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TECHNICAL REPORT

Development and application of the FISHTRAC real-time remote monitoring tool for digital twinning of river basins in southern Africa

Angelica Kaiser-Reichel[1,2], Matthew Burnett[3,4], Christopher Dickens[5], Tristan McNiel[2], Hugo Retief[6],Vanessa Süßle[7], Mariangel Garcia Andarcia[5] and Gordon Craig O'Brien[1,2]

[1]Gulbali Institute, Charles Sturt University, 386 Elizabeth Mitchell Drive, Albury, New South Wales, Australia. [2]Faculty of Agriculture and Natural Sciences, University of Mpumalanga, Private Bag X11283, Nelspruit 1200, South Africa. [3]School of Life Sciences, University of KwaZulu–Natal, Pietermaritzburg, South Africa. [4]Ecosystems, Institute of Natural Resources NPC, Pietermaritzburg, South Africa. [5]International Water Management Institute–Colombo, 127, Sunil Mawatha, Battaramulla, Colombo 10120, Sri Lanka.. [6]Association for Water & Rural Development (AWARD), PO Box 1919, Hoedspruit 1380, South Africa. [7]Department of Computer Science, University of Applied Sciences, Darmstadt, Germany

INFORMATION

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ABSTRACT

The natural world consists of various complex physical, biological and social systems that are connected and interact with each other. New technological developments are improving the ability of the managers of natural resources, to understand and contribute to the way we are developing using and sometime abusing our resources. Through the Digital Twin for management of water resources in the Limpopo River Basin we have an opportunity to integrate available sustainable environmental flows and water resource management technology into an integrated system, that will allow stakeholders of the Limpopo River and surrounding regions to understand, monitor and manage these resources for current and future generations.

Fish are good ecological indicators and have been used for over 100 years by scientists to understand how ecosystems respond to changes in environmental conditions. The development of and use of water resources for agriculture, mining and industry and urban and peri-urban communities has affected the quality, flows and habitat of rivers. Scientists routinely use established biological methods or tools to evaluate the ecological consequences of changes, but these methods are usually reactive and used after impacts occur.

The FISTRAC tool has been developed through the Limpopo River Digital Twin approach to allow stakeholders to use established fish behavioural monitoring methods in real-time to evaluate changes in river condition. The approach includes the integration of radio telemetry tagging and tracking methods with real-time monitoring approaches into an online web-based system. The FISHTRAC tool monitors the behaviour of tagged fish and water quality and flow variables in the real world. This is represented in real time on the Digital Twin systems. If pre-determined abnormalities in fish behaviour is observed and is correlated to changes in river flow or water quality the FISHTRAC Tool automatically evaluates the severity of the behavioural change and as such the environmental variable change, summarizes the information and alerts users to the information in real time.

This tool developed for the Digital Twin has been tested in the Sabie and Crocodile Rivers in southern Africa and shows how new technology can be used to not only monitor ecosystems, but we can consider the biota of these ecosystem and use them to determine the consequence of how we use ecosystems in real to near-real time. The FISHTRAC tool has the potential to make a considerable contribution to the sustainable water resources in southern Africa through the Digital Twin system.

INTRODUCTION

Mankind is totally dependent on the ecosystem services derived from freshwater water resources that are being used excessively and in varying state of health (Kuehne et al. 2023, Thieme et al. 2023). Global water resource users need to attain a balance between the use and protection of water resources to ensure sustainability (Arthington et al. 2023). Many approaches, tools and or techniques have been established to help understand, manage and monitor these vulnerable water resources (Kuehne et al. 2023). Good international practice currently includes the establishment of suitable sustainable water resources management approaches, their implementation, river health monitoring and in an adaptive context learning from historic plans, implementation and monitoring to continually improve the management thereof (Arthington et al. 2023, Kuehne et al. 2023, Thieme et al. 2023). Holistic environmental flow (e-flow) determination, and the establishment of and implementation of frameworks that can contribute to implementation and monitoring is being advocated globally for the sustainable use or development and monitoring of the health of water resources (Arthington et al. 2023). Recent digital Innovation methods that incorporate the use of advanced monitoring equipment and apparatus, internet of things (IOT) and more recently artificial intelligence are being established to contribute to sustainable water resources management (Henriksen et al. 2022, Wenzheng and Yifeng 2022). These developments offer new opportunities for technological developments and IOT to contribute to the sustainable management of water resources.

Fish are used in a variety of environmental monitoring, conservation, and research programs globally as indicators of aquatic ecosystem well-being, health, or status (Harris 1995, Kleynhans 1999, O'Brien et al. 2009, Humphries et al. 2016). Fish have inter- and intraspecific tolerances and environmental preferences (Scott et al. 2006, Kleynhans et al. 2007, Kuehne et al. 2023) and respond to a multitude of physical, chemical, and biological variables in aquatic systems (Fausch et al. 1990, Barbour et al. 1999, Whitfield and Elliott 2002, Wepener et al. 2011). These variables can be natural (e.g., seasonal cycles and drought) or anthropogenic (e.g., pollution, altered flows) and include multiple stressors that fish assemblages respond to in predictable ways (Schinegger et al. 2016, Lima et al. 2017, Lin et al. 2017, Ramesh et al. 2018, Zucchetta et al. 2021). An increased understanding of how fish respond to these multiple stressors such as altered flows is important to increase the knowledge of the effects of multiple stressors and associated changes to aquatic ecosystem health and the resilience of these ecosystems to change (Lucas and Baras 2000, Burnett et al. 2018, O'Brien et al. 2018). Attributes of the various levels of biological organisation for fish have been used to identify the impacts that affect and/or determine the ecological state of freshwater aquatic ecosystems (Fairbrother 2003, Wepener 2008, López-López and Sedeño-Díaz 2015, O'Brien et al. 2018,). The behavioural responses of fish are shown to be 10-100 times more sensitive to environmental stressors than any other established line of evidence (Gerhardt 2007).

Globally, behavioural studies have been used to evaluate how fish respond to altered water quality (Gerhardt 2007), altered flows (Cambray et al. 1997, Taylor et al. 2012), habitat variability, other chemical alterations to the environment (Lucas and Baras, 2000) and biological events like migration (O'Brien et al. 2013, Jacobs et al. 2016, Burnett et al. 2018, Ramesh et al. 2018). Understanding fish movement contributes to using them as ecological indicators (Cooke et al. 2016), so it is important to understand their behaviour and spatial requirements when determining management objectives (such as e-flow requirements) for sustainable usage of freshwater ecosystems (Dickens et al. 2019, Burnett et al. 2021). Various techniques are used to track and monitor fish individual movements such as trapping, mark-recapture, and telemetry (Lucas and Baras 2000, Cooke et al. 2013).

Telemetry techniques are the preferred method used to monitor fish behaviour (Lucas and Baras 2000) to determine various stressors affecting fish (Koster et al. 2017, Thiem et al. 2018, Block et al. 2019), understand fisheries capacities (Crossin et al. 2017), characterise invasive species impacts (Bacheler et al. 2015) determine their migration pathways (Melnychuk 2014, Trancart et al. 2018), observe the interaction with other organisms and monitor fine-scale movements (Cooke et al. 2013, Thiem et al. 2018, Block et al. 2019, Burnett et al. 2020). Advancements in telemetry studies have allowed for fish behaviour to be observed in real-time, remotely. This provides prospects for enhanced management activities to ensure the sustainability of natural resources (Cooke et al. 2017, Abecasis et al. 2018, Block et al. 2019).

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. 2024). Radio telemetry methods are the preferred method to conduct fish behavioural studies within freshwater ecosystems 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. 2022). These telemetry studies have been conducted across various fish species including *Hydrocynus vittatus* (Tigerfish), Labeobarbus spp. (Yellowfish), Labeo spp. (Mudfish), and Anguilla spp. (Eels) (Burnett et al. 2021). These are good indicators species of changes in water quality, flow alterations and river connectivity (Burnett et al. 2021, Hanzen et al. 2021).

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, a perceived lack of market and high variability within aquatic ecosystems have restricted the use of fish telemetry methods in the region (Hocutt et al. 1994, Cooke et al. 2013, Lennox et al. 2017, Burnett et al. 2024). 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.

The FISHTRAC programme includes an approach to monitor the flows and water quality components of the ecosystem and how the ecosystem responds to changes in these components using the behavioural ecology of fish in real-time, remotely. The approach makes use of smart radio telemetry devices that send and receive information (transceivers) from rivers and impoundments in real-time. These devices include fish tags and water quality and quantity probes that transmit a range of water quality, flows and fish behavioural response data using base and relay receiver stations set up in the field, or portable receivers to a data management system (DMS) in real-time, remotely (Burnett et al. 2020). Once received the data is automatically uploaded to the DMS and can be accessed in real time via the Internet or sent to any mobile device. The DMS can also be structured to receive the data, carry out some simple statistical analyses and or queries and send results and or alert messages to any mobile device in real-time (Burnett et al. 2020).

To thoroughly evaluate the ecological impact of multiple stressors, understanding the 'normal' behaviour of fishes as a baseline is crucial. From this baseline, 'abnormal' behaviour can be utilised to identify the stressor. While there are various metrics and indices to measure and monitor the ecological response to stressors, they often involve invasive, time-consuming, and resource-intensive methods that cannot provide real-time and remote ecological responses. Utilizing fish behaviour to alert managers to threshold (TPC) breaches allows for subsequent assessments using more sensitive methods, such as biomarkers, fish health and community indices, and the assessment of aquatic macro-invertebrates. These organisms, serving as food sources for many fish species, are exposed to similar stressors.

Changes in fish behaviour, whether sudden or chronic, can guide managers to pollutants that may otherwise go undetected or persist within the aquatic ecosystem due to the infrequent testing of such variables. The FISHTRAC program employs fish telemetry methods to monitor these behavioural changes, and through continuous monitoring of known stressors and fish behaviour, it can identify chronic and event-based stressors for further investigation. The FISHTRAC program continuously updates baseline and response data, making it an ongoing, real-time, and adaptable approach. Integration into existing real-time water quantity and ecological monitoring programs, such as those by Pollard et al. (2012) and Agboola et al. (2019), allows for the adoption of the FISHTRAC program to better achieve nationally set objectives. Alternatively, the FISHTRAC program can be employed as a Line of Evidence (LOE) when establishing ecological reserves and can contribute to an adaptive relative risk model.

Considering the numerous stressor impacts, such as flow reductions, augmentation through water schemes, wastewater treatment works (WWTW), and discharges from the large mining sector in southern Africa, fish are continually exposed to these stressors, leading to changes in their behaviour. The FISHTRAC program can remotely and in real-time detect and evaluate these movements and responses, providing managers with evidence-based data to inform the decision-making process. Its applicability extends across freshwater ecosystems in the region and globally.

As a part of the Digital Innovation Initiative of the CGIAR, FISHTRAC data is being live-streamed into a Digital Twin (Garcia Andarcia et al., 2024) where it is integrated into multiple other streams of data including river flows, e-flows, water use amongst others still to come. Alerts generated by FISHTRAC will become part of the overall management stream of information enabling managers to respond immediately and in concert with other data streams facilitated by the Digital Twin.

In this study we aimed to continue to develop the FISHTRAC system through the automation of the approach to provide the ecological response of altered river flows, and other stressors, in real-time remotely, and to use this information in a digital twin environment to contribute to the implementation and monitoring of e-flows. We aim to demonstrate how the real-time remote ecosystem response monitoring approach FISHTRAC can contribute to the digital innovation for sustainable water resources monitoring in southern Africa. This paper presents the development and application of the FISHTRAC real-time remote ecosystem response monitoring tool in the Crocodile and Sabie Rivers as a part of the greater Incomati Basin in southern Africa. The approach has been developed to test the potential of incorporating the FISHTRAC approach into the digital innovation approach and if the FISHTRAC approach can provide real time evidence of how the ecosystem responds to these changes.

METHODOLOGY

The approach includes the FISHTRAC development in the study, the development of the online monitoring or FISHTRAC application tool and the Incomati River case study including application in the Crocodile and Sabie Rivers.

Wireless Wildlife (WW) has developed a commercial radio tracking and monitoring system primarily for large domesticated terrestrial livestock (WW 2013). These systems have been extensively used in South Africa, tracking over

4,100 animals over five years, to monitor the collective behaviour of livestock and certain wildlife species for security purposes (WW 2013). The WW radio telemetry system works by equipping a portion of the monitored animals with small radio transceivers (tags) that track their location and behaviour (movement). These tags transmit data periodically—typically hourly—or when a violation of "normal" behaviour is detected, to a receiver or base station within range, generally less than 10 km from the tagged animals.

Fish are sentient animals, and as such the use of fish as ecological indicator animals requires ethical consideration including consideration of how tagging and tracking research can affect the biology, ecology and survival of the tagged and tracked fish (Naef-Daenzer et al. 2005; Thorsteinsson 2002; Burnett et al., 2020). Consideration of the availability of fish for tagging and tracking research should be considered and the cost-benefit of using fish in the research compared to the potential benefit to conservation and management to manage and conserve populations. Through the FISHTRAC programme development and testing the non-lethal ethical considerations of capturing, tagging, releasing and tracking fish has been made (Benette et al., 2016). Recommendations for ethical use of fish for FISHTRAC include the aim to minimise impacts on individual fish and ensuring that the use of fish for such monitoring process provides scientifically valuable data, including maximise the value from every individual tagged and tracked which includes consideration of the tags used, timing of tagging and tracking experiments (Cooke et al. 2013; Burnett et al., 2020). Ethical considerations also include the need to use skilled, experienced fisheries scientists to undertake the anesthetising and tagging procedures to make the process as fast as possible and to minimise harm to the fish used (Benette et al., 2016). Following the tagging period external tags fall off the tagged fish while fish live with inert internal tags (not considered in FISHTRAC) for the rest of their lives. The cost benefit of using some fish to allow us to understand and monitor ecosystems is considerable. This results in better manged ecosystems for the fish, their populations and for other biodiversity (Burnett et al., 2020).

This paper follows initial development of a tool available to describe the "normal" and "abnormal" behaviour of fish and to use this information to identify impacts associated with multiple stressors affecting water resources. The application of radio telemetry methods incorporating smart tags and manual and remote monitoring techniques has contributed to the FISHTRAC programme's development (Figure 1). This system uses radio tags and water probes (transceivers) that send data to base and relay receiver stations or portable receivers. The collected information is uploaded to a web-based Data Management System (DMS), where it can be accessed online or sent directly to mobile devices (O'Brien et al. 2013). The DMS is designed to receive and store data and to process it statistically and send alert messages or reports to stakeholders in real time. Fish behaviour and abiotic data, reported every 30 minutes, allow resource managers to monitor and mitigate anthropogenic stressors remotely. The FISHTRAC system has been developed to provide stakeholders with real-time access to river flow, water quality, and fish behaviour data, facilitating a deeper understanding of the ecological consequences of altered flows and other environmental stressors (Burnett et al. 2023a).

To expand the coverage area, additional receivers, known as "repeater stations," can be placed throughout the study area. These stations relay data from the tags to the base station, if necessary, effectively extending the network's range (Figure 1). The base and relay stations are solar-powered and have an RF link to the tags and between themselves. Only the base station transmits data to the data management system via a GSM link to the server of the data management system. Data is safeguarded through a combination of on-site and off-site backup systems. This allows users to access real-time information on the location and behaviour of tagged animals, as well as the status of the telemetry system, through a secure web-based interface.

The bidirectional communication channel, from tags to the end user, enables remote adjustments to the parameters of the tags or tracking system via either a web browser or mobile Short Message Service (SMS).

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).

The tags consist of a main electronic circuit, to which several additional peripheral sensory components can be added to extend the functionality of the tag. The electronic circuit consists of a high-speed central processing unit (CPU) which executes the firmware (i.e. the program) that is stored in its internal memory. It also has a built-in analogue to digital converter (ADC). The ADCs make it possible to connect the circuit directly to additional sensors. It also has extremely low power consumption (<1uA) in sleep or standby mode. When active, the power consumption depends on which built-in components are used, making it possible to manage the active power by only using the required components. The electronic circuit also has a radio frequency (RF) transmitter (>10 dBm output power) and a sensitive receiver (<120 dBm) to send and receive the radio signals. The circuits are light (0.1 g) and cheap (a few US$) when compared with the remaining components of the tags. The CPU of tags can be connected to various peripheral components such as motion or movement, temperature, and pressure sensors (for depth), and data storage component (memory):

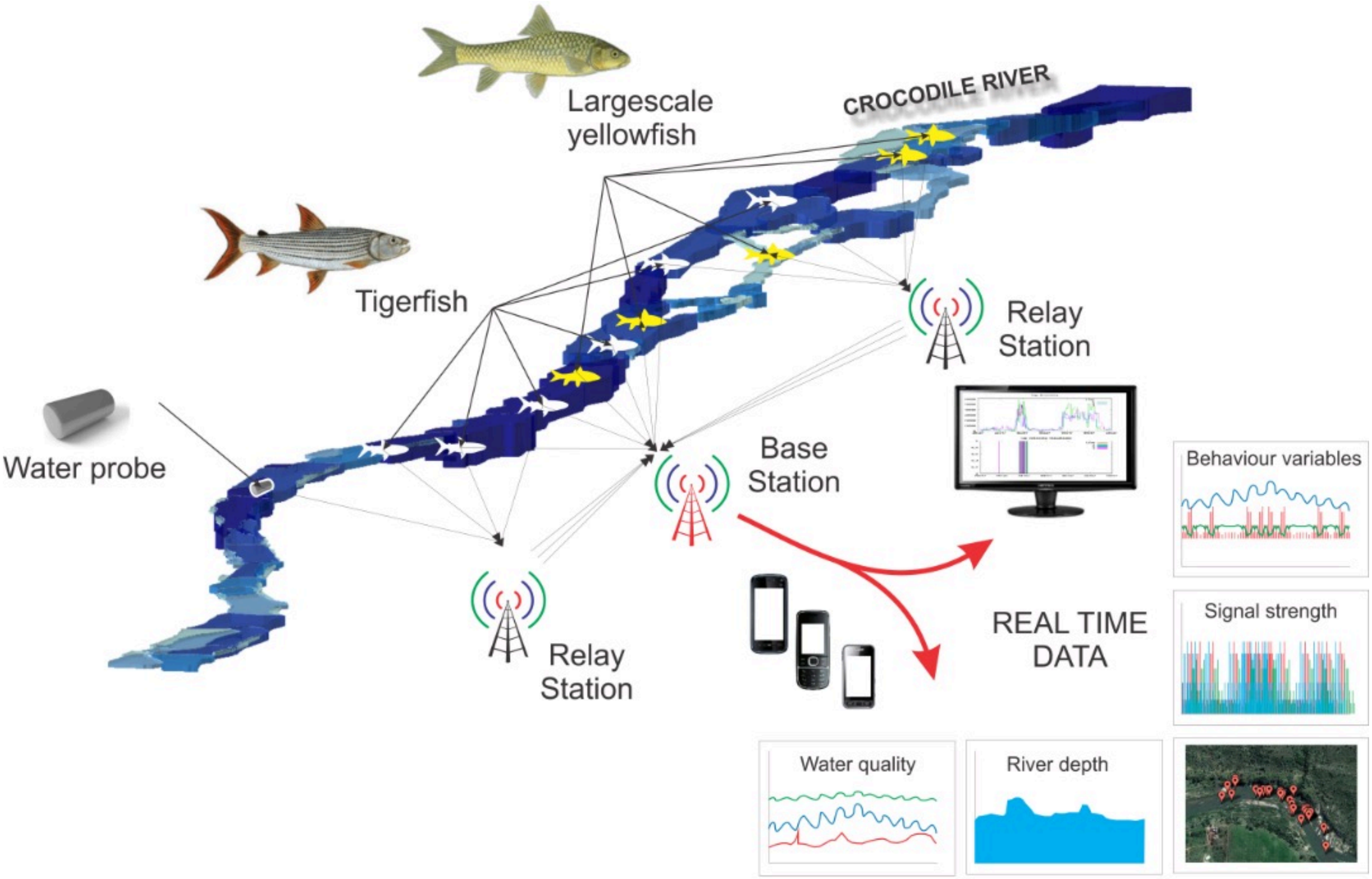


Figure 1: Schematic representation of the FISHTRAC network with Wireless Wildlife remote monitoring system. The system incorporates tagged fish and an abiotic tag within a river that has base and relay stations positioned on the banks to generate a coverage area for the study.

1. Motion sensor: An omnidirectional tilt and vibration sensor is used to monitor the movement of the tags (or animals). The sensor acts as a switch which chatters open and closed as it is tilted or vibrated. It is connected to one of the CPU's internal counters so that motion results in a higher count rate over a specified period (usually every 10 minutes). The values of the counter therefore give the integrated motion of the animal over a defined period.
2. Temperature: A temperature sensor with an accuracy of 0.5°C after calibration was connected to the CPU to measure the ambient temperature.
3. Pressure sensor (depth): By adding a pressure sensor, it is possible to monitor and record the depth of a tag at certain time intervals. The output of these sensors, which are proportional to the absolute pressure, was connected to the CPU and calibrated (proportionality constant of 33 ADC counts per meter water depth). The sensors have a linearity of 0.2% over the full scale and are connected to the ADC with a resolution of 3 cm.
4. Data storage capabilities (memory): During application in aquatic ecosystems the tags will not always be within radio reception of the base/relay stations. To preserve data generated by tags which would otherwise have been lost by the transmission from the tags not being received, the data can be stored in the data storage component on the tag and only transmitted to the base/relay stations when the tag is in range and the data is requested. Based on a 30-minute transmission scenario, the storage capacity of the memory components can allow for more than one year of remote monitoring data to be stored and downloaded. This generally exceeds the lifespan of the transmitter suggesting that the storage capacity on the tags cannot be reached.

The manual system operates similarly to that of traditional radio techniques, the conservation of battery life through schedule changes allows for the use of both manual and remote tracking when needed. This function requires more tag management but can be beneficial in the long run, to retrieve expelled tags or tagged fish that have been predated on by manually tracking the tag. Switching to manual monitoring in the occasion of an event detected using remote systems, allows for the researcher to investigate the event further by tracking finer movements. This is important as manual monitoring must not be abandoned once the remote system is established and can instead be used to ground truth findings from remote monitoring.

Tag size currently limits the size of fish used (> 500 g), while smaller fish can be used in short-term applications. The stored data on tags can be obtained without the retrieval of the tag, if the tagged fish returns to the range of an established remote network, this allows for continual data retrievals over the study period. Static water probes can last up to three years, while fish tags will last up to a year depending on the variables needed and the 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 position is a valuable feature and can grow as technologies improve. Tagged fish can then be tracked using these techniques so that the movement, activity and habitat associations (as examples) can be linked to water quality variables recorded by the probe.

The WW system makes it possible for behavioural studies of several animals to be undertaken remotely over a large period (WW 2013). The large amount of data collected (a year's data from one tag transmitting hourly amounts to 8760 data points) requires management. To do this, a data management system was developed consisting of a database where all the information is stored on a server that collects the data from the tags and makes it available to the user. When combined with the removed receiver station network, any tag's data can be accessed from anywhere in the world immediately when the tag is in range. 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.

The FISHTRAC system incorporates data storage devices including data storage capabilities of all tags. If tagged fish for example leave the radio monitoring or coverage area and or dive to depths (> 5 m) in which areas the radio transmissions do not reach listening base and or relay stations the data is stored on the tag and transmitted as soon as the tag is back in range of a station. The FISHTRAC programme is ideal for rivers, large instream pools or lakes that do not generally exceed >10m in depth and/or for the 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.

The database stores the data collected by each tag and keeps track of the type of tag (i.e. peripherals, battery, firmware), the status of the tag (e.g. if it is in network range, battery power available) and the history of the tag (when it was configured in a different configuration). The database also has a security feature where user information is stored including the data accessed and setting changes. The server has several capabilities, including the ability to receive and send data to tags via the internet or GSM network. It is equipped with an SMS interface that can send alert messages to users when specific conditions are met, and it also allows users to change the settings of a tag by sending SMS commands. Additionally, the server features a web interface, enabling users to log in, monitor the status of their tags, access data, and modify tag settings as needed.

FISHTRAC application

The FISHTRAC web application presents data for both scientific analysis and client use, incorporating a Fish Alerts system that uses predictive analytics to forecast fish activity and notify managers of significant behavioural changes. The platform provides interactive graphs and tables, allowing users to explore, download, and analyse data efficiently.

Designed to integrate advanced data representation and analysis, the FISHTRAC system supports real-time fish tracking and predictive insights, addressing the needs of scientists and managers in freshwater ecosystem management. By offering a comprehensive platform for data handling, FISHTRAC facilitates decision-making in river and freshwater environments.

Figure 2 outlines the data processing pipeline. Data is collected through the FISHTRAC network and processed by a machine learning algorithm, which identifies changes in fish activity and environmental data. This information is stored in a database and displayed through the web application. When alerts are detected, the system (Alert Bot) sends notifications via WhatsApp to relevant stakeholders, enabling prompt action.

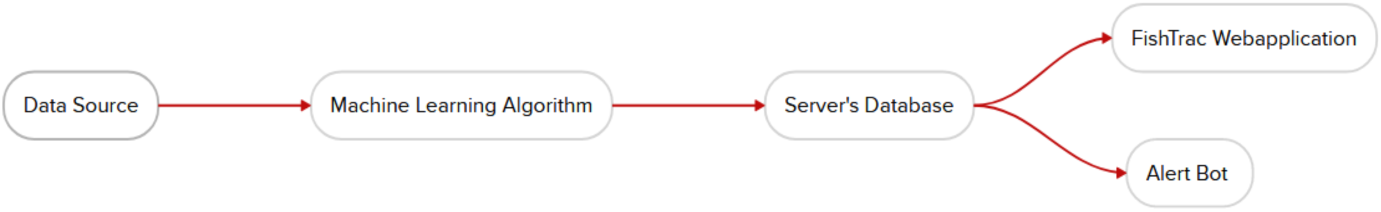


Figure 2: The view of how the FISHTRAC data is processed, displayed on the FISHTRAC Web application and when the Alert bot sends out messages.

The data from Wireless Wildlife is processed within a Docker image that contains both the Python-based machine learning algorithm and a SQL database. This setup enables advanced analytics and real-time insights.

Data Transformation and Storage: Data is transformed and stored within the Docker image, with the SQL database serving as a centralized repository for diverse datasets.

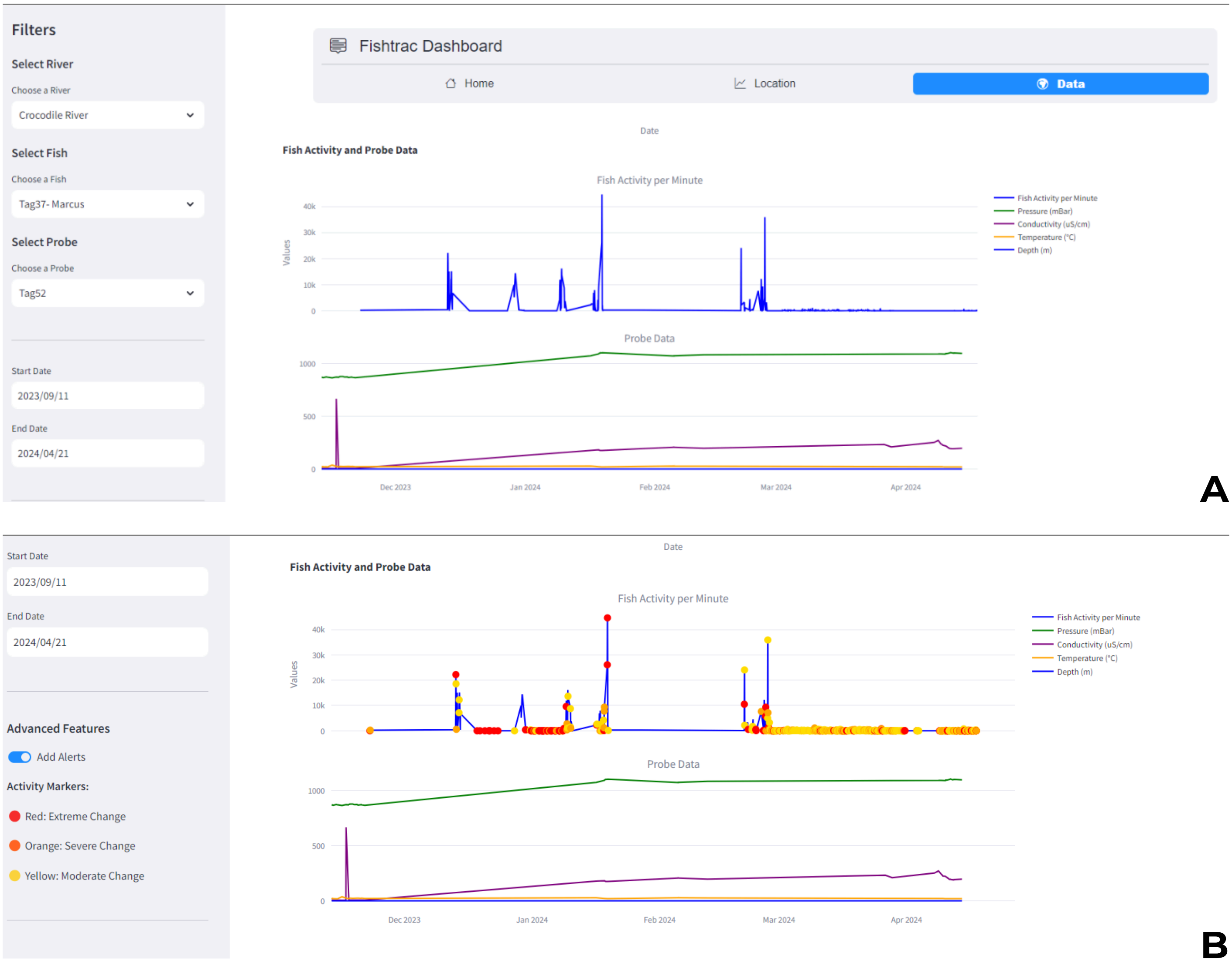
Machine Learning Algorithm: The Python-based machine learning algorithm uses the Exponentially Weighted Moving Average (EWMA) model to detect trends and extreme changes in fish activity, temperature, and pressure.

Alert Generation and SQL Integration: The algorithm identifies deviations in fish activity and environmental parameters, generating alerts that are stored in the SQL database for further analysis.

SQL Database: Powered by MySQL, the database supports optimized data queries and ensures efficient integration with both the front end and the machine learning algorithm, maintaining data integrity and facilitating complex interactions.

This integration of data processing, machine learning, and SQL database management forms the core of the system.

The web application is crafted using Python 3.10, with Streamlit and Plotly serving as the cornerstone libraries. These technologies collectively contribute to a powerful and dynamic platform designed to meet the diverse needs of the users. Below is an example of how the frontend looks (Figure 3).



Filters

Select River

Choose a River: Crocodile River

Select Fish

Choose a Fish: Tag37- Marcus

Select Probe

Choose a Probe: Tag52

Start Date: 2023/09/11

End Date: 2024/04/21

Advanced Features

Add Alerts: on

Activity Markers:

- 🔴 Red: Extreme Change
- 🟠 Orange: Severe Change
- 🟡 Yellow: Moderate Change

Figure 3: An example of the FISHTRAC Web application front end. A: The activity blue line), Pressure (Green Line), Conductivity (Purple line), and depth (Blue line) for a selected fish over a month. B: Indicate the Alerts that the algorithm for the FISHTRAC early warning system have created. These alerts included extreme changes (Red dots), severe changes (Orange dots) and moderate change (Yellow dots).

Incomati River case study

To track tagged indicator fish species remotely and in real-time, a remote network of receivers (Base station and relay stations) has been installed as per the fish tracking methodology (FISHTRAC) described by Burnett et al. (2020) Figure 4 and Figure 5. The relay and base receiver stations detected the signal from the tagged fish in situ and detected the tag identification, signal strength of the transmission and any sensory data (Burnett et al. 2018). This data was transmitted directly to a Data Management System (DMS) as real-time and stored data (Jacobs et al. 2016, Burnett et al. 2018). The real-time data included records of the time of detection and what station it was in the range of, while the stored data recorded the sensory data over the stipulated schedule.

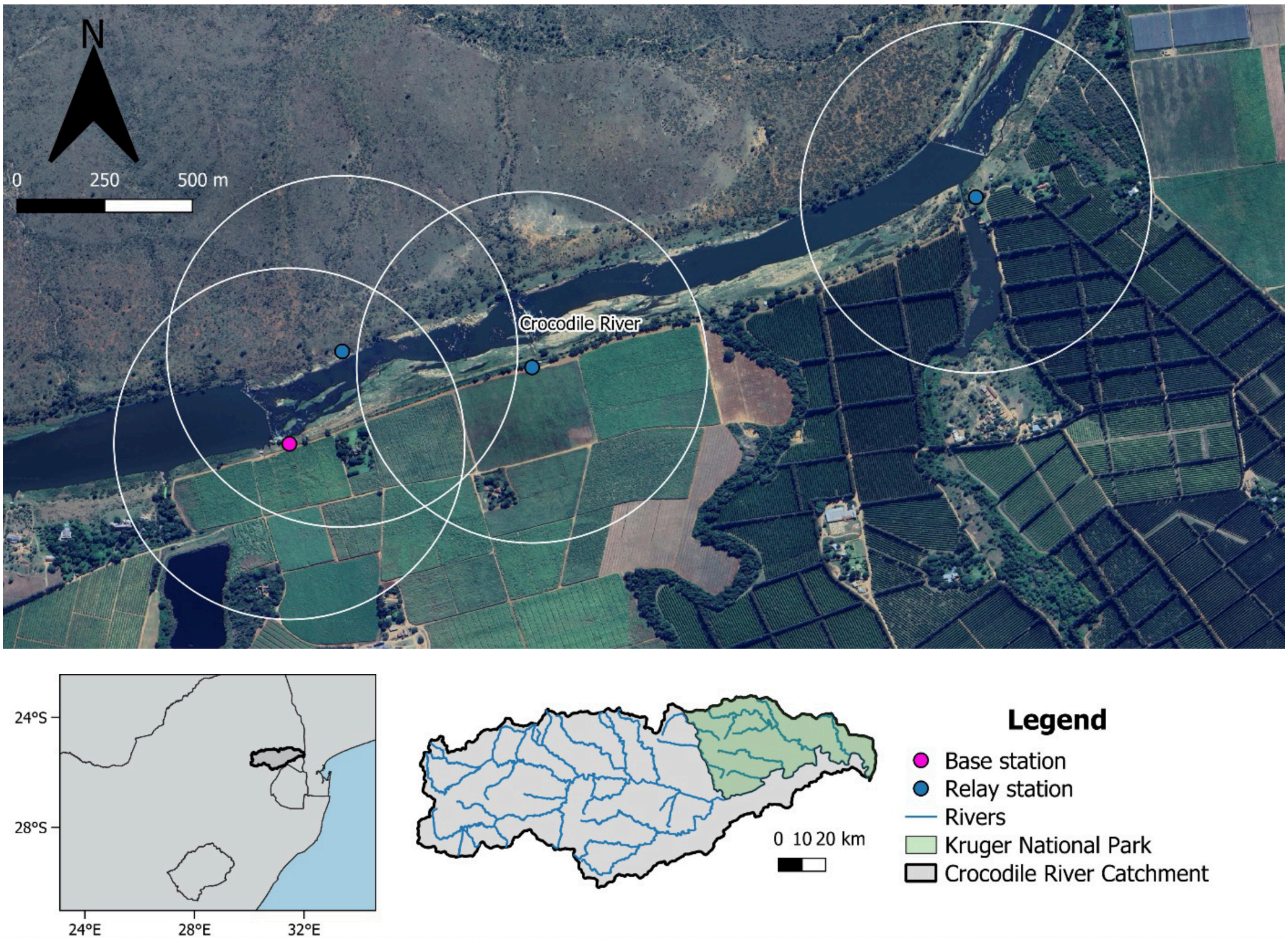


Figure 4: The locations of the Base station (pink) and Relay stations (blue) for the FISHTRAC network at Van Graan on the Crocodile River. The range of detection by the stations are also indicated

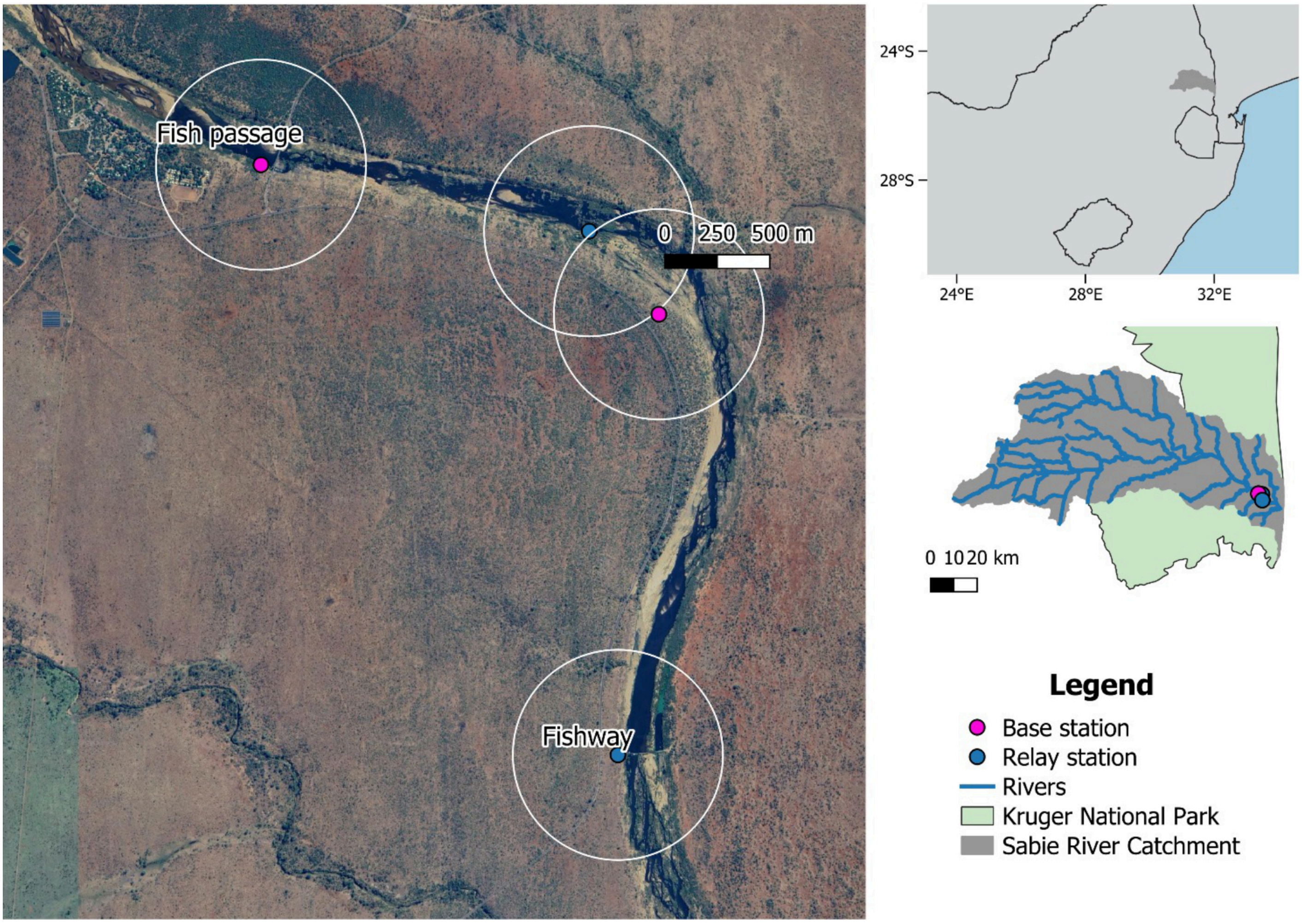


Figure 5: The locations of the Base station (pink) and Relay stations (blue) for the FISHTRAC network at Lower Sabie on the Sabie River. The range of detection by the stations, Fishway and Fish passage are also indicated.

To determine the real-time and remote monitoring application of fish telemetry methods and their application within the Crocodile and Sabie Rivers, *Hydrocynus vittatus* (Tigerfish) and *Labeobarbus marequensis* (Largescale yellowfish) were tagged (Figure 6). Tigerfish and yellowfish were sampled with angling techniques (Table 1). The total length (from the tip of the head to the end of the tail), the standard length (from the tip of the head to the base of the tail before the caudal fin starts), the fork length (from the tip of the head to the middle of the caudal fin), the girth length (length around the peduncle) and weight of the fish were collected and photographed. Only adult fish were considered in the study where the fish-to-tag weight is greater than 2% as per best practice telemetry or >1.5 kg fish, to ensure that the fish's mobility was not compromised (Jepsen et al. 2014). Suitable individuals were anaesthetised in a water-filled bath with 0.4 mL/L of clove oil. Before tagging, we looked for signs that the individual fish were under anaesthesia like reduced fin activity and involuntary upside-down swimming motion (O'Brien et al. 2013a, Burnett et al. 2020). Once this sign was identified we surgically attached the Wireless Wildlife external radio tags (WW series IV). Fourteen gauge sterilized surgical needles was inserted into the muscular tissue of the fish below the base of the dorsal fin. An antibiotic (Terramycin®) was then injected into the cavity of the needles and surgical wire (0.5 mm thick) attached to the tag was inserted through them (Burnett et al 2020). The needles were then removed, a protector plate threaded onto the surgical wire and the wire then tightened securing the tag onto the fish (Figure 6). An antibiotic (1.0 mL/kg of Terramycin® containing oxytetracycline) was administered into the surrounding muscular tissue followed by wound care gel (Aqua Vet, Veterinary Hospital, Lydenburg, South Africa) to minimise infection and assist with wound recovery (Burnett et al. 2020). Once fully recovered from the anaesthetic, fish were released back into the river near the point of capture. The tagging procedure took approximately 30 minutes per fish, from capture to the time the fish was released to recover (Burnett et al. 2020).

Figure 6: A: The complete set-up of the tagging station with clove oil, an air pump and a bulge pump; B: Inserting of the sterilised surgical needles through the body of a Tigerfish; C: Threading through the surgical wire and the tag before removing the needles; D and E: Securing the tag and the baseplates to the Tigerfish; F: Injecting the tigerfish with antibiotics; G: Measuring the different required lengths of the tigerfish; H: The Tigerfish after it has been tagged with a radio tag.

Table 1: Summary of Tigerfish tagged during 2021-2024. This includes the different measurements, the date the individual was tagged, the river system the individual was tagged in and when the last activity has been reported.

Tag codes	Girth length (mm)	Standard length (mm)	Total length (mm)	Weight (g)	Date Tagged	Last reported	Days tracked	River
Tag 81	680	570	680	4200	2021/07/13	2021/10/07	86	Crocodile
Tag 82	540	430	540	1750	2021/07/13	2021/10/13	92	Crocodile
Tag 80	480	420	485	1600	2021/07/13	2021/07/30	17	Crocodile
Tag 83	399	525	630	2780	2021/09/03	2022/01/07	126	Crocodile
Tag 84	-	-	-		2021/09/17-	2021/09/21	4	Crocodile
Tag 85	310	515	610	2445	2021/10/29	2022/06/11	225	Crocodile
Tag 86	310	510	610	2270	2021/10/29	2022/01/24	87	Crocodile
Tag 87	380	530	635	3340	2021/10/29	2021/12/11	43	Crocodile
Tag 88	240	425	525	1250	2021/10/29	2021/10/30	5	Crocodile
Tag 89	350	495	595	2000	2021/10/29	2022/06/19	233	Crocodile
Tag 90	310	540	660	2070	2022/11/25	2023/02/09	76	Crocodile
Tag 97	375	485	575	2000	2022/12/09	2023/01/12	34	Crocodile
Tag 95	315	500	600	2030	2022/12/09	2023/02/16	69	Crocodile
Tag 91	350	570	650	3110	2022/12/09	2023/10/16	307	Crocodile
Tag 100	420	585	710	4175	2023/09/11	2023/10/16	35	Crocodile
Tag 101	360	545	670	3200	2023/09/11	2023/10/01	20	Crocodile
Tag 102	330	520	640	1980	2023/09/14	2023/09/14	0	Sabie
Tag 93	330	540	660	2690	2023/07/30	2023/07/30	0	Sabie
Tag 48	335	530	650	2570	2024/01/09	2024/09/21	256	Sabie
Tag 41	295	503	560	1645	2024/02/22	2024/05/02	70	Sabie
Tag 40	330	490	590	1860	2024/02/23	2024/09/24	214	Sabie
Tag 37	355	420	520	2420	2024/02/27	2024/05/22	85	Crocodile
Tag 38	365	600	700	3400	2024/02/27	2024/03/27	29	Crocodile
Tag 46	290	465	565	1600	2024/02/27	2024/10/21	237	Crocodile
Tag 43	365	610	755	3100	2024/02/28	2024/08/19	173	Sabie
Tag 47	310	530	660	2620	2024/04/24	2024/09/24	153	Sabie
Tag 45	350	580	690	3700	2024/04/24	2024/09/24	153	Sabie
Tag 39	358	515	620	2720	2024/09/24	2024/09/24	0	Sabie
Tag 42	340	550	650	2740	2024/09/25	2024/09/25	0	Sabie
Tag 44	360	550	670	3030	2024/09/25	2024/09/25	0	Sabie

To validate the effects and add to our understanding, the potential correlations between the behavioural data of the tagged fish and multiple water quality, flow and habitat variables were tested using a range of statistical methods (Littell et al. 1996, Burnham and Andersons 2002, Impson et al. 2008, Ramesh et al. 2018).

Fish activity rates were recorded in real-time and remotely stored on the DMS. Data was then downloaded for analysis as normalised data and recorded per hour intervals and then processed through the algorithm and plotted using Microsoft Excel © as developed by Burnett et al. (2020). The water quality variables were then overlaid on top of the alerts to evaluate the potential cause and effect of environmental variable trends in real-time. The algorithm uses the activity rates of fish to alert managers of any disruptions in the behaviour of tagged fish per unit time (every hour). The algorithm considers a range of activity rates around the average activity rate from the preceding two weeks and sets them as a baseline for normal activity for each individual. Consequently, any activity rate falling above or below this normal range, are considered high or low activity alerts respectively. The algorithm considers the reoccurrence of these breaches in normal activity and sets an "Alert" when three or more breaches occur consecutively, if not the behaviour is regarded as normal (Table 2). This is done as not every breach may be considered worth investigating if it is isolated and not in response to circumstantial interactions (i.e., Intra-species relationships). These results in combination with a Bayesian Network decision support system to send alert messages to stakeholders and managers in real-time.

Bayesian Networks (BN) are probabilistic modelling networks that graphically represent joint probability distributions over a set of statistical values (Chen and Landis 2005, Ayre and Landis 2012). They include parent or input nodes and child or conditional nodes with links that represent causal relationships between nodes combined by Conditional Probability Tables (CPTs) (Landis et al. 2017). Conditional Probability Tables describe conditional probabilities between the occurrence of states in the parent nodes and the resulting probabilities of states in the child nodes (Landis et al. 2017). The Bayesian Network made use of the NeticaTM BN software by Norsys Software (http://www.norsys.com/).

The management alert sensitivity can be determined through the decay factor (Burnett et al. 2024). The decay factor ranges from 0.1 to 0.9. The lower the decay factor (for example 0.2) the more sensitive the management alerts are and thus there will be an increase in high alerts compared to a higher decay factor (for example 0.8) for the same individuals' behavioural responses.

In addition to the algorithm alerts, binomial generalised linear modelling (GLM) and generalised additive modelling (GAM) with mixed effects regression as a function of covariates was used to unpack the causal environmental variables resulting in behavioural changes (Ramesh et al. 2018). Multicollinearity was tested using the Pearson's correlation co-efficient test ($p < 0.50$) for the selection of covariates (Graham 2003). Burnham and Anderson's (2002) approach for Akaike's information criteria (AIC), standardised residuals and observed versus predicted values were used to determine the model's best fit. The minimum AIC values of these models were selected to determine the linear regression of each covariate. The p-values ($p < 0.05$) calculated within the best-fit model were used to test for significance. The statistical programme R version 6.3 (RStudio 2020) with added packages MuMIn (Broell et al. 2013) and lme4 (Bates et al. 2014) were used to statistical analyses data and determine GLM regressions.

Table 2: Categories of relevance to the change in behaviour using the adapted exponentially weighted moving average (EWMA) formula and the probability of risk classification to determine the management alerts used in the present study. Adapted from Burnett et al. (2024).

Change in behavioral category		Management alerts	
Categories	**Deviation (% Absolute value)**	**Probability of Risk**	**Classifications**
Expected	<25	Zero	One extreme category detection
Moderate	(25,50)	Low	Two extreme category detection
Severe	(50,75)	Moderate	Three extreme category detection
Extreme	>75	High	Four extreme category detection

RESULTS

To illustrate the development of FISHTRAC, we present eight radio telemetry case studies conducted in southern Africa over the past decade. These studies include developmental experiments undertaken that played a key role in shaping the FISHTRAC program and refining the use of radio telemetry techniques (Table 3). Focusing on large and charismatic fish species the case studies advanced both manual and remote monitoring methods, utilizing tags with sensors to track water quality, quantity, and fish behaviour, and employing remote networks for data collection and analysis (Kuklina et al. 2013, Burnett et al. 2018). The outcomes of these studies helped establish guidelines for FISHTRAC.

The first seven case studies transitioned from using beacon tags to smart tags with both methods applied in lotic and lentic systems. While beacon and smart tags were equally effective for manual monitoring, smart tags proved superior for remote monitoring techniques. In the first two case studies, beacon tags were used to evaluate radio telemetry in southern Africa's lotic and lentic systems, yielding successful results . The third study employed both beacon and smart tags, showing their compatibility. This study also demonstrated similarities between MDPM and activity (integer counts), which served as behavioural variables in manual and remote monitoring. Case studies three and four further showed that the new activity variable, measured in integer counts, worked well for manual monitoring in detecting daily and seasonal behavioural rhythms. Remote monitoring in these cases also captured spatial movement by tracking fish through a network of stations, revealing patterns of site fidelity or migration, as seen in studies three and six.

Case studies four to six used smart tags to overcome some of the challenges in strengthening FISHTRAC. In case study seven, the integration of a water probe enabled real-time monitoring of environmental variables such as habitat and water quality. This development made FISHTRAC a comprehensive program that tracks both aquatic conditions and fish behaviour, offering a holistic approach to ecosystem monitoring. Finally, case study eight explored additional applications of fish telemetry, incorporating findings on tagging procedures, recovery periods, and predator influences observed throughout the development of FISHTRAC.

The FISHTRAC programme was successfully evaluated in these studies on the Olifants River (Burnett et al. 2020, Somamzi et al. 2020, Sonamazi 2020) and is an effective monitoring tool for understanding the biological response and synergistic effect of environmental and anthropogenic stressors on fish in the Olifants River system, Kruger National Park. The FISHTRAC programme is effective in collecting data remotely and providing spatial movements of fishes. Further, the real-time and remote applications fed into an alert system that can adequately be used to determine important changes in behaviour events that managers need to be aware of. The added benefits of the FISHTRAC programme to understand important biological and ecological behaviour of fishes demonstrate the versatility of the programme to adaptively manage multiple stressors on the environment. Below is a summary of the Case studies that used the FISHTRAC network on the Olifants River.

Crocodile River case study using cyprinids

Behavioural response of *Labeobarbus marequensis* and *Labeo congoro* to environmental variables using the FISHTRAC programme on the Olifants River, Kruger National Park. The Olifants River in South Africa is identified as one of the most polluted rivers due to various altered water quality variables from human activities. The river is crucial for supplying drinking water and supporting ecosystems, including the Kruger National Park, a major contributor to South African tourism. Fish telemetry, specifically focusing on Large-scale yellowfish (*Labeobarbus marequensis*) and Purple Labeo (*Labeo congoro*), was employed to monitor the river's lower reaches in real-time.

The study successfully implemented the FISHTRAC program, using algorithms to detect changes in fish behaviour in response to environmental variables. While sample sizes were suboptimal, the individual fish's sensitivity outweighed interspecies variability. The FISTRAC EARLY WARNING SYSTEM effectively alerted stakeholders to deviations in fish behaviour, indicating potential environmental issues.

Labeobarbus marequensis exhibited altered behaviour during flood events and seasonal temperature changes, with a notable impact on activity rates during spawning. *Labeo congoro* also showed changes in behaviour during flood events and temperature fluctuations, highlighting the importance of understanding the ecological indicators for this species. The study emphasized the significance of pH for both species and identified discharge and electrical conductivity as crucial drivers for *Labeobarbus marequensis*, while water temperature played a significant role for *L. congoro*.

The study concludes that the FISHTRAC program, along with the FISTRAC early warning system, effectively monitors fish ecology and provides valuable data for water resource management. The program's real-time monitoring capabilities offer insights into the impacts of multiple stressors, including pollution incidents and natural predation events, on fish behaviour. The integration of FISHTRAC with standard biological methods is recommended for a comprehensive understanding of freshwater ecosystem drivers and effective sustainability management.

ase study two: Assessing the vulnerability of Tigerfish (*Hydrocynus vittatus* castelnau, 1861) to predation in a water-stressed system using telemetry methods.

The study focuses on *Hydrocynus vittatus*, a large migratory alestid, as an indicator species for environmental change in

Table 3: 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 (derived from Burnett et al. 2020). Countries: ZA = South Africa, BW = Botswana, LS = Lesotho

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)	No	2006-2008	O'Brien et al. 2013, Ramesh et al. 2018
				Labeobarbus aeneus (n=13)	No		
2	*Hydrocynus vittatus* relocation, recruitment and predation strategies, Schoda and Letsibogo Man-made Lake, 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, O'Brien et al. 2014a
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)	Yes	2011-2013	Burnett et al. 2018
				Labeobarbus marequensis (n=16)	Yes		
4	A comparative *Labeobarbus aeneus* behavioural ecology between Boskop Man-Made Lake 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 man-made lake 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 man-made lake 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 limitation of different fish behaviour on the working out of techniques.	*Labeobarbus natalensis* (n=53)	Yes	2014-2019	2014 – 2019
				Micropterus salmoides (n=2)	Yes		
				Oreochromis mossambicus (n=2)	Yes		
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, River southern Africa	Okavango Delta, BW	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)	Both	2010	Smith et al. 2009, O'Brien et al. 2013b, Burnett et al. 2018

riverine ecosystems. The species is sensitive to water temperature and oxygen levels, making it valuable for telemetry studies. The research aims to explore the impact of predation on *H. vittatus* populations in the Olifants River, Kruger National Park (KNP), with a focus on anthropogenic influences.

The study successfully employs radio telemetry methods, specifically monitoring activity rates, to assess *H. vittatus* vulnerability to predation and the effects of multiple stressors on the population. The recovery period after tagging is examined, indicating a decrease in activity immediately post-tagging, followed by an exponential increase within two weeks.

The findings reveal that 43% of the monitored *H. vittatus* individuals were preyed upon, primarily by African fish eagles. Predation events were linked to specific environmental conditions, such as lower temperatures during the day. Other potential predators, such as otters and Nile crocodiles, are considered, emphasizing the complex interplay of natural predation in the ecosystem. The study also highlights the impact of low flows resulting from water abstraction and drought, leading to the formation of isolated pools. *Hydrocynus vittatus*, dependent on oxygen, exhibits abnormal behaviour during low flows, making them susceptible to predation. The study suggests that environmental flows and the removal of unused dams could mitigate stress on *H. vittatus* and improve ecosystem resilience.

The research emphasizes the importance of environmental flow management for the conservation of *H. vittatus*. Telemetry studies provide valuable insights into fish behaviour, aiding in understanding responses to environmental stressors. The findings contribute to the broader understanding of freshwater ecosystem dynamics and underscore the significance of conserving *H. vittatus* as a keystone species in South Africa.

Case study three: FISHTRAC Early Warning System in the Kruger National Park and recommendations for continued monitoring in the Olifants River.

The study focuses on the FISHTRAC program as a tool for monitoring ecosystem well-being in South African rivers. Ecosystems in these dynamic rivers face challenges from both natural events and anthropogenic stressors. The lack of adequate monitoring data and limited understanding of biological responses to multiple stressors hinder effective management interventions.

FISHTRAC utilises smart radio telemetry devices, including fish tags and water quality probes, to monitor water quality and fish behaviour in real-time, remotely. The program aims to provide water resource managers with a cost-effective solution to monitor ecological consequences quickly and respond to changes in environmental variables.

The research demonstrates the implementation of FISHTRAC in the Olifants River within Kruger National Park, a protected area facing pollution challenges. The study involves tagging and monitoring four fish species, namely *Hydrocynus vittatus*, *Labeo congoro*, *Labeobarbus marequensis*, and *Oreochromis mossambicus*, to understand their behavioural responses to environmental variables.

Key findings include the identification of factors influencing fish behaviour, such as pH, electrical conductivity, and discharge. The study highlights the potential of FISHTRAC in providing valuable ecological data, understanding the biological responses to stressors, and detecting anomalies in fish behaviour. Additionally, the research explores the impact of predation on tagged fish and emphasizes the importance of considering disturbance from predators in environmental stressor management.

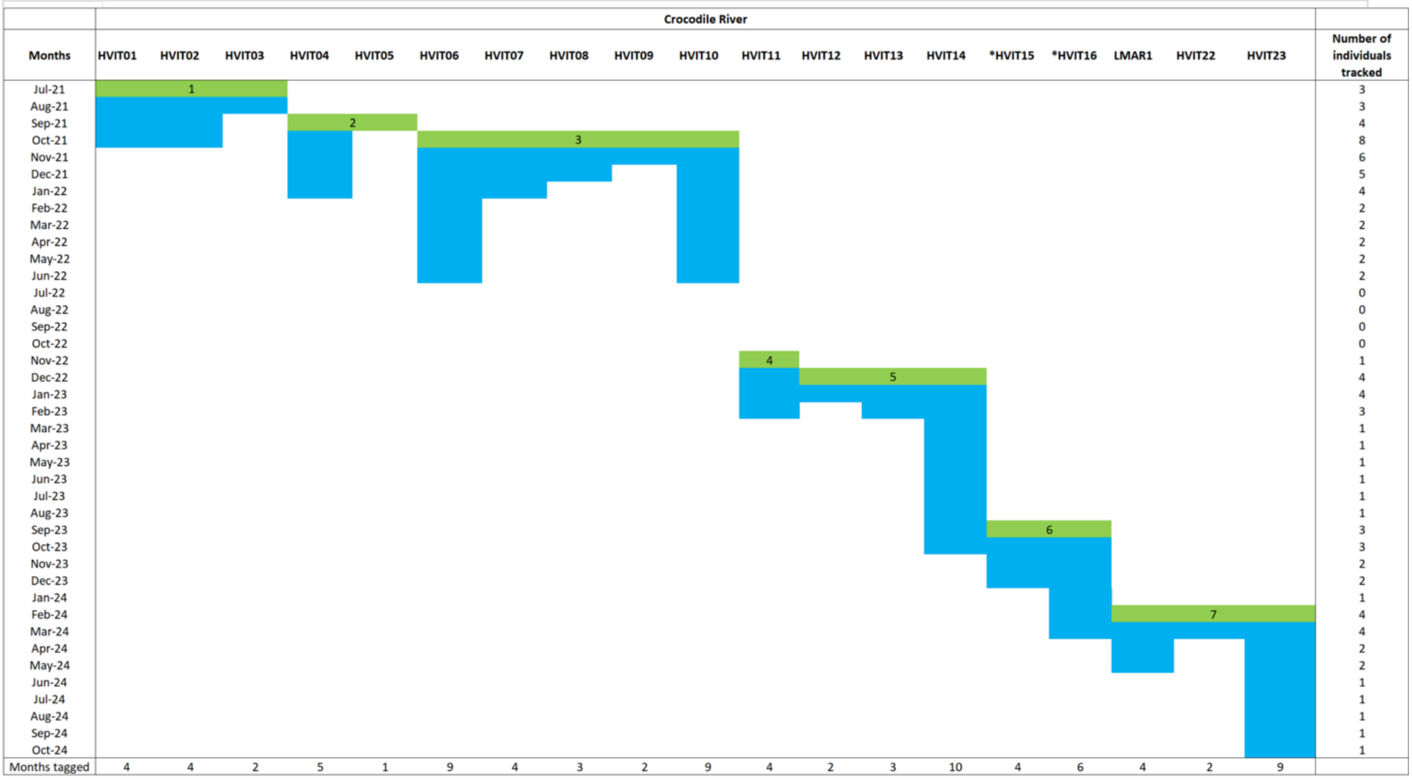
In conclusion, FISHTRAC emerges as a valuable tool for real-time monitoring of multiple stressors in river ecosystems, offering insights into the behavioural ecology of fish and aiding in effective environmental management. The study emphasizes the significance of such programs in improving our understanding of the intricate dynamics within freshwater ecosystems.

Crocodile River case study using Tigerfish

Eighteen suitable Tigerfish and one suitable Largescale yellowfish were successfully captured and tagged on the Crocodile River at Van Graan (Figure 7 and Table 1). The Tigerfish were captured mostly in deep glides (≥ 1m) and shallower runs. The Tigerfish were tagged at seven different events and were monitored over 39 months from July 2021 to October 2024. Five individuals were tagged for over 100 days (Figure 7 and Table 1). There were a few tags that were set to only call in once a day and could not be used for the alert analyses. HVIT03, HVIT05, HVIT09, and HVIT22 did not obtain enough data (fish with less than two weeks of data) to run the alert analyses. Fifteen individuals had sufficient environmental variable data which is critical to understanding the individual's behavioural response (O'Brien et al. 2018).

The environmental variables captured during the study range from 2022/11/25 to 2023/07/01 and December 2023 to October 2024. There are some gaps in the data due to malfunctioning of the probes or the data from the IUCMA that is incomplete. Several events happened during this study such as five flooding events, the probe malfunctioning (2023/01/08 to 2023/01/23), and the water quality probe that was out of the water from 2023/03/03 to 2023/03/05 (Figure 8 and Figure 9). Systems are being established to interpret the ecological consequences of altered flows and other environmental variables at this site.

Hydrocynus vittatus HVIT04 was tagged and monitored for 126 days (Table 1). This individual seems to have moved out of range with the decrease in the discharge observed from 2021/12/08 to 2021/12/22 (Figure 10). The peak in activity rate



	Crocodile River																			
Months	HVIT01	HVIT02	HVIT03	HVIT04	HVIT05	HVIT06	HVIT07	HVIT08	HVIT09	HVIT10	HVIT11	HVIT12	HVIT13	HVIT14	*HVIT15	*HVIT16	LMAR1	HVIT22	HVIT23	Number of individuals tracked
Jul-21	🟩	🟩 1	🟩																	3
Aug-21	🟦	🟦	🟦																	3
Sep-21	🟦	🟦		🟩 2	🟩															4
Oct-21	🟦	🟦		🟦		🟩	🟩	🟩 3	🟩	🟩										8
Nov-21				🟦		🟦	🟦	🟦	🟦	🟦										6
Dec-21				🟦		🟦	🟦	🟦		🟦										5
Jan-22				🟦		🟦	🟦			🟦										4
Feb-22						🟦				🟦										2
Mar-22						🟦				🟦										2
Apr-22						🟦				🟦										2
May-22						🟦				🟦										2
Jun-22						🟦				🟦										2
Jul-22																				0
Aug-22																				0
Sep-22																				0
Oct-22																				0
Nov-22											🟩 4									1
Dec-22											🟦	🟩	🟩 5	🟩						4
Jan-23											🟦	🟦	🟦	🟦						4
Feb-23											🟦		🟦	🟦						3
Mar-23														🟦						1
Apr-23														🟦						1
May-23														🟦						1
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Aug-23														🟦						1
Sep-23														🟦	🟩 6	🟩				3
Oct-23														🟦	🟦	🟦				3
Nov-23															🟦	🟦				2
Dec-23															🟦	🟦				2
Jan-24																🟦				1
Feb-24																🟦	🟩	🟩 7	🟩	4
Mar-24																🟦	🟦	🟦	🟦	4
Apr-24																	🟦		🟦	2
May-24																	🟦		🟦	2
Jun-24																			🟦	1
Jul-24																			🟦	1
Aug-24																			🟦	1
Sep-24																			🟦	1
Oct-24																			🟦	1
Months tagged	4	4	2	5	1	9	4	3	2	9	4	2	3	10	4	6	4	2	9	

Figure 7: A Gantt chart of the seven tagging events(green) and during which months there were tagged tigerfish being monitored (blue). The last column indicates the number of tagged individuals for the month whereas the last row indicates the number of months the individual was tracked for. The Asterix (*) indicates tags that were in sleep mode.

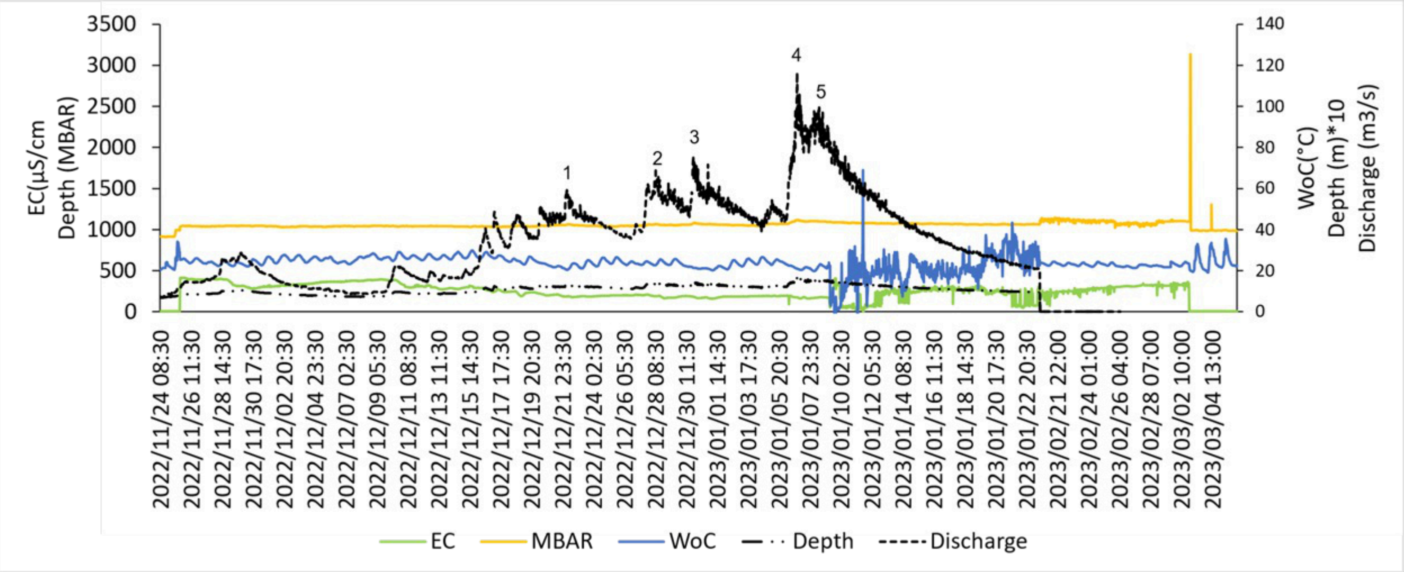


Figure 8: An example of the environmental data recorded in real-time at Van Graan, Crocodile River between 2022/11/24 and 2023/03/04. Electrical Conductivity (green line) (EC) (µS/cm), MBAR (yellow line) is depth measured in pressure, and WoC (blue line) is the temperature (°C) measured by the water probe. The stripped black line is depth (m times 10), and the dotted line is the discharge (m^3/s) taken from the X2H046 Riverside station (IUCMA).

Figure 9: The increase in water level at Van Graan on the Crocodile River during flooding event from November 2022 to February 2023.

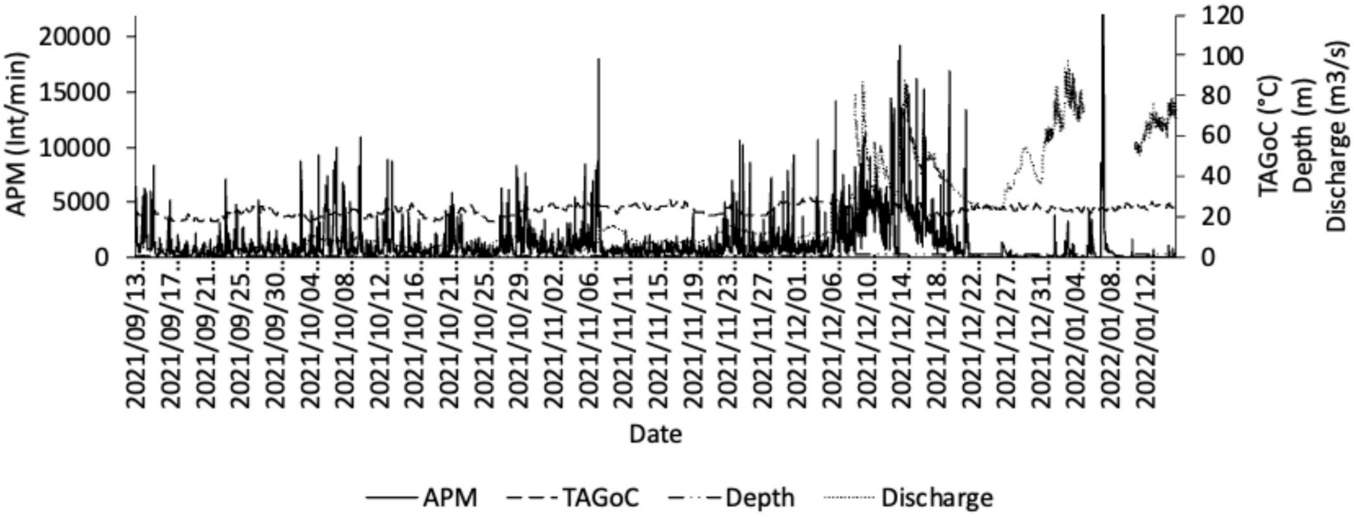


Figure 10: Real-time monitoring of the individual HVIT04 (Hydrocynus vittatus), tagged at Van Graan on the Crocodile River with the environmental variables overlaid. APM (solid black line) stand for activity per minute (int/min), and TAGoC (stripped black line) stands for the temperature (°C) measured by the tag. The black line with strips and two dots is depth (m times 10) and the dotted line is the discharge (m³/s) taken from the X2H046 Riverside station (IUCMA).

has a positive correlation with the peak discharge observed. After this flood there was a spike in activity rate (13297.97 int/min) on 2021/12/22 at 09:00 followed by an activity rate (0.57 int/min) on 2021/12/22 at 15:00. This lowered activity rate seems as if the individual died as its activity rate reduced to almost zero. There was another peak of 34628.97 int/min which indicates that it probably washed down. The management alerts show high alerts during this time frame for decay factors 0.2, 0.5 and 0.8 (Figure 11).

Individuals HVIT11, HVIT12, HVIT13 and HVIT14 were tagged at the beginning of the wet session (November and December 2022). During their tracking time, there were a few flooding events that occurred (Figure 9). Most of the individuals moved out of range during the flooding periods. HVIT14 went out of range but came back after a few weeks and downloaded all the data that was stored on the tag. For demonstration purposes, only HVIT12 management alerts will be shown (Figure 12 and Figure 13).

Hydrocynus vittatus HVIT12 was tagged and monitored for 34 days (Table 1). This individual moved out of range on 2023/01/12 at 21:00. There was an increase in the rate of activity on 2022/12/16 at 11:00 which correlates with an increase in discharge from 18 m^3/s to about 34.2 m^3/s. These behavioural responses triggered high alert responses with decay factors 0.2, 0.5 and 0.8 (Figure 12 and Figure 13). There were two other peaks in the activity rate on 2023/01/03 at 11:00 (APM of 764.06 int/min) and 2023/01/05 at 17:30 (APM of 785.24 int/min) but there is not a noticeable change in the environmental variables to explain this behavioural response. These behavioural responses triggered high alert responses for decay factors 0.2 and 0.8. From 2023/01/09 16:00 the environmental variables (WoC and EC) had extreme changes and were variable. This did not correlate with an increase or decrease in depth, discharge or the fish tag's temperature and could indicate that something happened with the water quality probes. There were no high alerts triggered for decay factors 0.2 and 0.5 during this time. Decay factor 0.8 had a few high alerts. Some of the alerts did correlate with changes in temperature and conductivity.

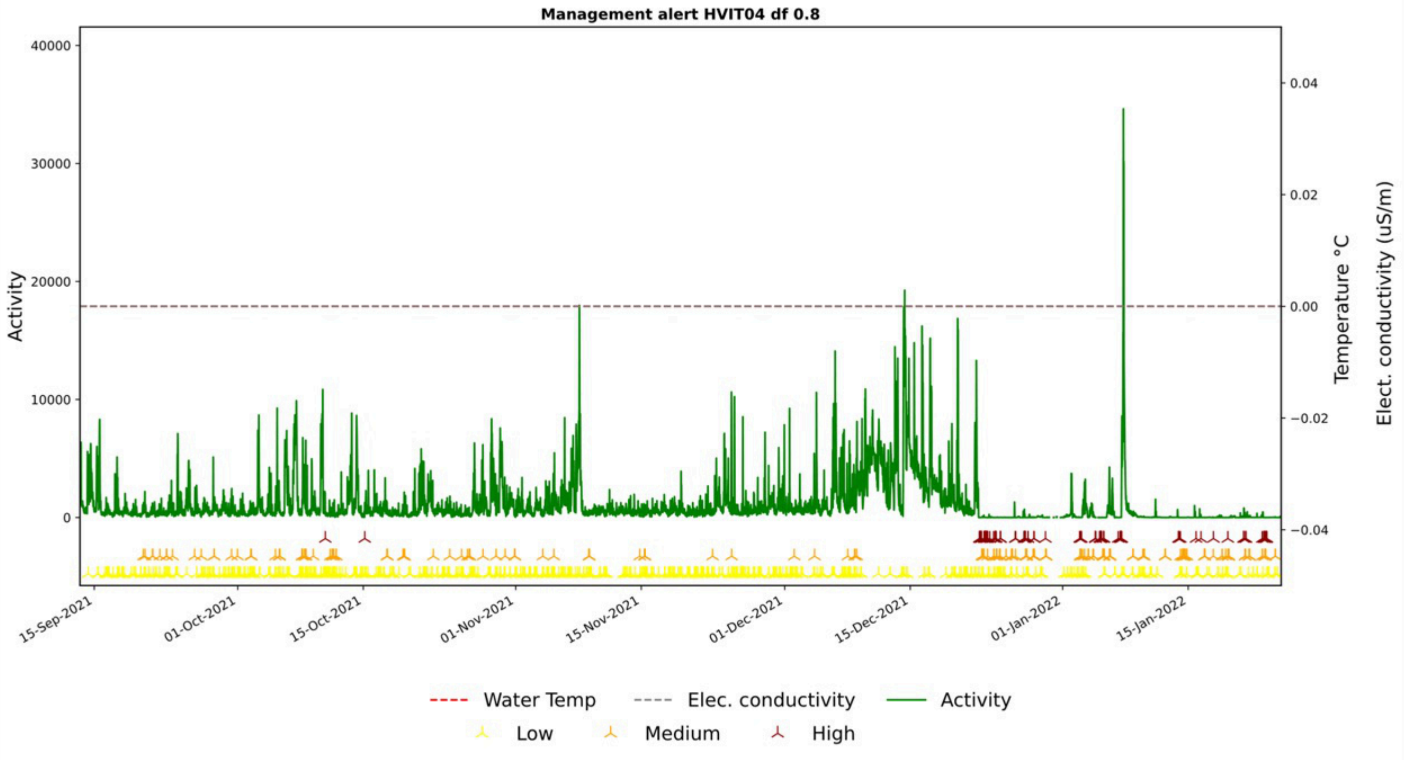


Figure 11: The estimated occurrence of changes in behaviour for individual HVIT04 (Hydrocynus vittatus), tagged at Van Graan on the Crocodile River depicted as "Alerts" using a real-time algorithm. The yellow represents the low management alerts (two extreme category detection), the orange represents the medium management alerts (three extreme category detection), and the red represents the high management alerts (four extreme category detection). The management alerts were calculated with a decay factor of 0.8. These alerts can be compared with water quality variables such as water temperature, and electrical conductivity.

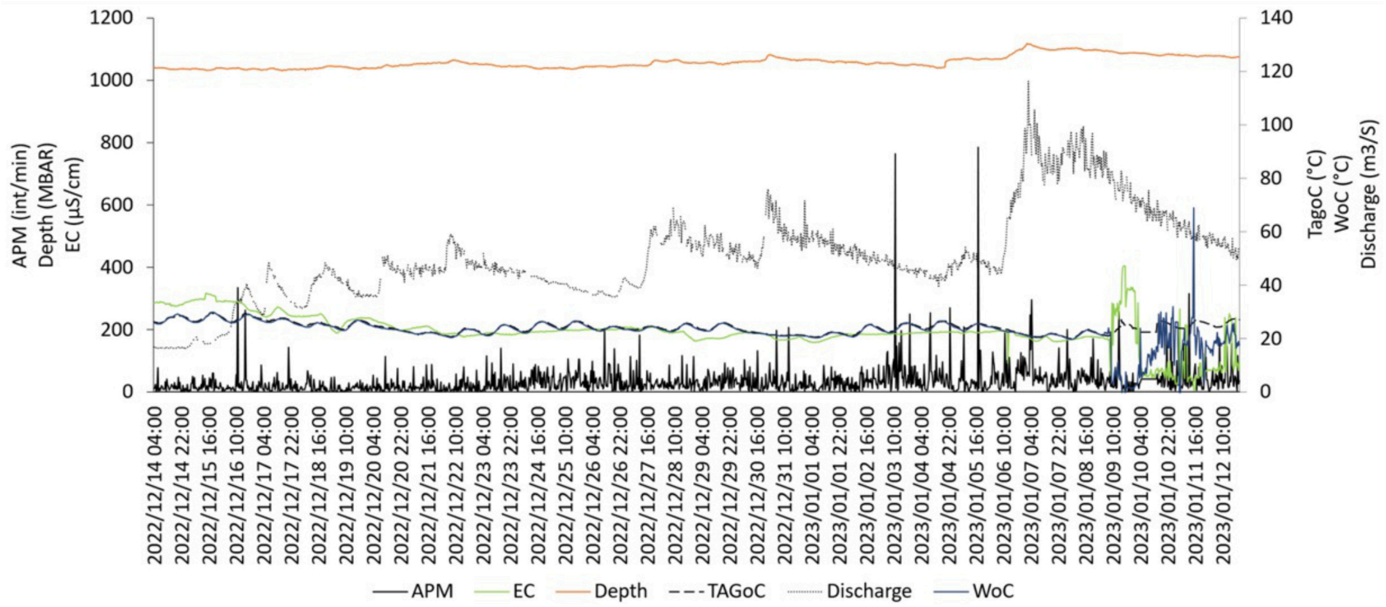


Figure 12: Real-time monitoring of the individual HVIT12 (Hydrocynus vittatus), tagged at Van Graan on the Crocodile River with the environmental variables overlaid. APM (Solid) stand for activity per minute (int/min), EC (green) stand for electrical conductivity (µS/cm), TAGoC (stripped) stands for the temperature (°C) measured by the tag and WoC (blue) stands for temperature measured by the water probe. Depth (orange line) is measured in pressure with the water probe. The black line with strips and two dots is depth (m times 10) and the dotted line is the discharge (m³/s) taken from the X2H046 Riverside station (IUCMA).

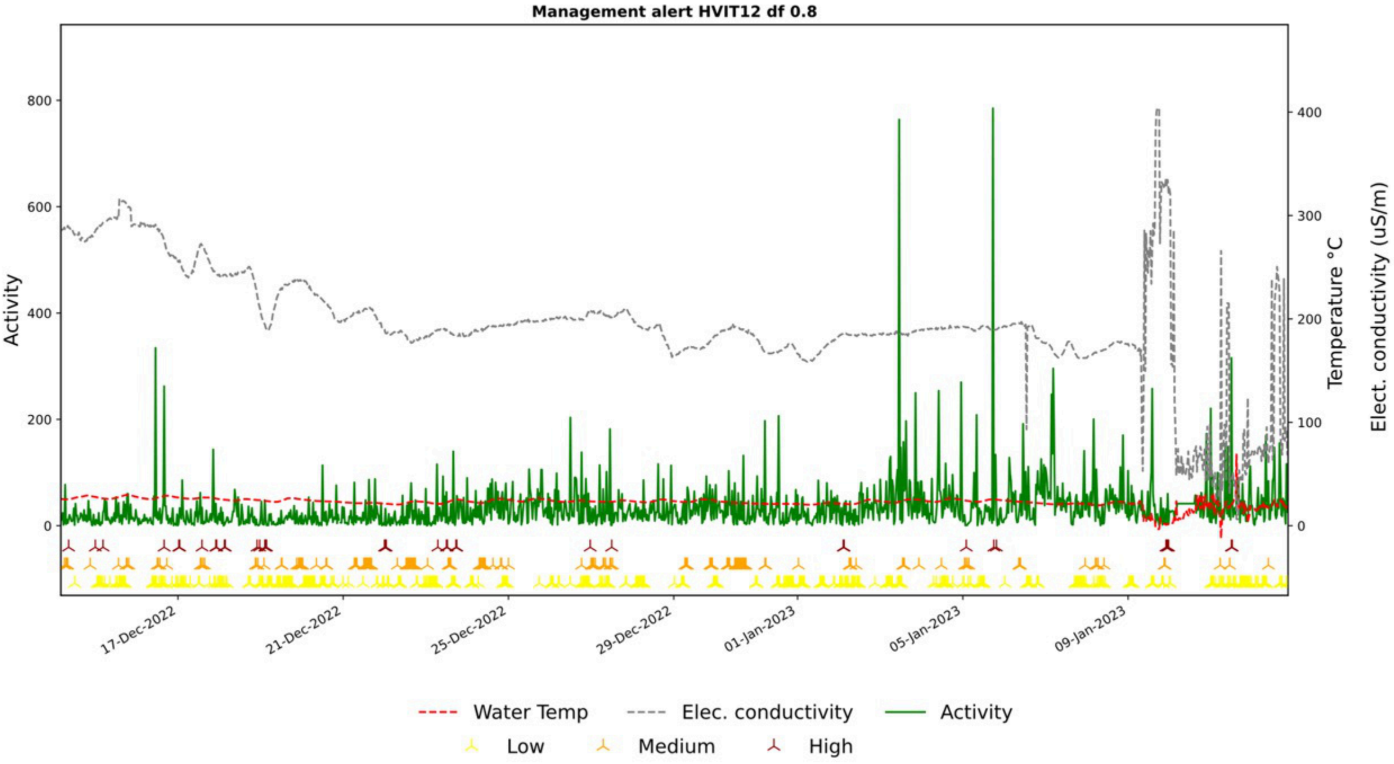


Figure 13: The estimated occurrence of changes in behaviour for individual HVIT12 (Hydrocynus vittatus), tagged at Van Graan on the Crocodile River depicted as "Alerts" using a real-time algorithm. The yellow represents the low management alerts (two extreme category detection), the orange represents the medium management alerts (three extreme category detection), and the red represents the high management alerts (four extreme category detection). The management alerts were calculated with a decay factor of 0.8. These alerts can be compared with water quality variables such as water temperature, and electrical conductivity.

The high management alerts based on the population response with a decay factor of 0.8 only had two individuals that responded at a time. There were more high management alerts between December and January for decay factor 0.8 compared to the other decay factors 0.2 and 0.5 demonstrated (Figure 14; Figure 15 and Figure 16). The management alerts for high alerts with a decay factor of 0.5 only had two individuals that responded and were similar to the responses of decay factor 0.2 for two individuals. The management alerts for high alerts with a decay factor of 0.2 had two events where three individuals responded at a time. Some of the population responses in January 2022 and January 2023 only had two individuals tagged and thus there could have been larger population responses if more individuals were tracked (Table 1).

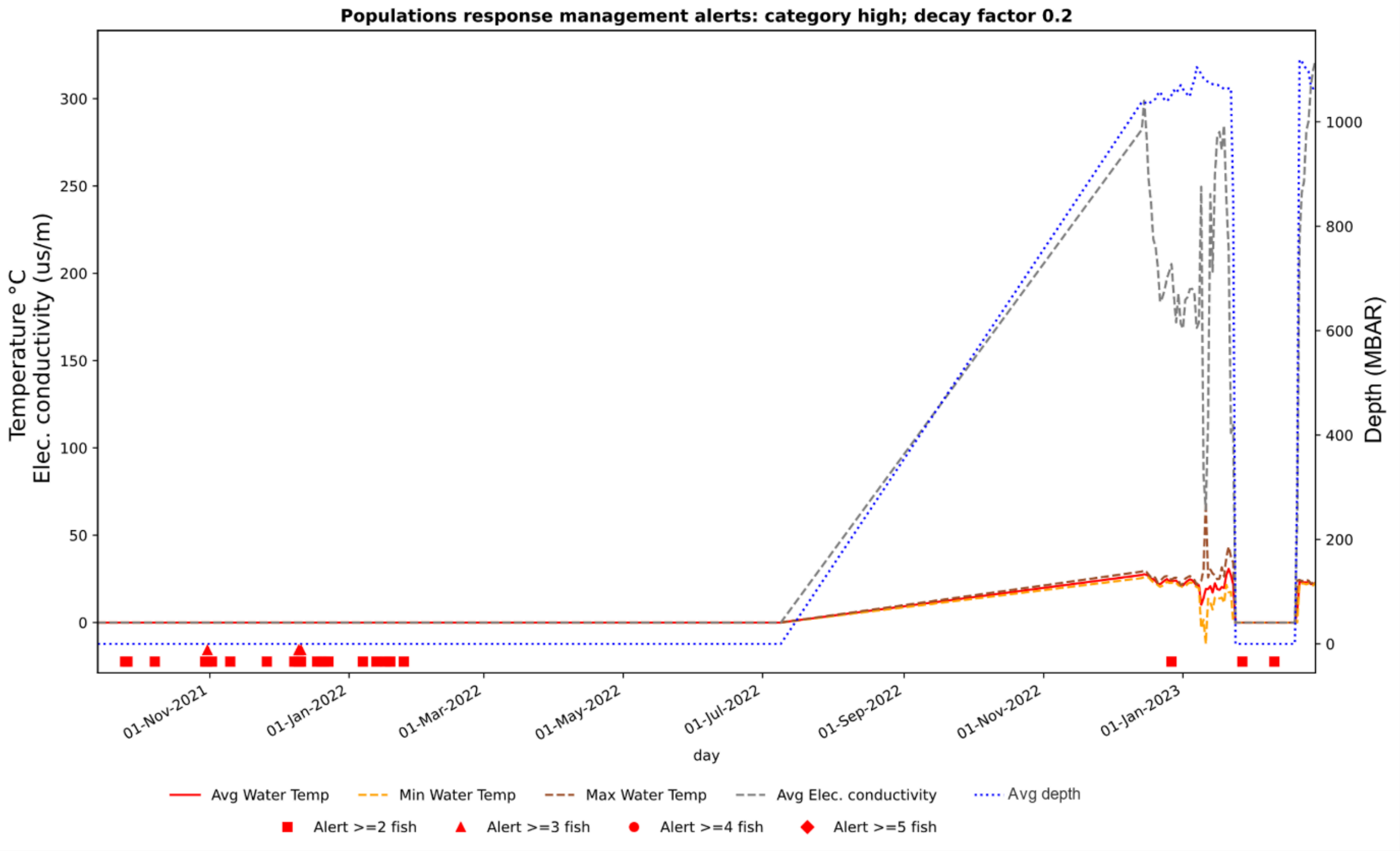


Figure 14: The estimated occurrence of changes in the behaviour of the tigerfish population tagged at Van Graan on the Crocodile River depicted as High management alerts (four extreme category detection) using a real-time algorithm. The red square is indicative of two individuals' behaviour triggered a high alert, the red triangle is indicative of when three individuals' behaviour triggered a high alert, the red circle is indicative of when four individuals' behaviour triggered a high alert, and the diamond is indicative of when five or more individuals' behaviour triggered a high alert. The management alerts were calculated with a decay factor of 0.2. These alerts can be compared with water quality variables such as average water temperature, depth, and electrical conductivity.

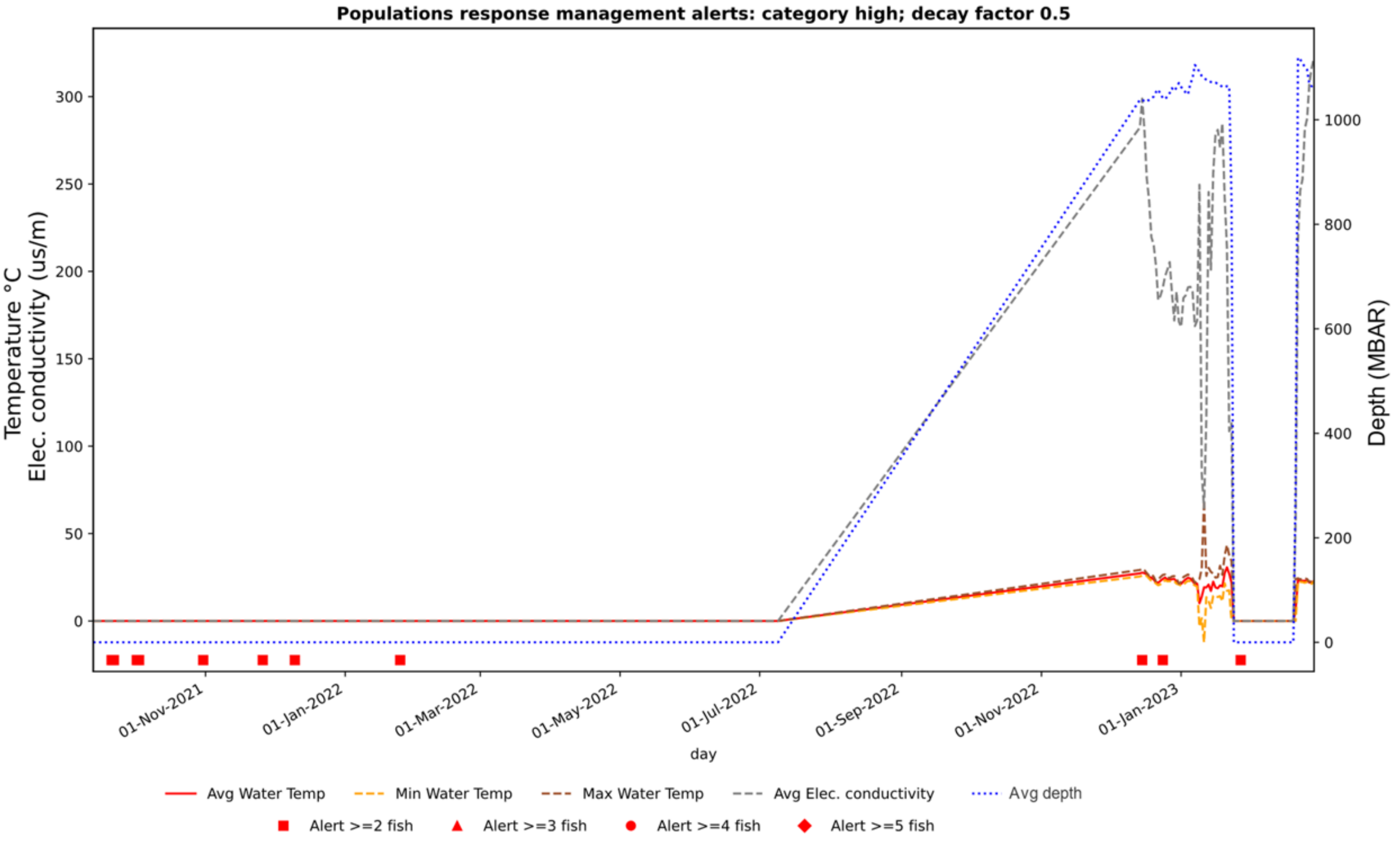


Figure 15: The estimated occurrence of changes in the behaviour of the tigerfish population tagged at Van Graan on the Crocodile River depicted as High management alerts (four extreme category detection) using a real-time algorithm. The red square is indicative of two individuals' behaviour triggered a high alert, the red triangle is indicative of when three individuals' behaviour triggered a high alert, the red circle is indicative of when four individuals' behaviour triggered a high alert, and the diamond is indicative of when five or more individuals' behaviour triggered a high alert. The management alerts were calculated with a decay factor of 0.5. These alerts can be compared with water quality variables such as average water temperature, depth, and electrical conductivity.

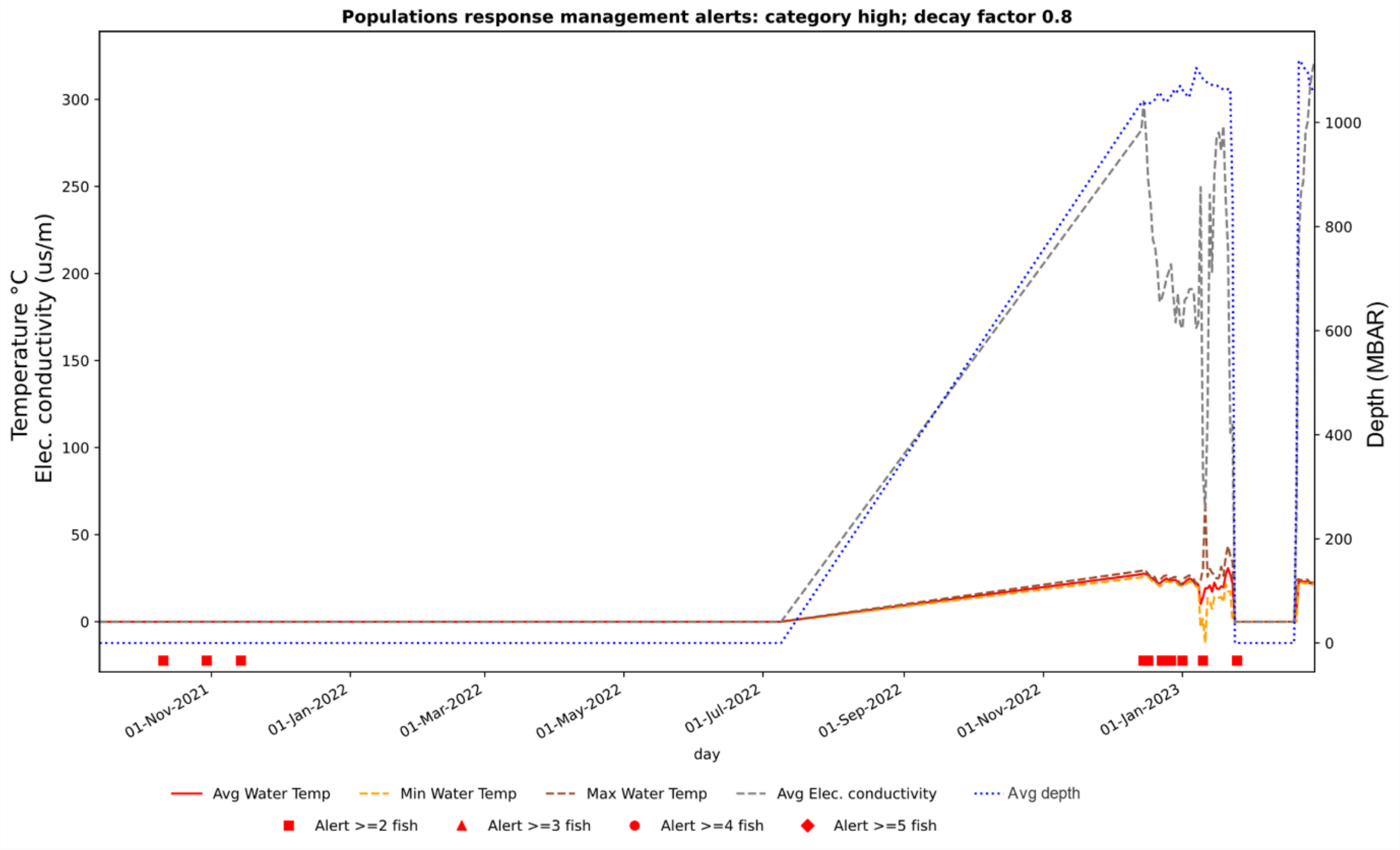


Figure 16: The estimated occurrence of changes in the behaviour of the tigerfish population tagged at Van Graan on the Crocodile River depicted as High management alerts (four extreme category detection) using a real-time algorithm. The red square is indicative of two individuals' behaviour triggered a high alert, the red triangle is indicative of when three individuals' behaviour triggered a high alert, the red circle is indicative of when four individuals' behaviour triggered a high alert, and the diamond is indicative of when five or more individuals' behaviour triggered a high alert. The management alerts were calculated with a decay factor of 0.8. These alerts can be compared with water quality variables such as average water temperature, depth, and electrical conductivity.

All the environmental variables recorded in the study had a Pearson's value of <0.05 and could be used in the GLMs analyses. There was a significant relationship between the activity rate and environmental variables (Table 4). There was a significant relationship between the activity rate and all the environmental variables modelled together. The activity rate increased with an increase in temperature, discharge, and depth but decreased with an increase in electrical conductivity (Figure 17). The relationship between all environmental variables and activity rate was also tested using GAM models. This showed that the relationship between the activity rate and temperature (temperature on the tag) that the range for highest activity for the Tigerfish seem to be between 22°C and 25°C. This emphasises the importances of where water is released from the dams and how it could affect the activity of these key indicator species. The significant relationship with electrical conductivity and fish activity suggests that multiple water quality impacts affect the fish's behaviour (Figure 17).

Table 4: Summary of the generalized linear model (GLM) showing the environmental variables selected for Hydrocynus vittatus.

Selected model	**Estimate**	**Standard error**	**P-value**
Activity + Temperature	2.59	0.84	<0.01
Activity + Electrical conductivity	-0.18	0.06	<0.01
Activity + Discharge	1.76	0.12	<0.01
Activity +Depth	508.36	14.72	<0.01

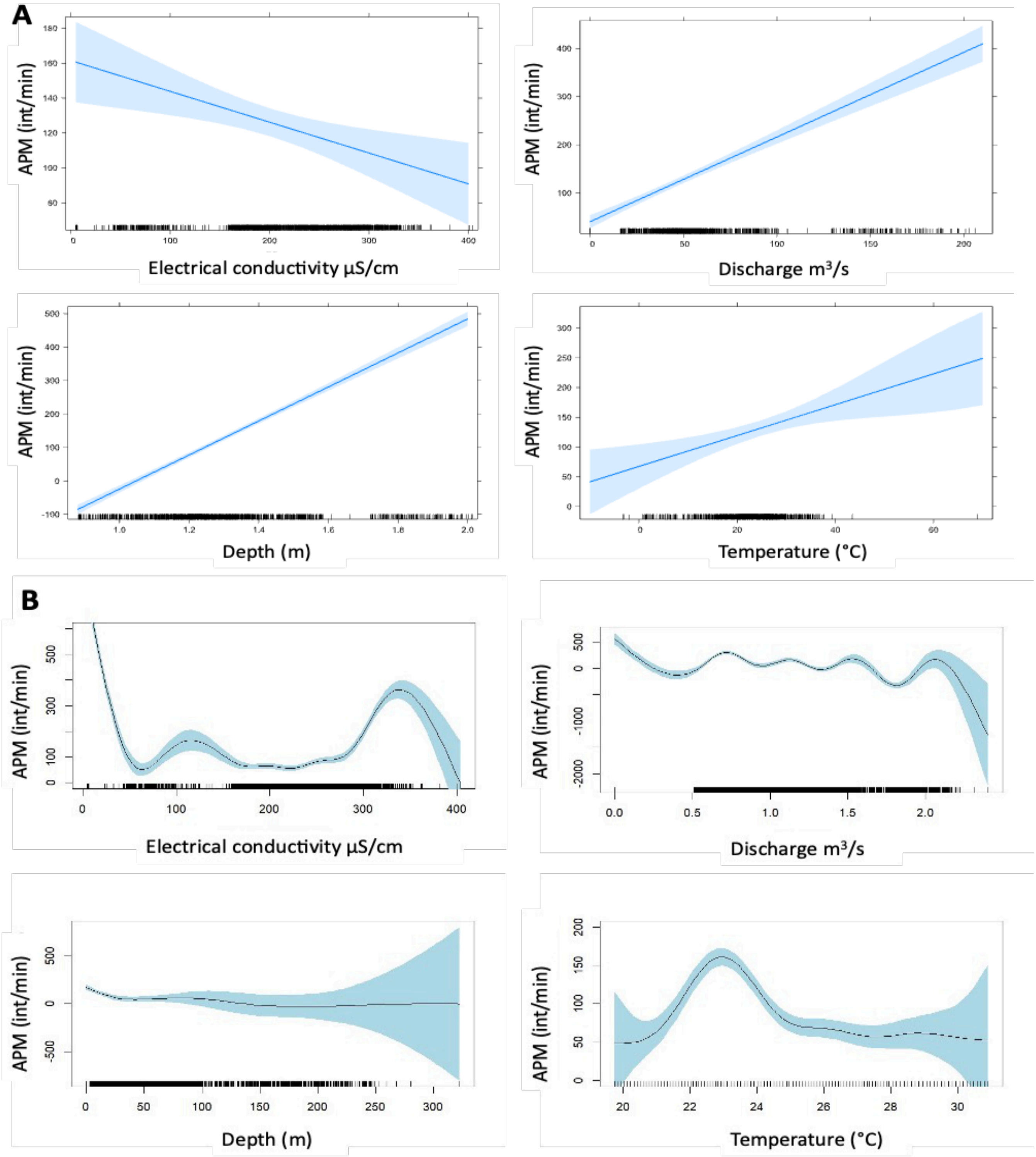


Figure 17: A: The relationship between Hydrocynus vittatus activity rates per minute (APM)(int/min) and environmental variables where electrical conductivity (µS/cm), discharge (m³/s), depth (m) and temperature (°C) all showed significant ($p < 0.01$) trends. B: The Generalized additive models between Hydrocynus vittatus activity rates per minute (APM)(int/min) and environmental variables where electrical conductivity (µS/cm), discharge (m³/s), depth (m) and temperature (°C) all showed significant ($p < 0.01$) trends.

Bayesian Networks are probabilistic modelling networks that graphically represent joint probability distributions over a set of statistical values (Figure 18). They include parent or input nodes and child or conditional nodes with links that represent causal relationships between nodes combined by Conditional Probability Tables (CPTs) (Landis et al. 2017). Conditional Probability Tables describe conditional probabilities between the occurrence of states in the parent nodes and the resulting probabilities of states in the child nodes (Landis et al. 2017). The two PROBFLO case studies presented here made use of the NeticaTM BN software by Norsys Software (http://www.norsys.com/).

In this study the BN established was designed to interpret real-time fish response and associated water quality monitoring data obtained from the FISHTRAC system (). The model uses CPTs that integrate the probable response of the water quality variables into a water quality state and altered flow data with fish response data into a probability of a negative impact state and associated response required by stakeholders.

The nodes incorporated in the study include:

Temperature: in this study, water temperatures have been monitored remotely in real-time and shown to be an important determining factor affecting the well-being of the population of Tigerfish used in the study. In this study water temperatures observed ranged from 14°C to 36°C. Although we were able to determine response curves between fish movement and changes in water quality we used existing Resource Quality Objectives data as thresholds for the BN to represent temperatures for the Crocodile River that are proposed to be a too low (LOW), threshold of potential concern for low temperatures (LTPC), ideal temperature range (Ideal), threshold of potential concern for high temperatures (HTPC) and high temperatures. The ranges used for this BN include:

- LOW State: 0°C - 14°C
- LTPC State: 14°C - 18°C
- IDEAL State: 18°C - 24°C
- HTPC State: 24°C – 28°C
- HIGH State: 28°C - 36 °C

Note that these ranges can be changed, and better thresholds and associated relationships can be used in other case studies.

Electrical Conductivity (EC): similarly, in this study, electrical conductivity represents primarily salt-related water quality constituents that affect the EC of the river. Here Resource Quality Objectives for EC were available and used to query the range of EC observed in the study between 4.8 uS/cm – and 417 uS/cm. Thresholds for the range of states of the EC node representing this part of the ecosystem include:

- NATURAL: 0uS/cm – 350uS/cm
- IDEAL: 350uS/cm – 750uS/cm
- TPC: 750uS/cm – 989uS/cm
- HAZARDOUS: 989uS/cm - 2000uS/cm

Oxygen (O2): Oxygen levels are also a very important water quality variable that has been shown to affect the well-being of fish communities and has been included in the network. This study did not measure oxygen levels. The Resource Quality Objectives were used to guide the selection of thresholds to represent the probable state of the water based on oxygen loads including:

- HAZARDOUS: 0mg/l - 4mg/l
- TPC: 4mg/l -5mg/l
- IDEAL: 5mg/l -6mg/l
- NATURAL: 6mg/l -12mg/l

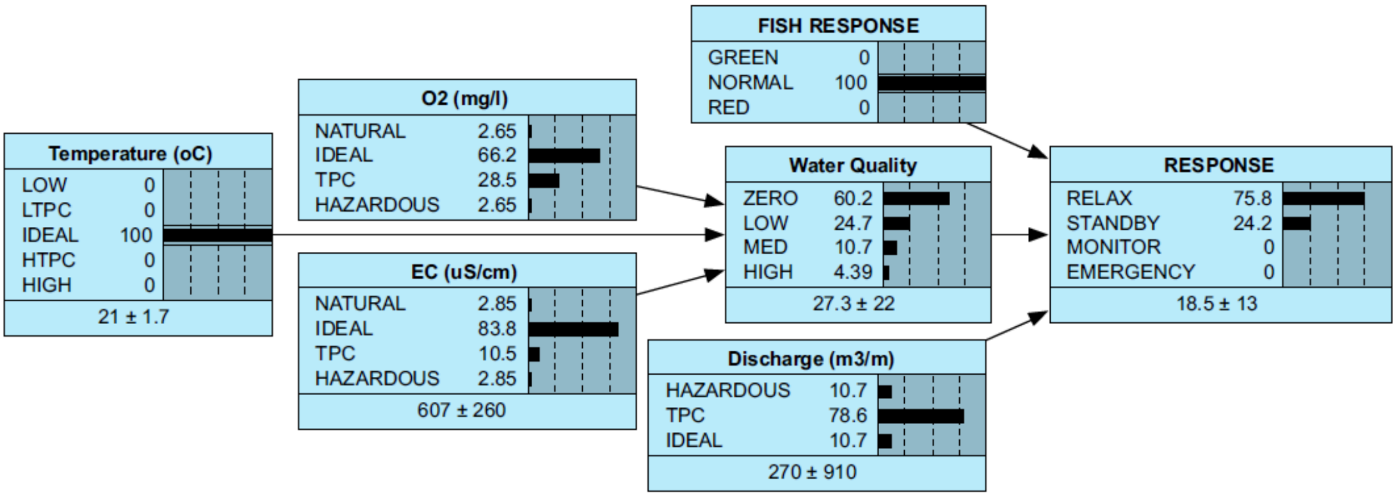


Figure 18: Bayesian Network decision support tool established to evaluate the probability of a need to respond to fish response and associated potential environmental variable condition data monitored in real time in the study.

Discharge (m³/s): flow (measured as discharge in m³/s) in the Crocodile River was also considered in this assessment as an important contributor to the state of the ecosystem. Similarly, Resource Quality Objective requirements for the Crocodile River were considered in this assessment. During this study flows ranging between 7 m³/s to 116 m³/s were observed and using RQO thresholds states were considered in this assessment representing:

- HAZARDOUS: 0m³/s – 1.8m³/s
- TPC: 1.8m³/s -3.8m³/s
- IDEAL: >3.8m³/s

Note that the ranges selected here were used in this demonstration of the FISHTRAC Early Warning System and that thresholds can change based on new data.

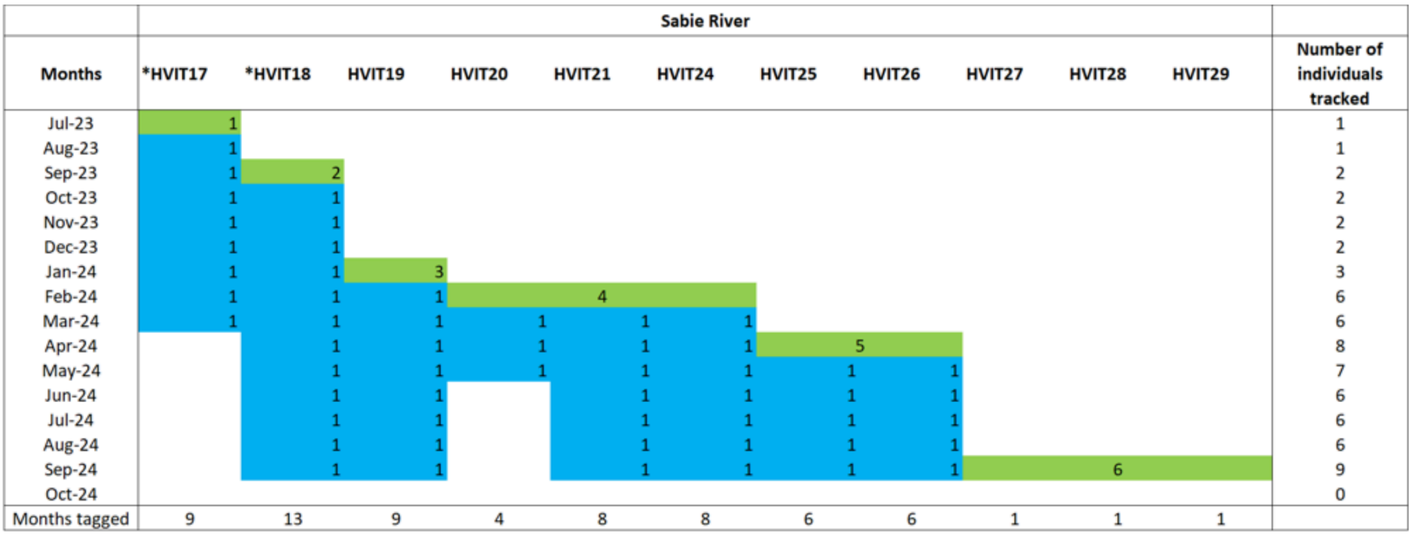
Fish response: The system requires the integration of the fish response data into the FISHTRAC Early Warning System. The outcomes of the study demonstrate that the FISHTRAC approach can identify significant shifts in behaviour including significant increases and decreases in behaviour. Here we identify abnormal increases as red alerts and reduced movement as green alerts. In the BN the three opportunities for fish behaviour (red, normal and or green) have been identified.

Sabie River

Eleven suitable Tigerfish were successfully captured and tagged on the Sabie River at Lower Sabie Weir (Figure 19 and Table 1). The Tigerfish were captured mostly in deep glides (≥ 1m) and shallower runs. The Tigerfish were tagged at seven different events and were monitored over 39 months from July 2021 to October 2024 (Table 1). Five individuals were tagged for over 100 days (Figure 19 and Table 1).

The FISHTRAC system on the Sabie River has been initiated with base stations and relay stations to provide an initial network (Figure 5). A total of four stations have been set up in the field (two Base station and two relay stations). The locations were chosen to look at the functionality of the Fishway and Fish Passage on the Sabie River. There are a total of six fish tagged in the Sabie River (Table 1) with abiotic probes collecting the environmental data (Figure 20) .

For demonstration purposes similar to graphs shown for the Crocodile River Figure 21 is the activity per minute and environmental variables recorded for HVIT24. This fish has been tagged for 29 days for the data represented below. The tag temperature and water quality temperature are very similar suggesting that this individual is located in the same area as the water quality (above the weir).



	Sabie River											
Months	*HVIT17	*HVIT18	HVIT19	HVIT20	HVIT21	HVIT24	HVIT25	HVIT26	HVIT27	HVIT28	HVIT29	Number of individuals tracked
Jul-23	1											1
Aug-23	1											1
Sep-23	1	2										2
Oct-23	1	1										2
Nov-23	1	1										2
Dec-23	1	1										2
Jan-24	1	1	3									3
Feb-24	1	1	1	4								6
Mar-24	1	1	1	1	1	1						6
Apr-24		1	1	1	1	1	5					8
May-24		1	1	1	1	1	1	1				7
Jun-24		1	1		1	1	1	1				6
Jul-24		1	1		1	1	1	1				6
Aug-24		1	1		1	1	1	1				6
Sep-24		1	1		1	1	1	1	6			9
Oct-24												0
Months tagged	9	13	9	4	8	8	6	6	1	1	1	

Figure 19: A Gantt chart of the six tagging events(green) and during which months there were tagged tigerfish being monitored (blue). The last column indicates the number of tagged individuals for the month whereas the last row indicates the number of months the individual was tracked for. The Asterix (*) indicates tags that were in sleep mode.

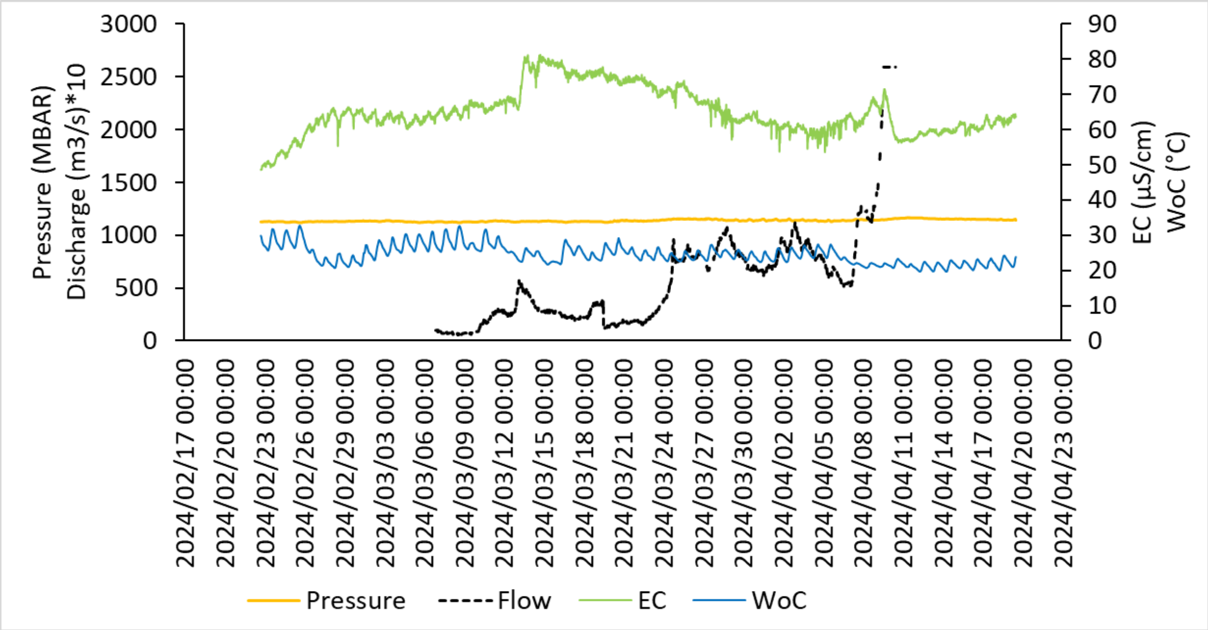


Figure 20: The environmental data available recorded in real-time at Lower Sabie Weir, Sabie River. Electrical Conductivity (green line) (EC) (µS/cm), MBAR (yellow line) is depth measured in pressure, and WoC (blue line) is the temperature (°C) measured by the water probe.

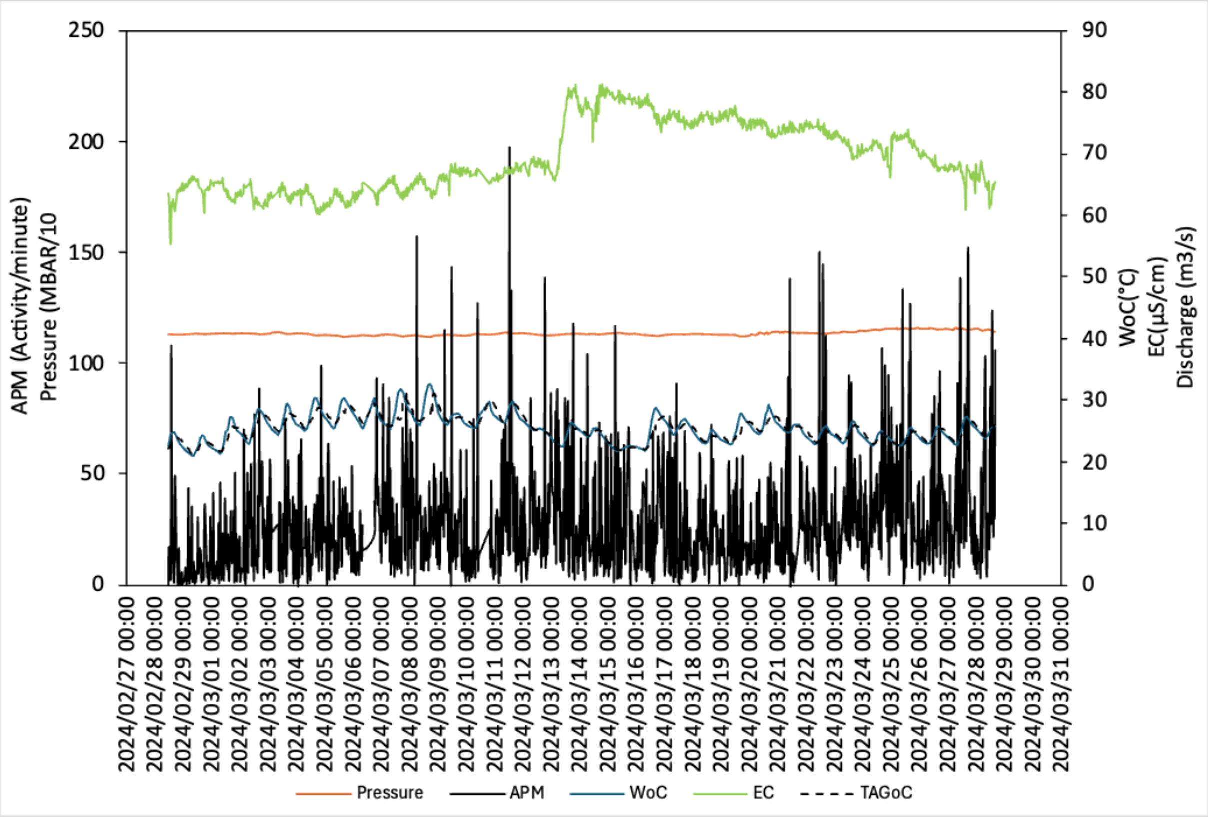


Figure 21: Real-time monitoring of the individual HVIT24 (Hydrocynus vittatus), tagged at Lower Sabie Weir on the Sabie River with the environmental variables overlaid. APM (Solid) stand for activity per minute (int/min), EC (green) stand for electrical conductivity (µS/cm), TAGoC (stripped) stands for the temperature (°C) measured by the tag and WoC (blue) stands for temperature measured by the water probe. Depth (orange line) is measured in pressure with the water probe.

DISCUSSION

Fish telemetered studies, like this one, have a valuable contribution towards the management of freshwater ecosystems (Burnett et al. 2020). The behavioural responses of fish are shown to be 10-100 times more sensitive to environmental stressors than any other established line of evidence (Gerhardt 2007). The real-time remote monitoring application was successfully implemented, with a sample size of 29 Tigerfish (*Hydrocynus vittatus*) and 1 Yellowfish (*Labeobarbus marequensis*) tracked over 40 months. The environmental variables amount of data such as temperature, depth and electrical conductivity were below optimum per individual and the suggestion going forward is to ensure there is a working abiotic probe that can record the environmental variables. Wireless Wildlife have improved the water quality probes and the durability will be tested over time. The deployment of more than one abiotic probe per site is recommended. This environmental data is important to understand the fish behaviour changes based on changes in the environmental variables (O'Brien et al. 2018). This study included the behavioural responses of Tigerfish (June 2021 to October 2024). From June 2022 to October 2022 there were no Tigerfish tracked as all the individuals tagged had either moved out of range or died. It is recommended to increase the sample sizes or space out the tagging events to ensure that there are fish tracked at all times. It is also recommended to tag fish in the dry season or at the beginning of the wet season when the river systems are stable to ensure a higher survival rate and a longer tracking time.

The study demonstrated that individual fish have different basal activity rates and that they respond differently to the same environmental event. For example, the basal activity rate of individual HVIT 11 was lower than most of the other tagged individuals. This demonstrates the intraspecies sensitivity, similar to what Sonamzi (2020) found with *Labeo congoro*. This should be taken into consideration in the development and application of the FISHTRAC program. Fish that died or moved out of range during the study had a spike in the activity rate followed by a very low activity rate or stopped recording the activity rate for that individual. This could be attributed to the flooding events that possibly caused the fish to move downstream out of range (Jacobs et al. 2019). The DMS is in development to indicate what relay or base stations downloaded the data. This would provide the information needed to understand if the fish moved upstream over the weir at Van Graan or moved downstream and could not return to their home range for example. There were a few perceived predation events with a spike in the activity rate followed by a zero-activity rate. In this case, the temperature range did not change suggesting that the tag remained in the water after the predation event. Fish eagles (Haliaeetus vocifer) otters (Lutrinae family) and Nile crocodiles (Crocodylus niloticus) are possible predators that are known to feed on Tigerfish (Sonamzi et al. 2020). The predation event was probably not caused by Fish eagles as there was no change in the temperature from freshwater to terrestrial environments (Sonamzi et al. 2020). Alternatively, the tags could have been dislodged after the burst of activity observed.

This study has demonstrated that the algorithm works to detect and generate alerts based on the activity rate per individual and population (if there are more than two individuals that respond to the same event) (Burnett et al. 2024). The FISHTRAC Early Warning System can adequately inform stakeholders of when there are breaches in the normal activity of fish and they can respond by sending managers to investigate what is the cause in the field (Burnett et al. 2020). Alerts generated by the FISHTRAC Early Warning System for all individuals were often aligned with notable changes in environmental variables and sometimes showed population responses. The changes in environmental variables were most notable in water temperature and discharge, with electrical conductivity and depth remaining consistent throughout the study. As the flood events took place, the concentrations of the water variables changed, which is expected, as flow is highly correlated to changes in water quality (Gunaratne et al. 2017, Zuraini et al. 2018). Tigerfish had an increased response in activity rate during flooding events compared to a decreased activity rate with *L. marequensis* and *L. congoro* (Burnett et al. 2018). This could indicate that Tigerfish use floods as ques as these species are large migratory species that make extensive use of river reaches (Jacobs et al. 2019, Roux et al. 2018). Further investigation is necessary, but it does demonstrate that flooding events influence the behaviour of fish. The cause of the alerts being natural (for example feeding) or anthropogenic (for example changes in water quality) is limited by the lack of environmental data.

The relationships between the environmental variables and the activity rates of tagged fish correlated with what was seen by the alerts. The GLMs and GAMs indicated that there was a significant relationship between the activity rate and all environmental variables tested. The activity rate of Tigerfish increased with an increase in temperature, discharge, and depth but decreased with an increase in electrical conductivity. The GAMs demonstrated that the relationship between the activity rate and temperature (temperature on the tag) that the range for highest activity for the Tigerfish seem to be between 22°C and 25°C. This emphasises the importances of water management especially releases from dams and how it could affect the activity of these key indicator species. The significant relationship with electrical conductivity and fish activity suggests that multiple water quality impacts affect the fish's behaviour. Alerts that were shown during periods where environmental changes took place indicate that other variables could be at play that through the FISHTRAC Early Warning System could direct water resource managers and researchers to find out why there are these changes. As little information for the timing and conditions required for certain biological functioning exists, these alerts could point towards these important biological processes, and investigation of water quality variables during these alerts would prove valuable in understanding the condition required to facilitate these biological functions and improve ecosystem resilience.

Discharge is an important driver in the system (Arthington and Balcombe 2011), and the excessive change in flows (as seen in this study, 7 m^3/s to 161 m^3/s) can be disruptive to the activity rates of fish. Maintaining higher baseflows or meeting the environmental flow can mitigate the change in these flows and improve ecosystem well-being and the resilience of species to cope with these changes. It is important to understand the relationship and threshold of other water quality variables like temperature and the response of fish species. The FISHTRAC program is a means for various stakeholders to continually monitor the synergistic effects of multiple stressors emanating from upstream water polluters such as mines, agriculture, water treatment plants, factories and other industries on the behaviour of fish. Monitoring of fish in real-time, along with the FISHTRAC Early Warning System, will enable rapid action to be taken at the time of the pollution incident. Such incidents may include rapid changes in water quality and quantity variables that are used as indicators of potential concern, as well as natural predation events. Such incidents result in the disruption of activity rates of fish outside the expected range and that are not ecologically and biologically related. The growing use of FISHTRAC in South Africa presents an opportunity to explore the much-needed ecological and biological data to improve the management of water resources, including fisheries (Burnett et al. 2020, O'Brien et al. 2018). This study has gained knowledge on the ecology of Tigerfish, but simultaneous monitoring of other species can provide a holistic approach to using fish as ecological indicators.

The FISHTRAC program has been applied successfully in the current study to test its real-time monitoring aspect. Using this tool, fine-scale activity rates for Tigerfish individuals were detected from the natural environment of the fish without the need for recapture, allowing remote monitoring. Through the analysis of activity rates recorded in real-time, predation of several tagged individuals was successfully determined as a cause of death. The FISHTRAC Early Warning System could detect mortality through predation or environmental stress, and this is an important consideration, as in the study of Sonamazi et al. 2020, the environmental stress related to extended "no flow" periods saw the predation of tigerfish by fish eagles elevated above normal conditions (Sonamazi et al. 2020).

CONCLUSION

River flows and management of stressors in river catchments are important for the future sustainability of water resources especially as growing populations will impose greater demands on available freshwater and associated ecosystem services. Environmental flows are critical to promoting sustainable development, tackling poverty reduction, and sharing benefits, but inefficient water resource management alters flows and reduces downstream ecosystem services, which are vital to the livelihoods of many communities. A better understanding of the e-flow requirements of the rivers in the basin is necessary to achieve a sustainable balance between the use and protection of these water resources.

The FISHTRAC tool has been established to monitor fish in real time remotely and to then use the knowledge of how fish respond to changes in the condition of water resources to stakeholders. This information provides stakeholders with information of the condition of the river that the fish live in in real time, using fish as ecological indicators. To evaluate the ecological impact of multiple stressors, understanding the 'normal' behaviour of fishes as a baseline is crucial. From this baseline, 'abnormal' behaviour can be utilised to identify the stressor. While there are various metrics and indices to measure and monitor the ecological response to stressors, they often involve invasive, time-consuming, and resource-intensive methods that cannot provide real-time and remote ecological responses. Utilising fish behaviour to alert managers to changes in the condition of ecosystems allows for subsequent assessments using more sensitive methods, such as biomarkers, fish health and community indices which are similarly exposed to the same stressors as the fish.

Changes in fish behaviour, whether sudden or chronic, can guide managers to the presence of pollutants that may otherwise go undetected or persist within the aquatic ecosystem due to the infrequent testing of such variables. The FISHTRAC program employs fish telemetry methods to monitor these behavioural changes, and through continuous monitoring of known stressors and fish behaviour, it can identify chronic and event-based stressors for further investigation. The FISHTRAC program continuously updates baseline and response data, making it an ongoing, real-time, and adaptable approach. Integration into existing real-time water quantity and ecological monitoring programs, such as those by Pollard et al. (2012) and Agboola et al. (2019), allows for the adoption of the FISHTRAC program to better achieve nationally set objectives. Alternatively, the FISHTRAC program can be employed as a Line of Evidence (LOE) when establishing ecological reserves and can contribute to an adaptive relative risk model.

Considering the numerous stressor impacts, such as flow reductions, augmentation through water schemes, wastewater treatment works (WWTW), and discharges from the large mining sector in southern Africa, fish are continually exposed to these stressors, leading to changes in their behaviour. The FISHTRAC program can remotely and in real-time detect and evaluate these movements and responses, providing managers with evidence-based data to inform the decision-making process. Its applicability extends across freshwater ecosystems in the region and globally.

The FISHTRAC program contributes to the expanding body of work showcasing the remote capabilities of radio telemetry methods for real-time monitoring of fish behaviour and water quality issues. The cost of the telemetry equipment is reduced with the equipment being manufactured in South Africa. The Data Management System (DMS), which stores, presents, and evaluates data for alerts regarding breaches in Total Permissible Catch (TPC), enables remote and rapid access to information. This facilitates prompt action to mitigate pollution events or disruptive behavioural changes. The successful development and implementation of FISHTRAC, as highlighted through the eight case studies, demonstrate how radio-telemetry methods can effectively address critical management questions in southern Africa. This is particularly pertinent for freshwater ecosystems facing pressures from anthropogenic land use and climate change.

The implementation of the FISHTRAC program to monitor the ecological response of Tigerfish was successfully conducted. The use of the FISHTRAC Early Warning System to monitor changes in activity rates of fish did show to positively co-relate to changes in environmental conditions. This is important in developing a way forward when managing multiple stressors and using free-swimming fish response to determine ecosystem well-being. The impact that these multiple stressors have on the ecosystem's well-being shows that through the "status quo" regarding management, they are still increasingly being placed under stress. Using the FISHTRAC program alongside standard biological methods is strongly suggested, as the integration of these techniques can further answer important questions about what the drivers of the freshwater ecosystem are and how these can be managed to adequately achieve sustainability by improving ecosystem resilience. The FISHTRAC program can alert stakeholders to key events that need to be taken note of by responding through additional water quality sampling or biological investigation and research.

The FISHTRAC Web application is designed to present data in a format conducive to both client and scientific understanding. This sophisticated platform incorporates a range of features, including an innovative Fish Alerts system. This advanced functionality employs predictive analytics to anticipate fish activity, notifying managers in the event of substantial changes.

For FISHTRAC results to be of value, an understanding of 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 (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 routinely (O'Brien et al. 2018).

These probes need to be fully submerged at depths of 0.2 to 3 m to avoid signal loss and remain submerged through variable flows (Jiang and Georgakopoulos 2011). Additional snapshot or grab sampling, hydraulic analyses (habitat modelling) and remote sensing (unmanned aerial vehicles (UAV) and satellite imagery) approaches should be used to characterise environmental variable conditions around the probe (O'Brien et al. 2018). Water quality variables can be readily measured within this framework.

Further developments include the addition of variables such as metals, organics and nutrients and new sensors can be fitted to the probes for real-time monitoring (Mercante et al. 2017, Belikova et al. 2019). 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, Roger and White 2007, Ramesh et al. 2018). Basic data analyses can be derived from 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 its response to changes over time (O'Brien et al. 2012, 2013b, Jacobs et al. 2016, Burnett et al. 2018). These alerts can be deployed into the Digital Twin in real-time, allowing the alerts to be integrated with other management parameters in a platform where managers can respond to the alerts in an informed way.

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ANNEXURE

Annexure 1: Stakeholder access to FISHTRAC Data online.

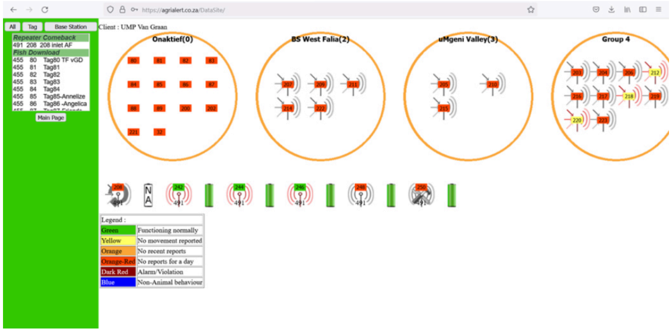
Initial demonstration of real-time remote access to the tagged and tracked fish and abiotic probes established in the Crocodile, Sabie and Olifants Rivers for stakeholders of the study. This online portal will be used and developed to contribute to the real-time remote monitoring and evaluation of the behavioural response of tagged fish to flows and water quality drivers. This approach and outcomes will be aligned to established environmental flow to automatically report on:

1. Monthly discharge and associated flow variability relative to the minimum e-flow and proposed flow variability.
    a. This includes volume (discharge measured in m^3/s) observed monthly (initially monthly but this will increase as and when the need arises) and the variability of volume over the month.
    b. Variability of flow event (if an event such as a freshet or flood occurred during the month) and the requirements to ensure that event durations are met. Here any rapid changes in flows (like hydropeaking events) will be assessed.
    c. Seasonal timing of events related to e-flow requirements.
    d. Frequency of events associated with e-flow requirements in the context of the number of events observed prior to the evaluation month.
2. Report on the behaviour of tagged fish during the evaluation month including baseline movement characteristics and abnormalities associated with seasonal ecological/biological process that are expected and abnormal behavioural responses potentially aligned to altered flows and or water quality changes.
3. Possible alignment between fish responses (significant increased, decreases and or changes in behaviour) and flow or water quality variability. This is where the FISHTRAC approach to monitor and contribute to the implementation of e-flows is possible and important.

The service provider who provides online access to the FISHTRAC system is Agrialert Pty. Ltd. (www.agrialetr.co.za). The website provides a review of the services Agrialert provides and for special reference to the FISHTRAC programme consider www.wirelesswilflife.co.za (also Agrialet website) and www.riversoflife.co.za.

Through www.agrialert.co.za stakeholders can access the data online in real-time (fish/abiotic probes and stations report in every 15 minutes) to view the raw data. This demonstration includes:

- Login landing page for a FISHTRAC study including summary of tags (circles) and base and relay receiver stations for the FISHTRAC programme. This example includes all existing tags used thought the region with the three tags (abiotic probes and fish tagged at Van Graan) included in group 4 (Figure 22).



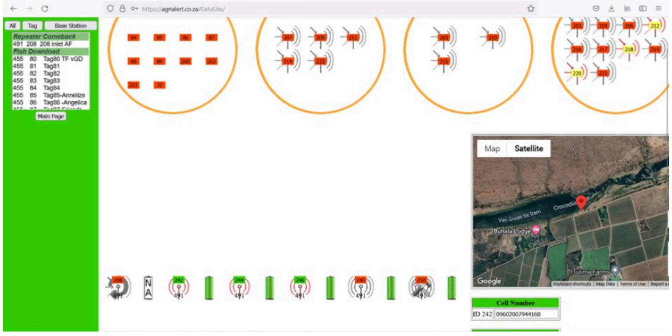
Client : UMP Van Graan

Repeater Comeback
491 208 208 inlet AF
Fish Download
455 80 Tag80 TF vGD
455 81 Tag81
455 82 Tag82
455 83 Tag83
455 84 Tag84
455 85 Tag85-Annelize
455 86 Tag86 -Angelica

Legend :	
Green	Functioning normally
Yellow	No movement reported
Orange	No recent reports
Orange-Red	No reports for a day
Dark Red	Alarm/Violation
Blue	Non-Animal behaviour

Figure 22: Login landing page for a FISHTRAC study including summary of tags (circles) and base and relay receiver stations for the FISHTRAC programme. This example includes all existing tags used thought the region with the three tags (abiotic probes and fish tagged at Van Graan) included in group 4.

- Screenshot of the access to station location information by clicking on station number. Note station colour "green" represents charged operational station. Notice station 250 is under repairs which is indicated with repair symbol (Figure 23).
- Screenshot of how to access data from tags including behavioural data from tagged fish and abiotic probes. Once selected you can choose the data to present, query the period and either download or view the data (Figure 23).



ID 242 09602007944160

Figure 23: Screenshot of the access to station location information by clicking on station number. Note station colour "green" represents charged operational station. Notice station 250 is under repairs which is indicated with repair symbol.

ANNEXURE 2: FISHTRAC WEB APPLICATION

The FISHTRAC dashboard, although thoroughly planned out, still requires consistent development and improvements, as the capability of the application grows, to meet the ever-developing needs of customers and scientists alike. That aside the application has steamrolled its development and achieved great feats considering the time allocated to its development. It stands as a potential integration of simplicity within scientific procedures.

Setup instructions

Prerequisites

Before setting up the project, ensure that the following prerequisites are installed:

1. Docker – Guide HERE

2.Docker-Composer – Guide HERE

Setup

1. Git clone

```
git clone -b Release-0.0.3 git@github.com:PineApple-Logic/FISHTRAC-IN.git
```

2. Build docker image

```
docker-compose up --build
```

3. Run the docker image

```
docker-compose up -d
```

Structure

The application source code can be viewed using its GitHub repository however due to security reasons access is limited to a few people. The structure of the code consists of a few layers, the first layer is the dockerfiles and app directory, within the second layer (inside the app directory) is the application layer, where the main files are found, in the last layer (Modules directory) are all the scripts and classes, this is where the backend and front-end code resides.

Tree Structure

```
app
   |__ .streamlit
       |__config.toml
   |__Models
       |__ Database
           |__ database_connection.py
           |__ MySQL.py
        |__ EWMA
            |__ alarm_definition.py
            |__ calculations.py
            |__ EWMA.py
       |__ Hydro
           |__ Calculator.py
           |__ depth.py
           |__ discharge.py
           |__ tables.py
        |__Webapp
            |__ .streamlit
                 |__ config.toml
             |__ development
                  |__ alerts.py
             |__ style
                  |__ home.css
                  |__ style.css
       |__Data.py
       |__Home.py
       |__Location.py
   |__Wireless_Wildlife
       |__ data_weangler.py
   |__Fishtrac.py
   |__main_realtime.py
   |__ requirements.txt
docker-compose.yaml
Dockerfile
README.md
supervisord.conf
```

Challenges

Some challenges to address are consistency, signal is not always available at the study areas, leading to times of blackout, where the data is still being collected however it can't make the transfer. Another challenge to consider is that the probes and tags have a battery life, meaning that they will need to be regularly replaced, it also leads to the final challenge which is fish monitoring. The more real-time it gets the quicker the battery will die, leading the tagged fish to be in semi-real time. Reading every 30 mins to 1 hour.