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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

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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

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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.

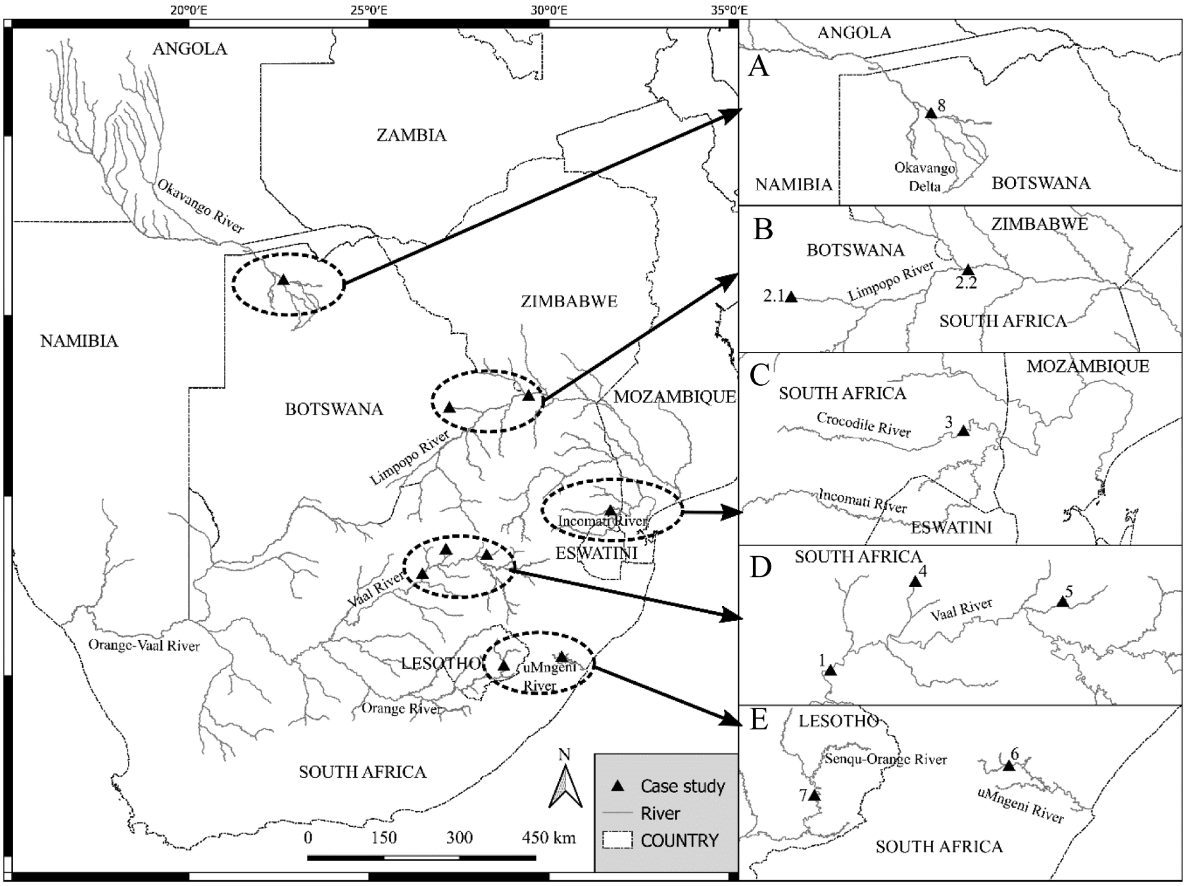


Fig. 1. Locations of the eight study sites across southern Africa where inset A. shows case study 8 in the Okavango Catchment; B. shows case studies 2.1 on the Letsibogo and 2.2 Shroda Impoundments in the Limpopo Catchment; C. shows case study 3 in the Inkomati Catchment; D. shows case studies 1, 4 and 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

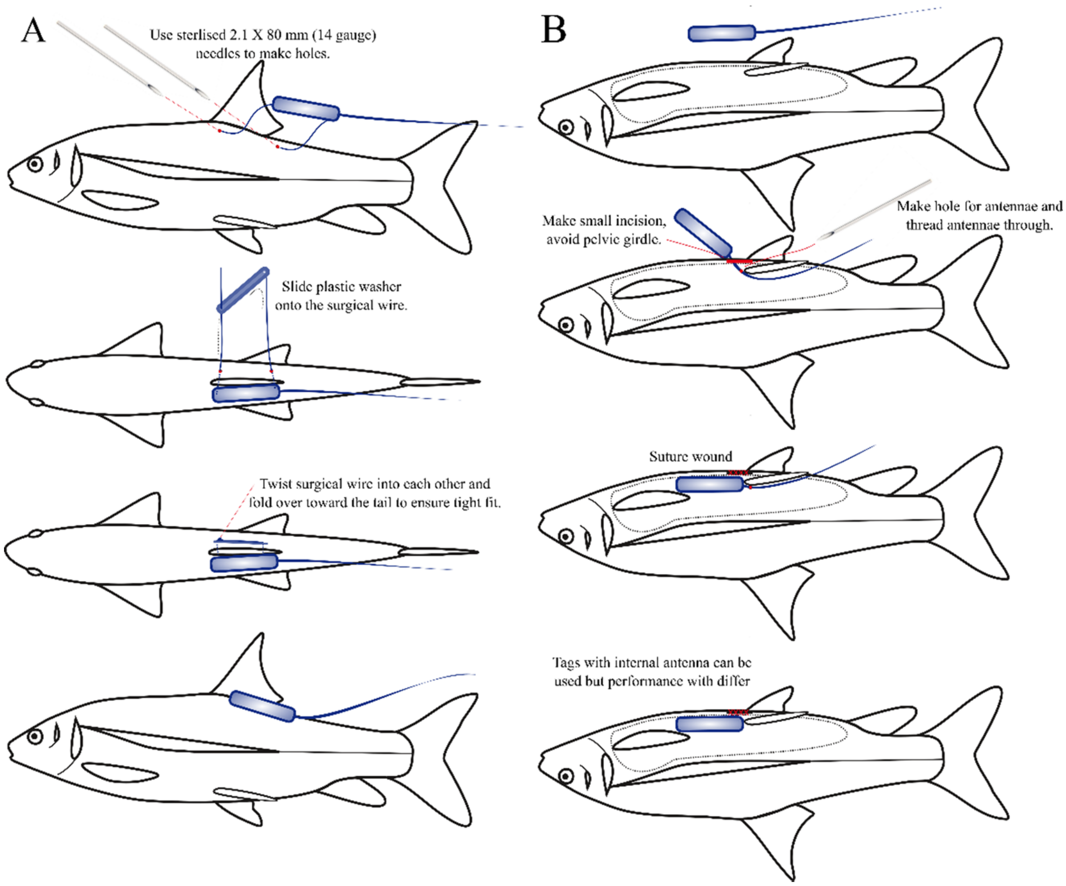


Fig. 2. A graphical representation of the two commonly used tagging procedures A) external and B) internal tagging (Modified from Bridger and Booth, 2003).

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).

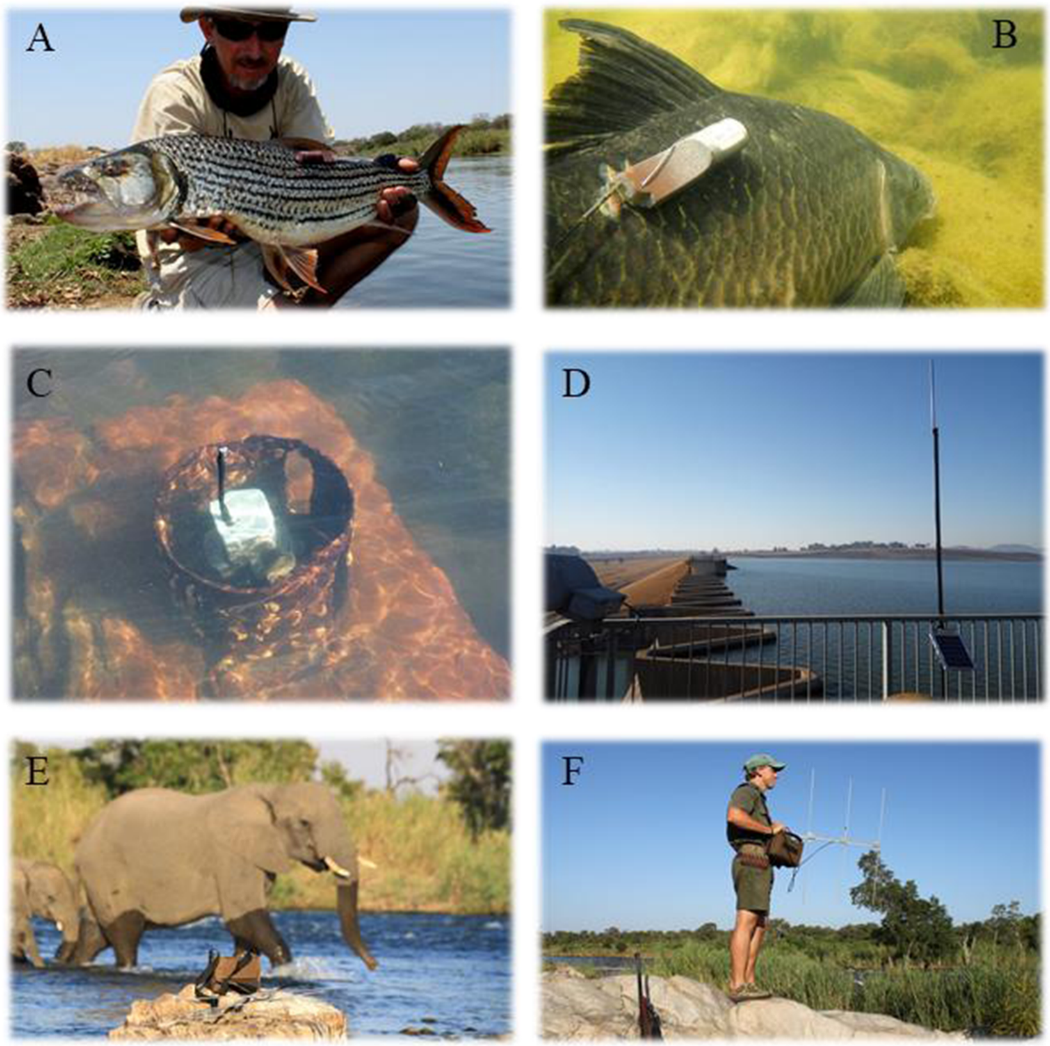


Fig. 3. Photographs to detail various aspects of the study where the positioning of external tags on A. tigerfish (*Hydrocynus vittatus*) and B. purple labeo (*Labeo congoro*) during the recovery from the anesthetic are shown; C. depicts the water probes used; D. the remote stations used within the FISHTRAC 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

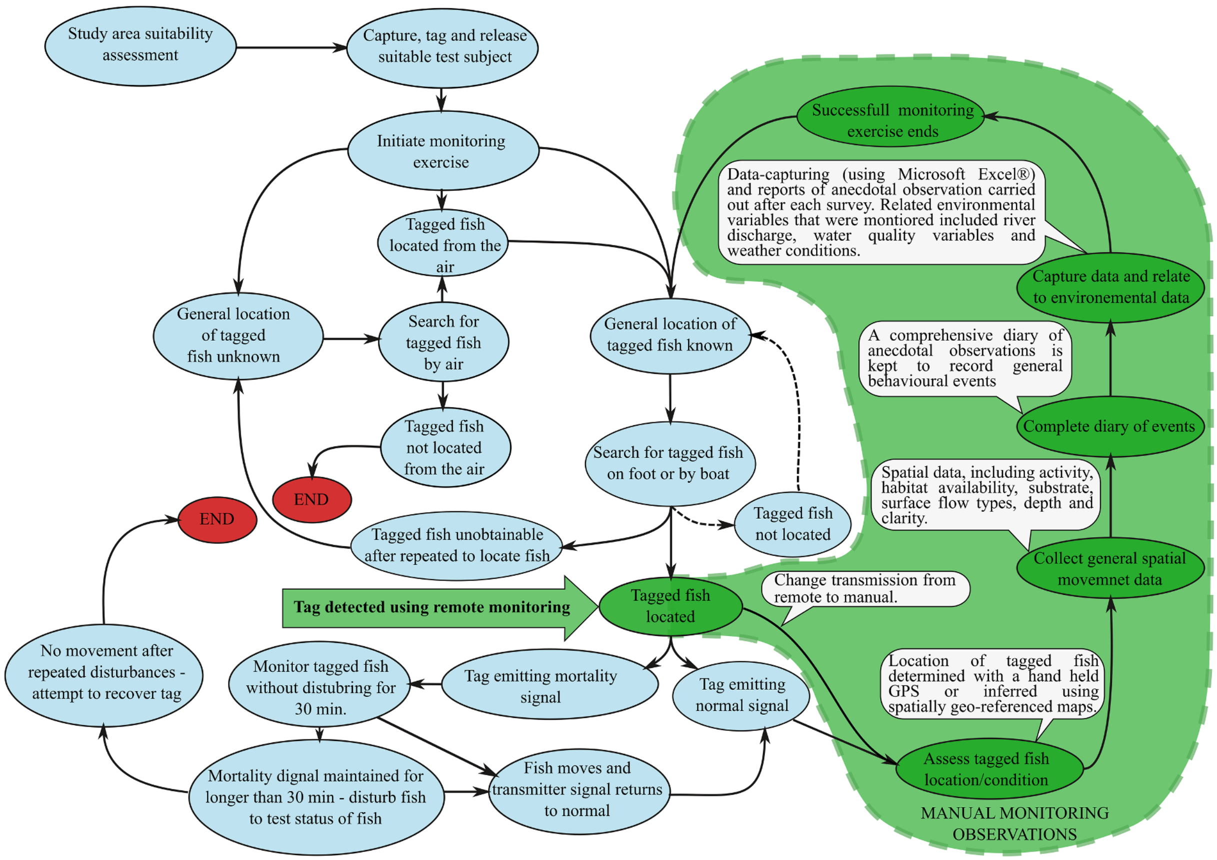


Fig. 4. A schematic diagram depicting the route taken to find tags during manual monitoring surveys. The shaded area shows the manual monitoring exercise followed by the researcher once fish were located. The arrow indicating the contribution of remote monitoring techniques by downloading stored data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

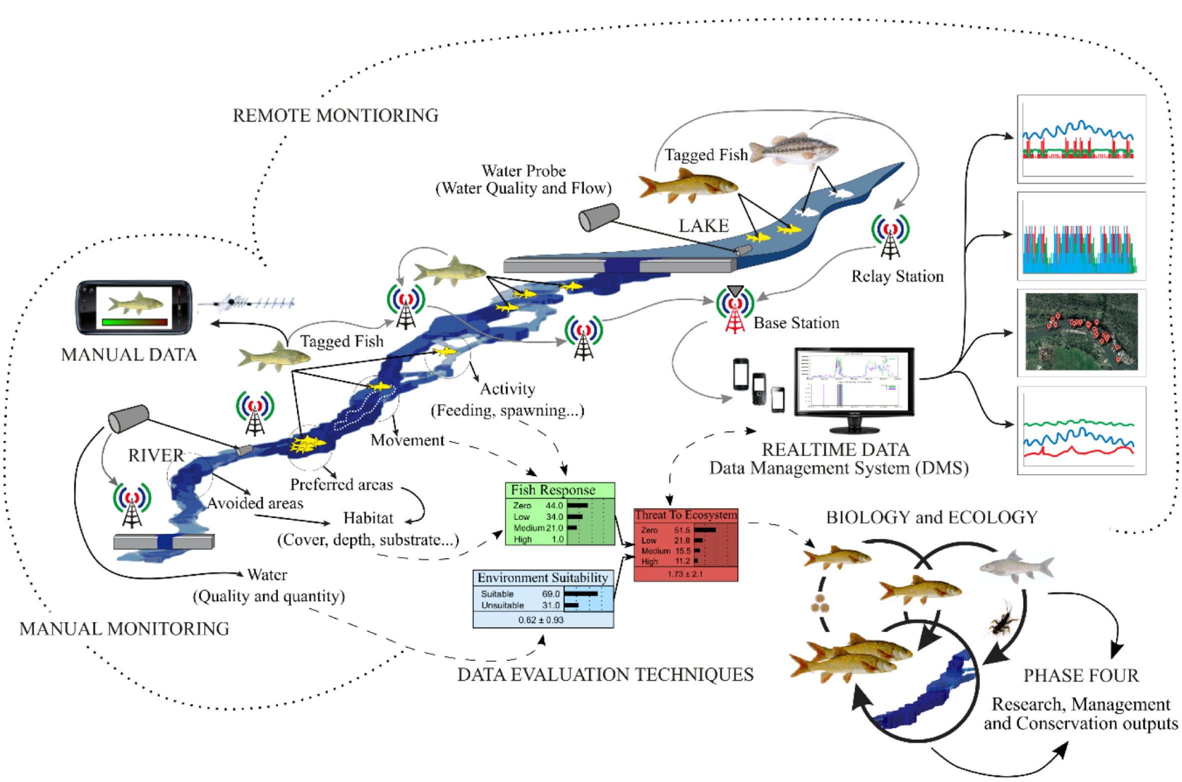


Fig. 5. A schematic diagram showing the communication pathways of data obtained using remote and manual monitoring through to the data presented on the data management system (DMS) and to water resource managers as developed in the present study.

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).

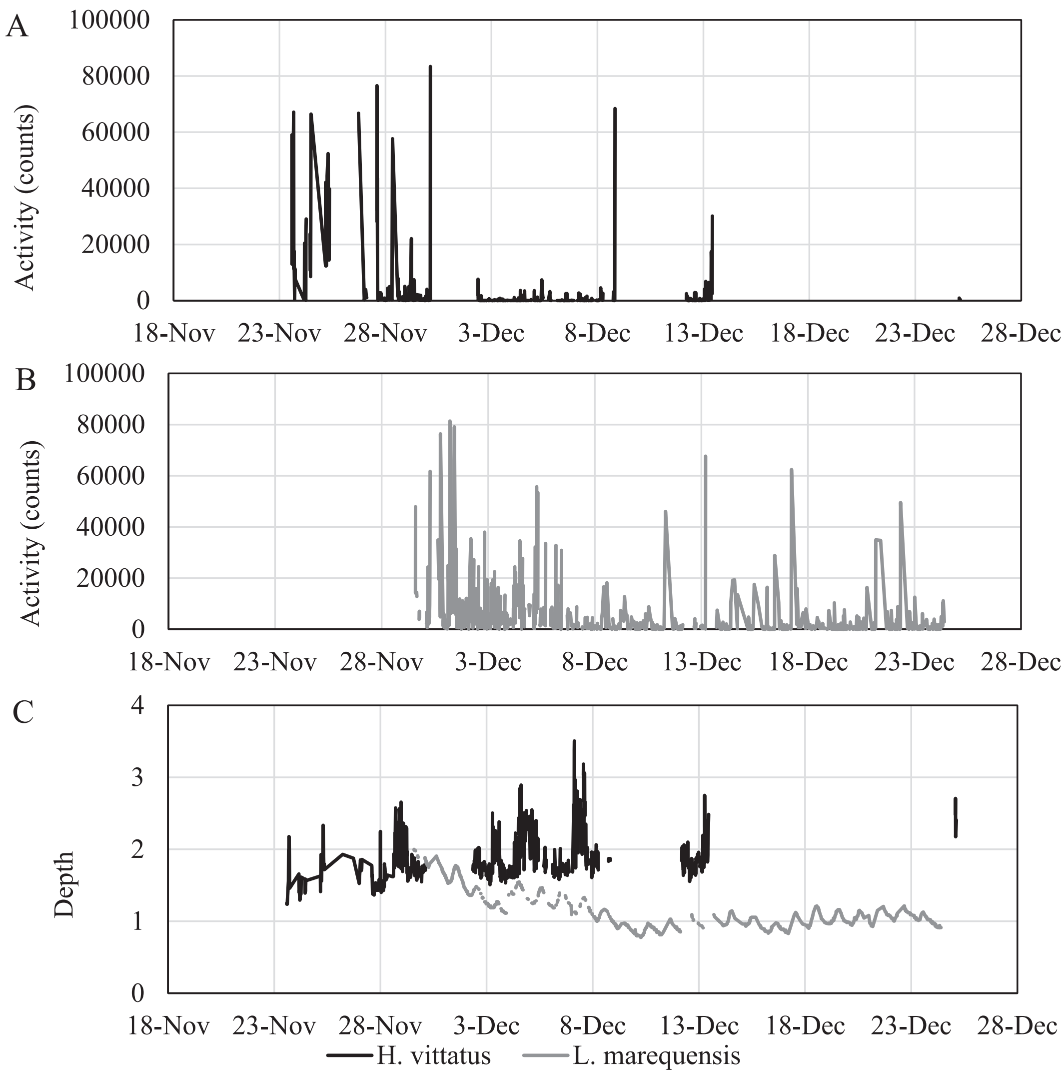


Fig. 6. Real-time (remote) data depicting the activity integer counts of (A) *Hydrocynus vittatus* and (B) *Labeobarbus marequensis*. The depth (m) profiles (C) of *H. vittatus* (Black) and *L. marequensis* (Grey) showed different usage of the depth of the river. The gaps in the data show when the smart 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

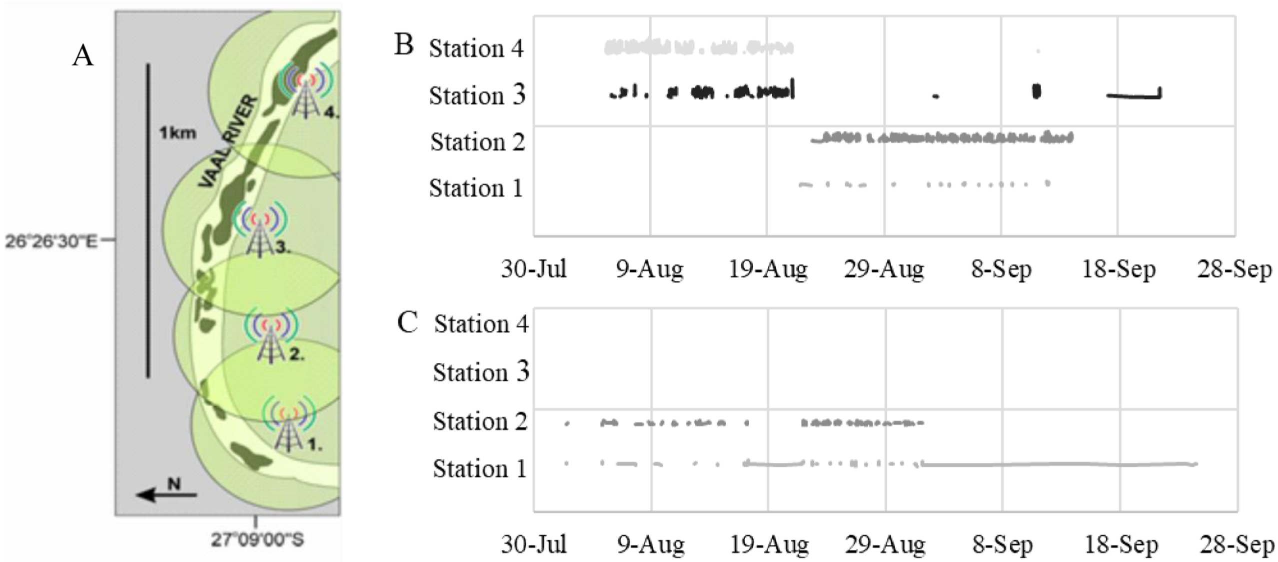


Fig. 7. The spatial use of the river by two individuals of *Labeobarbus aeneus* (Tags 20 and 52) in the Vaal River, South Africa, in case study 4 (A) detected by remote stations situated along the River, (B) the location of tag 20, and (C) tag 52 at the established stations showing the spatial movement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

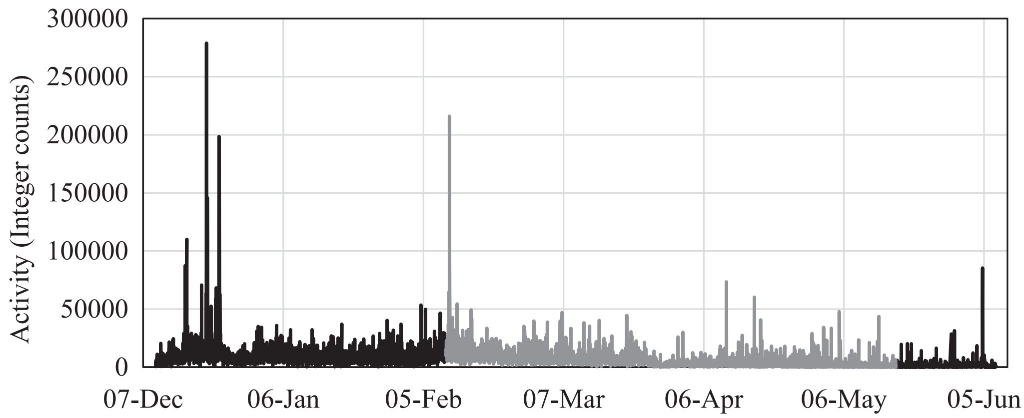


Fig. 8. Example of remote monitoring activity (integer counts) data from a *Labeobarbus natalensis* tagged in Albert Falls, KwaZulu-Natal, South Africa. Real-time data (black) obtain from the fish when in range of the remote network on the lake and stored data (grey) recorded while out of range and downloaded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

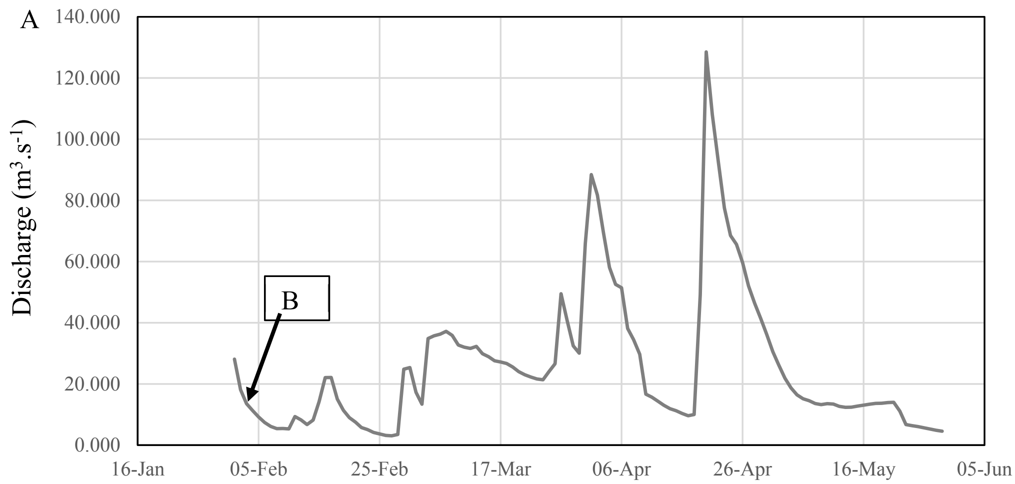
A telemetry study was conducted on *H. vittatus* (n = 4) in the Okavango River to assess angling stress and tag attachment procedures (Table 1; O'Brien et al. unpublished data). This study formed part of a greater study to evaluate the effect of angling on *H. vittatus* in the Okavango River and demonstrated 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



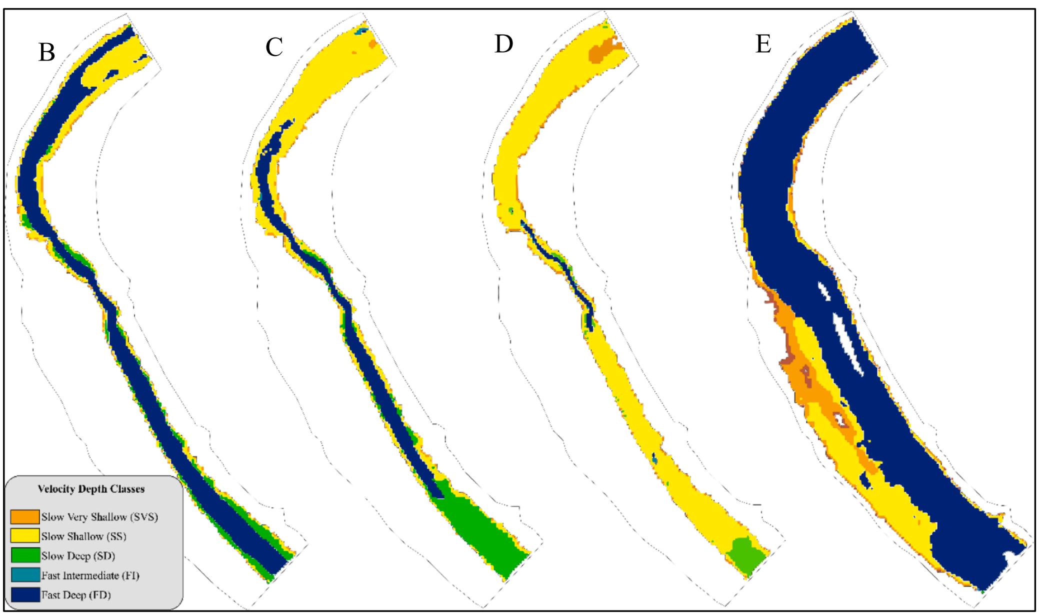


Fig. 9. The hydrograph (discharge) determined using the depth (mm) data from water probes (A) and then used to model the velocity depth classes on the Senqu (Orange) River, Lesotho, (B) at 16.54 $m^3.s^{-1}$ using River 2D hydraulic/hydrology modelling techniques. Velocity depth class models C, D and 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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