged individuals during the study. Flows during the study showed little fluctuation because of Midmar Dam filling to full capacity as a result of the reduction in flows from preceding drought conditions and the late rains; overspill was only experienced in March of 2019 (Kusanga et al. 2018; pers. obs.).

Table 5.3: Water temperature from the environment (water probe) and the fish (tag) during the study, included is the location of the tags between Albert Falls and uMngeni River.

	River Water temperature				**Fish tag water temperature**				**Difference (Fish-Env)**			**Location**
	Mean	**±SD**	**Max**	**Min**	**Mean**	**±SD**	**Max**	**Min**	**Mean**	**Max**	**Min**	
Year	16.69	4.15	27.96	6.64	18.85	2.99	28.29	8.97	2.16	0.33	2.33	**N/A**
August	13.08	1.39	17.16	8.85	14.61	1.21	22.44	10.89	1.53	5.28	2.04	Transition
September	15.33	2.05	21.33	8.72	16.21	1.87	22.77	8.97	0.89	1.44	0.25	Transition
October	16.80	2.34	23.82	12.40	18.03	2.28	24.70	13.01	1.23	0.88	0.61	uMngeni
November	18.46	2.67	25.26	13.31	19.74	2.49	26.52	14.16	1.28	1.26	0.85	uMngeni
December	20.56	2.16	27.96	15.90	21.56	2.01	28.06	15.74	1.00	0.10	-0.16	uMngeni
January	21.02	2.32	27.63	16.62	21.55	2.21	28.29	16.07	0.53	0.66	-0.55	uMngeni
February	20.64	1.46	25.17	17.46	20.57	1.55	25.63	17.01	-0.06	0.46	-0.45	uMngeni
March	19.78	1.33	23.01	16.62	20.10	1.41	23.82	16.55	0.32	0.81	-0.07	Transition
April	17.70	0.95	20.05	15.49	17.60	0.97	20.51	15.06	-0.10	0.46	-0.43	Transition
May	15.29	1.46	18.26	10.66	17.01	1.17	20.51	13.40	1.72	2.25	2.74	Transition
June	10.52	2.85	18.26	7.48	15.56	1.12	17.68	9.96	5.04	-0.58	2.48	Albert Falls
July	9.93	1.47	13.69	6.64	13.77	0.56	16.15	12.71	3.85	2.46	6.07	Albert Falls

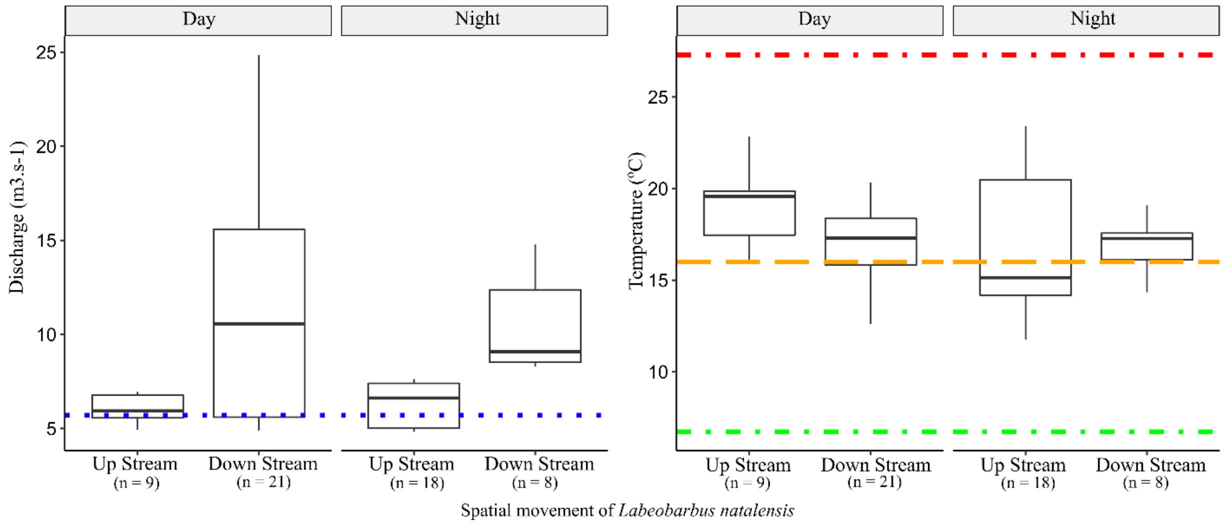

Fig. 5.4 Box-plot showing the flow discharge and water temperature readings at the time of movement for *Labeobarbus natalensis* up and down stream in the present study. (Note: Dotted blue line shows baseline low flows during the study; dashed orange line shows mean water temperature, and dashed dot shows the maximum and minimum water temperatures during the study).

Activity profiles of *L. natalensis* showed them to be highly active (Fig. 5.5), with rest periods shown by low locomotive activity with zero counts seldom seen. There was a significant difference in their activity between day and night ($p < 0.001$), with generally low locomotive activity generally associated with nocturnal periods (Fig. 5.5). Although activity of *L. natalensis* over the time of day (TOD) showed higher activity generally during the day than at night, this varied at times during the study when *L. natalensis* had extended periods of activity, without peaking during the day nor dropping at night. This type of activity was initially observed prior to reach scale movement and associated with activity of *L. natalensis* when in the uMngeni River (Fig. 5.6 and Fig. 5.7). The activity of *L. natalensis* further differed significantly between the two habitat types, Albert Falls and the uMngeni River ($p < 0.001$), with diurnal activity higher in Albert

Falls than in the uMngeni River (Fig. 5.6). The signal strength observed for *L. natalensis* in Albert Falls consistently increased at night and decreased during the day, showing that they came to the surface at night to rest when in refugia habitats and feed at depths > 10 m during the day (Fig. 5.7). The activity within Albert Falls reached counts of < 20 000 per minute during the day dropping down to > 200 per minute at night. This was not as evident in the river with counts of < 10 000 per minute during the day and > 500 per minute at night (Fig. 5.7).

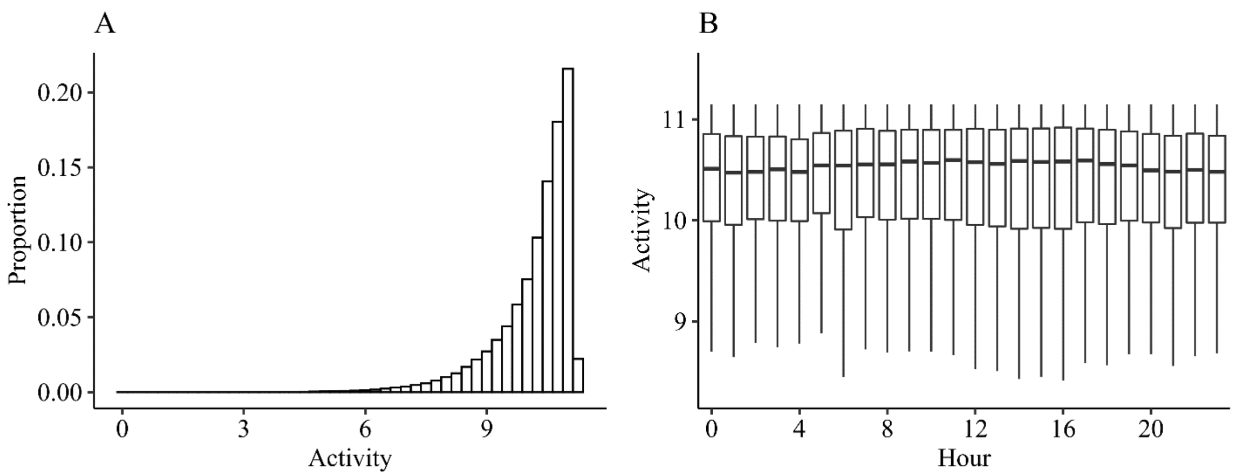

Fig. 5.5 *Labeobarbus natalensis* activity where (A) is the frequency distribution of locomotive activity for during the study, indicating highly active fish; and (B) a boxplot of hourly locomotive activity through the day during the study.

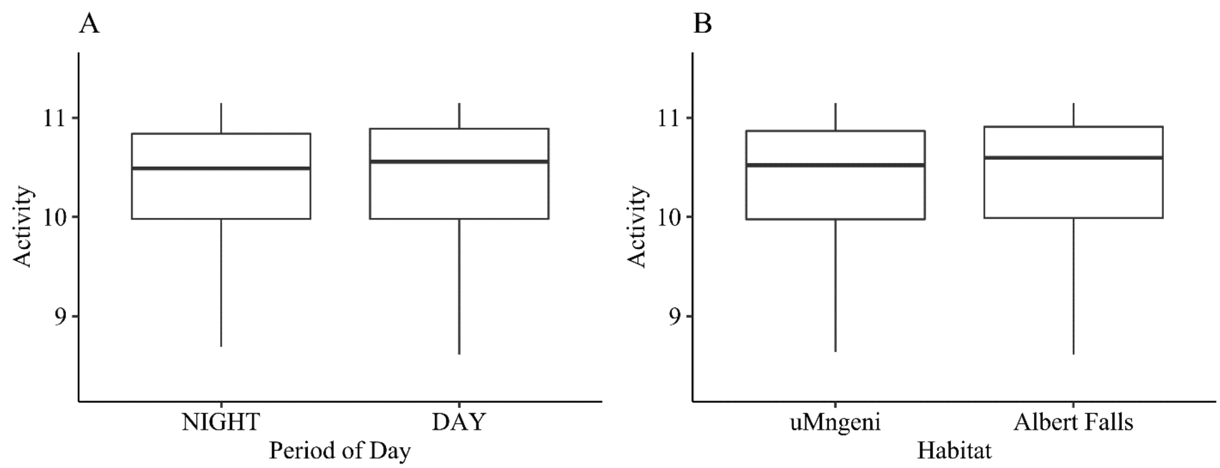

Fig. 5.6 *Labeobarbus natalensis* showed significant differences in activity between (A) day and night; and (B) between the uMngeni River and Albert Falls Dam ($p < 0.001$).

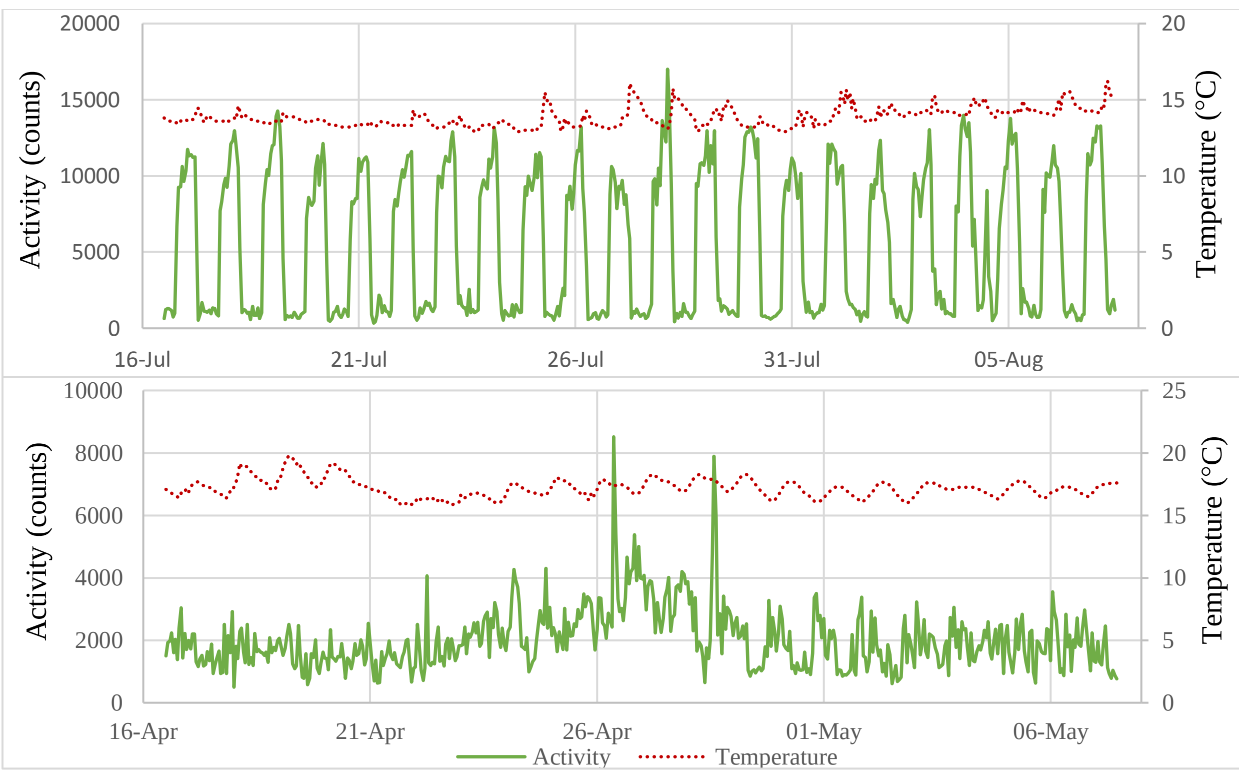

Fig. 5.7 Locomotive activity (solid line) from *Labeobarbus natalensis* (individual LNAT41), during two periods, (Top) in Albert Falls from 17 July to 7 August 2019 and (Bottom) in uMngeni River from 17 April to 7 May 2019. The heightened activity was observed during the day and low activity at night in Albert Falls, diel behaviour patterns were observed periodically in the uMngeni

River (early May). Water temperature (dotted line) associated with the tag from LNAT41 is also shown.

5.5 Discussion

The high presence of predators within the study area was showed to impact tagged *L. natalensis*. Predation by otters on *L. natalensis* is known to occur (Rowe-Rowe 1977; Perrin and Carugati 2000) while the main diet of *H. vocifer* is fish (Hockey et al. 2005; Cowley et al. 2017). Predation on tagged fish have been found in other fish telemetry studies (Beland et al. 2001; Halfyard et al. 2017; Schultz et al. 2017) and shown to be a considerable disturbance to fish in the present study. Six tag retrievals indicated that either otters or an avian predator had taken the tagged individual, with one caught by subsistent anglers and discarded near a fishing site.

In Albert Falls Dam signal strength from tagged fish was regularly highest during the night, and sometimes disappearing at times during the day in the present study. This change in signal strength showed that *L. natalensis* generally rested at night near the surface in Albert Falls Dam. Similarly, signal strength was used to determine depth use of African lungfish (*Protopterus aethiopicus*) with loss of signal at depths > 10 m (Mlewa et al. 2007). The risk from aerial predation at night is reduced allowing fish to rest near the surface at night undisturbed by them. States of torpor by *L. natalensis* have been observed in low water temperatures (5 °C) in winter (Crass 1964). The lack of movement increases the risk to predation in areas where predators are in abundance and water temperatures critically low. Water temperatures observed in the uMngeni River dropped to 6 °C in winter, close to the lower threshold limits for *L. natalensis*, increasing the need for *L. natalensis* to seek out refugia habitats during these unfavourable conditions. The water temperatures recorded on the fish tags showed that *L. natalensis* seek our micro-habitats to tolerate cooler temperatures. The lowest water temperature recorded on a fish tag was 9 °C. These micro-habitats consist of environments with stable water temperatures such of pools and large bodies of water with depths greater than a meter that buffer the extremities of temperatures found in shallower waters (Karssing et al. 2008). During the summer, the uMngeni River water temperatures closely matched the fish tag water temperatures indicating higher water temperatures being favoured by *L. natalensis* (Table 5.2).

Labeobarbus natalensis are known to inhabit boulder-strewn rivers associated with rapids and pools (Crass 1964; Karssing 2008). The use of these habitat types generally varies seasonally, as was also shown in the present study. The possibility that these fish moved out of the upper reaches prior to the construction of Albert Falls Dam is high because of low water temperatures of instream habitats. Alternatively, Albert Falls Dam does provide stable refugia habitat for the winter months, as indicated by the fish tag temperatures. Albert Falls was found to be a key habitat for *L. natalensis* in the austral winter months (June, July and August). Use of the uMngeni River during the summer months is likely because of *L. natalensis* seeking suitable spawning habitat and/ or better feeding grounds when water is warmer. The use of deep pools in winter helps buffer extreme water temperature ranges experienced in the river during this period. This is similar to *Labeobarbus* spp. in larger systems such as the Vaal River, South Africa, where they make use of deep in-stream habitats (O'Brien et al. 2013). Tagged fish that did not move into Albert Falls may have used these in-stream pool habitats as refugia during the winter. An increase in water temperature during spring and early parts of summer may serve as a cue for fish to move up into the river as seen in the present study. This cue determined upstream migration more than flows in the present study where the study period followed a severe drought with rains arriving six months later than expected in March 2019 (Kusangaya et al. 2018). Base flows were generally maintained at 4-5 $m^3.s^{-1}$ in the uMngeni River because of consistent dam releases. These relatively low summer base flows did not completely deter upstream movement but can hinder the ability for *L. natalensis* to navigate instream barriers effectively.

Only one of the six fish that made upstream reach-scale movements moved past Morton's Drift. The limited movement past this semi-permeable barrier highlights the negative impact of these anthropogenic structures during low flow. However, Crass (1964) stated that generally large adult *L. natalensis* do not undertake large-scale movements. In the present study, all tagged fish were mature adults, and this could have contributed to tagged fish not passing Morton's Drift. The use of fishways by juvenile and smaller *Labeobarbus* spp. adults have been observed in other studies where few large adult fish were present (Meyer 1979; Fouché and Heath 2013). The presence of instream barriers such as Albert Falls (both upstream and downstream effects) still need to consider its implication towards the *L. natalensis* population's resilience to pollution events, changes in flow regime and the reduction of habitat availability for *L. natalensis* (Mantel et al. 2017; O'Brien et al. 2019).

The tagged *L. natalensis* individuals that did not move out of their tagged location showed high site-fidelity. The lack of reach-scale movement supports the hypothesis that yellowfish are facultative by nature (O'Brien et al. 2013a; Burnett et al. 2018). All sites used to tag fish were deep pools > 6 m near (< 10 m) to rapid habitats. The availability of these habitat types is important for the biological functioning of *L. natalensis* and need to be maintained. The establishment of anthropogenic impoundments such as Albert Falls may provide adequate winter refugia for *L. natalensis*. However, instream barriers and poor flow regimes may cause the siltation of important habitats, creating them inaccessible and unsuitable for *L. natalensis,* negatively affecting their ability to recruit (Karssing et al. 2008).

Activity profiles of *L. natalensis* showed them to be highly active fish, with diurnal habits being shown in both habitat types. The strong diel activity patterns were seen within refugia habitats and less so in river habitat. Crass (1964) and Karssing et al. (2008) found *L. natalensis* will spawn at any time of the day. The distinct diel activity patterns shown in this study for refugia habitat show *L. natalensis* to take up different behaviour during different biological events such as spawning, feeding, resting and recovery and will adapt their behaviour accordingly. Diurnal habits were seen in river habitat types periodically possibly indicating that *L. natalensis* would hold in instream pools moving into rapids to spawn and then back into pools to rest or recover from these lengthened periods of activity. This correlates with energy budgets observed in several other fish species, further indicating the ability to use activity as an indication of energy use (Broell et al. 2016; Metcalfe et al. 2016; Beltramino et al. 2019).

In the present study prolonged non-diel like activity patterns were often between periods of distinct diel activity matching the circadian cycle. It is unclear as to the exact location within the river where fish were during these periods and is hypothesised that these diurnal periods within the activity of *L. natalensis* could coincide with the use of pools within the river in between spawning periods in rapids, where slow-moving water allowed for fish to rest. This use of fast-flowing and slow-moving water supports the rheophilic nature of the species (Karssing 2008). Wright and Coke (1974a, 1974b) and Crass (1964) found *L. natalensis* carry several developmental stages of eggs suggesting multiple spawning events, spawning both during the day and at night within rapids. The higher locomotive activity in Albert Falls than the uMngeni River questions the energy budget shifts between the two habitats. Habitat such as boulders have higher velocities associated with them and one would assume higher activity to maintain position and obtain food resources (Gretener 1985; Woldegiorgis et al. 2018). This associated activity pattern was not shown, suggesting *L. natalensis* are better adapted for instream habitats in acquiring food resources and spawning than in their refugia habitat. The movement between these two habitat types was shown to be highly correlated with water temperature, with flow assisting in habitat availability during these periods. Temperature changes could be the driving cue for behavioural change, with more food being available and spawning requirements met in boulder-strewn habitats, dominant in the river during the summer (Crass 1964; Karssing 2008). This seasonal change forces *L. natalensis* to take up refugia habitat (water temperatures < 10 °C) and can be regarded as secondary habitat used to wait out naturally/induced unfavourable conditions. The importance of these river habitats emphasises the need for adequate flows to be maintained to allow the scouring of rivers preventing the siltation of these important habitats as further pressure on water demand is expected (Liu et al. 2016; Tilman et al. 2017).

Although the flow regime in the uMngeni River has been compromised because of anthropogenic development and severe drought in the region, there has not been a total collapse of the *L. natalensis* population. However, concern for the population has been expressed because of increased anthropogenic pressures, repeated fish kills and decline in abundances (Karssing 2008; Sibanda et al. 2015). The facultative behaviour for *L. natalensis* has seen it persist beyond the establishment of large impoundments within the uMngeni River, with recent concerns primarily being driven by water stressors (Sibanda et al. 2015). Water temperature cues within the uMngeni River Catchment have largely remained natural, despite the system being regulated (Kusangaya et al. 2018). These temperature cues have triggered the movement of *L. natalensis* from their refugia habitat to their spawning grounds, despite the reduction in flow observed over the last decade (Kusangaya et al. 2018).

5.6 Conclusions

Understanding the main drivers of *Labeobarbus* spp. behaviour is important when managing the sustainability of rivers and improves on the foundational work set to establish them as ecological indicators by Impson et al. (2008). The importance these species have towards managing regulated rivers within the region is becoming more important towards understanding the biological response of an aquatic ecosystem to changes induced anthropogenically. Temperature is seen as the main driver for *L. natalensis* in seeking out refugia habitat with this habitat type being important towards surviving unfavourable water temperatures experienced in winter.

The increase in flows during spawning months (December-February) may increase the available habitat for *L. natalensis* to spawn, creating a higher chance of successful recruitment of juvenile fish. The availability of anthropogenic impoundments such as Albert Falls for *L. natalensis* serves as an important refugia habitat, but only provides a portion of the habitat required for their life cycle. Without instream pools and rapids, *L. natalensis* is unable to spawn during the summer nor maintain body condition for the subsequent winter when food resources generally become scarce. Maintaining these instream habitats are as important as maintaining their refugia habitats.

The impact of obstructions to large-scale reach movement by *L. natalensis* such as Albert Falls is largely lacking. However, the facultative nature of the species has shown them to survive the onslaught of impoundment development in the uMngeni catchment to increase water supply to users, this cannot be said for other migratory species such as the anguillid taxon (Hanzen et al. 2019). Using the behavioural and spatial ecology of fishes and managing rivers to maintain their biological functioning is important when it comes to meeting the sustainable use of water resources.

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CHAPTER 6

Evaluating the behavioural response of fishes towards management flows in a regulated river using fish telemetry methods

Matthew J. Burnett[1,2], Gordon C. O'Brien[1,3], Thomas Rowe[4], Graham Jewitt[2,4], Colleen T. Downs[1*]

[1]Centre for Functional Biodiversity, School of Life Sciences, P/Bag X01, Scottsville, Pietermaritzburg, 3209, South Africa

[2] Centre for Water Resource and Research, School of Engineering, P/Bag X01, Scottsville, Pietermaritzburg, 3209, South Africa

[3] School of Biology and Environmental Sciences, Faculty of Agriculture and Natural Sciences, University of Mpumalanga, Nelspruit, South Africa, 1200

[4] Institute for Water Education, IHE Delft, Westvest, South Holland, Netherlands, 2611

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* Corresponding Author: Colleen T. Downs
Email: downs@ukzn.ac.za
Tel: +27 (0)33 260 5127
ORCID: http://orcid.org/0000-0001-8334-1510
Other emails: matthewburnett014@gmail.com, ORCID: https://orcid.org/0000-0002-6237-1697; gordon.obrien@ump.ac.za, ORCID: https://orcid.org/0000-0001-6273-1288; victor.wepener@nwu.ac.za, ORCID: https://orcid.org/0000-0002-9374-7191; g.jewitt@un-ihe.org, ORCID: https://orcid.org/0000-0002-7444-7855

Running header: Evaluating the behavioural response of fish to an environmental flow using activity sensors.

6.1 Abstract

To secure water in areas where demand for water is high is to increase storage through the development of impoundments which place pressure on the well-being of aquatic ecosystems. Fish are indicators of changes to aquatic environmental conditions and used to evaluate the ecological status of aquatic ecosystems. In this study, we assess the fish response to a management flow release on the economically important regulated uMngeni River, KwaZulu-Natal Province, South Africa. The release took place between Midmar and Albert Falls impoundments on the uMngeni River and increased flows from 2 $m^3.s^{-1}$ to 20 $m^3.s^{-1}$ from the 3rd to 5th of April 2019. Water quality samples were collected using *in situ* fixed water probes and grab samples pre-, during and post the release and included a control site in the adjacent Karkloof tributary. To evaluate the biological response, activity sensors from ten tagged *Labeobarbus natalensis* were analysed using fish telemetry methods to determine spatial and non-spatial movements during the release. In addition, a fish community assessment was conducted within the Karkloof and uMngeni Rivers during the study. Water quality variables increased in concentration at the front of the release, tapering down as flows were maintained at 20 $m^3.s^{-1}$. Fish behavioural response exhibited in three types; Type 1; activity peaked with changes in diurnal behaviour, Type 2; no activity peak with changes in diurnal behaviour and Type 3; mortality (LNAT37). No fish moved into the Karkloof River, and there was no change in community structure. However, in the uMngeni River fish community classes did show a change in structure, with an increase in abundances of smaller size classes (<300 mm) for *L. natalensis*. Managing flow release is important for meeting biological requirements, improving

water quality and gaining a better understanding of the effects they have on the aquatic ecosystem. Continual monitoring of flow releases using fish telemetry techniques with activity sensors can improve our understanding of the timing, duration and quantity of environmental flows needed.

Keywords: anthropogenic stressors, fish telemetry, electronic tags, activity, yellowfish, environmental flow,

6.2 Introduction

The increase in demand for water and its growing scarcity has resulted in the development of instream water storage impoundments altering flow regimes and water quality concentrations (Dudgeon 2014; Rodell et al. 2018; Du Plessis 2019; Sabater et al. 2019). Amongst the challenges of managing large impoundments is the need to meet environmental flow requirements to minimise the loss of aquatic biodiversity and maintain ecological integrity downstream of impoundments (King and Brown 2006; O'Brien et al. 2018; Sabater et al. 2019). The downstream effects on the freshwater environment by impoundments can be detrimental towards aquatic organisms (Van Looy et al. 2014; Yarnell et al. 2015; Poff and Schmidt 2016; Ramulifho et al. 2019). The implementation of environmental flow requirements is continually being tested, especially in areas where the demand for water exceeds the capacity for a catchment to supply these (Pollard et al. 2012; Dudgeon 2014; Zhuang 2016; Du Plessis 2019). To adequately evaluate these impacts, there is a need to monitor the biological component and assess their response to the changes brought about by instream barriers, altered flow regimes and changes in water quality associated with management releases (Wepener 2008; Mehdi et al. 2018; Dickens et al. 2018).

Fish are considered good indicators of environmental changes and are known to respond to multiple stressors within the aquatic ecosystem (Schiemer 2000; Depledge and Galloway 2005;

O'Brien et al. 2014; Arthington and Balcombe 2011; Baumgartner et al. 2014; Fouchy et al. 2019). Various levels of biological organisation in fish are used when assessing anthropogenic stressors on an aquatic ecosystem's well-being (Wepener 2008; McCallum et al. 2019; Sharma 2019). Fish behaviour is regarded as one biological organisation level that can assess the whole organism response to the ecosystem and is considered to be more sensitive than other bioassay methods (Bietinger and McCauley 1990; Wepener 2008; Sharma; 2019). Fish telemetry is one method that can adequately evaluate the behaviour of fish within aquatic ecosystems that are often difficult to sample (Cowley and Naesje 2004; Thorstad et al. 2013; Cooke et al. 2013; Lennox et al. 2017). The application of fish telemetry to answer management questions is increasing, especially with the use of accelerometers and activity sensors that can detect the locomotive movement of fishes (Cooke et al. 2016; Cooke et al. 2017; Hounslow et al. 2019). These sensors have been used to reveal energy budgets, activity patterns, parasitic influences, responses to the environment and behaviour abnormalities in fishes; all factors which are important for managing regulated rivers and implementing environmental flows (Broell et al. 2016; Metcalfe et al. 2016; Beltramino et al. 2019; Burnett et al. 2018; Thiem et al. 2018).

Flow management is a key approach to deliver water to users in the catchment and meet environmental flow requirements (King and Brown; 2006; O'Brien et al. 2018; Dickens et al. 2019). Understanding how the behaviour of fishes respond to management releases can improve the timing and quantity of flows, mitigate the impact of an altered flow regime and improve the environmental flow management (Cooke et al. 2016; O'Brien et al. 2018). Fish responses to changes in flow and temperature differ between species depending on their biological requirements (Flitcroft et al. 2016). It is important to assess the biological components of a catchment affected by flow regime changes as the biological response is unique per catchment because of anthropogenic impacts, regional climatic factors and local fauna present in the aquatic ecosystem (Saraiva Okello et al. 2015; Vilmi et al. 2017). Fish telemetry is an appropriate method to monitor these impacts and has been implemented within southern Africa to determine the behaviour of fish in the region (O'Brien et al. 2013; Jacobs et al. 2016; Burnett et al. 2018; Ramesh et al. 2018). The *Labeobarbus* family in South Africa are good indicators of aquatic ecosystem well-being because of their abundance, economic importance and occurrence in many South African Rivers (Impson et al. 2008; Brand et al. 2009; Rivers-Moore and Goodman 2010). They are long-lived, large growing cyprinids that have shown to be tolerant to poor water quality yet are sensitive to changes in flow and temperature (Impson et al. 2008; Fouché and Heath 2013; O'Brien et al. 2013; Burnett et al. 2018). *Labeobarbus natalensis* can be found throughout the rivers of KwaZulu-Natal Province and occur within the uMngeni catchment which is a nationally economically important but highly regulated river (Hughes et al. 2018a, b). However, despite their value as an indicator species, relatively little is known of the species response to altered flow regime and water quality changes (Crass 1964; Karssing et al. 2008).

For this study, we hypothesised that there is a response by *L. natalensis* to management releases and that fish activity rates detected using fish telemetry methods can be used to evaluate the response to these changes when monitored in real-time and remotely. Furthermore, we assessed the response of fish to the changes in flow and water quality to determine the over-riding stressors during a flow release.

6.3 Methods

For this study, an environmental management flow release was organised on the 3rd of April 2019 from Midmar Dam into the uMngeni River, KwaZulu-Natal Province (Fig. 6.1). Due to late seasonal rains and artificially sustained baseflows during this period, the uMngeni River had not experienced a first-flush during the rainy season. An inter-basin transfer from Spring Grove Dam in the adjacent Mooi River catchment gave a reprieve from the drought for water users regulating the release downstream as needed through Midmar Dam (99 %) (Mander et al. 2017). As the dry conditions persisted and flow release were maintained (between 1 and 2 $m^3.s^{-1}$) the storage levels of impoundments in the lower reaches were critically low and in need of water to meet water use demand, Albert Falls Dam (40 %) (DWS 2019). The decision was made to release water to alleviate the water storage stress and provide an environmental flow during this extended dry period. The release contained both the bottom and topwater to mimic near-natural conditions. The management flow release started at 08:00 and increased from the baseflow of 2 $m^3.s^{-1}$ by 5 $m^3.s^{-1}$ hourly until flows reached 20 $m^3.s^{-1}$. Once the peak of 20 $m^3.s^{-1}$ was reached, it was maintained for 38 h before flows were dropped by 10 $m^3.s^{-1}$, 5 $m^3.s^{-1}$and 3 $m^3.s^{-1}$ hourly and returned to initial baseflows. During the flow release, water quality grab samples were taken from four sites (Water probe A - D) hourly for the first 24 h and then every two hours until baseflows had returned (Fig. 6.1). Water quality parameters tested for and used in the study included chemical oxygen demand (COD), biological oxygen demand (BOD), ammonium (NH3), nitrate (NO3), soluble reactive phosphorus (SRP), total phosphorus (TP), turbidity and levels of *Escherichia coli*. The Karkloof River, a control site (Water probe D), was included in the four sites and was available for fishes responding to the flow release. The uMngeni and Karkloof Rivers both face different water quality challenges because of varying upstream land uses, with the Karkloof River maintaining better water quality conditions (Namugize et al., 2018). The Karkloof site lies within Ihlanze Game Reserve that limited access to daylight hours for safety reasons.

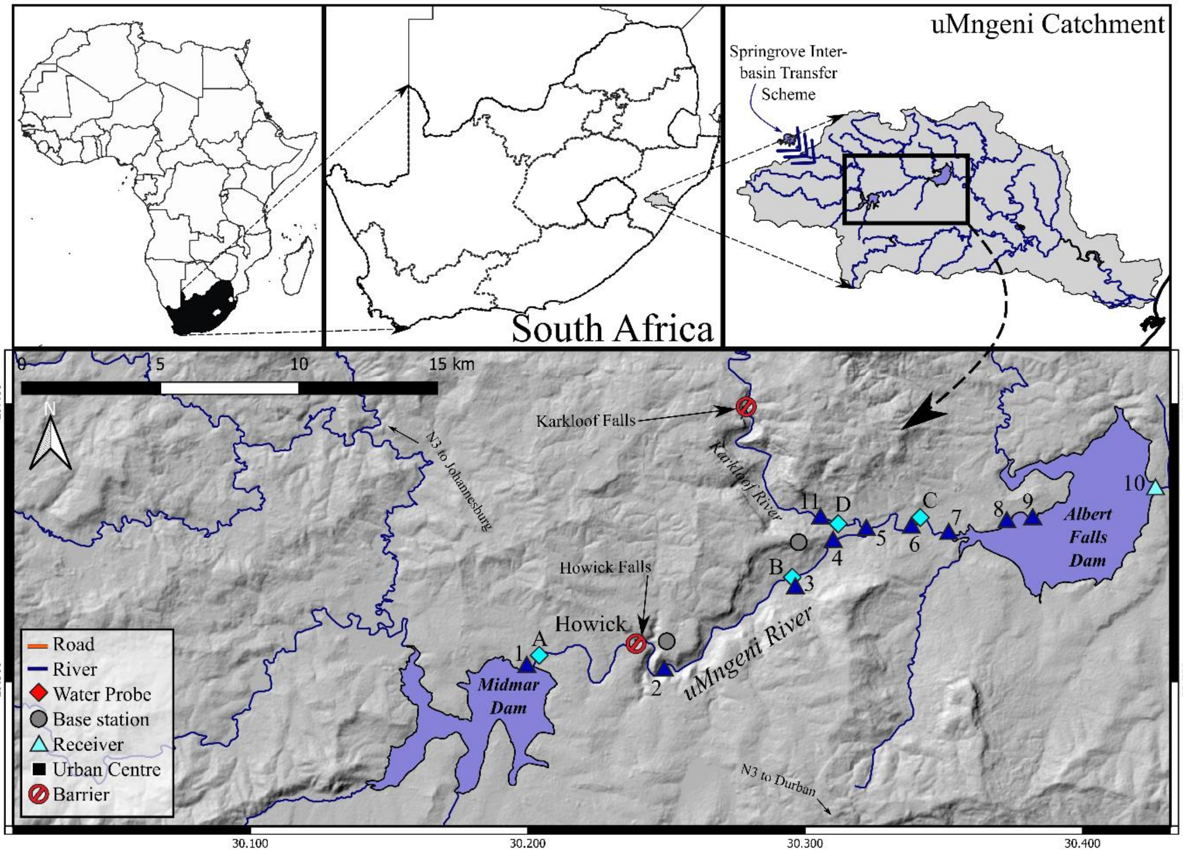

Fig. 6.1 The location of the present study area, showing the positioning of receivers and water probes within the uMngeni and the Karkloof River, the instream barriers are included.

In addition to the water quality samples, two water quality probes, (Wireless Wildlife series IX; WW, 13 Forsman Street, Potchefstroom, 2531) were used to evaluate the flow at each site in real-time, taking a reading every 30 min. These probes recorded discharge (flow), temperature and electrical conductivity (EC). Flows were recorded using a pressure sensor and converted to water depth (Thompson and Taylor 2008) which was then used to derive flow as follows. Selected transects were demarcated for repeatability and surveyed perpendicular to flow (a cross-section) for water levels, depth and velocity (Rowlston et al. 2008). Survey equipment consisted of a land-based Leica total station (Leica, Wetzlar, Germany) and an OTT MFPro electromagnetic current meter (OTT Hydromet, Ludwigstrasse 16, 87437 Kempten, Germany) was used to capture flow velocity and estimate flow by dividing the channel into more than 20 vertical sections to calculate flow (Gordon et al. 2004). Flow, energy slope and transect data were extracted from the field measurements, with roughness calculated using the Manning's n formula based on the measured data (Gordon et al. 2004). In order to extrapolate the observed hydraulic data to other stage levels and develop a continuous rating function, 1-dimensional hydraulic modelling was done using the HEC RAS (Hirschowitz et al. 2007; Birkhead 2010). Output from the modelling and field measurements were plotted in MicrosoftExcel (MS-excel; ©2017, Microsoft Corporation) and second-order polynomial equations were used to describe the flow-stage relationship for each transect based on the depth calculated by the WW series IX water probe (Hirschowitz et al. 2007). On obtaining the discharge readings for each water probe, the rate of flows downstream was assessed during the release flows as scheduled from Midmar Dam. The gauging station UR001 obtained from the department of water and sanitation (DWS) monitored the release directly below Midmar Dam (DWS 2019).

To evaluate the biological response of the fishes, electronic tags were attached to *L. natalensis* (n = 43) downstream of Midmar Dam at the confluence of the Karkloof and uMngeni Rivers (Fig. 6.1; Table 6.1). Albert Falls Dam serves as a refugia habitat for *L. natalensis* during the low flow season (May to August) while the uMngeni and Karkloof River are available during the high flow season (September to April) (Crass 1964). The spatial movement in response to a management release could then be assessed based on the accessibility of these two rivers during different flows. Tags used for the study were WW series III tags equipped with activity (SQ-SEN-200, SignalQuest, Inc, Lebanon, NH) and temperature sensors and communicated data across a radio telemetry-based network of receivers every hour as per Burnett et al. (2019a) (Fig. 6.1). The receiver network determined the spatial movement of fish, while the activity sensor determined the non-spatial movement (activity) of fish during the study.

Table 6.1: Fish tagged during the study; SL is the standard length of fish tagged.

Fish ID	SL (mm)	Weight (g)	Tagged location		Start	End	Days tracked
LNAT22	415	1750	-29,446287	30,321621	05-Sep-18	30-Apr-19	237
LNAT30	540	3010	-29,446287	30,321621	14-Nov-18	09-May-19	176
LNAT32	430	1680	-29,446287	30,321621	30-Nov-18	26-May-19	177
LNAT36	440	1760	-29,446287	30,321621	06-Feb-19	14-May-19	97
LNAT37	420	1740	-29,446287	30,321621	06-Feb-19	10-Apr-19	63
LNAT38*	440	1680	-29,446287	30,321621	07-Feb-19	17-Jul-19	160
LNAT39	445	1340	-29,446287	30,321621	14-Mar-19	07-May-19	54
LNAT40	440	1530	-29,446287	30,321621	14-Mar-19	06-May-19	53
LNAT41	440	1700	-29,446287	30,321621	21-Mar-19	16-Aug-19	148
LNAT42	450	1620	-29,446287	30,321621	21-Mar-19	27-Aug-19	159

*Tag malfunctioned during the release

For the study, fish were captured and tagged at receiver 5 (Fig. 6.1). Gill nets were the preferred means of capture and constantly monitored for movement to improve retrieval time of fish. Fish that fell within the 2 % tag to body mass ratio guideline were held in a container with circulating river water (Childs et al. 2011; Jepsen et al. 2015; Burnett et al. 2020). Before performing surgical procedures, the fish were placed in an anaesthetic bath containing clove oil (0.1 ml l^{-1}) and monitored for signs of narcosis (Fernandes et al. 2017). Tags were then attached externally through the muscular tissue below the dorsal fin (Bridger and Booth 2003; Jepsen et al. 2015; Burnett et al. 2020). Once the tag was attached, the fish was returned to the holding container to recover from the anaesthetic. At this stage wound care gel (Aqua Vet, Veterinary hospital, Lydenburg, South Africa) and antibiotics (Terramycin® containing oxytetracycline) were applied onto and around the wound respectively. Once fully recovered from the anaesthetic, the fish was released back into the river at its point capture.

To assist with validation of fish movement populations and community structures of fish responded, a fish community assessment on the uMngeni and Karkloof Rivers was conducted using fyke nets and an electro-shocker. These surveys were conducted at 12 h intervals from the day before the release until the morning after the release flows had subsided. Fish caught were identified, and the standard length of each fish measured and then classed according to size and species (Table 6.2). *Labeobarbus natalensis* size classes were differentiated using juveniles (< 145 mm), sexually mature adults between 146 – 300 mm and sexually mature adults greater than 300 mm (Crass 1964; Karssing et al. 2008).

Table 6.2 Results of the fish community assessment pre-, during and post-management flow release in the present study.

Karkloof River					
			Size class (mm)		
	Species	**Total**	**<145**	**146-300**	**>301**
Pre-release	*Labeobarbus natalensis*	27	27	-	-
	Tilapia sparrmanii	10	-	-	-
	Amphilius natalensis	6	-	-	-
During release	*Labeobarbus natalensis*	19	17	2	-
	Tilapia Sparrmanii	4	-	-	-
	Amphilius natalensis	2	-	-	-
	Enteromius palludinosus	*1*	-	-	-
Post release	*Labeobarbus natalensis*	5	5	-	-
uMngeni River					
			Size class (mm)		
	Species	**Total**	**<145mm**	**146-300**	**>301**
Pre-release	*Labeobarbus natalensis*	2	-	2	-
	Tilapia sparrmanii	1	-	-	-
	Pseudocrenilabrus philander	2	-	-	-
During release	*Labeobarbus natalensis*	17	11	6	-
	Tilapia sparrmanii	1			
	Pseudocrenilabrus philander	1			
Post release	*Labeobarbus natalensis*	8	5	3	-
	Clarius gariepinus	1	-	-	-

6.3.1 Data analyses

Data from fish community and activity from tagged fish were evaluated against the water quality parameters collected in this study. Data were assessed using time-series graphs depicted in MS Excel and then analysed in RStudio using the mvabund, and vegan packages (RStudio 2015). A principal component analysis (PCA) was used to compare the behavioural variable (Activity) of tagged fish and fish community abundances to the environmental variables from the water probes and grab sampling leading up to, during and post the release period (Van den Brink et al. 2003; Bengraïne and Marhaba 2003; O'Brien et al. 2009; Nasir et al. 2011). The PCA determines the linear response for behaviour and fish communities between dependent and independent variables and plots the relationship on an ordination graph (Van den Brink et al. 2003; Nasir et al. 2011). In addition to the PCA, a redundancy analysis (RDA) was undertaken and graphically represented together to create a bi-plot that depicts the best fit directional pull by the environmental variables (O' Brien et al. 2009; Nasir et al. 2011).

6.4 Results

Water was released from Midmar Dam as scheduled. The 20 $m^3.s^{-1}$ was reached and maintained for 32 h before returning to the baseflow condition. There was a delay of 8 h between the release point and water probe B's monitoring site (Fig. 6.1). The HEC-RAS model calculation differed to that of the gauging weir at U2R001 (provided a daily average), however, was 16152 m downstream and was able to provide changes in flow every 30 min. and was sufficient to detect changes in the flow that reflected the flow release. Water quality concentrations did change with the changes in flow, while the control site (Water probe D) on the Karkloof River remained consistent with little to no change as was expected (Fig. 6.2). The results from turbidity followed similar trends for all the other water variables measured depicting a sharp increase in concentrations at the front of the release, slowly decreasing as high flows were maintained and returning to pre-release conditions post-release (Fig. 6.2). The *E. coli* count was > 6000 mln/100ml pre-release and climbed to as high as 24196 mln/100ml at the peak of the flow, dropping down to 609 mln/100ml. While the peak flow was maintained, post-release levels return to 6000 mln/100ml (Fig. 6.2). All tagged fish were exposed to the experiment along with the changes in water quality downstream of water probe B.

Water quality coming out of Midmar at water probe A had low concentrations of water quality variables in comparison to water probe B, while water probe C resembled similar trends to that of water probe B monitoring site (Fig. 6.1).

A total of 10 fish with tags active during the flow release experiment period were used and their behaviour assessed from the 24th March through to the 24th of April 2019 over the flow release experiment (Table 6.1). The individual LNAT38 activity sensor fail during the period of the release and was not used in the analyses of the study. All tagged fish were plotted visually on a time series graph to depict the changes in activity when flows increased (Fig. 6.3). There were three type responses observed, Type 1 (n=4); activity peaked with changes in diurnal behaviour over the duration of the flow, Type 2 (n=4); no activity peak with changes in diurnal behaviour and Type 3 (n=1); activity peak with mortality (LNAT37) (Fig. 6.3). Spatial movement was observed for one individual that moved downstream during the release (LNAT39), while all tagged fish remained within the uMngeni River with no spatial movement of fish into the Karkloof River. Individuals LNAT 32 moved downstream several days after the release and LNAT42 moved downstream several days before the release.

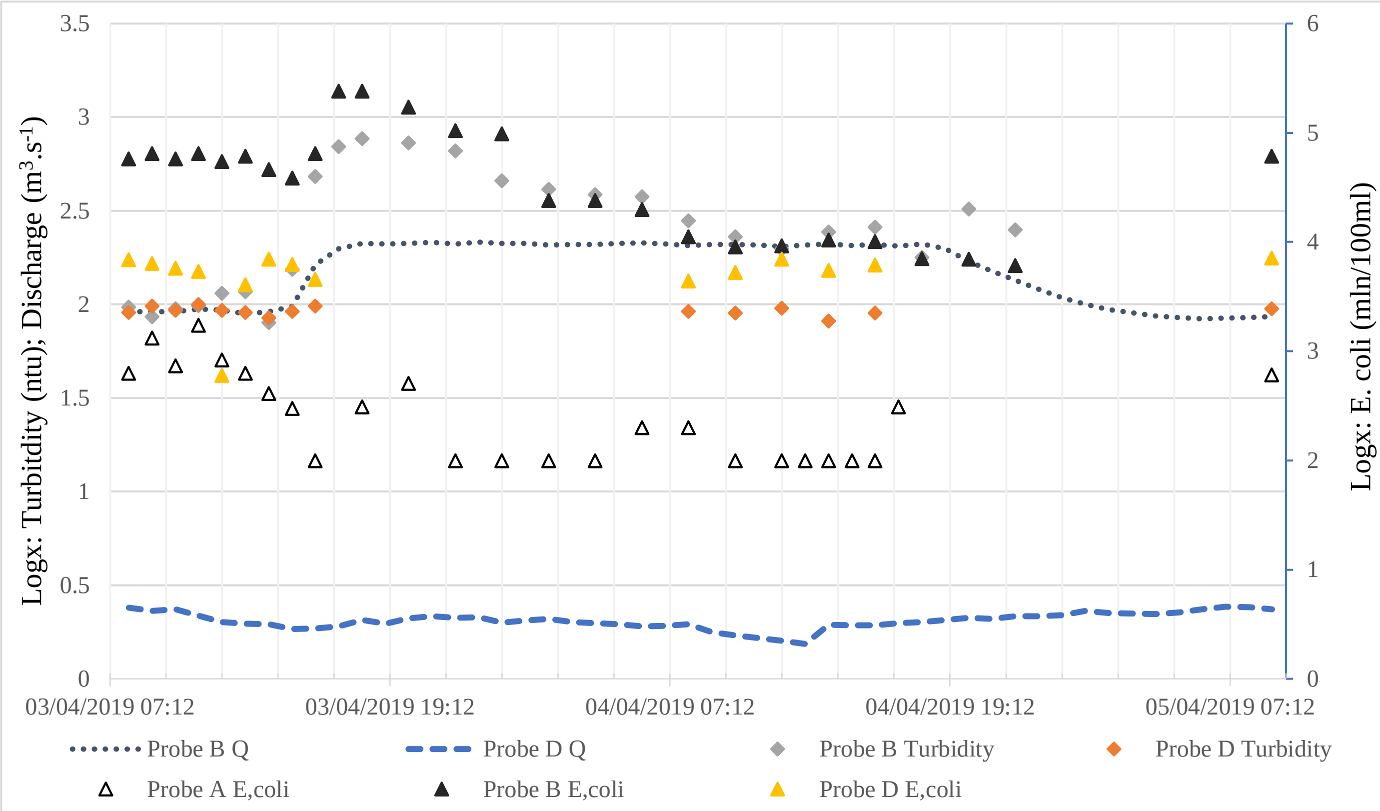

Fig. 6.2 A pollutograph depicting the changes in water quality parameters during the flow release from Midmar Dam in the present study.

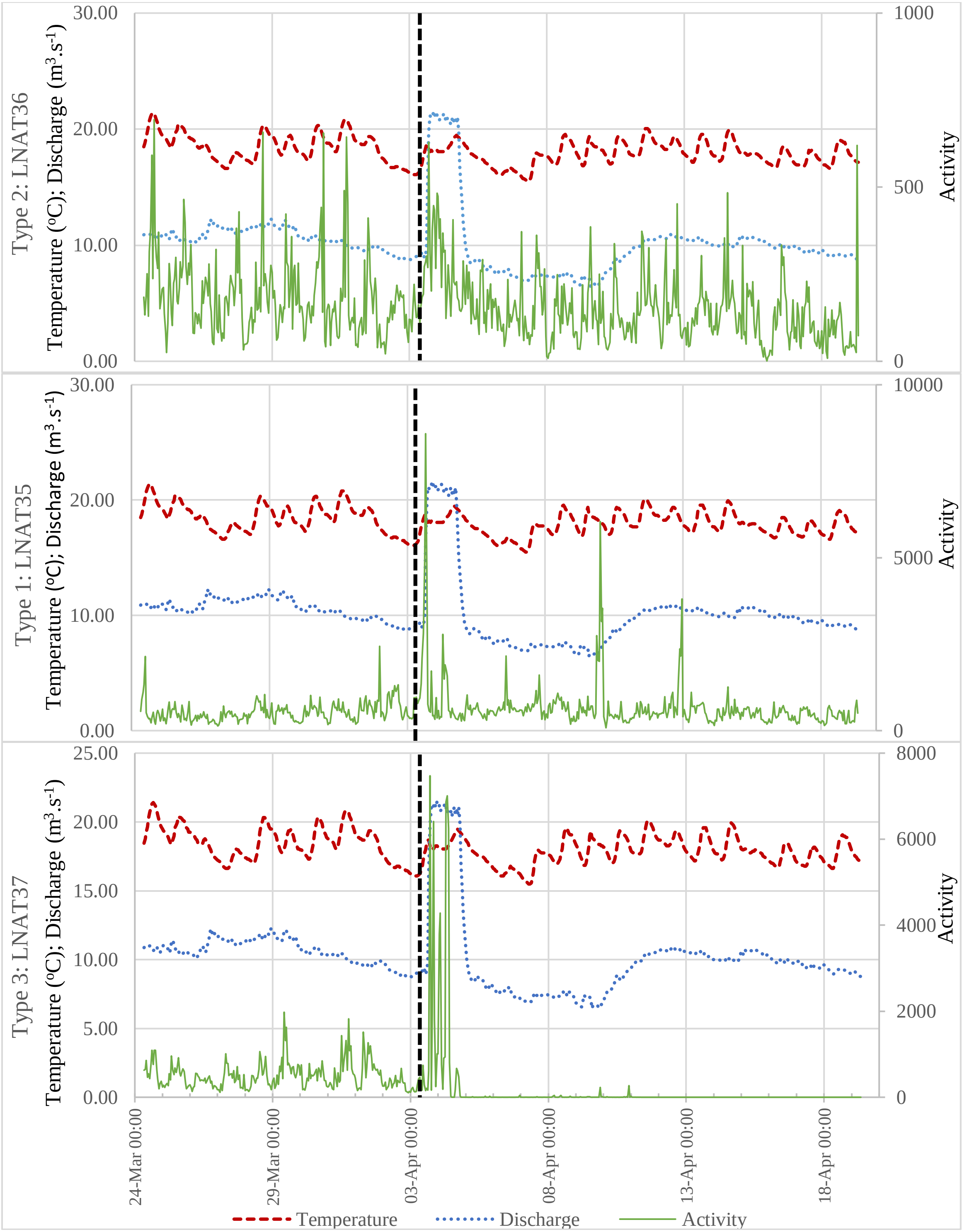

Fig. 6.3 Type 1; 2; 3 responses represented by three individual fish as observed during the water release from Midmar Dam (the black dotted line) moved downstream through the study area, flow and temperature were representatives of readings at water probe B (see Fig. 6.1).

The PCA analyses detected a significant relationship for flow and water temperature for fish activity ($p < 0.001$ and $p < 0.01$ respectively), while EC did not have a significant relationship (Fig. 6.4). Significant differences were found for most water quality variables obtained through grab sampling; however, BOD did not have any significant relationship towards fish activity ($p < 0.001$). The directional pull from the water quality parameters on fish activity was similar and correlated strongly with the flow (Fig. 6.4). The PCA analysis undertaken for the fish community component showed no significant relationship towards the changes in flow or water quality. Despite this, the size class of fish found during the community assessment on the uMngeni River changed in response to the release. There was an increase in abundances in size classes <300 mm for *L. natalensis*. The largest *L. natalensis* caught was 201 mm during the pre-release period in the uMngeni River. Other species caught at the site included *Pseudocrenilabrus philander, T. sparrmanii* and *Clarius gariepinus* with their abundances showing little change over the study period (Table 6.2). The fish community structure on the Karkloof River remained unchanged throughout the study period and largely consisted of juvenile non-breeding *L. natalensis*. Other species collected at the site included *Amphilius natalensis*, *Enteromius palludinosus* and *Tilapia sparrmanii* (Table 6.2).

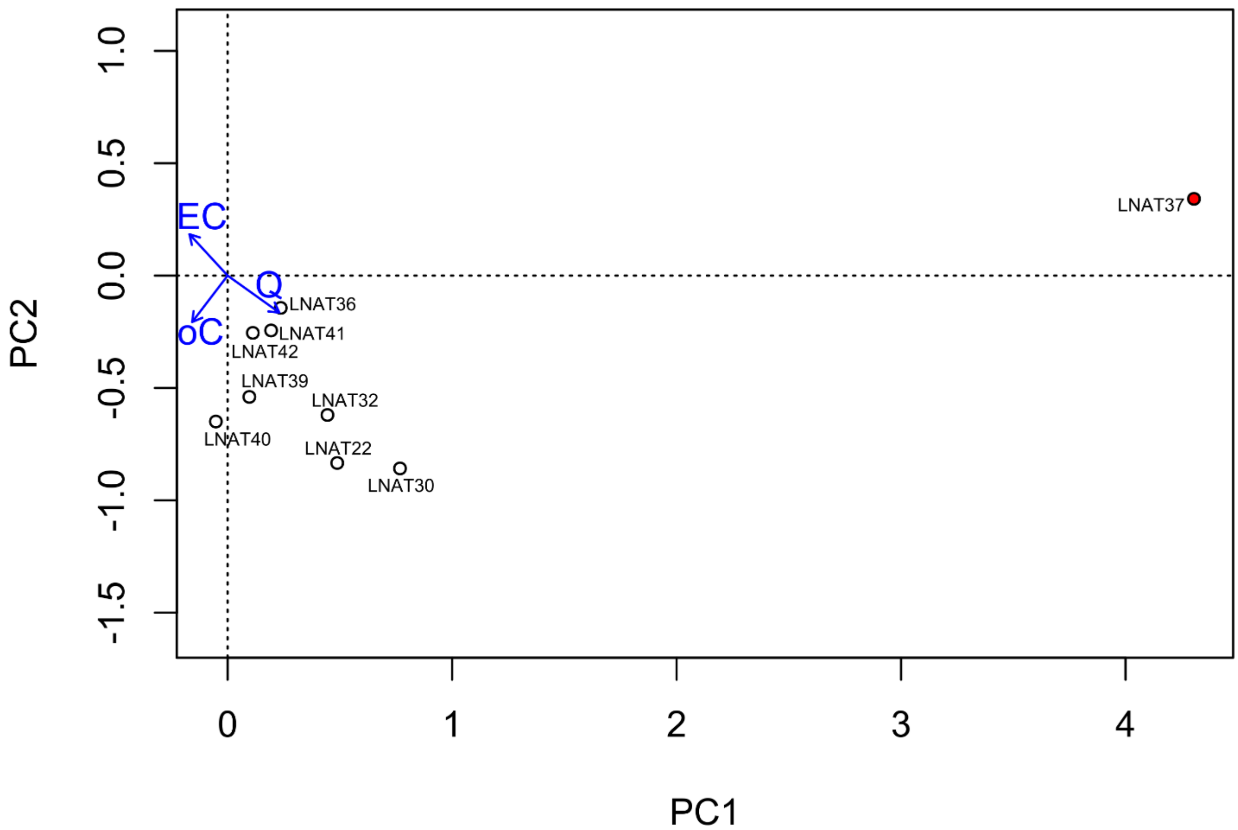

Fig. 6.4 The principle component analysis (PCA) bi-plot showing the relationship and response from fish tagged with activity sensor to water quality during the Midmar Dam release, LNAT37 (shaded) did not survive the release period, flow (Q) and Temperature (C) show significance while electrical conductivity (EC) did not ($p < 0.001$ and $p < 0.01$ respectively).

6.5 Discussion

The management flow release from Midmar Dam downstream to Albert Falls Dam did change the water quality on the receiving river ecosystem. The calculated flow from the HEC-RAS model for water probes adequately detected the timing of the flow release down the catchment and could be related to changes in activity as a result as to when the front of the flood moved through the study area. The effects of the water quality changes resembled that of a first flush phenomenon characteristic of areas that experience seasonal rainfall (Zuraini et al. 2018). When the flow release reached the 20 $m^3.s^{-1}$ flood level, it encompassed physical and chemical factors from the banks at this level along the main stem of the uMngeni River. The previous drought and low rainfall experienced before the release allowed the accumulation of pollutants within the 20 $m^3.s^{-1}$ flood line to be flushed out during the release. Water quality concentrations upstream of the urban environment were lower than downstream, having the resemblance of a first-flush pollutograph (Gunaratne et al. 2017; Zuraini et al. 2018). The high turbidity associated with the management release indicated the degree of disturbance of sediments mobilised during the release, that could have collected pollutants allowing them to re-enter the system (Woldegiorgis et al. 2018). The elevated levels of *E. coli* within the uMngeni River before the release and subsequentially elevated at the front of the release are as a result of residual organic matter disturbed in the floodplain and outputs from the WWTW (Namugize et al. 2018; Comber et al. 2019). The remedial action during base flows is disturbed with the change in flows and compounded by floodplain disturbance before settling as the release maintains its peak (Oberholster et al. 2013; Comber et al. 2019). The initial spike of *E. coli* was followed by below the normal level for *E. coli* in the uMngeni River, indicating that sustain high levels of flow does dissipate or dilute pollutants during sustained peak flow. This was shown for the other water quality parameters, whereby the sustained level of flows reduced concentrations to below normal levels before the release or return to pre-release concentrations (Fig. 6.2) and suggests that the change in conditions is what disrupts the system. These concentrations may have been higher had the management release coincided with high rainfall, which would have been more representative of a catchment first flush. The source of pollutants and relationship between tributaries, run-off and mainstem accumulation will need further investigation, especially if management flows such as this flow release become a norm because of increased stressors and climate change predictions for the region are required to maintain sustainability (Hughes et al. 2018a,b; Kusangaya et al. 2018; Dickens et al. 2019). The front of the flow release correlated with a spike fish activity for five (56 %) fish, this was when water quality concentrations also peaked, indicating that the front of a flow release is when fish are most responsive, negatively impacting LNAT37 that did not survive the front of the flow release.

The low sample size in this study should be considered, when interpreting the response of *L. natalensis*, as a low confidence result. Despite this, *L. natalensis* behaviour did alter during the flow release in the present study. The individuals with a Type 1 response indicated that the front of the flow release is a crucial moment for fish as this was when changes in behaviour were greatest. During Type 1 and 2 responses, the change in diurnal behavioural patterns showed a disruption in the normal behaviour of *L. natalensis* (Crass 1964; Burnett et al. 2019). *Labeobarbus natalensis* are known to spawn throughout the day resulting in loss of distinct diel behaviour patterns. Environmental cues for spawning are largely unknown with spawning events occurring periodically in one season (Crass 1964; Burnett et al. 2019). The disruption in diurnal patterns in the present study was attributed directly towards the changes in flow and consequentially water quality indicating a response to survive these changes as with similar studies where activity changes in a response to adverse conditions (Noda et al. 2014; Broell et al. 2012; Broell et al. 2016; Thiem et al. 2018). Other periods of diurnal disruption in similar studies were not always associated with changes in flow suggesting that this disruption is not always orientated around spawning and could be attributed to avoidance or holding behaviour during changes in water quality (Beltramino et al. 2019; Burnett et al. 2019).

The changes in behaviour in the present study were related to the change in discharge that resulted in increasing concentrations affecting water quality. These increased concentrations exposed fish to higher pollutant concentrations associated with anthropogenic stressors. Not all individuals have the resilience to handle sudden increases in concentrations as observed with the Type 3 response by *L. natalensis*. When water quality levels are sustained at higher than natural levels, chronic stress may result in Type 3 responses being more evident when management flow releases take place. Furthermore, if first-flush flows are experienced and/ or if pollution spill events occur more frequently, then population resilience is reduced (Namugize et al. 2018). The use of activity sensors to monitor behaviour can indicate these changes in behaviour in real-time and through the FISHTRAC programme can be monitored remotely as seen in the present study (Burnett et al. 2020). The behaviour of tagged fish in the present study detected the subtle biological changes otherwise not detected with other biological assessment methods, such as fish community assessments. In addition, the behaviour was shown to be effective in monitoring and evaluating the biological response to a management flow release in real-time. The significant results from the PCA analyses detected the influence of flows and temperature on the behaviour of fishes but also detected the individual variability in response to these changes (as with LNAT37). The fish community response detected population structural changes related to the flow release. However, the detection was limited in evaluating the biological response of these changes as the detection time was slower and not always conducive to handling elevated flows (Wepener 2008). The activity of tagged fish during the present study (24th March to 19th April 2019), showed that their responses to changes in flow were more significant than temperature. This response was despite temperature been shown to be a stronger cue to trigger biological response in the absence of flow changes (Burnett et al. 2019, Flitcroft et al. 2016). These responses highlighted the importance of both these variables on fish behaviour when regulating rivers.

The results from the fish community assessment indicated that smaller fish undertook increased movements during a change in flow compared with larger size classes in the present study. This was similar to results from other *Labeobarbus* spp. studies (Fouché and Heath 2013; O'Brien et al. 2013; Burnett et al. 2018). The presence of instream barriers could hinder larger individuals from undertaking such movements. The high abundances of juvenile fish in the Karkloof River could also indicate that different size classes utilise different habitats, similarly to *L. marequensis* (Burnett et al. 2018), and can access streams with lower flows. The diversity of species differed for each river, the absence of sensitive species such as *A. natalensis* in the uMngeni River indicates the increased stress placed on the uMngeni River because of anthropogenic stressors (Kleynhans and Louw 2008). However, the lack of abundances hindered further assessment of sensitive species within a degraded aquatic ecosystem and supports the use of *L. natalensis* as indicator species because of their tolerance to pollutants, high abundances and mobility within the system (Impson et al. 2008).

The Karkloof River was not selected by fish, this site (Water probe D) remained consistent in its fish community structure and tagged fish did not move into the river in response to the flow release. The lack of movement into the Karkloof River demonstrated the preference these fish have to higher flows despite the increase in water quality variables concentrations. The tapering down in these concentrations was seen as flows were maintained at peak flow indicating that despite the front of the release being potentially negative towards fish the sustained high flows bring other benefits not associated with baseflows, as example; creates habitat, improves food resources and provides access to habitats (Poff and Schmidt 2016; O'Brien et al. 2018; O'Brien et al. 2019). The downstream movement seen by LNAT39 can be associated with the movement of *L. natalensis* seeking refugia habitat late summer, early autumn (Crass 1964; Burnett et al. 2019). *Labeobarbus natalensis* are largely cued by temperature to move in between refugia and spawning habitats and aided by seasonal high flows during periods of increased temperature (Crass 1964; Burnett et al.

2019). The release was during a period when *L. natalensis* was expected to start moving back into their refugia habitat. The flow release facilitated the downstream movement of LNAT39 and showed the importance of how a management flow release can facilitate the biological functioning of a species when correctly implemented. Reversely, a management flow timed during the beginning of the season could facilitate upstream migration. These flow managements highlight the importance to provide environmental flows that mimic flood events to facilitate and cue biological events needed by fish adapted to seasonal rainfall (Arthington and Balcombe 2011). The anthropogenic stress placed on the aquatic ecosystem from upstream of the study area does impact downstream ecosystem functioning and alters the flow regime. Managing and mitigating these impacts are crucial to ensure the long-term survival of aquatic species and assist in measuring sustainability in regulated rivers.

6.6 Conclusions

The uMngeni River is a highly regulated river and primarily managed to supply water to the surrounding area that exceeds 4 million people and is growing (Roberts and O'Donoghue 2016; Ethekwini, 2018). The recent droughts and associated management responses have placed large stress on the aquatic ecosystem highlighting the importance of river ecosystem not only for human use but also in providing ecosystem services (Tilman et al. 2017). Drought events often place added stress on the aquatic ecosystem and are expected to increase in frequency because of climate change predictions (Kalungisa et al. 2018). Evaluating the trade-offs have seen an increase in sustained stressors on aquatic ecosystems and providing the minimum requirements for environmental flows (Liu et al. 2016; Namugize et al. 2018). Management releases such as the one in this study are important towards meeting biological requirement, improving water quality and gaining a better understanding of the effects of management releases on the aquatic environment when monitored. Monitoring using fish telemetry techniques with added activity sensors can improve our understanding of management flows reducing mortality results. Longer sustained high flows were shown to improve water quality and fish behaviour responses in this study. However, this may not always be feasible when water is limited because of demand and drought conditions. Timing of environmental flows in this study supported other studies and should make provision for flood events preferable when natural high flows are expected (McGane et al. 2016; Poff and Schmidt 2016; Ramulifho et al. 2019). Environmental management flow releases can facilitate the movement of fish downstream into refugia or upstream into spawning habitats improving the ecosystem's response despite naturally dry conditions.

The Mooi River inter-basin transfer scheme played an important role in drought reprieve, allowing for a management flow release and assisted in maintaining environmental flows. The reprieve as more water becomes available for use in a stressed catchment; however, the negative impacts of inter-basin transfers must not be ignored (Zhuang et al. 2018). Monitoring for environmental flows can be done using fish as indicator species. *Labeobarbus* spp. are good indicators of aquatic ecosystem well-being and coupled with fish telemetry methods can be used to monitor and evaluate the flow regimes within regulated rivers. Fish behaviour in the present study showed that a managed flood event during a drought timed within the period of expected natural high flows can positively affect the well-being of the ecosystem. This effect can be by providing better flows during upstream movement, during spawning events or downstream movement. These large water storage impoundments, despite highly regulating flows, can meet aquatic ecosystem requirements and be monitored to determine whether these objectives are achieved by using fish telemetry methods as has been demonstrated. Fish telemetry methods need to be coupled by other biological assessments and water quality testing especially when behavioural changes occur assisting in developing best practices to mitigate anthropogenic stressors within the aquatic ecosystem.

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CHAPTER 7

Detecting changes in fish behaviour in real-time to alert managers to thresholds of potential concern within an urban river

Matthew J. Burnett[1,2], Gordon C. O'Brien[1,3], Graham Jewitt[2,4], Colleen T. Downs[1*]

[1]Centre for Functional Biodiversity, School of Life Sciences, P/Bag X01, Scottsville, Pietermaritzburg, 3209, South Africa

[2] Centre for Water Resource and Research, School of Engineering, P/Bag X01, Scottsville, Pietermaritzburg, 3209, South Africa

[3] School of Biology and Environmental Sciences, Faculty of Agriculture and Natural Sciences, University of Mpumalanga, Nelspruit, South Africa, 1200

[4] Institute for Water Education, IHE Delft, Westvest, South Holland, Netherlands, 2611

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* Corresponding Author: Colleen T. Downs
Email: downs@ukzn.ac.za
Tel: +27 (0)33 260 5127
ORCID: http://orcid.org/0000-0001-8334-1510
Other emails and ORCID: matthewburnett014@gmail.com, ORCID: https://orcid.org/0000-0002-6237-1697; gordon.obrien@ump.ac.za, ORCID: https://orcid.org/0000-0001-6273-1288; victor.wepener@nwu.ac.za, ORCID: https://orcid.org/0000-0002-9374-7191; g.jewitt@un-ihe.org, ORCID: https://orcid.org/0000-0002-7444-7855

Running header: Developing and testing an algorithm to determine changes in fish behavioural activity

7.1 Abstract

Aquatic ecosystems that flow through urban environments are increasingly faced with anthropogenic stressors associated with them. These stressors affect the well-being of freshwater ecosystems and their ability to provide ecosystem services. Fish behaviour is one biological organisational level that is regularly used to assess aquatic ecosystem well-being and can be monitored using fish telemetry methods. The development of activity sensors incorporated into fish telemetry allows for non-spatial movement to be detected as locomotive activity and is increasingly being used to determine budgets, response to environmental variables, predicting and determining abnormal behaviour for fishes. The ability to detect fish remotely and in real time highlights the need to process the activity data from fishes in near real-time to make it applicable to research questions and mangers in the water resource sector. This study developed and tested an algorithm that considers previously known behaviour of fishes and evaluates the current behaviour against is to determine if there is a notable change in behaviour. When change is detected an alert is triggered. The study showed that the algorithm could adequately detect changes in behaviour on both individual and population level. Further, generalised linear models were tested using the same activity data and showed that fish behaviour was significantly affected by water temperature. Discharge and electrical conductivity did not have strong correlation with behaviour. The predictive model help determine the potential drivers for changes in behaviour where the algorithm could detect this. Change in behaviour as a result of environmental variables provide thresholds of potential concern and are important when managing for ecosystem well-being in urban rivers. Knowing when behavioural changes happen can alert managers to take

further action in determining the causal effects on behaviour change and assist in mitigating when these changes are a result of unnatural changes in environmental variables.

Keywords: Fish behaviour, regulated river, fish telemetry, fish activity, algorithm, ecological indicators

7.2 Introduction

Urbanising environments are increasing placing anthropogenic stressors onto the aquatic ecosystems that flow through them (Rodell et al. 2018; Du Plessis 2019; Sabater et al. 2019). These aquatic ecosystems find themselves on the receiving end of daily changes to water quality and flow (Saraiva Okello et al. 2015; McGrane 2016; Du Plessis 2019). The increased development and human population growth have resulted in increased pressure on Waste Water Treatment Works (WWTW) that service these urban areas to maintain water quality standards for river ecosystems as set out by governing authorities (DWAF 1996; Dudgeon 2014; Nel et al. 2017; McGrane 2016). The failure to keep up with the demand in providing services affects the aquatic ecosystem and the potential for effective remedial action to take place naturally downstream (Oberholster et al. 2013; Mehdi et al. 2018). To assess the impact these changes in water quality have on the freshwater ecosystem, there is a need to monitor the biological component and understand how they respond to changes in water quality (Mehdi et al. 2018; Dickens et al. 2018).

Fish are regarded as good ecological indicators towards aquatic ecosystem health, as they are easily monitored, long-lived organisms and charismatic by nature (Harris 1995; Depledge and Galloway 2005; Brand et al. 2009; Baumgartner et al. 2014). Various biological organisation levels of fish are used when assessing water quality and the effects on ecosystem well-being (Wepener 2008; McCallum et al. 2019; Sharma 2019). In particular, fish behaviour has shown to respond when exposed to multiple stressors and is 10-100 times more sensitive than other levels of biological organisation (Beitinger 1990; Bietinger and McCauley 1990; Sharma 2019).

Fish telemetry methods are one means to study the behaviour of fish *in situ* and have been used globally to determine the behaviour of wild fishes (Cooke et al. 2013; Thorstad et al. 2013; Hussey et al. 2015; Lennox et al. 2017). Fish telemetry was initially developed to determine spatial movements of fish and is now able to determine energy budgets and activity of fish within their natural environments with the use of activity sensors (Lucas and Baras 2000; Broell et al. 2013; Metcalfe et al. 2016; Beltramino et al. 2019; Theim et al. 2018; Hounslow et al. 2019). The development of these high resolution activity sensors has led to the use of activity of fishes as a means to determine abnormal behaviour, monitoring behaviour, predicting fish behaviour and understanding energy budgets of fish (Wong et al. 2012; Broell et al. 2013; Wright et al. 2014; Cooke et al. 2016; Beltramino et al. 2019; Fuchs and Caudill 2019). The use of fish activity has been growing and has been used to assess changes in behaviour evaluated on residentiary fishes (Cooke et al. 2016; Beltramino et al. 2019). Recently the use of these activity sensors has been used to identify when certain fish activities happen such as spawning, holding, swimming and digging (Fuchs and Caudill 2019).

Fishes are known to be habitual in their behaviour, exerting periods of activity that coincide with circadian and diel cycles (Reeb, 2002; Jacobs et al. 2016; Burnett et al. 2018). Changes to the habitual behaviour of fishes can point towards abnormal (behavioural) patterns, often exerted in response to a change within the environment (Reebs 2002; Broell et al. 2016). Stressors downstream of wastewater treatment works are known to affect fish behaviour altering fish community structures (McCallum et al. 2019). Knowing when changes in behaviour happen is important to understanding changes in water quality within an aquatic ecosystem, especially one exposed to stressors from an urban environment (Chimienti et al. 2016; Beltramino et al. 2019; Mehdi et al. 2018). *Labeobarbus* spp. within South Africa are recognised as indicator species and have recently been the focus of fish telemetry studies to determine their behavioural ecology and relationship with water stressors (Impson et al. 2008; Rivers-Moore and Goodman 2010; O'Brien et al. 2013; Jacobs et al. 2016; Burnett et al. 2018; Ramesh et al. 2018; Fouchy et al. 2019). With recent developments in fish telemetry to monitor fish activity in real-time and remotely within the region, the use of fish behaviour to monitor river health has resulted in new applications (Burnett et al. 2019a). One species, *Labeobarbus natalensis*, has gained recent attention with water stressors often causing fish kills downstream of urban environments (Karssing et al. 2008; Sibanda et al. 2015). Recently the use of locomotive activity as a behavioural variable has been shown to be effective in monitoring fish in real-time and remotely with potential to alert managers to environmental changes that need attention (Burnett et al. 2019a).

Thresholds of potential concerns (TPC) are used in the adaptive management of ecosystems, where the monitoring of resources is fed back into management structures (Bigg et al. 2011; Capon et al. 2015). These TPC use the tolerance ranges of species, the structure of ecosystems and the effect of anthropogenic stressors to adapt management and improve on practice (Mcloughlin et al. 2011; Rogers et al. 2013). Monitoring fish behaviour in real-time and remotely can set TPCs for fish behaviour and adapt them based on the responses to and impacts from anthropogenic stressors (Mcloughlin et al. 2011; Capon et al. 2015; Burnett et al. 2019a). Establishing TPCs for fish behaviour requires known behavioural ecology and tolerant ranges of fish that can then determine at which point these changes in behaviour need to warrant the adaption of management decisions to improve the freshwater ecosystem (Biggs et al. 2013; Capon et al. 2015). The large datasets accumulated through the FISHTRAC programme need to be analysed and alongside known behavioural thresholds assessed to determine TPC associated with changes in behaviour (Burnett et al. 2019a).

The collection of large amounts of data in short periods is growing with field biological studies using technology, for example with the use of sensor tags on fish and accessing the data in real-time and remotely (Greene et al. 2014; Cooke et al. 2016; Lv et al. 2017; Thum et al., 2018; Burnett et al. 2019a). Linking fish activity data to environmental variables in real-time can be problematic because of the processing time associated with analysing large datasets, reducing the responsive action by managers (Cooke et al. 2016; Lv et al. 2017; Burnett et al. 2019a). Hourly obtained data creates a large dataset that needs to be processed on an hourly basis to relay relevant information to managers (Callebaut 2012; Burnett et al. 2019a). Models and algorithms that aid in the interpretation of real-time data need to be developed to process data into tangible outcomes that can be used by researchers and managers alike (Callebaut 2012; Leonelli, 2014). These algorithms and data processing dashboards have the potential to develop early warning systems, reduce response time and improve ecosystem well-being (Leonelli 2014; Burnett et al. 2019a)

For this study, we developed an algorithm for *L. natalensis* to detect when changes in their behaviour occur. We then ran the algorithm using data from individual fish tagged with activity sensors to determine whether these changes are in response to environmental variables or biological functioning. We hypothesised that the current behaviour of fish compared to its average preceding behaviour can be used to alert managers to changes in the environment and that this will contribute to the detection of aquatic ecosystem stress. In support of this, we conducted analyses of environmental variables on fish activity to evaluate the relationship of the fish behavioural response towards water stressors to determine probable casual relationships of *L. natalensis* activity.

7.3 Methods

To develop an algorithm and test it 43 *L. natalensis* were tagged with activity sensors in the uMngeni River between Midmar and Albert Falls impoundments, South Africa (Fig. 7.1.; Table 7.1). This reach is downstream of the town Howick and its wastewater treatment works (WWTW) and has varying levels of water pollution (Namugize et al. 2018) (Fig. 7.1). The reach of river maintains a population of *L. natalensis* that utilise the uMngeni River and Albert Falls impoundment at various times of the year occurring downstream of the town of Howick and it's WWTW (Crass 1964; Burnett et al. 2019b).

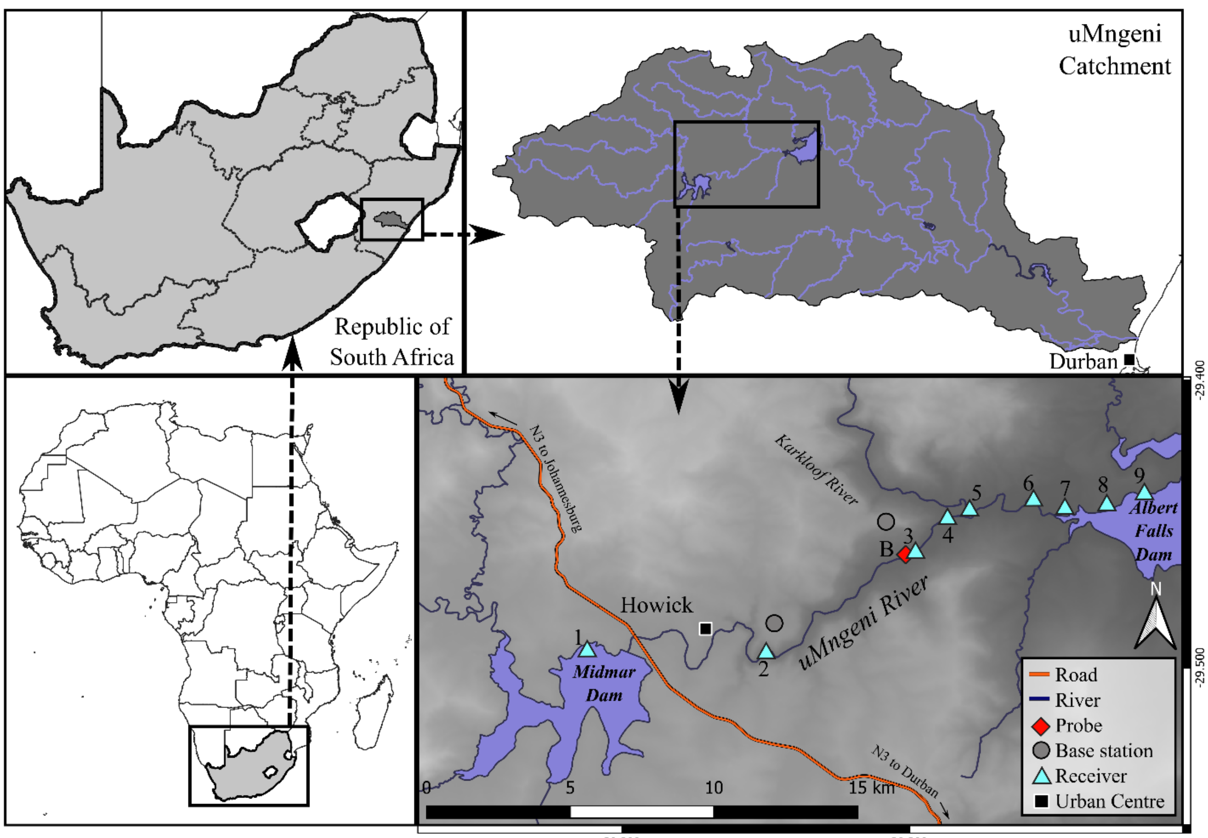


Fig. 7.1 The study area's location in KwaZulu-Natal, South Africa, showing the positioning of stations that received data from fish tags and the water probe used within the uMngeni near the Howick urban area and Midmar impoundment.

Table 7.1: Fish tagged for the study indicating the tagging location, size, weight and comments on the last activity reading.

Tag code	ID	SL (mm)	Weight (g)	Tagging location		Start	End	Days tracked	End track status
455:57	LNAT22	415	1750	-29,446287	30,321621	05-Sep-18	30-Apr-19	237	Tag became inactive
455:41	LNAT02	505	2370	-29,448404	30,355185	09-Aug-18	21-Feb-19	196	Tag became inactive
455:46	LNAT07	460	1650	-29,448404	30,355185	22-Aug-18	03-Mar-19	193	Fish moved out of network
455:53*	LNAT32	430	1680	-29,446287	30,321621	30-Nov-18	26-May-19	177	Fish moved out of network
455:60	LNAT30	540	3010	-29,446287	30,321621	14-Nov-18	09-May-19	176	Fish moved out of network
455:56	LNAT21	410	1690	-29,446287	30,321621	05-Sep-18	15-Feb-19	163	Fish moved out of network
455:54	LNAT15	430	1540	-29,448404	30,355185	22-Aug-18	28-Jan-19	159	Fish moved out of network
455:55	LNAT20	465	2030	-29,446287	30,321621	05-Sep-18	21-Jan-19	138	Fish moved out of network
455:40*	LNAT28	445	1640	-29,446287	30,321621	14-Nov-18	11-Mar-19	117	Fish moved out of network
455:48	LNAT09	410	1280	-29,448404	30,355185	23-Aug-18	16-Dec-18	115	Fish moved out of network
455:64	LNAT35	455	1560	-29,446287	30,321621	30-Nov-18	24-Mar-19	114	Tag became inactive
455:47*	LNAT29	410	1410	-29,446287	30,321621	14-Nov-18	25-Feb-19	103	Fish moved out of network
455:29	LNAT36	440	1760	-29,446287	30,321621	06-Feb-19	14-May-19	97	Fish moved out of network
455:63	LNAT34	440	1550	-29,446287	30,321621	30-Nov-18	03-Mar-19	93	Tag became inactive
455:45	LNAT06	440	1720	-29,448404	30,355185	22-Aug-18	15-Nov-18	85	Tag became inactive
455:65	LNAT41	440	1700	-29,446287	30,321621	21-Mar-19	31-May-19	71	Fish moved out of network

For the purpose of this study Wireless Wildlife Series IV tags (WW, 13 Forsman Street, Potchefstroom, 2531) equipped with a tilt-vibration motion sensor (SQ-SEN-200, SignalQuest, Inc, Lebanon, NH) recorded the fish's movement as count activity (activity) were attached externally to fish. Data were recorded every hour and sent via a radio telemetry network to a central data management system (DMS) to be analysed (Burnett et al. 2019a). The network consisted of receivers and transmitters (stations) strategically placed in the study area to detect the signal from tagged fish (Fig. 7.1; Burnett et al. 2019a). Fish were caught using gill nets near station 5 and 7 and placed in a holding container with circulating river water using a submersible pump (Burnett et al. 2018). Fish were then selected on weights > 1200 g to exceed the minimum 2% tag to body mass ratio (Childs et al. 2011; Jepsen et al. 2015; Table 7.1). Chosen fish were placed in an aerated anaesthetic bath containing clove oil (0.1 ml l^{-1}) as the active drug and monitored for signs of narcosis (Fernandes et al. 2017). Once under anaesthetic, two 14-gauge needles were inserted through the muscular tissue below and to the back of the dorsal fin to maintain consistent placement of the tag (Bridger and Booth 2003; Jepsen et al. 2015). Surgical wire (0.508 mm) was then threaded through needles which were then removed. The wire was threaded through the backplate of the tag and twisted together to secure the tag. (Thorstad et al. 2013; Burnett et al. 2018). An antibiotic (Terramycin® containing oxytetracycline; Zoetis, Johannesburg, South Africa) was then injected (1 ml/kg) into the muscular tissue around the wound and Wound Care Gel (Aqua Vet, Veterinary Hospital, Lydenburg, South Africa) was applied over the wound. Descriptive morphological measurements were taken, and the fish returned to the holding container to recover from the anaesthetic. Once fully recovered the fish was then returned into the river at its capture location.

In addition to the activity data from the fish, one water probe (Probe A; WW) was positioned in the river to record the discharge ($m^3.s^{-1}$), temperature (°C) and electrical conductivity (uS/m) of the aquatic environment (Fig. 7.1). These probes recorded data at hourly intervals and sent data through the same network to the DMS to be analysed.

7.3.1 Algorithmic input

The large amounts of data obtained hourly need to be processed in near real-time to relay information that is relevant to managers (Burnett et al. 2019a). To assess the change in behaviour, an understanding of the behaviour as measured by locomotive activity needed to be determined for tagged fish (Broell et al. 2016; Beltramino et al. 2019). The basis of the algorithm took into consideration known behavioural activity patterns of *L. natalensis* and the distribution of activity data for the species (Burnett et al. 2019b). These activity patterns remain within a range of 200 to 15 000 counts per minute, with incidental spikes reaching 50 000 counts per minute. Locomotive activity varied between rest periods (200 to 2000) and active periods (2 000 to 12 000) which coincided with known diurnal behaviour for *L. natalensis* (Burnett et al. 2019b). *Labeobarbus natalensis* diurnal activity patterns were periodically altered, showing distinct non-diurnal patterns often associated with spawning (Crass 1064; Burnett et al. 2019b). Individual plasticity has been shown by *L. natalensis* but does not override the diel behavioural patterns (Burnett et al. 2019b). The variability in locomotive activity between individuals and the habitual activity patterns showed activity data to have a left-skewed distribution. This type of data distribution meant the algorithmic assessment had to meet non-parametric mathematical criteria (Olivier et al. 2008; Burnett et al. 2019b). The diel behaviour is well documented for fish species and needed to be an important consideration when developing the algorithm (Reebs 2002; Baktoft et al. 2012; Gleiss et al. 2017; Burnett et al. 2018;). The algorithm needed to detect abnormal behaviour outside the understood diel behavioural changes (Reebs 2002; Gleiss et al. 2017; Watson et al. 2019). To compensate for diel and individual plasticity behaviour, the algorithm treated locomotive activity from individuals separately and evaluated previously recorded activity as an arithmetic mean ($\bar{x}$) against the current activity reading. The evaluation considered the hour of the day (t_x) equal to t_x of the current activity's day (d_0) against t_x of the previous activity's days (d_{x-y}). Using t_x accounted for the diel behaviour shown by *L. natalensis* (Burnett et al. 2019b). The previous days recorded activity for t_x was averaged over the previous two (d_{1-2}), three (d_{1-3}), seven (d_{1-7}), and 14 (d_{1-14}) days to assess at what point the previous days behavioural $\bar{x}$ provided a representation of normal behaviour. Considering that the current activity ($APMd_0t_x$) will always be above or below the $\bar{x}$ preceding it. Therefore, a range above or below the $\bar{x}$ used a geometric mean (G_x) calculated from the same dataset used to determine the $\bar{x}$ at d_x. The G_x accounts for high variability in counts characteristic of skewed distributions associated with non-parametric data whereby the standard deviation cannot be used (Olivier et al. 2008). The range (R) was then determined by adding or subtracting the G_x to the $\bar{x}$ to provide a calculative means of deriving a range that was replicable across all individuals consistently. The $APMd_0t_x$ was then evaluated against R associated directly with its preceding activity $R(d_0)$, the following day would then shift the range forward incorporating $APMd_0t_x$ into R allowing the assessment to use a trailing average to assess the next day's activity as $APMd_0t_x$. Therefore, the following formula could be used to determine when the behaviour was normal:

$$R(d_0) = \bar{x}\left(d_{x-y}t_x\right) \pm G_x\left(d_{x-y}t_x\right)$$

Where d_{x-y} was the number of preceding days used to determine the range as an example the preceding 14 days was represented as d_{1-14}.

The current activity ($APMd_0t_x$) was evaluated against $R(d_0)$ and assessed as to whether the activity value fell within this range ($\in R$); if $APMd_0t_x$ fell out of R, a change in behaviour was registered. Therefore, a sub-formula in the algorithm

$$APMd_0t_x = \in R$$

determined no change in behaviour and

$$APMd_0t_x \neq \in R$$

determined a change in behaviour for $APMd_0t_x$. The $APMd_0t_x$ that was flagged as $\neq \in R$ is tested to see if it falls below or above Rd_0 and determined if change was lower or higher than expected.

After testing for behavioural change and if the $APMd_0t_x$ indicated a change, the persistence of this change was evaluated in order to determine if the change was an isolated incidence or not and thus warranted further investigation. When a change in behaviour was detected at d_0t_1 and then followed on by another detection of behavioural change at d_0t_2 this indicated that the change in behaviour is not an isolated incidence and could warrant further investigation. The detection of these behavioural changes was then referred to as an "alert". The number of hours consecutively detecting change was tested between three and five hours. Each consecutive test including testing for alerts above the range and below the range as "Alert 1" and "Alert A" for three hours and "Alert 2" and "Alert B" for five hours. These algorithmic scenarios were compared and flagged continual behavioural changes and removed isolated alerts that could be considered as false.

7.3.2 Data analyses

Data for running the algorithm were sourced from the DMS and aligned by date, formulated in Windows Excel, (©2017, Microsoft Corporation) and then plotted on a timeline to evaluate and visualise trends. Results from the algorithm were tabulated and assessed against environmental data from probe A along the same time scale (1 hour). Alerts triggered when running the algorithm for each individual were evaluated for frequency of occurrence and relevance to observed changes in activity patterns. Alerts determined for each individual were then compared against one another to determine any population behavioural changes. Continuous days, where there were more than eight tagged fish providing activity data, were selected to detect the number of individuals triggering alerts per day. Daily behavioural changes by various individuals were assessed on the daily occurrence of an alert regardless of the hour the alert occurred and assessed based on the presence of alerts across all individuals for the day to determine how many individuals changed behaviour.

To understand the causal environmental variables resulting in behavioural changes, a test using binomial generalised linear modelling (GLM) with mixed effects regression as a function of covariates was used (Ramesh et al. 2018). Covariates were tested for multicollinearity and selected for based on Pearson's correlation co-efficient test ($r < 0.60$) (Graham 2003). The Akaike's information criteria (AIC), standardised residuals and observed versus predicted values were used to determine the models best fit using the approach of Burnham and Anderson (2002). Models with the minimum AIC values were then selected and used to determine the linear regression of each covariate. Significance was evaluated using the p-values ($p < 0.05$) calculated within the best fit model. Models were ranked and selected on the minimum AIC value where delta AIC values $\leq$ 2 provided evidence for use of the model and used to explain the movement of *L. natalensis* (Burnham and Anderson 2002). Statistical analyses and GLM regressions were done using Programme R version 3.0 (RStudio 2015) with added packages MuMIn (Bartoń 2013) and lme4 (Bates et al. 2014).

7.4 Results

A total of 15 fish out of the 43 fish tagged were used in the present study, as they had the longest tracked days and recorded activity consistently through the remote network and onto the DMS from August 2018 to August 2019. The longest period of activity data for one fish was 237 days by LNAT22 with the shortest period used was 71 days by LNAT09 (Table 7.1). All 15 fish were assessed using the algorithmic equation develop in this study and could detect when changes in behaviour were evident (Table 7.2; Fig. 7.2). Using the arithmetic mean as the centralised point in the data set and the geometric mean (G_x) to determine the range plus or minus $\bar{x}$ was effective through all individuals without extending below zero or above the maximum recorded activity (Fig. 7.2), this also adequately detected the normal range that behaviour would fall within. The range detected more frequently activity changes above the range (R) than below R, and was effective in detecting consecutive readings of zero (Table 7.2, Fig. 7.2 - 7.3). The 14-days of previous known behaviour was shown to detect behavioural changes and on average provided more alerts across all individuals than other days tested (Table 7.2). The evaluation of these alerts to changes in behaviour occurred when there were distinct changes in activity patterns and was consistent across the individuals tested. The two-day evaluation of previous activity had little consistency when evaluated using the frequency of alerts and linking alerts to changes in activity patterns. This result was similar for three- and seven-days evaluations (Fig. 7.3). The differences in consecutive alerts between Alert 1 and Alert 2 criteria were notable with fewer alerts for Alert 2 effecting the sensitivity to detect behavioural change (Table 7.2). This result was similar between Alert A and Alert B and times eliminated all alerts to changes below the range for Alert B (Table 7.2). Therefore Alert 1 and A were then selected for further analyses.

Behavioural changes on a population scale were tested for 13 individuals from 21 September 2018 to 22 January 2019 over 124 days (Table 7.2) using the Alert 1 and A detected with 14 days of known behaviour. Only one alert by five individuals occurred on the 13 December 2018 (Fig. 7.2). With more frequent alerts detected by four, three and two individuals, respectively (Fig. 7.2). There were distinct days where there were behavioural changes on a population level (> 3 individuals responding). These changes occurred periodically during the assessment and seemed to correlate with changes in flow and temperature (Fig. 7.4). Data that had gaps in them, such as LNAT41, would still detect change or no change if gaps were eliminated and data treated as continuous from the previous time of known behaviour.

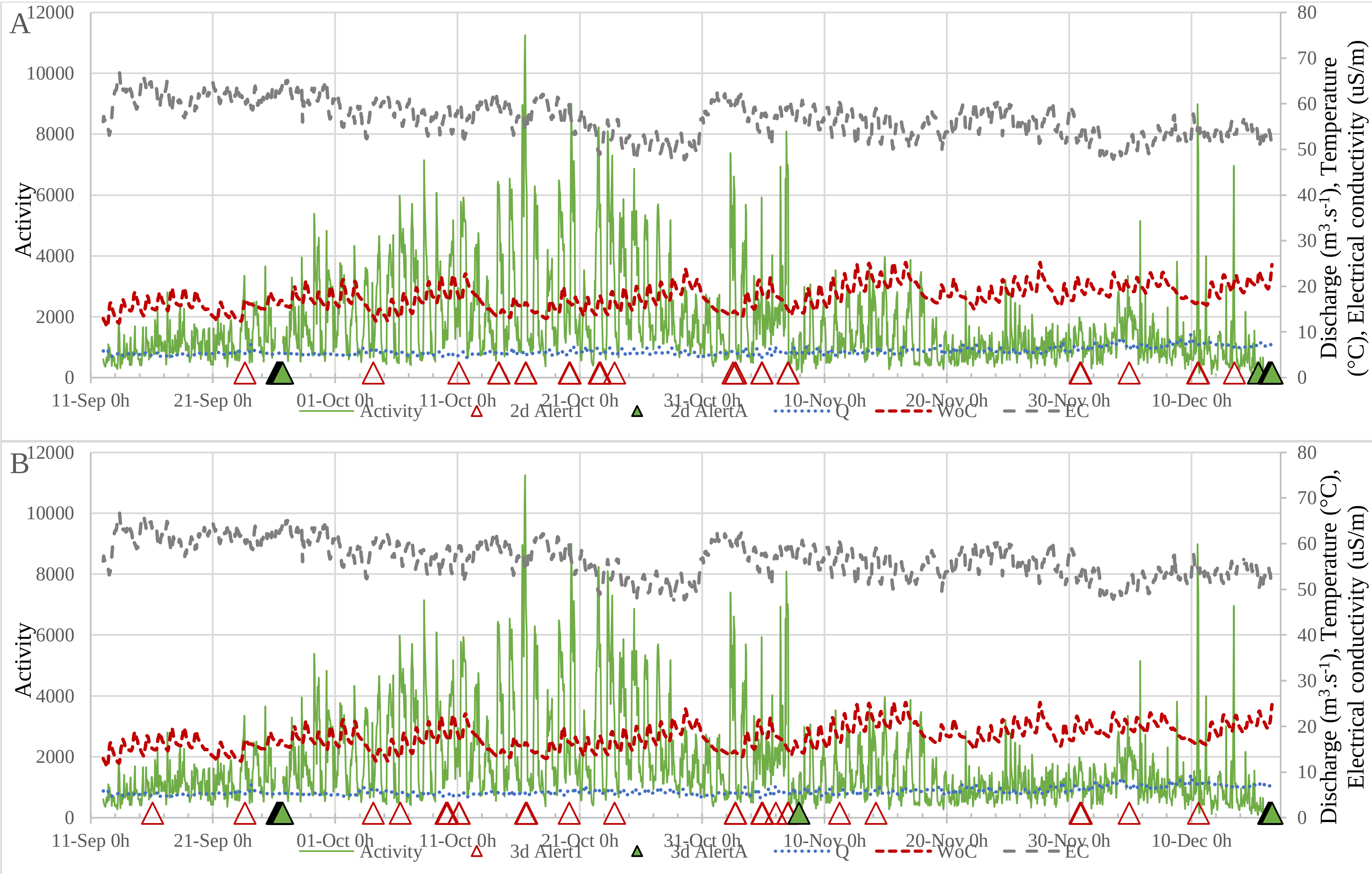
Generalised linear modelling was used to evaluate all 15 *L. natalensis* against the environmental variables measured on probe A. These environmental variables all had a Pearson's value < 0.60, showing low correlation between discharge, water temperature and electrical conductivity. The models selected were composed of combinations of the environmental variables recorded at probe A (Table 7.3). Models with AICc value (delta AIC $\leq$ 2) were selected for further analyses in evaluating the relationship variables had on the activity of *L. natalensis* (Fig. 7.5). These models were composed for combinations of discharge, water temperature and electrical conductivity with temperature being present in all combinations (Table 7.3). The best fit model showed water temperature to have a significant relationship with activity of *L. natalensis* (β = 0.01261 ± 0.001554, $p < 2^{e-16}$). Discharge was significant to $p < 0.1$ in the best fit model (β = -0.00345 ± 0.001866, $p < 0.0639$) and electrical conductivity did not show significance.

Table 7.3: The number of alerts triggered and the percentage of the alerts in relation to the days each individual was monitored for alerts when running the various algorithmic scenarios.

Tag ID	Period of assessment			d(1-2) Alert1	d(1-2) AlertA	d(1-2) Alert2	d(1-2) AlertB	d(1-3) Alert1	d(1-3) AlertA	d(1-3) Alert2	d(1-3) AlertB	d(1-7) Alert1	d(1-7) AlertA	d(1-7) Alert2	d(1-7) AlertB	d(1-14) Alert1	d(1-14) AlertA	d(1-14) Alert2	d(1-14) AlertB
	Start	End	Days																
LNAT02	03-Sep-18	21-Feb-19	171	59	23	6	3	63	25	9	4	47	21	8	3	35	15	6	3
			% Alerts	35%	13%	4%	2%	37%	15%	5%	2%	27%	12%	5%	2%	20%	9%	4%	2%
LNAT06	05-Sep-18	15-Nov-18	71	40	18	10	6	42	20	13	7	51	25	14	8	61	29	11	6
			% Alerts	23%	11%	6%	4%	25%	12%	8%	4%	30%	15%	8%	5%	36%	17%	6%	4%
LNAT07	06-Sep-18	03-Mar-19	178	59	22	7	1	67	29	10	1	72	35	8	2	98	51	3	1
			% Alerts	35%	13%	4%	1%	39%	17%	6%	1%	42%	20%	5%	1%	57%	30%	2%	1%
LNAT09	12-Sep-18	16-Dec-18	95	29	3	13	10	30	5	13	10	33	5	16	10	43	12	15	10
			% Alerts	17%	2%	8%	6%	18%	3%	8%	6%	19%	3%	9%	6%	25%	7%	9%	6%
LNAT15	07-Sep-18	28-Jan-19	143	79	37	25	14	75	35	30	15	68	30	29	20	52	22	45	26
			% Alerts	46%	22%	15%	8%	44%	20%	18%	9%	40%	18%	17%	12%	30%	13%	26%	15%
LNAT20	20-Sep-18	21-Jan-19	123	36	11	2	0	37	9	2	0	42	16	1	0	66	36	2	0
			% Alerts	21%	6%	1%	0%	22%	5%	1%	0%	25%	9%	1%	0%	39%	21%	1%	0%
LNAT21	20-Sep-18	15-Feb-19	148	122	36	18	10	113	27	35	22	142	49	66	37	168	77	81	44
			% Alerts	71%	21%	11%	6%	66%	16%	20%	13%	83%	29%	39%	22%	98%	45%	47%	26%
LNAT22	21-Sep-18	29-Apr-19	220	135	36	5	0	130	35	14	2	158	50	30	3	214	78	67	15
			% Alerts	79%	21%	3%	0%	76%	20%	8%	1%	92%	29%	18%	2%	125%	46%	39%	9%
LNAT28	29-Nov-18	11-Mar-19	102	28	7	0	0	28	9	0	0	22	5	0	0	33	8	0	0
			% Alerts	16%	4%	0%	0%	16%	5%	0%	0%	13%	3%	0%	0%	19%	5%	0%	0%
LNAT30	29-Nov-18	09-May-19	161	107	52	3	0	100	49	7	0	65	30	11	4	65	24	18	7
			% Alerts	63%	30%	2%	0%	58%	29%	4%	0%	38%	18%	6%	2%	38%	14%	11%	4%
LNAT29	29-Nov-18	25-Feb-19	88	102	57	5	0	90	56	12	1	101	64	25	16	138	89	20	12
			% Alerts	60%	33%	3%	0%	53%	33%	7%	1%	59%	37%	15%	9%	81%	52%	12%	7%
LNAT32	15-Dec-18	26-May-19	162	37	7	21	5	24	4	37	13	28	5	66	34	32	8	62	37
			% Alerts	22%	4%	12%	3%	14%	2%	22%	8%	16%	3%	39%	20%	19%	5%	36%	22%
LNAT34	15-Dec-18	03-Mar-19	78	26	7	26	22	25	2	23	17	23	4	25	21	32	9	25	21
			% Alerts	15%	4%	15%	13%	15%	1%	13%	10%	13%	2%	15%	12%	19%	5%	15%	12%
LNAT35	15-Dec-18	24-Mar-19	99	34	18	17	11	33	16	19	11	27	13	25	19	16	3	24	19
			% Alerts	20%	11%	10%	6%	19%	9%	11%	6%	16%	8%	15%	11%	9%	2%	14%	11%
***LNAT36**	21-Feb-19	14-May-19	82	33	15	2	0	20	7	1	0	31	12	6	0	36	16	12	2
			% Alerts	19%	9%	1%	0%	12%	4%	1%	0%	18%	7%	4%	0%	21%	9%	7%	1%
***†LNAT41**	06-Apr-19	16-Aug-19	75	29	16	3	0	37	21	3	0	70	46	1	0	77	53	1	0
			% Alerts	17%	9%	2%	0%	22%	12%	2%	0%	41%	27%	1%	0%	45%	31%	1%	0%

* Fish not included in population

† Included to evaluate the algorithm when gaps in data occur



A
B
Activity
12000
10000
8000
6000
4000
2000
0
80
70
60
50
40
30
20
10
0
Discharge (m³.s⁻¹), Temperature (°C), Electrical conductivity (uS/m)
11-Sep 0h
21-Sep 0h
01-Oct 0h
11-Oct 0h
21-Oct 0h
31-Oct 0h
10-Nov 0h
20-Nov 0h
30-Nov 0h
10-Dec 0h
Activity
2d Alert1
2d AlertA
3d Alert1
3d AlertA
Q
WoC
EC

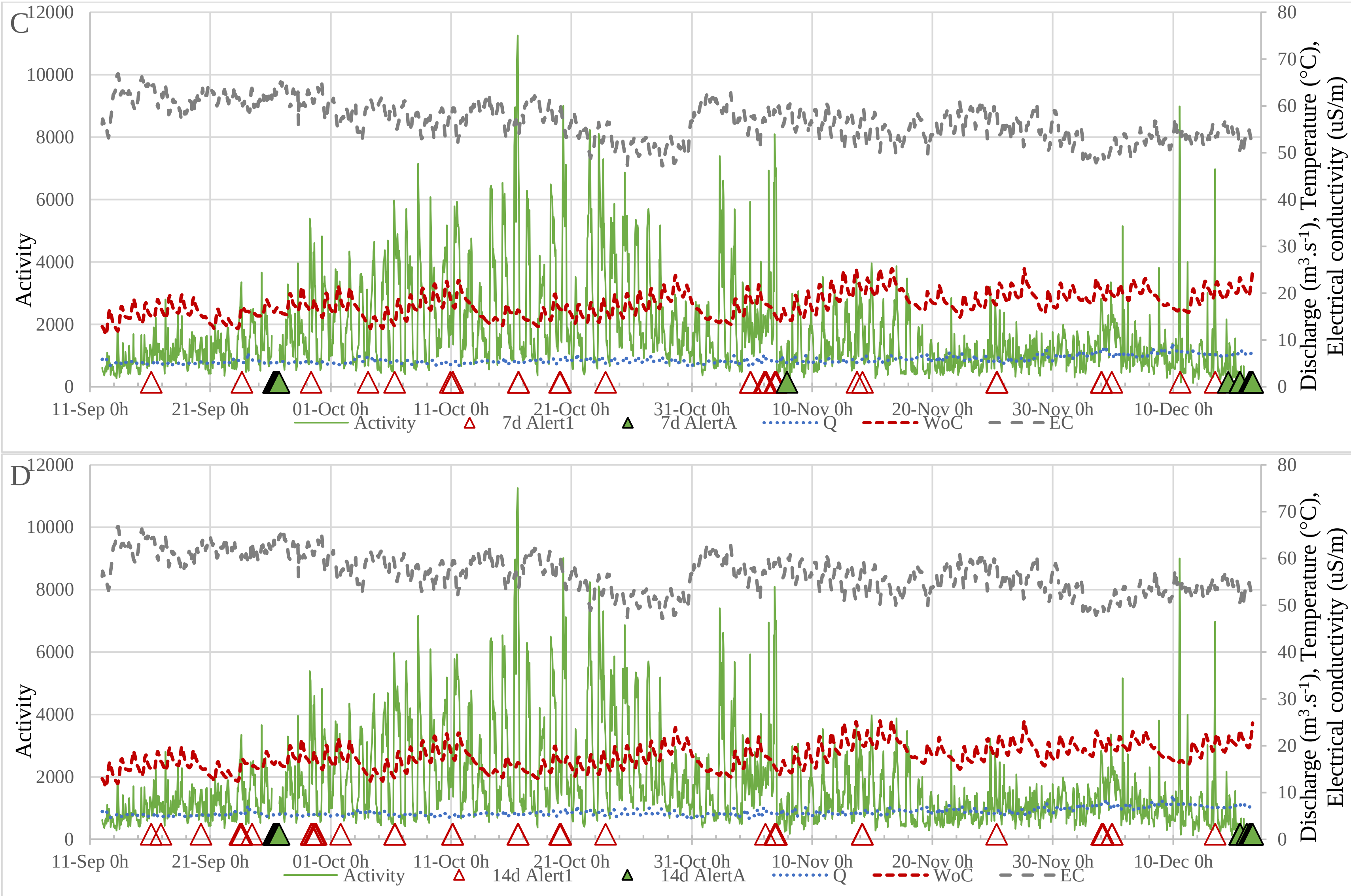


Fig. 7.2 Alert 1 (high activity) and A (low activity) as determined for LNAT22 by A) two, B) three, C) seven and D) 14 days of previous known behaviour evaluated against current behaviour, triangles indicate time of behavioural change (alerts), Q = discharge ($m^3.s^{-1}$), WoC = water temperature (°C) and EC = Electrical conductivity (uS/m).

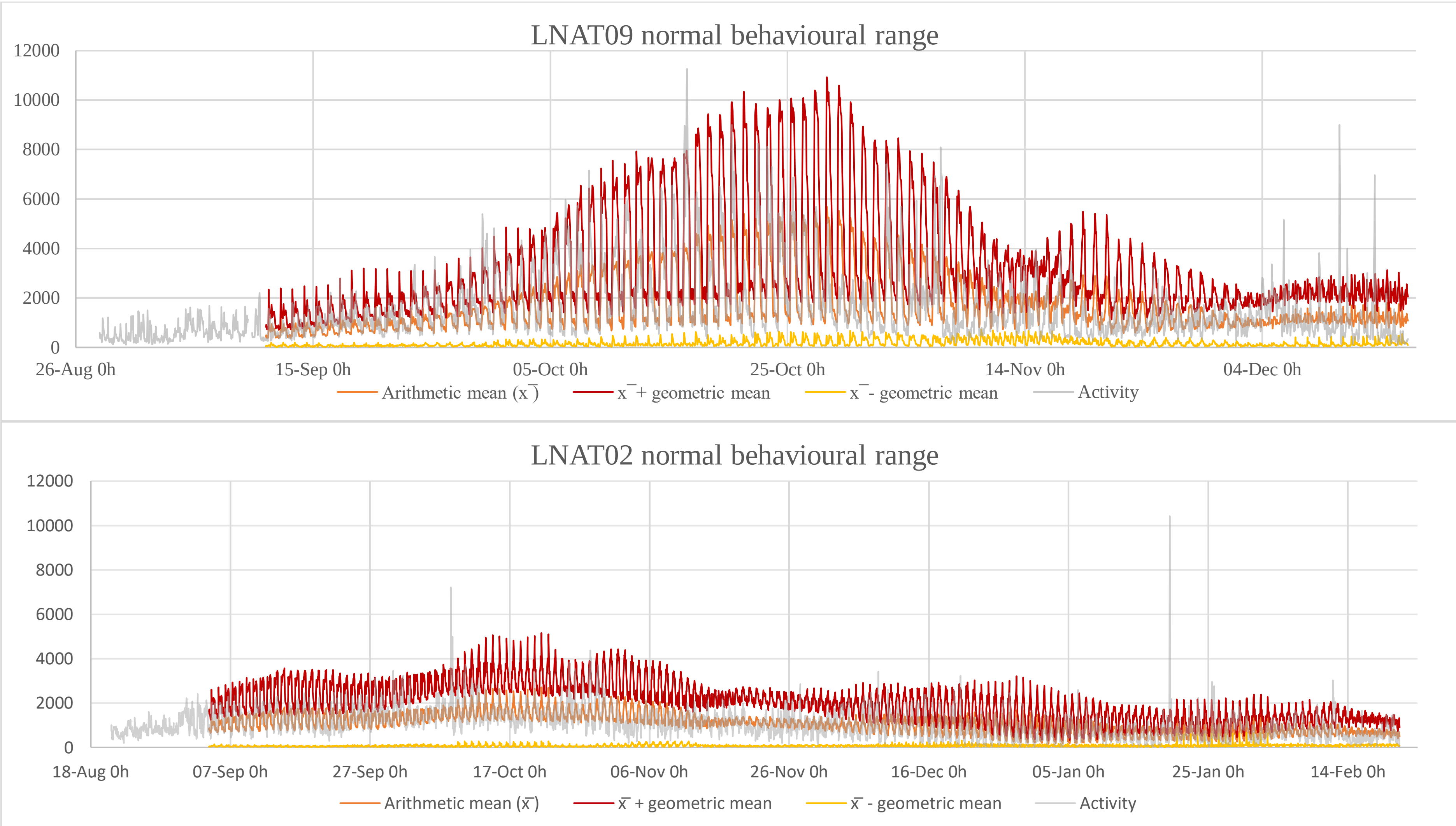


Fig. 7.3 The 14 day range preceding current activity calculated for LNAT 09 (above) and LNAT 02 (below),as examples, using the arithmetic mean plus and minus the geometric mean to determine normal behavioural activity and detect when the behaviour occur outside the range and indicates a change in behaviour.

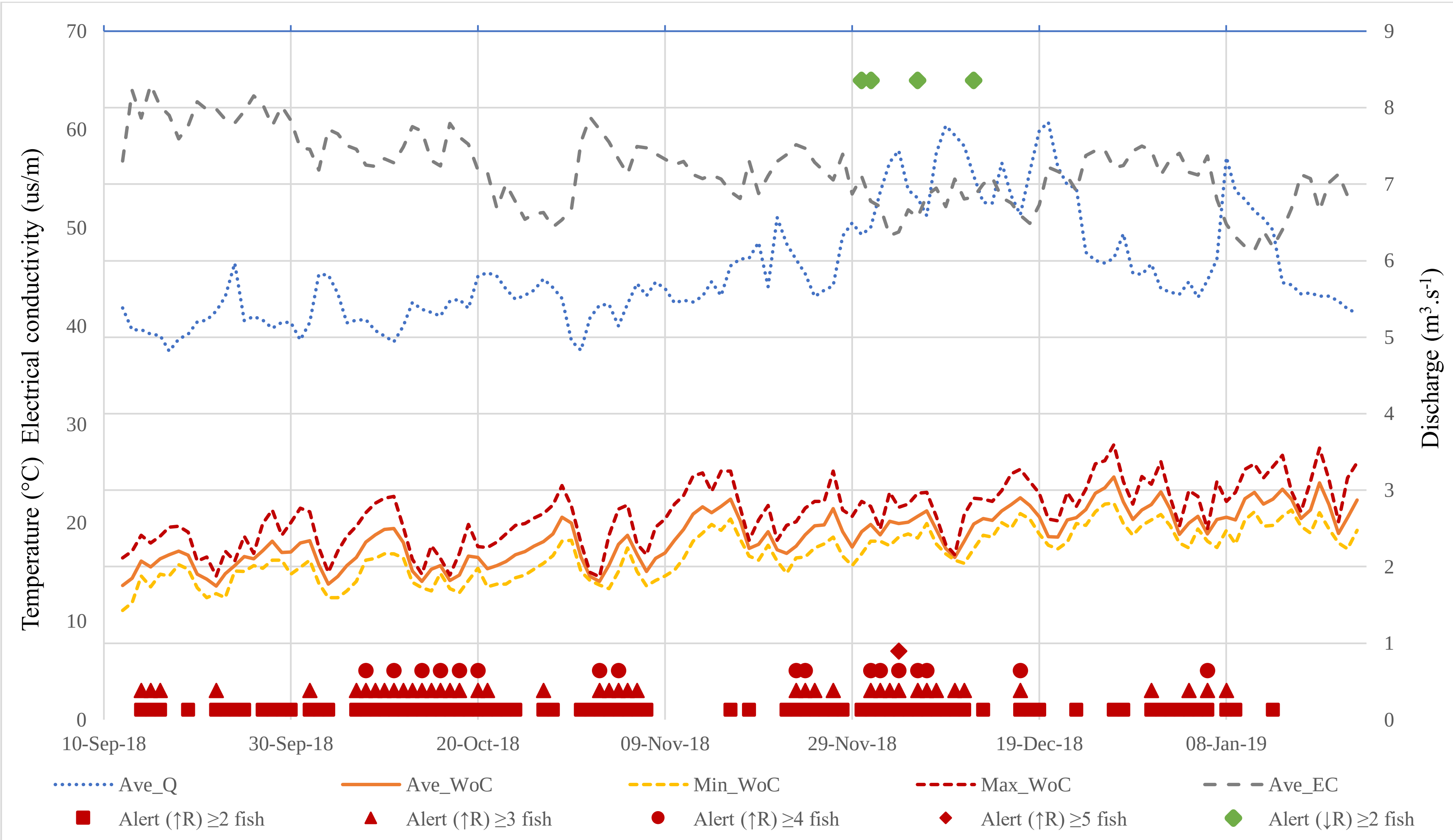


Fig. 7.4 Daily alerts for *Labeobarbus natalensis* behavioural change on a population scale (1 to 5 individuals responding together) and the daily environmental variables from 12 September 2018 to 22 January 2019, where Q is discharge ($m^3.s^{-1}$), WoC is water temperature (°C) and EC is electrical conductivity (uS/m).

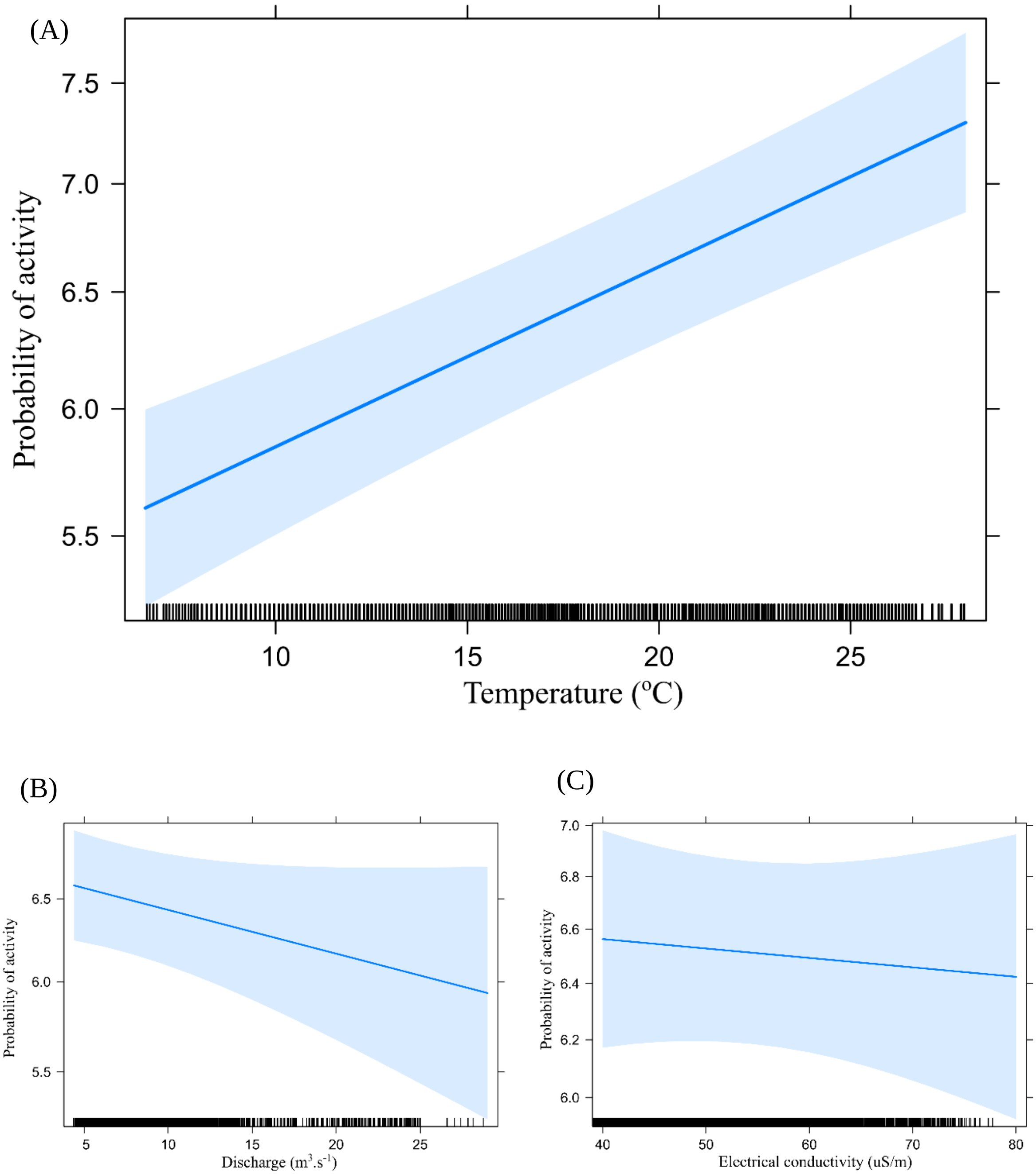


Fig. 7.5 The generalised linear mixed effects model depicting the predictive relationship between *Labeobarbus natalensis* activity for A) water temperature ($\beta = 0.01261 \pm 0.001554$, $p < 2e\text{-}16$), B) discharge ($\beta = -0.00345 \pm 0.001866$, $p < 0.0639$) and C) electrical conductivity for best fit models where delta AIC ≤ 2.

Table 7.3: Models selected for and the relevant Akaike's information criteria (AIC) needed to determine the best fit model

Models selected	df	logLik	AICc	delta AIC	Weight
Discharge	63866	-187874	375757	65.1	0
Water temperature	63866	-187842	375694	1.4	0.23
Electrical conductivity	63866	-187872	375754	61.1	0
Discharge + Water temperature	63865	-187840	375692	0	0.46
Discharge + Electrical conductivity	63865	-187863	375738	45.2	0
Water temperature + Electrical conductivity	63865	-187841	375695	2.5	0.13
Discharge + Water temperature + Electrical conductivity	63864	-187840	375694	1.8	0.19

7.5 Discussion

The methods developed in this study were able to aptly detect the behavioural movement of *L. natalensis* on an hourly basis. The algorithm developed successfully determined changes in behaviour from information derived from the DMS. The evaluation of activity through the algorithmic scenarios showed that changes in behaviour could be tested for and queried. Evaluating current behaviour using 14 days of known behaviour provided the best suitable timeframe to develop a real-time monitoring alert system. Alerts 1 and A and Alerts 2 and B can be used to adjust the sensitivity of alerts depending on the managers. The further development and testing of an alert system, such as the one developed here, can determine limitations and sensitivity of alerts to reflect when environmental variables affect changes in behaviour. Isolated alerts can be included as a level of alerts depending on the management question. As fish behaviour is 10-100 times more responsive than other biological organisation indicator levels, isolated changes in behaviour should be considered and tested whether they indicative of the environmental change or not (Beitinger and McCauley 1990; Sharma, 2019). The balance between receiving alerts based on behavioural changes, their ecological relevance and management action response and needs to be adapted to the management context (Wepener 2008). Fuchs and Caudill (2019) correlated seven behavioural activity types using activity data. These consisted of holding, spawning, digging, lateral movements, aggression, burst movement and coaxing all associated with normal biological functioning. Understanding what changes in behaviour reflect these biological functions may indicate to managers positive changes associated with effective management of the water resource. This type of information can prove valuable when detecting changes and understanding the behavioural activity of fishes when combined with real-time monitoring. The algorithm was effective at detecting peaks in activity indicative of an avoidance response towards unfavourable environmental conditions as seen in Burnett et al. (2019c) (Fig. 7.2). The relatively low detection of alerts to changes in behaviour below the normal behavioural range meant holding or rest periods as a result of sustained high activity did not always get detected. However, zero locomotive activity for sustained periods were detected and can be written into the algorithm to alert manages specifically to a response resulting in mortality. A mortality alert was detected in five tagged individuals, three of which occurred within four weeks of one another (Table 7.1). If fish move out of range and no data is sent to the DMS, this can be set as a criterion to alert managers to spatial movement by tagged fish until fish move back into range and data is uploaded. The scenarios are unlimited and can be further developed depending on the management question and ecological relevance (Leonelli 2014).

Individual behavioural plasticity has been documented in various fish species including *L. natalensis* and tagged fish activity varied greatly at times. It is recommended that multiple fish are tagged to improve confidence in alerts and adequately assess the behavioural changes on a population scale (Table 7.2; Fig. 7.4; Chevin et al. 2010; Burnett et al. 2019b). The population scale assessment in this study detected when various individuals changed behaviour simultaneously with at most five individuals (38 %). This coordinated behavioural change between individuals increases the relevance of the environmental conditions or biological requirements at the time. *Labeobarbus natalensis* were shown to move upstream in spring and early summer (Burnett et al. 2019b). Individuals LNAT09, LNAT07, LNAT02 and LNAT15 all displayed upstream spatial movement during the population assessment for this study explaining the clustered changes of activity for the population during the periods.

Understanding the changes in environmental variables further assisted in understanding these behavioural changes. The significant increase in activity as a result of increases in temperature correlated to this relationship. The period when the population behavioural change was highest (five individuals) happened during times of higher discharge and elevated water temperatures. The combination of discharge and temperature show the importance of these variables influencing the behaviour of *L. natalensis* and numerous other riverine fishes (eg. chinook Salmon *Oncorhynchus tshawytscha*, lamprey *Entosphenus tridentatus* and cutthroat trout *Oncorhynchus clarkii*) (McManamay et al. 2015; Flitcroft et al. 2016).

The water temperature had a greater effect on the activity of *L. natalensis* than other variables including discharge. Furthermore, increased water temperature increased the probability of change in activity for *L. natalensis*. Water temperature can have a stronger effect than discharge, especially in regulated rivers (McManamay et al. 2015), as was the case in the present study. The higher the discharge, the greater the variability in the activity of individual fishes. This variability was shown in the discharge GLM and the high individual plasticity as found in Burnett et al. (2019c). These results further supported *L. natalensis* responsiveness towards changes in flow and highlighted the importance of water temperature on activity. Crass (1964) indicated that cold water (<5 °C) inhibited movement of *L. natalensis* with ideal water temperatures > 19 °C shown to cue spawning and movement into rivers (Karssing et al. 2008; Burnett et al. 2019b). The probable relationship to water temperature in this study could also explain the importance of stable water temperatures in pool habitats. These habitats provide suitable refuge habitat during the winter when waters temperatures can reach as low as 5 °C (Crass 1964; Karssing et al. 2008; Burnett et al. 2019b). Similarly, this was seen for EC, where activity did not correlate well with a poor predictive co-relation of EC to activity. This showed the ability of *L. natalensis* to withstand various water quality levels and hence its persistence in rivers affected by anthropogenic related stressors. The relationship of *L. natalensis* activity and EC needs further investigation as EC is often used as an indicator variable for various pollutant types and could also explain the unpredictability of the activity of *L. natalensis* to EC (Thompson et al. 2012; De Sousa et al. 2014). The close relationship between discharge and water quality can explain the variability of activity towards the increased discharge and the EC concentration (Yarnell et al. 2015; Zuraini et al. 2018; Burnett et al. 2019c).

The development of algorithms to interpret activity data from fish are important when interpreting large data sets such as those acquired through tracking fish using activity sensors and the use of such data in existing telemetry networks (Cooke et al. 2016; Burnett et al. 2019a; Fuchs and Caudill 2019). The algorithm could form a means to formulate baseline data when querying fish behaviour and evaluate the population responses to environmental variables in real-time. Fish telemetry networks such as FISHTRAC that have developed the ability to monitor fish remotely and need methods through which to interpret data rapidly and effectively. Programmed algorithms are such a means to do this (Callebaut 2012; Leonelli 2014; Burnett et al. 2019a). The simplistic algorithm developed in this study is a step towards achieving the ability to set alerts around behavioural changes and is key to processing big biological data sets (Leonelli 2014). Using data from the DMS system meant that fish had to be in the signal range of a station in order to obtain real-time information. Stored data from the tag is delayed and can only be presented in hindsight alerting to any behavioural changes missed. The database in this study was used to demonstrate how an algorithm can assist in the real-time monitoring of fish behaviour in contexts of water quality management. When alerts are triggered, managers can respond and undertake additional water quality tests to determine the causal properties of the behavioural change. Whether these behavioural changes are as a result to maintain biological functioning or in response to changes in environmental variables both provide important information for the management of regulated rivers. Using two weeks of known behaviour to determine behavioural changes, highlights the importance of using a large sample size of tagged individual fish in the river system to provide continuity. Furthermore, large samples sizes can adequately alert to behavioural changes, detect population responses and overcome individual plasticity.

7.6 Conclusions

The ability to monitor fish in real-time and remotely is only as good as the data processing ability and the understanding of it. Determining if, and when fish behavioural changes occur, allows managers to monitor the well-being of the biological component as indicators of impacts on the ecosystem. With further understanding of these behavioural changes, the alerts can be used to develop thresholds of potential concern (TPC). These alerts highlight moments within the environment where managers can respond, as for example, ad-hoc water quality sampling, changing management operations temporarily if possible or relaying public warning messages if needed (McLoughlin et al. 2011).

Using the algorithms to alert managers to behavioural changes is important when it comes to managing ecosystems as it provides a non-biased means through which to interpret behavioural data. Developing an algorithm that suites both data distributions and the fish species in question can be challenging and this is an attempt to do that. The algorithm developed and tested in this study can be used and validated in the field to add to the growing body of work that uses activity sensors to understand *in situ* fish behaviour. Continual monitoring of behavioural changes by fish can, over time, improve our knowledge of the causal variables of behavioural changes and assist water resource managers in implementing management practices benefiting water users and freshwater ecosystems. The real-time and remote monitoring of fish behaviour through existing fish telemetry networks such as FISHTRAC can contribute to freshwater ecosystem management through the implementation of algorithms on fish activity sensory data such as the example presented in this study. This algorithm will further complement fish telemetry networks, such as the FISHTRAC programme, through continual monitoring and assessment of data in real-time and improve on sustainable evidence-based decision-making in water resource management (Cooke et al. 2017; Burnett et al. 2019a; Dickens et al. 2019).

Changes in behaviour as a result of water temperature and discharge show the importance these variables have in highly regulated urban rivers, such as the uMngeni, have on the behaviour of *L. natalensis*. The monitoring of water temperatures associated with bottom releases from impoundments and base-flows during the cold, dry months, is important as this could drop temperatures to below tolerance ranges for fish (Gillespie et al. 2014). Managing these flows are important and using changes in behaviour to do so can assist in correct management adaptation. Changes in discharge and altering of natural flow regime can be monitored using these algorithms to detect response to environmental flow releases and managed accordingly (Burnett et al. 2019c). The application can be extended to monitor and manage hydropower releases and interbasin transfer schemes that regularly alter flow to meet socio-economic endpoints. Understanding that the changes in behaviour point towards some change in the environment indicates a TPC that can be investigated further. These investigations should run concurrently with existing monitoring programmes with the possibility to adapt them as new information is acquired when behavioural changes are detected. These TPC's will greatly aid the understanding of fish behaviour and importantly concerning the management of regulated rivers and exposure to anthropogenic stressors.

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CHAPTER 8

"If the fish comes out of the river to tell you that the crocodile has one eye, you should believe it." ~ African Proverb

Conclusions

8.1 Overview

The condition of freshwater ecosystems in southern Africa continues to deteriorate because of the impact of anthropogenic stressors with a continual decline predicted for the future (Du Plessis 2019; Kusangaya et al. 2018). Managing freshwater ecosystems using the biological component has historically been in response to increasing stressors and associated pollution events and periodic monitoring to maintain its well-being (Wepener 2008; Kleynhans and Louw 2008). These methods generally limited to post-impact event monitoring and often exhibit weak causal relationships between indicators and stressors associated with past events (Dudgeon 2014; Du Plessis 2019).

Fish telemetry methods add to the many approaches available to managers responsible for the monitoring and management of water resources (Cooke et al. 2017). Fish telemetry methods have been established globally to management water resource use yet remain under-applied within Africa. Key management areas where fish telemetry can contribute to the management in African freshwater ecosystems were identified (Fig. 8.1; Chapter 2; Burnett et al. 2019a). The under-application of fish telemetry use in Africa for the monitoring and management of water resources is largely because of the shortage of resources. The increase in anthropogenic stressors without understanding the behavioural ecology of key indicators species threatens the sustainability towards African water resources (Du Plessis 2019).

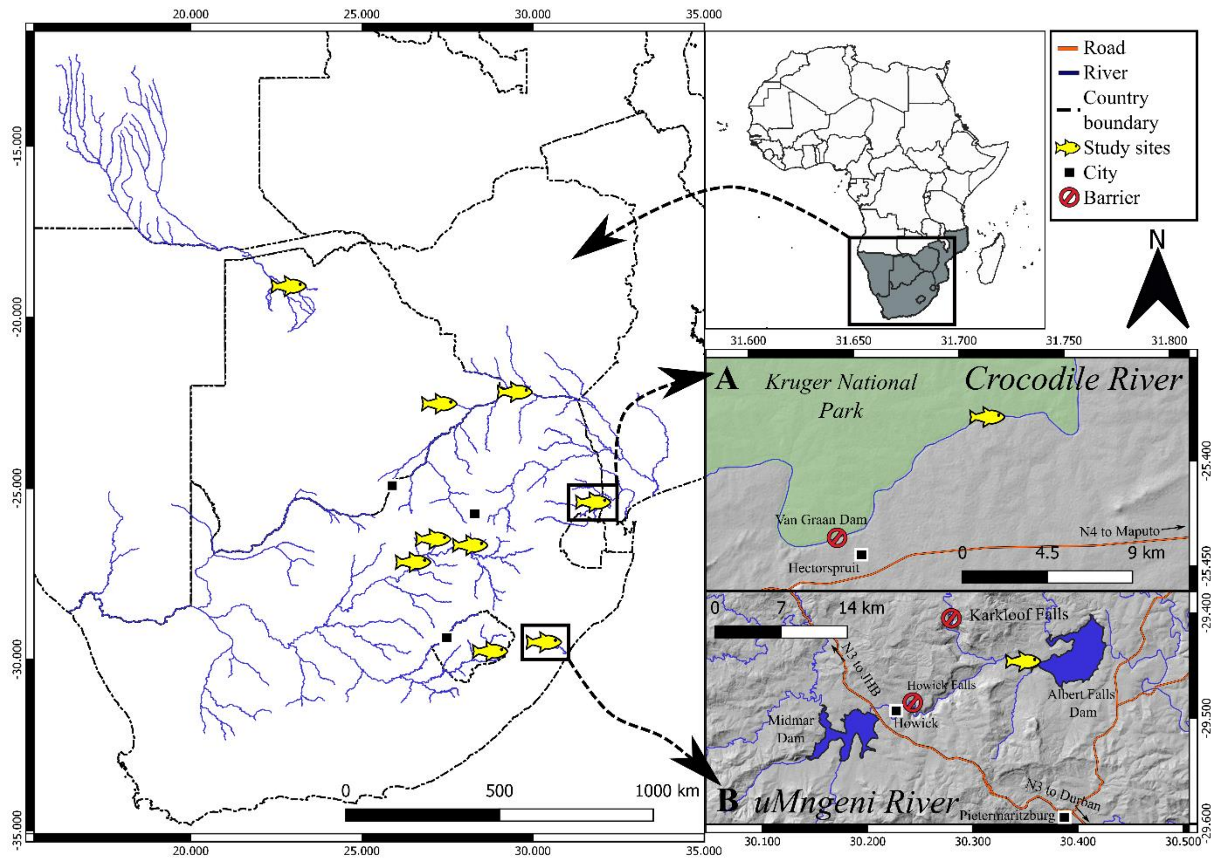

Fig. 8.1 Summary of the study areas in southern African used in the present study where The main insert shows the location of the eight case study sites used to develop the FISHTRAC programme (Chapter 3), inserts A) highlights the location of chapter 4 and B) shows the implementation site on the uMngeni Rivers (Chapters 5-7).

Fish telemetry can adequately address the need to understand the biology and ecology of fishes promptly and continuously in response to anthropogenic stressors and are considered worth the cost (Chapter 2; Burnett et al. 2019a; Cooke et al. 2016a; 2017). Passive integrated tags, despite their wide application in monitoring fishways, have not been implemented in Africa. Radio telemetry remains the preferred technique to monitor fish in rivers (Chapter 2; Burnett et al. 2019a). Acoustic techniques, well established in global fish telemetry networks, can greatly contribute to the management of Africa's great lake systems (Landsman et al. 2011; Lennox et al. 2017; Taylor et al. 2017; Krueger et al. 2017; Abecacis et al. 2018; Chapter 2;

Burnett et al. 2019a). Africa is highly dependent on its fisheries to sustain human livelihoods, yet few fisheries in Africa has considered fish telemetry to support the management of their fisheries (De Graaf and Garibaldi 2015). The cost-benefit of collaborations through these fish telemetry networks has aided in their establishment and can be replicated in Africa with the desired political will to do so (Lennox et al. 2017). These international fish telemetry networks are primarily base on the use of acoustic techniques. However, the FISTHRAC programme has successfully used radio-telemetry techniques to overcome some of the challenges faced with fish telemetry studies in the region.

The development of the FISHTRAC programme and its assessment sought to address many of the challenges faced when using fish telemetry in Africa as proposed by Hocutt et al. (1994), (Chapter 3; Burnett et al. 2020). This programme has seen the use of radio-telemetry techniques to monitor fish behavioural responses in real-time and remotely. The eight case studies describing the development of the programme from its use primarily to understanding behavioural ecology manually, to using remote networks to obtain data and incorporate water quality and quantities variables monitored alongside the fish behaviour (Chapter 3; Burnett et al. 2020). Recording basic environmental variables such as electrical conductivity, discharge and temperatures are important within the African context, where such baseline data is often non-existent or unreliable. The FISHTRAC programme monitors water quality and quantity variables alongside fish behaviour making it a valuable approach when understanding the biological response to environmental stressors (Chapter 3, Burnett et al. 2020). The FISHTRAC programme can provide useful baseline information, whereby other monitoring programs can run in parallel to improve on the behvaioural ecological knowledge base. The FISHTRAC programme contributed to the understanding of several ecological important fishes within southern Africa, including *Hydrocynus vittatus* and *Labeobarbus marequensis*, further assessed in this thesis (Chapters 3,4; Burnett et al. 2019b,c). The application of the FISHTRAC programme can greatly assist managers with real-time access to data and set alerts when changes in behaviour occur (Chapter 3; Burnett et al. 2020).

One challenge The FISHTRAC programme addressed was understanding the activity sensors as a behavioural variable for fish. These activity sensors successfully evaluated two species tagged over the same period in the Crocodile River and demonstrated the ability of the sensors to detect differences in species and their related responses to environmental stressors (Chapter 4; Burnett et al. 2019b). These findings further supported the use of *H. vittatus* and *L. marequensis* as suitable ecological indicators and there used in fish telemetry studies for the region. The use of activity sensors is becoming a standard when tagging fish with electronic tags, however, the use of these sensors on inland fish species through the FISHTRAC programme was a first of its kind for Africa (Chapter 2,3; Burnett et al. 2020). The novelty of activity sensory techniques for the region was tested and showed that a one-dimensional activity sensor could adequately be used to determine behavioural patterns and responses.

8.2 Ecological contributions

The activity sensors that record non-spatial movements of tagged species and remotely monitored, set-up as per the FISHTRAC programme, can adequately characterise fish behavioural ecology (Chapter 3,4,5 Burnett et al. 2019b,c, 2020). This feature added to tagged fish has allowed for the activity of fish to be assessed on a fine continual scale with non-observer bias often hard to achieve by manual monitoring (Chapter 2-3; Burnett et al. 2019a, 2020). Implementing these sensors on *L. natalensis* (a first for the species), *L. marequensis* and *H. vittatus* contributed to the behavioural ecology of these species and understanding environmental drivers towards behavioural changes (Chapters 4-7; Burnett et al. 2019b,c,d,e). Evaluating the activity sensors attached to *L. marequensis* and *H. vittatus* could be determine the behavioural difference between the two species (Chapter 4; Burnett et al. 2019b). Activity patterns between *L. marequensis* and *H. vittatus* differed significantly and could determine the extent to which drivers affected their behaviour (Chapter 4; Burnett et al. 2019b). This study supported the use of the two species could be used as ecological indicators throughout their distributions, highlighting the broader application of the *Labeobarbus* spp. in fish telemetry for the region (Chapter 4; Burnett et al. 2019b). The *Labeobarbus* family are large growing cyprinids found throughout the continent of Africa, where as *H. vittatus* are limited to tropical environments (Skelton 2016).

The tagging of *L. natalensis* with electronic tags in the uMngeni River, KwaZulu-Natal, South Africa was the first study of its kind and implemented the FISHTRAC programme on characterising the behavioural ecology of the species (Chapter 5; Burnett et al. 2019c). This study was the first successful fish telemetry study on *L. natalensis* dedicated to understanding the behavioural movements of *Labeobarbus natalensis* (Chapter 5; Burnett et al. 2019c). The study contributed new knowledge by identifying migrations cues and when important habitats are needed during the year (Chapter 5; Burnett et al. 2019c). Water temperature played a significant role in determining these movements rather than the change in flows often associated with the change in season (winter to summer) (Chapter 5; Burnett et al. 2019c). *Labeobarbus natalensis* showed their strict diurnal behavioural patterns in winter in refuge habitat while showing periods of activity through the diel period during the summer (Chapter 5; Burnett et al. 2019c). *Labeobarbus natalensis* maintained associated water temperatures greater than 9 °C, by seeking out microhabitats 3°C warmer than recorded river temperature during winter (Chapter 5; Burnett et al. 2019c). These findings highlighted the importance of maintaining all habitat types associated with seasonal movements for fish and how anthropogenic stressors impact the ecology of the species.

8.3 Management implications

Implementing the FISHTRAC programme on *L. natalensis* in the economically important uMngeni River allowed the demonstration of the use of activity sensors and water probe monitoring in detecting the type responses of tagged fish towards a management flow release within the regulated river (Chapter 6; Burnett et al. 2019d). The success of this study exhibited how the FISHTRAC programme can monitor fish behaviour and their responses to management decisions in real-time and remotely (Chapter 6; Burnett et al. 2019d). Water quality and quantity variables monitored in real-time successfully showed the changes in environmental variables associated with the flow release. The additional grab-samples provided insight into how a flow response to water quality concentrations changes during a flow release. These variables were successfully evaluated against the fish activity and the fish community indices and found that tagged fish were more responsive towards the changes in flow and water quality (Chapter 6; Burnett et al. 2019d). The association between flow and water quality changes was high and showed that fish favour the changes in flow despite the increase in the concentration of pollutants (Chapter 6; Burnett et al. 2019d). The importance of this finding for management is that flow releases need to be coupled with natural rainfall events or within the high flow season to mimic natural flooding that fish are accustomed to (Chapter 6; Burnett et al. 2019d).

To enhance its application, The FISHTRAC programme needs to process the large data sets accumulated through the real-time and remote feature of the programme into something that water resource managers can understand and use when managing the aquatic ecosystem (Chapter 7; Burnett et al. 2019e). In order to do this, an algorithm was developed to detect when behavioural changes occurred, and managers could be alerted to (Chapter 7; Burnett et al. 2019e). Such changes can detect shifts in diel behaviour that may indicate a response to an environmental event, stressor or biological function related to an environmental cue (Payne et al. 2013). This algorithm was a first of its kind for fish telemetry studies although other studies have evaluated activity sensor data to determine the behaviour of fishes (Broel et al. 2016; Fuchs and Caudill 2019). The one-dimensional activity sensor allows for extended battery life and manageable data-intensive packages that need quick analyses. The algorithmic equation could detect changes in behaviour on a low or high activity scale, with normal activity based on the average or medium activity (Chapter 7; Burnett et al. 2019e). These behavioural changes were then evaluated against water quality variables to understand the reason for these changes and found water temperature to be the main driver for behavioural changes (Chapter 7; Burnett et al. 2019e). The development of the algorithm to detect changes in fish behaviour is a start to setting up an alert system for managers based on known fish behaviour, but needs further research to implement the algorithm on a live platform (Chapter 7; Burnett et al. 2019e).

8.4 Collaborative research and inter-disciplinary development

The FISHTRAC programme has been a collaborative effort between water resource managers, technology and software developers, and aquatic ecosystem researchers (Chapter 3-7; Burnett et al. 2019b,c,d,e, 2020). The collaboration between these disciplines gave the FISHTRAC programme an edge in using a technologically advance method, applied in the aquatic field to be used within management decision-making (Chapter 3; Burnett et al. 2020). This development has contributed greatly towards using fish behaviour to answer management questions around the impact of anthropogenic water stressors and can continue to do so in the future. The FISHTRAC programme is intended for the use by managers who need to understand the anthropogenic stressors effecting aquatic ecosystem well-being and to mitigate against them using evidence-based decisions. The research collaborative works has seen the integration of hydrology, water quality and biological disciplines to develop the work presented in the thesis. The continual inter-disciplinary work between researchers and managers is encouraged to further develop the FISHTRAC programme, adding to it as technology improves and baseline data collected over time increases. These developments can assist in the process of creating cleaner and safe water for human consumption and ecosystem services while curbing the trends around water quality within South Africa.

8.5 Limitations and scope for future research

The numerous limitations in fish telemetry have been extensively researched and published (Cooke et al. 2012; Cooke et al. 2013; Thorstad et al. 2013). Within the study similar limitations were experienced and compiled as an overview of fish telemetry techniques in Africa (Chapter 2; Burnett et al. 2019a). Fish telemetry methods used in this study were limited to use within freshwater environments, however, were aided by radio telemetry techniques that are operational within unstable and highly turbulent aquatic environments. Alternative techniques, such as acoustic telemetry, are well studied and extensively used within saline, stable and non-turbulent environments (Chapter 2; Burnett et al. 2019a). The inland approach to the FISHTRAC programme overcomes some of these limitations and has developed best-practice within rivers that are unstable and turbulent (Chapter 3; Burnett et al. 2020). Radio telemetry techniques are limited to transmitting signal in shallow (< 10 m) water with deep waters not well suited for the approach. The FISHTRAC programme can be adapted to the use of acoustic data when suited although, it will need adjustments to determine real-time application through a radio network. Further, fish that move out of range of receivers cannot contribute to the real-time remote monitoring. This spatial movement can be overcome by increasing sample size and/or extending the receiver network range focusing on key habitat types. The data storage and download function on the tags allows for data outside of the range of the receivers to contribute to the fish behavioural data once back in range, so as not to lose data. This too can be evaluated using the developed algorithm and hindsight evaluation can be made (Chapter 7; Burnett et al. 2019e).

Sample size in fish telemetry is always tested to its lowest limit often due to the cost of equipment. This limitation is what has seen fish telemetry often under-utilised in developing countries as large sample sizes are often not affordable (Chapter 2; Hocutt et al. 1995; Burnett et al. 2019a). Understanding the cost-benefit of using fish telemetry is often over-looked when considering using these methods with continual pressure to increase samples size, this deters the use of the fish telemetry methods, especially when the benefits cannot be seen or understood. The risks often associated with using technology, such as theft, loss and damage are a further deterrent to using these methods in developing countries. This thesis hopes to provide an example of where fish telemetry methods can be used effectively to answer management questions, and pilot the use of fish telemetry in answering ecological relevant questions associated with freshwater ecosystems.

The activity sensor used is the study was an omni-direction tilt vibration sensor that records a one-dimensional activity as opposed to a three-dimensional activity from accelerometers (Cooke et al. 2016; Burnett et al. 2019b,c,d,e, 2020; Chapters 2-7). The one dimensional activity reading limits any behavioural assessment across the three axis (vertical horizontal and lateral), however, was still sufficient enough to evaluate fish behaviour (Chapters 3-7; Burnett et al. 2019b,c,d,e, 2020). Further laboratory studies of fish tagged with the activity sensor are needed to understand specific activities of fish such as spawning, holding and swimming as Fuchs and Caudill (2019) have conducted for *Oncorhynchus mykiss*. Similar studies on the ecological relevant species for the region (*Labeobarbus* spp. and *Hydrocynus* spp.) will greatly contribute to the use of the FISHTRAC programme, encourage fish telemetry studies and add to the behavioural knowledge of fishes in the region and other parts of the world where fish telemetry is lacking (Lennox et al. 2017).

Biological events are generally difficult to determine when monitoring remotely. It is thus strongly suggested that remote monitoring be combined with periodic manual monitoring to understand any behavioural changes that are linked to specific biological events that need validation on detection through changes in activity readings (Chapters 3 and 7; Burnett et al. 2019e, 2020). This was seen when *L. natalensis* behaviour changed to extended activity patterns and could relate to several fish activities such as migration movements or spawning and could have been validated had manual monitoring events taken place when these changes are detected (Chapters 4 and 7; Burnett et al. 2019c,e).

The effect of tagging and tags on fish well-being is still largely questioned for African species. An isolated study within an inland system showed retention failure using internal tags on *Cyprinid carpio* and set a precedent for using external tags on similar species in the region (Økland et al. 2003; Chapter 2; Burnett et al. 2019a). A recent study evaluated the abrasion of the external tag when implemented on *H. vittatus* and showed that the external tag was heavily abraded during the study (Jacobs 2018). Evaluating the abrasion of tags recovered in this study also showed heavy abrasion, suggesting fish actively attempting to remove the tag such as that observed during a study by Broell et al. (2016) when analysing accelerometer data (Fig. 8.2). The high retrieval rate of tags from predators in this study contributed to the abrasion of the tag once captured and also should be considered when evaluating the abrasion tags.

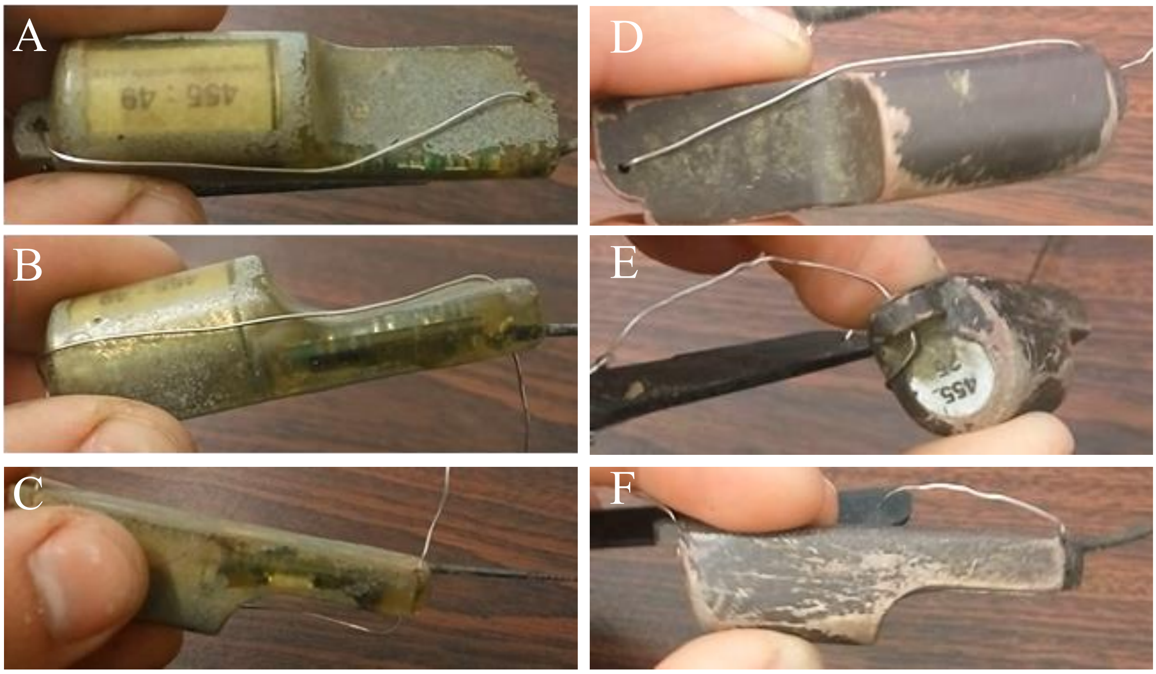

Fig. 8.2 The abrasion marks of tags recovered from fish that had lost the tag because of predation, mortality or expulsion in the present study. Once attached A and D are side views of the tag, B is the top of the tag, C and F the bottom and E the front.

Internal tagging was experimented with and evaluated for the purpose of the study. However, less tracked days than that of external tags was recorded, and tag size limited use to by larger individuals because of abdominal cavity sizes of *L. natalensis* (MB unpublished data). This component of the study needs to be researched in move depth to adequately determine the use of internal and external tags as suggested in the review and the FISHTRAC programme (Chapters 2 and 3; Burnett et al. 2019a, 2020). The variability in tracking days of fish for the study (mean n = 72 ± 66 days) indicated that there was either a high mortality rate or an element of tag expulsion when using external tags. This variability in tracking will need to be considered when planning projects using the FISHTRAC programme. The activity sensor can detect when tags no longer reflect fish behaviour and thus can accurately determine mortality or expulsion. During this study Terramycin (® containing oxytetracycline) was used to mark an individual on the event of a recapture of a tagged fish and suspicion of tag expulsion. One individual recaptured had injuries resembling that of a tag expulsion, however, on testing for the Terramycin marker on the otolith, the test was negative (Fig 8.3). This experience has highlighted the importance of the use of Terramycin as a marker for individuals and expand on our understanding on the retention of tags on fishes suitable for fish telemetry studies in the region.

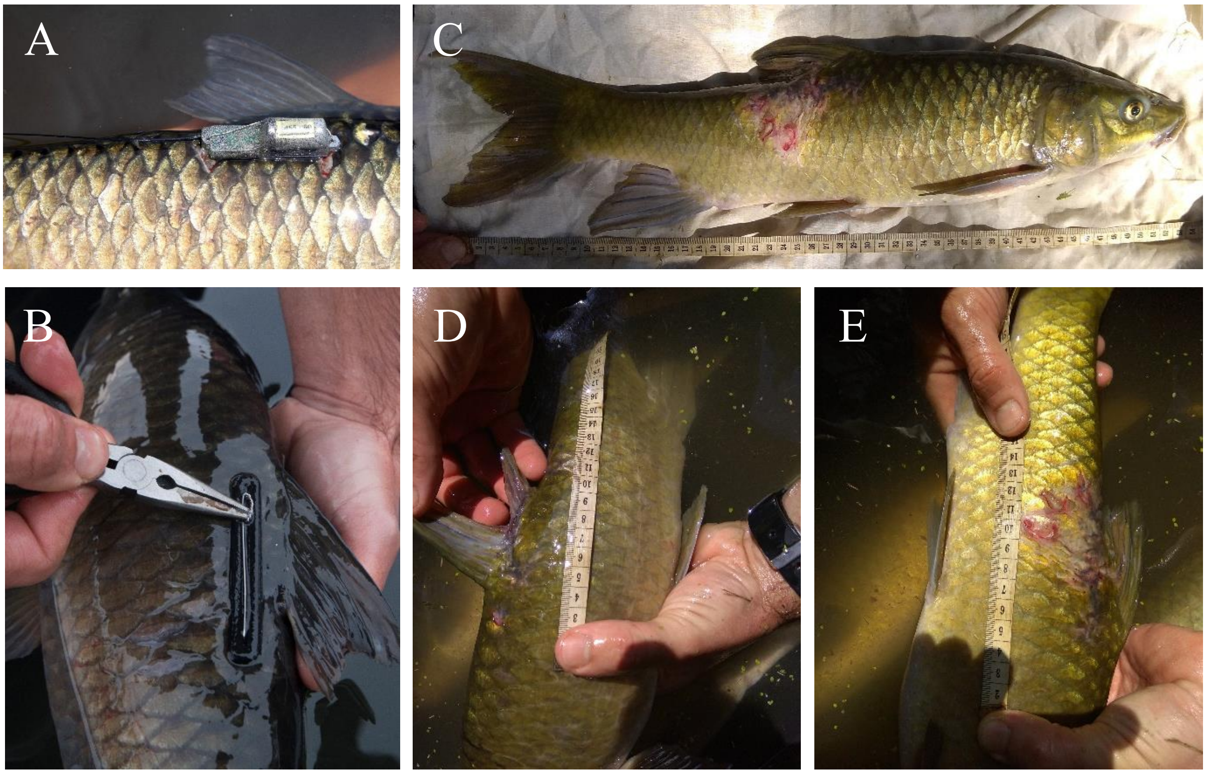

Fig. 8.3 A *Labeobarbus natalensis* shows injuries possibly associated with an expulsion of an external tag attachment tested negative for a Terramycin mark on the otolith. Photographs show A) The standardised placement of the tag on the right side of the fish; B) the attachment side of the tag of the left side of the fish; C) the suspected tag expulsion fish; D) wounds in the proximity of where the tag attachment would have been; and E) wounds in the proximity where the tag would have been.

8.6 Conclusions

The FISHTRAC programme has built on existing fish telemetry methods and been adapted to monitor anthropogenic stressors in real-time and remotely, specifically using fish behaviour as a variable to understand ecosystem well-being. The addition of water probes to determine environmental variables within the ecosystem complements the fish behavioural variable and can be used similarly. Monitoring these variables gives the FISHTRAC programme a more holistic approach to monitoring ecosystem well-being and understanding fish behavioural changes towards anthropogenic stressors. Continual monitoring of fish behaviour in such a manner can assist managers and researchers in understanding behavioural changes to anthropogenic stressor in real-time, adapting management planning and being responsive to biological events as they happen as opposed to waiting quarterly for data to come in from the field. The successful implementation of the programme in this study highlighted how the the behavioural ecology of fish species can be included in the management structures around water resources. The real-time application in managing flows in regulated rivers and the alert systems to behavioural changes can indicate when managers need to address thresholds of potential concerns to mitigate anthropogenic stressors. The responsiveness of the FISHTRAC programme provides managers and researchers with an ability to respond directly to fish behaviour fish behaviour and can continue to develop fish behavioural research, not just for Africa but globally (Fig. 8.4).

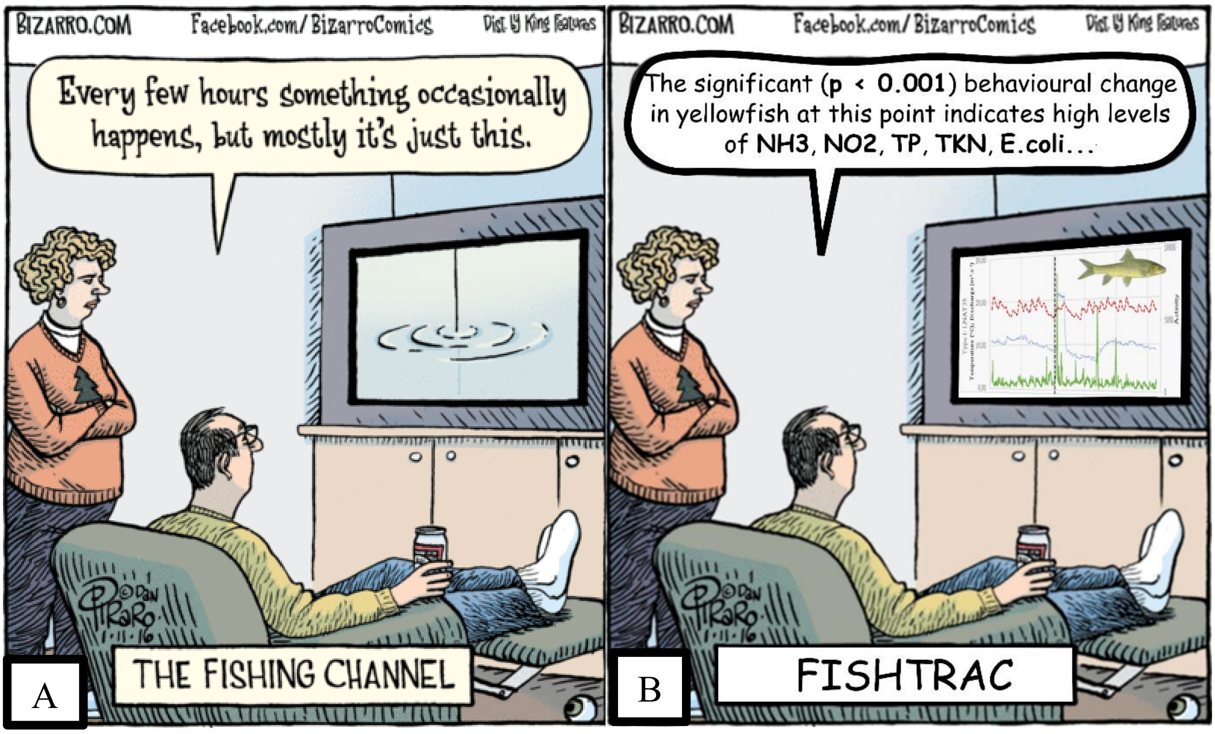

Fig. 8.4 A graphical depiction of A) the public perception of how frequently fish respond to changes in anthropogenic stress and B) the actual frequency and relevance of how fish respond

to anthropogenic stress monitored by the FISHTRAC programme (sourced and adapted from https://www.bizarro.com/cartoons)

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8.8 Appendices

Appendix 8.8.1 Article published in the South African Flyfishing Magazine, January-February 2019 (Sourced: www.saflyfishingmag.co.za) highlighting the benefits of tracking fish with electronic tags.

ENVIRONMENT

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By Matthew Burnett

RUNNING through Pietermaritzburg, the uMsunduzi River was once described as a "cheery sight, the beautiful, limpid pellucid river" by Sir Henry McCallum in 1903. His comments are a far cry from the reality of the river today. It does not take a keen eye to see the "plastic fish" migrating downstream or the black water coming from some tributaries or solid waste floating downstream of burst pipes. News headlines highlight this state: "Sewage Spill Threat to Dusi" and "Duzi Dirtiest in Years". And yet, do we see it? Does our daily hustle and bustle leave us without time to observe what is happening around us?

The once focal-point of the city now seems to silently crawl beneath us, only making an appearance when treated and re-designed as a form of "the beautiful, limpid pellucid river" flowing into our bath tub or kitchen sink at the turn of a tap. Fishermen (and paddlers) are regarded as heroes for taking an interest in the state of the river and highlighting its plight, while they venture near it with caution.

These concerns extend to the greater catchment, the uMngeni River, to which the uMsunduzi River is an important tributary. The uMngeni River is economically important for the uMgungundlovu and eThekwini Municipalities in KwaZulu-Natal. This river continuum fluctuates between healthy and unhealthy sections as it meanders down to the Blue Lagoon in Durban.

Within this river continuum, one group of inhabitants, the fishes, go about their daily and seasonal routines interacting with what gets washed downstream and contending with barriers that stop them from moving upstream. One must ask, with the increase in human impact on these two rivers (uMngeni and uMsunduzi) are these fish still around? If so, how are they coping? How do they navigate this now altered environment? Importantly, do they have any reprieve from the unhealthier sections of the river? How do these fish deal with what gets channelled downstream from the city? Do they seek out pockets within the river suitable for them? These questions spurred on a study at the University of KwaZulu-Natal in collaboration with Umgeni Waters to look at fish behaviour and their response to water quality and quantity variables within these rivers.

Behavioural studies have historically used telemetry techniques — attaching a radio transmitter to an animal to be researched — to determine their movement and habitat requirements. With telemetry on fish there is often an application conundrum with the size of the tags and attachment methods. More recently, however, telemetry tags for fishes in South Africa have gotten smarter, smaller and more readily available. In fact, the FISHTRAC programme developed here in South Africa can monitor water quality variables such as flow, temperature and electrical conductivity alongside of fish movement, all in real-time and remotely. The application in the field is ground-breaking towards understanding ecological responses to environmental variables. In fact, researchers are looking at using fish to alert water resource managers about changes in the freshwater environment that need to be monitored. Data acquired from these sensors is sent to a Data Management System (DMS) through a network set up specifically to receive the signal from these sensors within the river. The data is then acquired from the DMS and alerts can be set up to inform managers of important events taking place in the river.

The fish species selected for the UKZN study in the uMsunduzi and uMngeni Rivers is the well-known KwaZulu-Natal yellowfish *(Labeobarbus natelensis)*, also known as the "scaly". It was a good candidate because of its mobility within rivers and that it grows large enough to be tagged. Although the uMsunduzi River around Pietermaritzburg is not currently thought to be a good angling spot for 'scallies,' there are suitably-sized Yellowfish within the reach. It is an ideal place to study how they respond to Waste Water Treatment Works (WWTW) and other urban impacts on the uMsunduzi. Another area of interest and more pleasant angling spot is the section between Albert Falls dam and town of Howick. This area also lies downstream of a WWTW and urban impacts on the uMngeni River.

To date, 30 yellowfish have been tagged on the uMgeni River with external transmitters. Several of these yellowfish have moved out of range of the established network, but those that have remained behind continue to feed data into the DMS. Eleven water quality probes have been set-up to relay information about the aquatic environment to the DMS. These probes are stationed from Midmar Dam to the uMngeni inlet to Albert Falls Dam. Preliminary results show that yellowfish have diurnal activity patterns responding to day-night cycles. We called one of the tagged fish "Kobus". Kobus showed abnormal daily cycles for two days before it swam upstream and out of Albert Falls Dam. Kobus moved between stations 9 and 8 regularly before moving up past station 7 on November 6, 2018 (Figure 1 and 2). The cue to this movement still needs to be analysed to understand why it moved upstream at this time. A few days after Kobus' movement, while manually tracking the fish, we came across a large pool with hundreds of yellowfish milling around the surface. Kobus was not found there, but there may be a correlation between these events. Behavioural changes like Kobus dispplayed are important to try to understand as they can be caused by changes in water quality or engraved behaviour that respond to a series of cues provided by the environment.

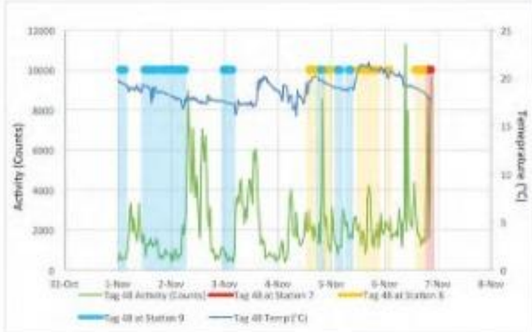
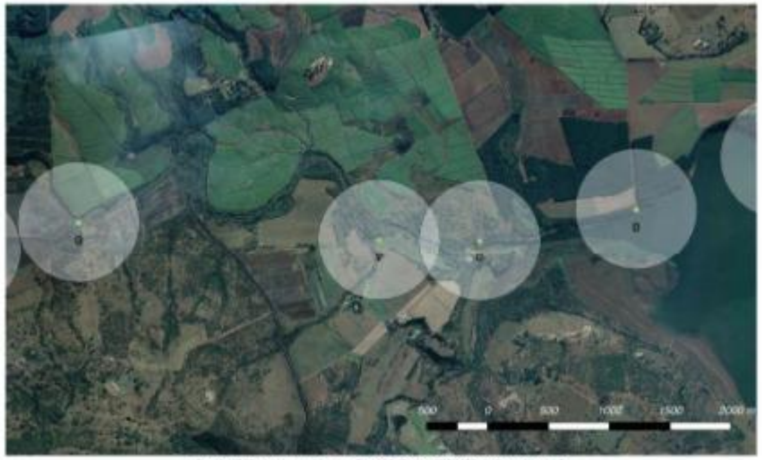


Figure 1: The activity of yellowfish (in green) showing diurnal behaviour up until 4 November, abnormal behaviour from 5 November until it leaves the day on 7 November. The temperature (in blue) shows a steady increase over the period from the tag on the fish. The shaded areas (in blue, orange and red) depict the stations the fish is at the time the variables are measured, these are stations 7, 8 and 9 depicted in figure 1.

Figure 2: All variables from water quality and quantity probes and fish tags measured remotely and in real-time overlaid onto the same graph to visually present the results from the same time frame as in figure 1 (1-8 November 2018). Added here is the water depth (in blue, presented as pressure), electrical conductivity (in grey) and water temperature at station 7 (in orange). Notable is the temperature change of the fish tag showing similar result to the probe at station 7 as it moves past. The shaded area represent the location of the fish at the time variables were measured.



Part of the remote and real time FISHTRAC network (including stations and water quality probes) in the uMngeni River .

Figure 3 shows a lot of information from both the fish tags and water quality and quantity probes used. This figure overlays the behavioural data from Kobus for the same period he left Albert Falls Dam, added is the environmental variables monitored by our water quality probes. The temperature of the probe and the fish meet when Kobus swims past station 7, where the probe is situated. The electrical conductivity during this period drops, while the temperature of the water slowly increases, also show by the temperature is a low pressure (ie. cold front) system present a few days before Kobus moved upstream.

Close up tagged fish.

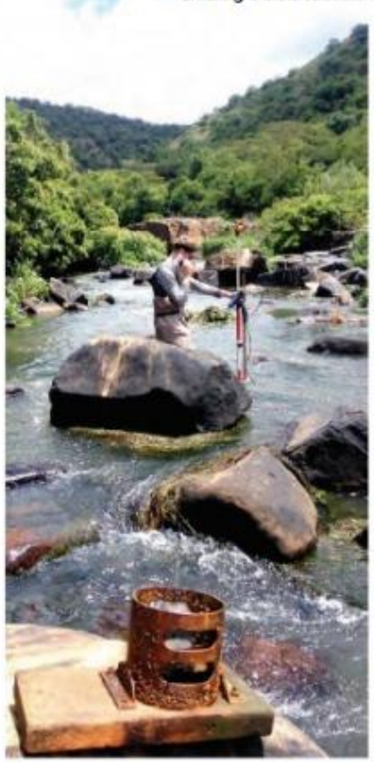
These deductions still need to be analysed for significance, but for the first time they can be plotted on the same timescale, in real-time and sourced remotely.

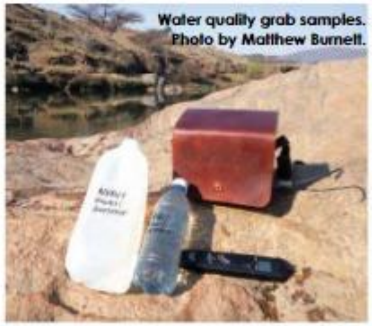
Observing behavioural data alongside of environmental variables will enhance our understanding of fish behaviour. Temperature sensors on the fish tags show a direct relationship to water temperature recorded by the nearest water quality probe to the tagged fish. This information is important because it shows how upstream impacts can directly affect fish downstream. A gradual change of water quality between Midmar and Albert Falls dam was reflected on the data acquired from the water quality probes. Water temperature, for example, increased on an average of 8°C from our upper site (Midmar Dam) to our lower site (Albert Falls Dam) in this study area. The change in water temperature during different seasons is visible as water temperature increases in summer. Weather plays an important role in water temperature as dips in water temperature occur when cold fronts move through. For the uMngeni reach, the water flow has remained consistent. The nature of the reach, being between two dams, shows relatively little change in discharge unless there are releases from Midmar Dam or heavy localised rainfall.

The uMsunduzi has Henley Dam regulating releases but this is on a smaller scale. With the success obtain from the uMngeni River, the next step in the study is to start a tagging fish on the uMsunduzi River. The continuation of the study for both rivers will shed light on the effects of dams and WWTW's on yellowfish. This is still largely unknown, but the use of radio telemetry will help to bridge this knowledge gap.

It is with these results and future developments in telemetry that researchers hope to improve the way river ecosystems are monitored. To do this kind of behavioural work remotely and in real-time far exceeds the expectations of scientist a few decades ago. It is exciting to think that water resource managers may be alerted by fish to go out and detect issues with water quality as they happen in the catchment. As managers "listen" to the data coming in, yellowfish have an active voice in the way our freshwater ecosystem are managed. What these yellowfish "tell" us in this study could be a turning point in the way we manage and understand the freshwater ecosystem. And maybe, the uMsunduzi River around Pietermaritzburg could once again be referred to as a "beautiful, limpid pellucid river" by the inhabitants living along its banks and within its waters.

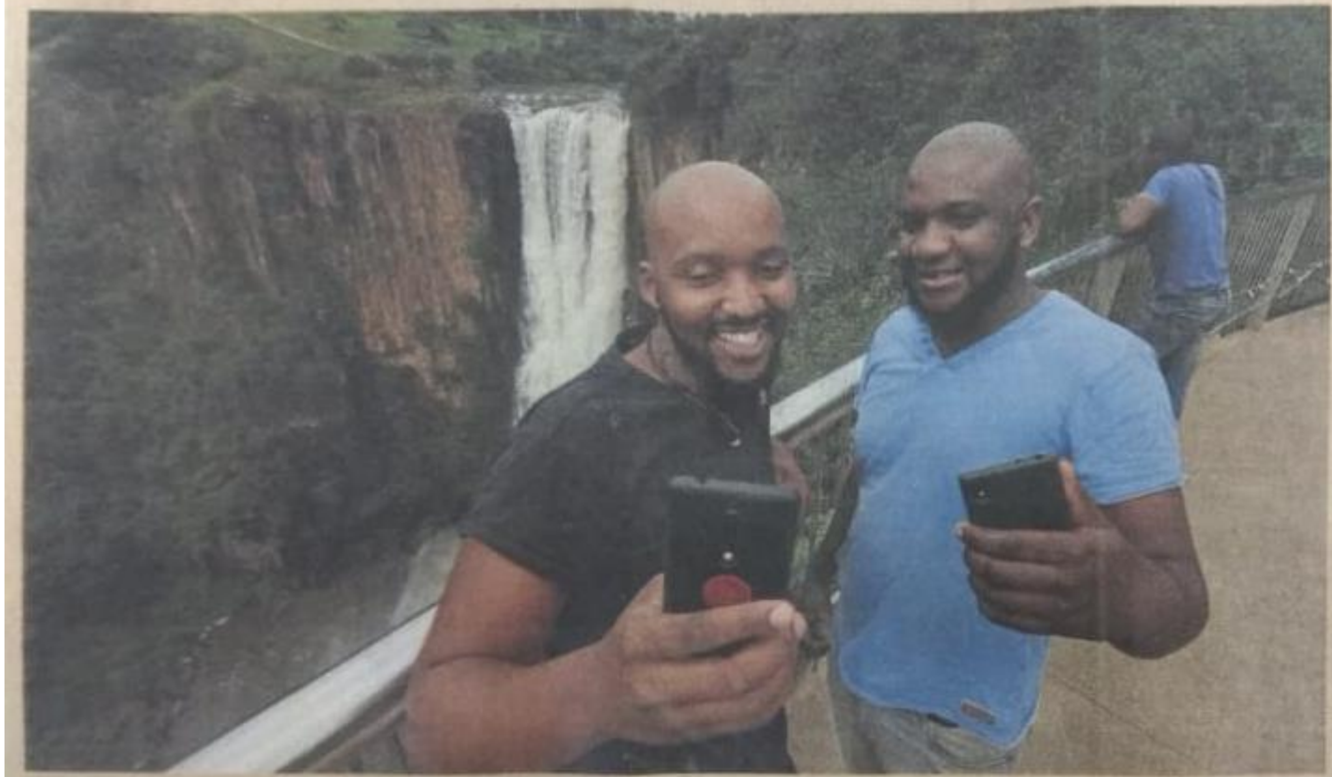
Creating a cross section.





Water quality grab samples. Photo by Matthew Burnett.

Appendix 8.8.2 Article published in the local newspaper "The Witness" on the 5 April 2019 highlighting the flow release experiment conducted on the uMngeni River to the public.



Howick locals Mlondi Gama (left) and Vusumuzi Sithole take a selfie with the Howick Falls in the background. The Falls were even more spectacular than usual thanks to extra water released from Midmar Dam. **PHOTO: IAN CARBUTT**

Falls thunder for fish research

UMGENI Water released extra water from Midmar Dam to help a study on the migratory habits of yellowfish.

Umgeni released 20 cubic metres of water for 25 hours as part of a research project called Fishtrac.

According to Shami Harichunder, Umgeni corporate stakeholder manager, the release, which had to be gradually increased and then decreased, took place last week. Harichunder said due to good rains in the catchments and transfers from Mearns Weir, Midmar Dam has been overflowing since mid-March.

"For the study, releases from Midmar Dam had to be marginally increased. The marginal increases in releases were made from the wall top gate and valve at the bottom of the wall — both of which are for environmental and river health purposes," he said. He said water that is released from Midmar Dam and when spills occur ultimately make its way into Albert Falls Dam. "There is no loss to the Mgeni System. The level of Albert Falls Dam has begun increasing steadily, which is a welcome development after this dam has consistently remained at levels of below 40% due to a protracted drought that has since come to an end."

Harichunder said the Fishtrac study will be beneficial to Umgeni Water as it will provide vital information on environmental matters and on river water quality and health downstream of Midmar Dam.

— Witness Reporter.

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