INITIATIVE ON
Digital Innovation
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TECHNICAL REPORT

Development of an Environmental Flow Implementation and Monitoring Approach: Using digital technology to construct accurate 3D hydrodynamic models of a river reach to monitor the implementation of environmental flows

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INFO

Submitted	30 November 2023
Keywords	Limpopo River Basin, Incomati Basin, Water Management, Environmental Flows, System Modeling, Hydrodynamic Model, 3D Model
Flagship	Digital Twin
Work Packages	3. System Modeling 4. Real-time Monitoring

ABSTRACT

This study presents a comprehensive approach to developing an effective monitoring system for e- flow implementation in river ecosystems using high-resolution 3D modeling and modern sensor technology. The research focuses on the Limpopo and Incomati basins in Southern Africa.

Environmental flows (e-flows) represent the volume and quality of water that needs to remain in a river to sustain the ecosystem and hence all those who benefit from a functional ecosystem (thus, society and the economy). The objective of this study is to support the implementation of e-flows around the world which has been poor despite a wide-spread acceptance of the philosophy. While monitoring e-flow volumes (and quality) is a relatively simple matter, monitoring the effectiveness of the prescribed e-flow requires that evidence of a sustained ecosystem is collected, ideally together with evidence of the impact on beneficiaries of that ecosystem. This project investigates whether appropriate digital tools and real-time data could assist with the management, education, awareness and implementation of e-flows. This project includes digital approaches to monitoring the change in river ecosystems following the implementation of e-flows in two river basins in southern Africa, facilitating an adaptive management approach for sustainable water resources management globally.

This report documents the development of an e-flow implementation monitoring approach based on a high-resolution 3D model (2D hydraulic modelling) of river sites that would be used to document changes in river ecosystem structure over time. This will be linked to the use of modern sensors that will be attached to fish as well as to hard substrates that will enable real-time monitoring of the ecological acceptability of e-flow implementation including water quantity and quality management. Coupled with this will be an upgrade of the PROBFLO e-flow framework to make it more accessible and usable, thus facilitating the use of the model outputs by basin authorities for long- term e-flow management that would include investigation of future scenarios.

The project aims to advance the PROBFLO e-flow framework, integrating 1D, 2D, and 3D hydraulic modeling to understand the intricate relationships between river flow dynamics and habitat availability. The study emphasizes the importance of eco-hydraulic models in predicting river changes and their impact on aquatic habitats, employing advanced survey technologies like LiDAR, ADCP, and hydrographic surveys.

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O'Brien, G. C.; Kaiser-Reichel, A.; McNeil, T.; van der Waal, B. W.; Huchzermeyer, N.; Singh, S.; Pringle, J.; Harvey, T. A.; Maharaj, U.; Singh, K.; Cronje, L. 2023. *Development of an environmental flow implementation and monitoring approach: using digital technology to construct accurate 3D hydrodynamic models of a river reach to monitor the implementation of environmental flows*. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Initiative on Digital Innovation. 25p.

1. Introduction

Environmental flows are the quality, quantity, and timing of water flows required to sustain estuarine and freshwater ecosystems and human well-being and livelihoods dependent on these ecosystems (Pahl-Wostl et al., 2013). One of the main processes of environmental flows is the link to the flow requirements of aquatic life (ASCE, 2000). They contribute to economic development and river health (Dyson et al., 2003). Maintaining the necessary environmental flow requirements will prevent disastrous consequences for rivers and river users (Dyson et al., 2003; King and Brown, 2006).

A river has multiple functions: transport, drainage, water supply, and recreation. Multiple stresses affecting the river include a growing population, pollution, climate change, and the presence of invasive fish species in rivers (Evans et al., 2022; Pahl-Wostl et al., 2013). Increasing demand for river functions requires better management of the rivers (Price and Samuels, 1980; King and Brown, 2006).

Additional river features include spatial heterogeneity, which provides a whole range of habitats for different organisms to live in, and a temporal dynamic feature where they continuously change, from a daily change to decadal and longer (James and King, 2010). Hydraulic patterns, variable discharge, nutrient loads, sediment loads, and thermal regimes characterise these Lotic environments. They are dynamic environments that change spatially and temporally (Maddock, 2013).

Predicting hydraulic conditions in a river and using scenario development can be used to predict river change and thus how the related ecosystems are affected. This is known as eco-hydraulic modelling (James and King, 2010). Eco-hydraulics is referred to as the relationship between the biotic environment and its abiotic processes.

Eco-hydraulics is the study of the relationship between discharge and the availability of physical habitat within the river ecosystem as well as understanding the optimal conditions for various species or communities (James and King, 2010). Eco-hydraulic modelling is used to predict how hydraulic conditions in a river might change under different scenarios and how the aquatic habitat of specific species or communities could be affected (James and King, 2010). The level of detail of flow depths and velocities required will determine the type of modelling approach undertaken. One-dimensional (1D) modelling is undertaken when the distribution of cross-section average velocities along a river reach is required and provides flow properties only in the downstream direction (James and King, 2010; Tonina and Jorde, 2013). Two-dimensional (2D) modelling presents flow properties in two dimensions and provides spatially explicit descriptions of flow depth and velocity by using velocity distribution equations to determine the distribution of local velocity through the water column. Three-dimensional (3D) models can accurately describe combined vertical and areal velocity distributions in three directions; longitudinally, transversally and vertically (Figure 1) (James and King, 2010; Tonina and Jorde, 2013).

The progression in available evidence to describe flow-ecosystem and flow-ecosystem service relationships using 1D, 2D and 3D models includes:

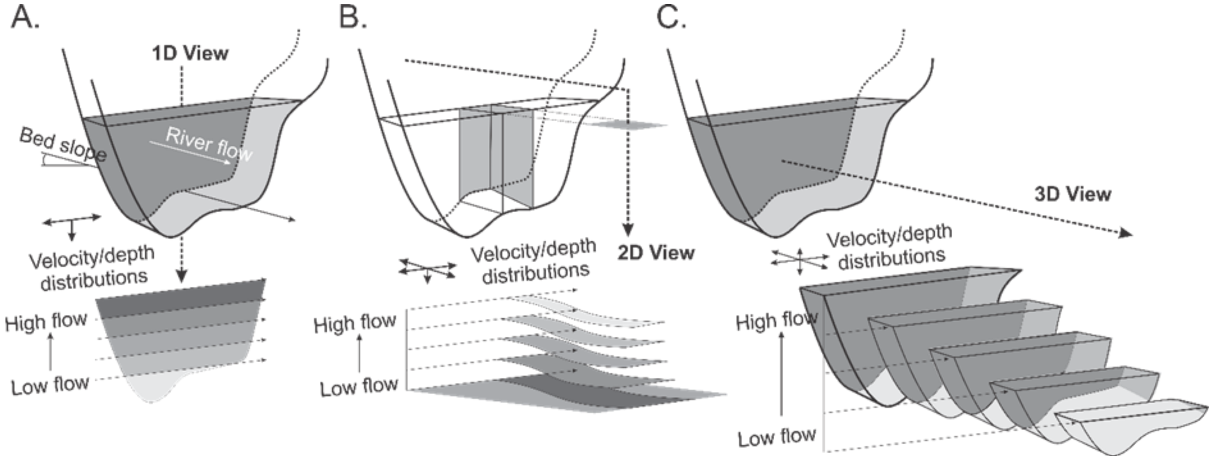

Figure 1 Velocity, water depth and shear stress results in a 1D, 2D and 3D numerical simulation (adapted from Tonina and Jorde, 2013)

- 1D: Evidence of the velocity-depth habitat variability for one or multiple cross section/s "slice/s" of a river that provides foundational information including modelled wetted perimeter, water depths (minimum, average and maximum), and velocity and depth data for any discharge. This approach supports evidence-based evaluations of discharge-ecosystem variables and discharge-ecosystem service relationships in e-flow determination processes and implementation. Of great im-portance to the social and ecological teams who establish flow-ecosystem and flow-ecosystem service relationships are flow (including a range of discharge points potentially from 0 to floods) and habitat relationship data usually provided in tabular or graphical forms. Note that hydraulic scientists and engineers using the 1D approach for an e-flow assessment trade-off habitat dynamism that would support diverse instream biological communities for a simple section with uniform flow for accurate discharge modelling. Accurate discharge modelling is required for at least one 1D cross-section they include in e-flow studies. This process often excludes socio-ecologically important habitat characteristics that often need to be inferred in e-flow determination, implementation, and monitoring processes.

- 2D: While the amount of data required for 2D modelling increases from re-quiring single cross sections to monitoring the velocity-depth and bathymetry of a reach of a river (sometimes 100s of meters to a few kilometres), the value and confidence of the data is exponentially greater than the 1D approach. Here all the in-formation available from the 1D approach is available and incorporated, which includes rated cross-sections from the 1D approach for accurate discharge determination. A 2D hydraulic model is useful because it is grid based and can integrate well with say a digital terrain model and 2D or even 3D habitat mapping. However, the 2D approach has the functionality to model critical habitats within reach of a river. The noticeable improvement from 1D to 2D modelling includes the opportunity to determine the availability of and condition of habitats (depth, substrates, velocities and direction of flow) for a reach of a river, rather than the dynamism of one cross-section. This approach results in considerably less uncertainty compared to the 1D approach.

- 3D: This approach includes all of the benefits from the 1D and 2D approaches and importantly includes additional data such as instream velocity dynamism and sediment movement including important deposition dynamics for a reach of river. The 3D approach is also valuable when considering how habitat dynamism varies during changing flow patterns. This approach provides opportunities for the e-flow determination and monitoring team to provide and test the social and ecological consequences of not only changes in the volume of flows but also the duration of flows. This allows data on past and existing flows to inform guidance on future sustainable flows that should be maintained in rivers in the context of important socio-ecological processes. From global reviews (Horne et al., 2017) of e-flow determination studies, 3D hydraulic modelling, which is generally not included in e-flow de-termination studies due to the difficulty to validate (3D flow field depends on the grid spacing and other things), price (economic and computational efficiency cost) and technological constraints, this approach results in the least uncertainty and has the greatest potential to contribute to accurate e- flow determination and monitoring with resulting social and ecological benefits. While historically expensive and requiring aircraft and or extremely expensive equipment the rapid acceleration in drone scanning technology and processing potential has made 3D hydraulic modelling possible for e-flow studies.

Stochastic eco-hydraulic models such as PROBFLO are used to map the relationships be-tween river flow and instream habitat. However, these models are limited to the availability of field observations that are significantly time-consuming and data sparse. These limitations affect the model's ability to predict the spatial heterogeneity of the river. The study entails evaluating existing and new innovative methods for the collection of field data to establish a 3D digital terrain model to support PROBFLO modelling of confident flow-habitat- ecosystem dynamics to support the implementation of e-flows. Existing Acoustic Doppler Current Profiler and LiDAR data will be tested as an innovative addition to existing hydrodynamic modelling methods to establish accurate ground, bathymetry and substrate characteristics above and below the water surface of flowing rivers, all linked to water level/s, and flows (including water velocities). Case study sites or reach of a river on the Crocodile, Sabie and Olifants Rivers have been selected for hydrodynamic modelling for e-flow assessments. The 3D model will describe the hydrological, hydraulic, geomorphological, riparian vegetation and instream ecosystem characteristics so that accurate dis-charge-habitat relationships can be established and trends over time can be described as an aid to e-flow management. The real innovation here would be a 3D picture and associated model of a reach of

Figure 2 Example of a 3D model generated in the study used to establish a hydraulic model for rivers

the river above and below the water surface that can be used for assessment of e-flows and implementation over time. The output would be an approach and associated model to demonstrate the approach that allows for confident monitoring of the implementation of e-flows based on detailed maintenance of habitat structure and water flows. For this study, the three-dimensional (3D) hydrodynamic model will contribute to the Digital Twin (Figure 2).

2. Materials and Methods

Multiple field surveys took place during this study comprising a team from Ground Truth and Rivers of Life Aquatic health services (Figure 3) for the collection of:

- Digital Terrain Models (DTMs)
- Bathymetry mapping
- Red, Green, and Blue (RGB) Orthomosaic imagery
- Multispectral imagery for the Crocodile, Sabie and Olifants rivers' models.

These models can accurately describe combined vertical and areal velocity distributions in three directions; longitudinally, transversally, and vertically (James and King, 2010; Tonina and Jorde, 2013).

After careful consideration, the surveys were done at selected areas of interest such as bridges, confluence points, and weirs. During the surveys, both floodplains and rivers were considered as areas of interest. The multispectral imagery was gathered using a Laquinta camera, and the Light Detection and Ranging (LiDAR) data were gathered using a Zenmuse LiDAR module with an RGB camera. The Bathymetry data were collected with the use of SonTek HydroSurvayor-M9.

The quantity of data collected was dependent on many factors, including but not limited to power (electric) supplies, safety, and most importantly landowner permissions. The Olifants River data are utilised to create hydraulic/eco-hydraulic models. The date, location and additional about the data collected during the surveys are summarised in Table 1.

2.1. Hydrodynamic modelling

To set up the 3D hydrodynamic model (or for any hydraulic model), field surveys need to be undertaken that include Bathymetry surveys at a very fine resolution (Tonina and Jorde, 2013). Bathymetry mapping is the method used to quantify depths to determine the topography of water bodies (Jawak et al, 2015). This was done using a Sontek M9 River Surveyor which was secured to a rope that are held on either side of the river by operators so that the device can be guided along the river in a range of directions to ensure optimal inclusion of benthic complexity (Figure 4 and Figure 5).

The River Surveyor M9 demonstrated its capability to capture bathymetric data through the execution of the HydroSurveyor

Table 1 Survey dates, sites and data collected per site for the Digital Twin study

Date	River name	Data
03 /11/2022	Crocodile	River cross-sectional profile
19-25 /11/2022	Crocodile	Sound Navigation and Ranging (SoNAR)
19-22 /11/2023	Crocodile	Bathymetry mapping
12 /09/2023	Crocodile	LiDAR RGB Imagery Multispectral Imagery River cross-sectional profile
13-14 /09/2023	Sabie	LiDAR RGB Imagery Multispectral Imagery
15/ 09/ 2023	Olifants	LiDAR RGB Imagery Multispectral Imagery Sound Navigation and Ranging (SoNAR) Point depth and velocities. River cross-sectional profile
17-23/11/2023	Crocodile, Sabie, Olifants	Sediment samplers

Figure 3 Field surveys for this study in 2023 by Rivers of Life Aquatic Health Services and Ground Truth researchers in the Crocodile, Sabie and Olifants Rivers

software. This integration enabled the River Surveyor to leverage its HydroSurveyor firmware and functionality effectively. By employing this specialized software, the River Surveyor M9/S5 not only showcased its versatility but also ensured precise and comprehensive bathymetric data collection, contributing to the accuracy and reliability of our hydrographic surveying efforts.

At sites where the flow was deep and/or with wildlife danger, discharge was determined using the SonTek River Surveyor M9/S5 acoustic Doppler profiler which also captures depth and velocity at a large number (>100) of vertical bins (these are calculated based on the depth and signal strength so they can vary drastically) along each transect. For very shallow depths where the River Surveyor cannot capture meaningful data, a handheld electromagnetic OTT MFPro was used: the channel was divided into at least 20 profiles to capture depth and flow velocity data to calculate discharge and capture the diversity of depth-velocity classes for shallower sites (Gordon et al., 2004).

The data collected from the field surveys is being analysed using MIKE HYDRO as an introduction to the modelling software by DHI, where the importance of modelling concepts such as grid generation and boundary conditions was identified. 1D verification was done using the Muskingum Method (MM). This approach was taken to determine the accuracy of the 1D model output by comparing outflow results from the MM method to what was obtained from the MIKE model. This demonstrated a 95% accuracy rate.

Figure 4 The location of the cross-section analysis (purple) and bathymetry mapping (red) undertaken at the site on the Crocodile River

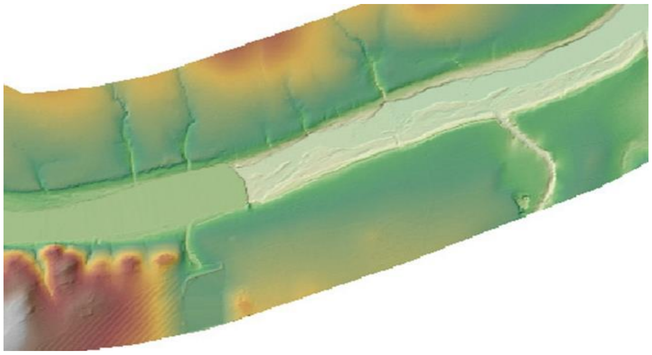

Figure 5 Manipulated Lidar data for the site on the Crocodile River to represent a 3D model

1.1. Discharge monitoring for the hydrodynamic model

In addition to the use of available LiDAR data to establish a digital terrain model and the ADCP for sub-surface scans and assessments, for this study flow rating curves were included to determine accurate rating curves to monitor water depths and model discharge for input into the hydrodynamic model. This included the modelling of rated cross-sections for discharge modelling. Cross-sections were established using a Leica TCR403 total station and associated staff and prism. Cross- sections provided information about profile shape, relative elevation, channel slope, and associated water level data. To allow for an accurate inclusion of alternative flow-depth relationships several benchmarks were installed which allow for the linking of datasets during the data processing phase and future replication/s. Here the SonTek M9 River Surveyor (ADCP) was used to acquire in-stream channel shape and to determine discharge which was later merged with coordinates acquired from the total station to produce a full channel profile which includes water depths greater than the depths observed in the field. Rated sections in this study were determined using Microsoft Excel and HEC-RAS 1D modelling software.

Rating curves will be produced with the use of coordinates of surveyed points, energy gradient (slope), discharge, and resistance (Manning's n). Rating curve accuracy will increase as more site visits are undertaken, specifically relating to hydraulic resistance values (Manning's n).

1.2. HEC-RAS 2D

The HEC-RAS software has been developed by the U.S. Army Corps of Engineers and is capable of simulating unsteady flow through a full network of open channels, floodplains, and alluvial fans. The unsteady flow component can be used to perform subcritical, supercritical, and mixed flow regime calculations to provide a precise depiction of the site's properties and hydraulic characteristics. In a HEC-RAS 2D model, several key inputs are required to simulate the flow of water in a more detailed and spatially distributed manner compared to a traditional 1D model. The main inputs to a 2D model are the terrain data, hydraulic roughness coefficient, geometric data and boundary conditions, and are described in the sections below.

1.3. Terrain Data

For any 2-dimensional surface flow model, a digital elevation model of the terrain to be assessed is required. For this particular model, GroundTruth carried out an independent UAV (drone) based LiDAR survey of the focused reach of the river to be modelled. This survey provided detail on the river floodplains, sandbars, rock ledges and vegetation, not only in elevation but with a high-resolution orthomosaic imagery for holistic visual information not always gathered whilst on site. As LiDAR does not penetrate through water, a separate survey of the channel bed was done using a single beam echosounder and altimeter. This was carried out through a Sound Navigation and Ranging (SONAR) device coupled to collect depth data with a GPS device which was attached to a flotation device and moved through the water using the drone. The SONAR data and LiDAR are still to be stitched together and will thereafter be used for the hydraulic modelling.

Whilst on site, a cross-sectional survey was taken across the width of the river using a total station. At the same time, velocity readings were taken using a velocity meter as well as an MF Pro sensor by OTT Hydromet. This information will be used to verify the processed LiDAR data as well as calibrate the model through manipulation of deriving the correct manning's roughness coefficient of the site's land cover by comparing modelled velocity to measured velocity for a particular flow.

1.4. Hydraulic Roughness Coefficients

A hydraulic roughness layer or Manning's roughness coefficient (n) layer is required for a 2D HEC-RAS model. These parameters will describe the resistance of different surfaces in which there is flow present, which is essential to calculating velocities. A parameter is crucial to an e-flow study. The present land cover descriptions with the corresponding manning's n value for the Olifants River have been provided Table 2 below. These will then be refined during the calibration process.

1.5. Geometry Data

Detailed information on the site's geometry needs to be included in the model. With the associated terrain data, the geometry file will use the elevation detail of the terrain. A 2D flow area needs to be established to indicate where the model is to be performed, with this, a grid size needs to be established which affects both the accuracy and stability of the model. Within each grid cell, the terrain resolution is fully conserved and thus is not reduced to the 2D grid resolution.

The result layers, however, are averaged within each cell. Therefore, each cell will contain an average depth, velocity, water surface elevation etc. Where the terrain is not smooth or even and contains inundations, the smaller the grid sizes the better. This does however make the model slightly more unstable, which can be rectified through the simulation times. To make the modelling time more efficient whilst ensuring stability, the grid structure can be manipulated through brake lines and refinement regions, which is done in the geometry data set-up.

Currently, a geometry file has been established that covers the combined model of the LiDAR and Bathymetric terrain.

Breaklines and refinement regions have been set up to depict the braided flow path system as well as the sediment plumes and rocky islands. Once the terrain data has been finalised and before the model is run for different flow rates, the geometry file will be refined along the way.

2.7. Boundary Conditions

The channel was set up with an inlet boundary condition based on a normal depth determined from the cross-sectional hydraulic characteristics, longitudinal channel slope, Manning's n value and flow hydrograph based on the flow depth to be modelled. The outlet boundary condition was set up as a normal depth boundary condition based on a friction slope.

Table 2 Table of current Manning's n Values for the Olifants River, Kruger National Park

Description	**River**	**Bare Soil**	**Grassed Bank**	**Light Shrub**	**Dense Shrub**
Manning's n	0.055	0.034	0.045	0.04	0.05

2.8. One-Dimensional Modelling

In the office, discharge, energy slope and transect data were extracted from the field observations. Roughness was calculated using the Mannings n formula based on the measured data (Gordon et al., 2004). To extrapolate the observed hydraulic data to other stage levels so that a continuous rating function can be determined for a wide range of discharges, 1-dimensional hydraulic modelling of higher flows was undertaken using the Mannings formula (Hirschowitz et al., 2007).

HABFLO, a 1 dimensional free-ware empirical hydraulic habitat-flow simulation model, was used to derive frequency distribution data for the various hydraulic habitats as recommended by Hirschowitz et al. (2007). HABFLO is designed to simulate flow-dependent, ecologically relevant hydraulic data for Reserve determinations (Hughes et al. 2012). HABFLO flow-depth frequency distribution calculations are based on the work of Lamouroux et al. (1995) and apply to riffle habitats.

One-dimensional (1D) modelling was done using MIKE Zero as an introduction to the modelling software by DHI, where the importance of modelling concepts such as grid generation and boundary conditions was identified. The basics of QGIS were learnt to convert shapefiles into Digital Elevation Models as well as x,y, and z point files. This was important as these file types are required as inputs into the modelling software.

2.9. Two-dimensional Modelling

A curvilinear grid for two-dimensional modelling was created and data elevation points in an x,y, and z format were saved onto the grid. Figure 6 shows the model grid that covers 375m of the river, which is what the current bathymetry data extends to. Data in Figure 6 indicates the elevation levels above mean sea level. Discharge data from the upstream and downstream gauges of the site were downloaded and processed for model calibration. A unit hydrograph was derived being a characteristic of the Crocodile River catchment. The hydrograph duration is proportional to the rainfall duration and the hydrograph volume is proportional to the rainfall intensity. The Road Drainage Manual (Van Dijk and Van Vuuren, 2007) was used to derive the graph as seen in Figure 19. This hydrograph was used to test the 2D model.

Hydrographs (Figure 7) to be used when running the model will be derived from the observed discharge reading from the measure gauges along the river. The 2D model was set up with flux boundary conditions, with the unit hydrograph as the input.

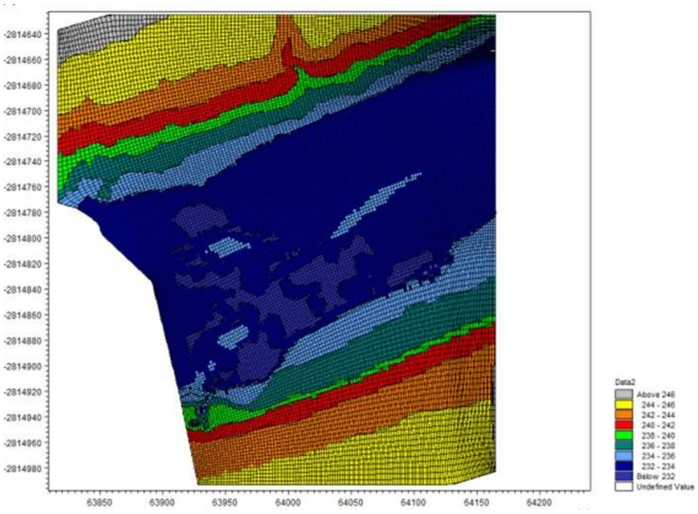

Figure 6 Bathymetry data covers 375m of the river on the model grid

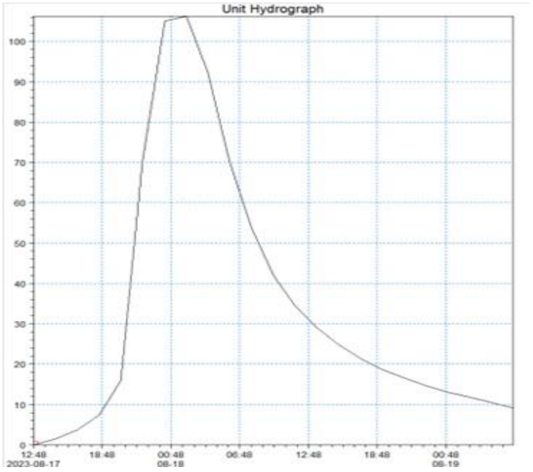

Figure 7 Hydrograph derived using the Road Drainage Manual

2.7. *Sediment Mapping and Trapping*

The geomorphic habitats available along the Olifants, Sabie and Crocodile Rivers will be mapped using high-resolution aerial images (Figure 8). To map the sediment substrates effectively (Figure 9), the main sediment types identified in the images were ground-truthed by sampling sediment sizes for distinct features in the field and logging the coordinates of the samples. The main sediment types included bedrock, boulder, cobble, gravel, sand, silt and clay. Sediment sizes were measured in the field using the Eikelkamp sand ruler or a tape measure (b-axis of 100 randomly selected particles) to see if the finer categories of sand, gravel and cobble could be determined from the aerial photos. The orthomosaic drone imagery provided by GroundTruth was imported into ArcMap 10.8.2. A total of 145 polygons were digitised off the orthomosaic at a scale of 1:100 or less and assigned a basic habitat type (Table 3 and Figure 7) as training data for the interactive supervised classification. The ground-truthed field survey points were used to aid in classifying the habitat types correctly. The digitised polygons were imported as training samples into the "Interactive Supervised Classification" tool in ArcMap 10.8.2. The classification was run for the entire reach to give an overview of the different habitat types present.

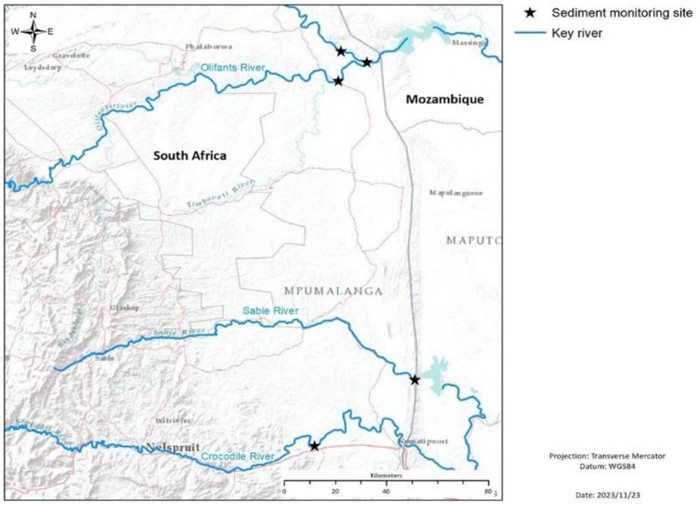

Figure 8 Sample locations along the Olifants, Letaba, Sabie and Crocodile Rivers

Time-integrated samplers (TIS) were installed along the channels where bedrock provided a solid anchor for the samplers. Figure 8 shows the locations where the samplers were installed. The Letaba River was included as it is a large tributary, possibly affecting the quality of the sediment (Figure 9) going into the Olifants Gorge and Massingir Dam. The samplers were constructed from heavy metal-free PVC. The outer diameter of the samplers was 110mm and they were

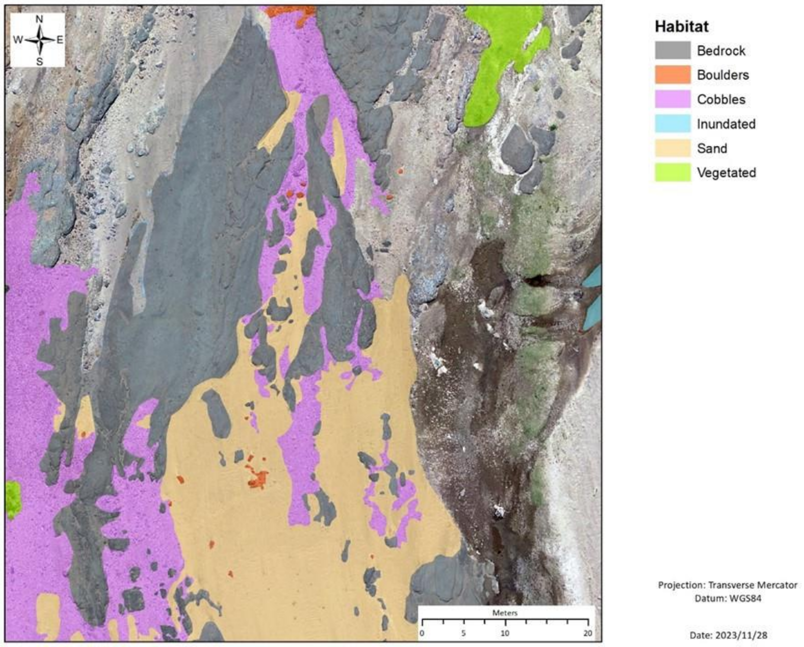

Figure 9 Areal image with sediment types overlaid

Table 3 Basic habitat types assigned to each polygon as part of the training dataset

Habitat	Description
Bedrock	Exposed bedrock areas
Cobbles	Visible substrate ranging <300 mm
Sand	Sand bars and beds
Boulders	Substrates >300 mm
Vegetated	Vegetated areas including trees, reeds and grasses
Inundated	Habitats inundated with water on the orthomosaic

Figure 10 Installation of a time-integrated sampler onto bedrock

1m long (Figure 10). The inlet hole of 5mm allows a small stream of water to enter the sampler, whereafter it expands 20-fold, slowing the flow velocity and allowing fine suspended sediment to settle out. The samplers will collect sediment throughout the wet season. The samplers will be emptied after the wet season, the sediment mixed thoroughly, and a subsample be sent for particle size analysis and chemical composition. This will inform the size and quality of the suspended sediment for the modelling.

2. Results

2.1. Crocodile River

The Crocodile River, Van Graan from a scientific standpoint, holds significant importance in the realms of hydraulics and geomorphology. Through detailed studies of its hydraulic dynamics, the river serves as a natural laboratory for understanding flow patterns, channel morphology, and sediment transport. Such investigations yield critical data on water velocity, discharge, and hydraulic processes, contributing to advancements in hydraulic engineering and the design of structures like bridges and dams.

Geomorphologically, the Crocodile River offers diverse landscapes, allowing researchers to explore various riverine landforms such as meanders and braided channels. This geomorphic diversity provides insights into sediment transport, erosion, and deposition processes, crucial for managing riverbanks, preserving habitats, and safeguarding water quality. Beyond the purely physical aspects, the interactions between geology and ecology within the Crocodile River ecosystem are integral to understanding how the river shapes habitats and influences biodiversity. As a result, scientific studies of the Crocodile River contribute not only to environmental management, water resource sustainability, and hazard assessment but also to the broader understanding of the dynamic interplay between natural forces and ecosystems.

Throughout our study, we meticulously conducted three cross-sectional surveys at multiple instances, aiming to enhance the precision and accuracy of our data collection. These surveys were strategically positioned across the cores of this project, each iteration contributing to the refinement of our understanding. The cross-sectional analyses, undertaken as pivotal components of our research methodology, provided comprehensive insights into the structural and hydraulic characteristics at key locations within the study area. This deliberate and repetitive approach to surveying allowed us to capture nuanced spatial variations and intricate morphological details inherent to the studied cores. The strategic placement of these cross sections not only bolstered the robustness of our findings but also underscored our commitment to ensuring the highest scientific rigour in our investigation.

Below lays a sample of one transect captured at Van Graan (X24F), Figure 11 showcases the 1D transect meticulously captured at the Van Graan site (X24F) on the 27th of July 2023. This graphical depiction was generated employing Microsoft Excel, illustrating the spatial characteristics of the transect with precision and attention to detail. Figure 12 is a simulation that was executed on the 1D transect using HEC-RAS 6.4.1, a robust hydraulic modelling software. The primary objective of this simulation was to generate a comprehensive rating curve Figure 13. This curve serves as a vital analytical tool, depicting the relationship between stage (water surface elevation) and discharge, essential for understanding the river's hydraulic behaviour. The utilization of HEC-RAS 6.4.1 underscores our commitment to employing advanced tools to derive accurate and scientifically sound results in our hydraulic analysis. Lastly, Figure 14 is a velocity-depth frequency distribution for various maximum depth levels at the Van Graan site (X24F) that were systematically modelled. This modelling effort employed advanced analytical techniques to portray the distribution patterns of water velocities at different depths within the specified location. By delineating the frequency of velocities at various depth levels, our analysis provides a nuanced understanding of the hydraulic dynamics at Van Graan. This meticulous modelling process contributes valuable insights to the characterization of the flow patterns and hydraulic behaviours within the studied area, enhancing the depth and comprehensiveness of our findings.

At Van Graan (X24F), bathymetric surveys were carried out to generate 1D and 2D hydraulic models and 3D bathymetric models of the Crocodile River. This includes the collection of geospatial, river velocity and river depth data using the River surveyor M9/Hydrosurveyor ADCP. The collected bathymetric data has been transmitted to professionals, such as those at the Olifants and Sabie, for in-depth analysis. This collaborative effort involves leveraging the expertise of specialists to scrutinize and interpret the bathymetric information comprehensively. By engaging with professionals, we ensure a meticulous examination of the data, drawing upon their proficiency to derive meaningful insights and conclusions from the bathymetric surveys at Van Graan. To illustrate the bathymetry at Van Graan, Figures 15 and 16 show the trace the Doppler took merged with images from Google Earth.

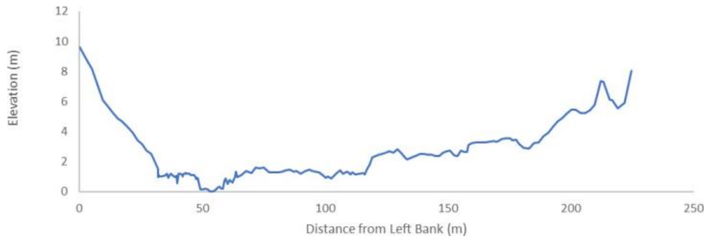

Figure 11 The 1D transect captured at Van Graan (X24F).

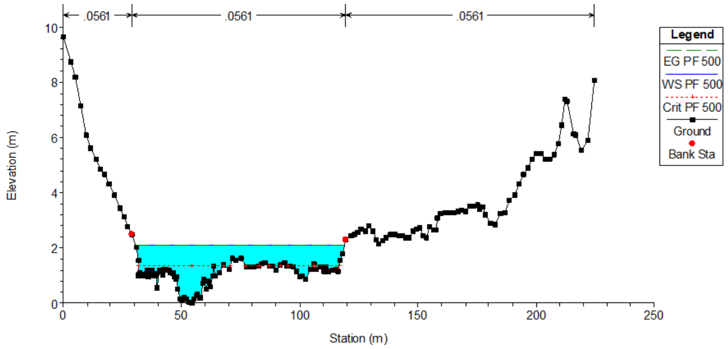

Figure 12 Simulation ran in the 1D transect using Hec-Ras 6.4.1.

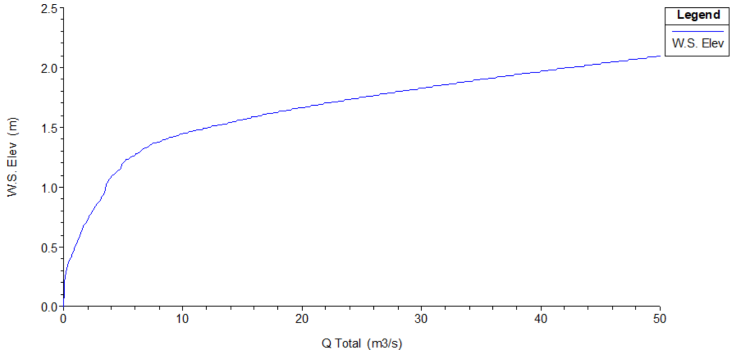

Figure 13 Rating curve for Van Graan (X24F) generated in Hec-Ras 6.4.1.

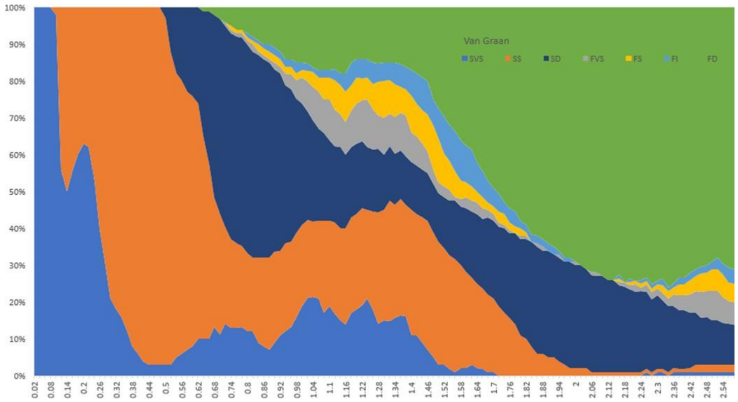

Figure 14 Modelled velocity depth frequency distributions for various maximum depth levels for Van Graan (X24F)

Figure 15 (left and right) Tracks of the River Surveyor generated at the Van Graan Weir on the Crocodile River including the 1D cross-section (purple) and bathymetry (green, red, white) results. Variable direction tracks of the Crocodile River used to generate depth-velocity data for the reach used in the modelling process.

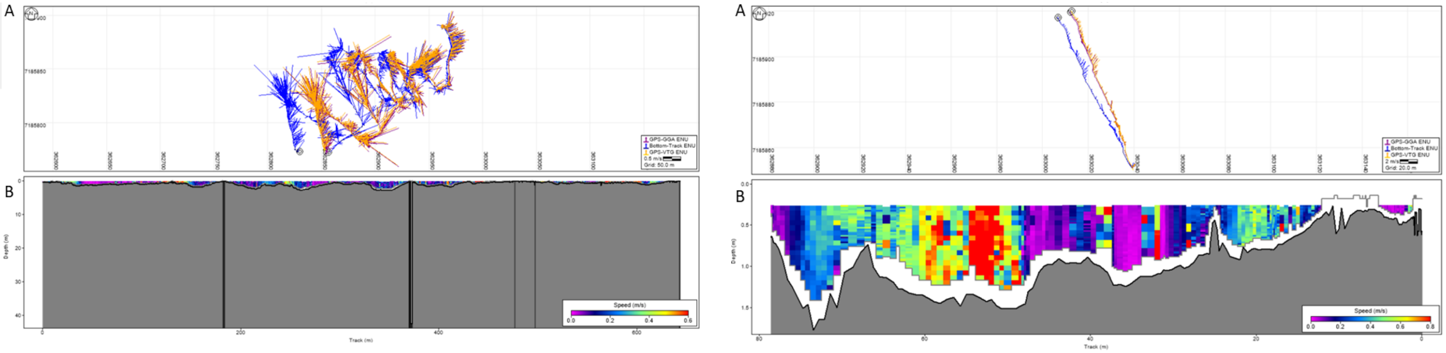

Figure 16 Coordinates of the M9 surveyor (Left A) used to generate a cross section of the Crocodile River and bathymetric velocity depth profile (Left B) of the cross -section used to generate 1D and 2D hydraulics models of the river in the study. A total station was used to generate bank bathymetry data for the cross-sections. (Right A) used to generate a 2D bathymetric model of a reach of the Crocodile River and bathymetric velocity depth profile (Right B) of the cross-section used to generate 2D hydraulics models of the river in the study.

Figures 16 (and Appendix) illustrates the bathymetry of the river, along with the height and length of the river in meters. The multi-colours represent the observed velocity of the water in m/s. In this study, available LiDAR data providing a digital elevation model of the reach of the Crocodile River is being used to model the bathymetry of the water above the water surface. Here the ADCP is then used to determine the bathymetry of the reach below the water surface. This includes using the ADCP to make tracks (zig-zag) throughout the channels of the reach of the river being considered (Figure 15). Together with the LiDAR data, the ADCP data and cross-section data for the rating curve to monitor discharge a 3D hydrodynamic model is being established for the reach. The results for the tracks are shown in the Appendix.

Additional comprehensive sub-surface bathymetric mapping for the Crocodile River reach using the SonTek Hydrosurvayor-M9 and Hummingbird 798ci HD is also available. One-dimensional (1D) modelling was done using MIKE HYDRO as an introduction to the modelling software by DHI, where the importance of modelling concepts such as grid generation and boundary conditions was identified. 1D verification was done using the Muskingum Method (MM) (Figure 17). This approach was taken to determine the accuracy of the 1D model output by comparing outflow results from the MM method to what was obtained from the MIKE model. This demonstrated a 95% accuracy rate.

A curvilinear grid for two-dimensional modelling was created and data elevation points in an x,y, and z format were saved onto the grid. Figure 18 shows the model grid that covers 375m of the river, which is what the current bathymetry data extends to. Data2 in Figure 18 indicates the elevation levels above mean sea level. Discharge data from the upstream and downstream gauges of the site were downloaded and processed for model calibration.

A unit hydrograph was derived being a characteristic of the Crocodile River catchment. The hydrograph duration is proportional to the rainfall duration and the hydrograph volume is proportional to the rainfall intensity. The Road Drainage Manual (Van Dijk and Van Vuuren, 2007) was used to derive the graph (as seen in Figure 19). This hydrograph was used to test the 2D model. Hydrographs to be used when running the model will be derived from the observed discharge reading from the measure gauges along the river.

In addition to the above, we have generated a 2D hydraulic model for the Crocodile River at Van Graan Weir for the study. The 2D model was set up with flux boundary conditions, with the unit hydrograph as the input. The current speed (Figure 20), surface elevation (Figure 21), and discharge flux (Figure 22) models were generated. This visual data was collected from the peak of the unit hydrograph to view the possible maximum values of the model. Figure 23 shows the survey extent of the Digital Terrain Models (DTMs) of the Lower Reach of the Crocodile River.

2.2. Sabie River

The selection of the Lower Sabie site (X33D), situated at coordinates -25.1093843, 31.9073264, as illustrated in Figure 24 was deliberate, chosen for its clear visibility along the banks. The unidirectional flow observed at this location lends itself to the development of precise hydraulic models, facilitating a more accurate representation of flow dynamics and enhancing the reliability of our hydraulic modelling efforts. Figure 25 visually presents the transect generated in Excel, offering a graphical representation of the spatial characteristics captured through our meticulous surveying efforts. Additionally, Figure 26 depicts the rating curve, providing a graphical representation of the relationship between stage (water surface elevation) and discharge. These figures collectively contribute to a comprehensive understanding of the hydraulic dynamics and morphological characteristics observed at the surveyed location, enhancing the scientific rigour of our study.

Lastly, Figure 27 presents the velocity-depth frequency distributions for various maximum depth levels at the Lower Sabie site (X33B). Similar to the methodology applied at the Van Graan site (X24F), these distributions were systematically modelled employing advanced analytical techniques. The modelling effort aimed to visually depict the distribution patterns of water velocities at different depths within the specified location. By delineating the frequency of velocities at various depth levels, our analysis provides a nuanced understanding of the hydraulic dynamics at Lower Sabie. This meticulous modelling process contributes valuable insights to the characterization of flow patterns and hydraulic behaviours within the studied area, thereby enhancing the depth and

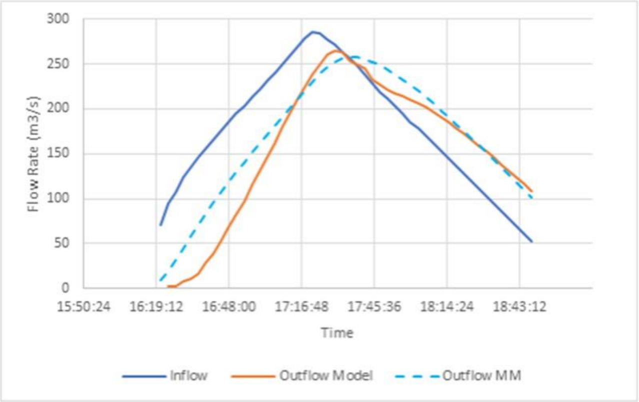

Figure 17 1D Verification at Van Graan, Crocodile River, using the Musk- ingum Method.

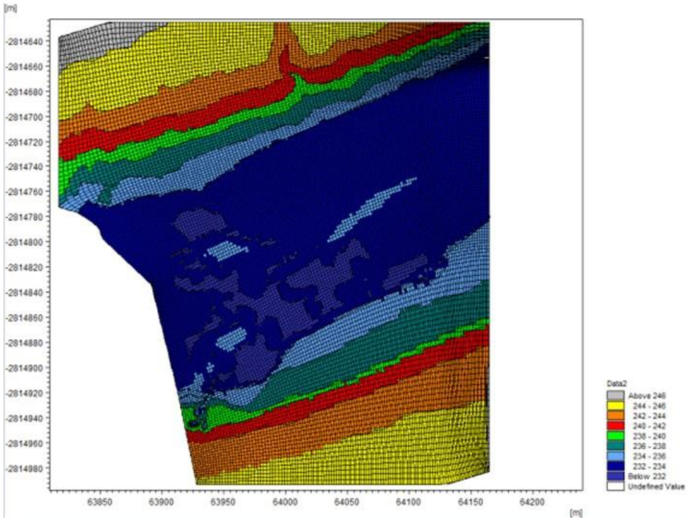

Figure 18 The model grid that covers 375m of Crocodile River at Van Graan. The different colours (Data 2) represent the elevation levels.

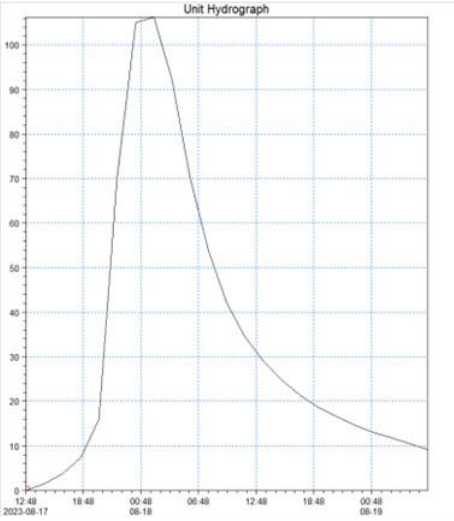

Figure 19 Characteristic unit Hydrograph of the Crocodile River.

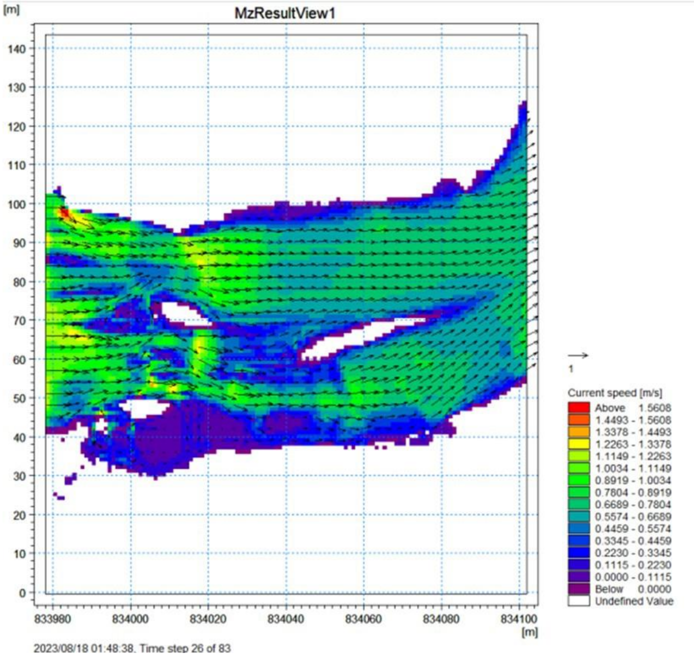

Figure 20 The current speed calculated from the 2D hydraulic model at Van Graan, Crocodile River.

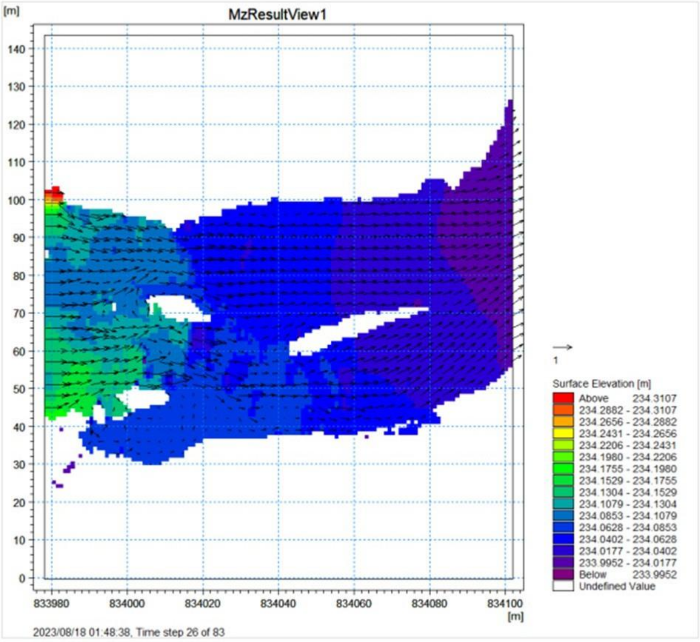

Figure 21 The Surface Elevation calculated from the 2D hydraulic model at Van Graan, Crocodile River.

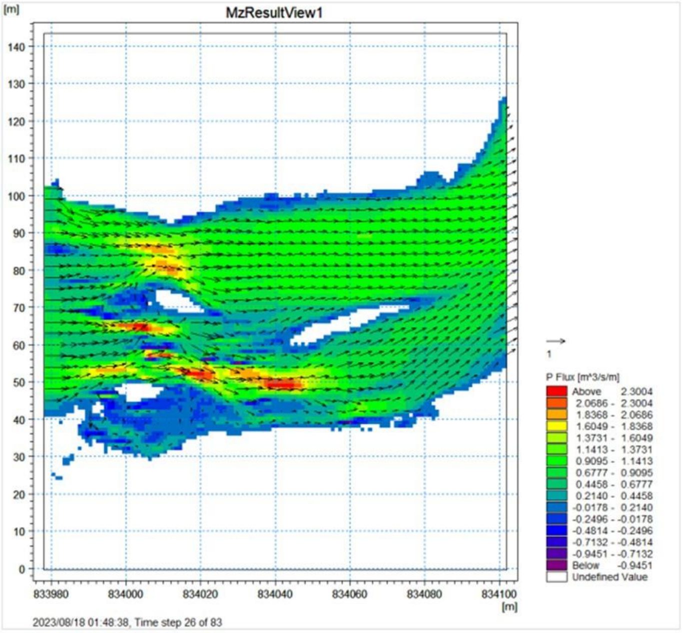

Figure 22 The Discharge flux calculated from the 2D hydraulic model at Van Graan, Crocodile River.

Figure 23 The survey extent for the Digital Terrain Models (DTMs) and Red, Green, Blue (RGB) Orthomosaic and multispectral imagery of the Lower Reach of the Crocodile River.

comprehensiveness of our findings at Lower Sabie (X33B).

However, it is crucial to note that the Sabie site presents distinct challenges, particularly in terms of safety, as the reeds masking the presence of wild animals introduce an element of risk. The need for caution in such an environment necessitates additional time for data collection.

The discharge, 1D hydraulic models have been developed and the rating curves have been tested for the Sabie River (Lower). Additional comprehensive sub-surface bathymetric mapping for the Sabie River reach using the SonTek Hydrosurvayor-M9 has been collected Linda Cronje has used this data to generate a draft 3D digital twin river model and 2D hydraulic model for the Sabie River at Lower Sabie for the study. The GroundTruth team have completed their field surveys to collect data to generate Digital Terrain Models (DTMs) and Red, Green, and Blue (RGB) Orthomosaic and multispectral imagery for the Sabie River (Figure 28).

The Digital Terrain Models were used to make Triangulated irregular network (TIN) models of the Upper and Lower Sabie Reach in ArcMap. The Elevation field was chosen for display with 20 equal intervals of classification distribution for display. The colour chosen for display on all the maps is called the Bathymetric Scale in ArcMap. The maps were exported to ArcScene to view in 3D. The imagery unfortunately does not include enough of the banks to make a beautiful map but there is enough to show that the Sabie River has a flat broad flood plain (Figure 29 to Figure 33)

The Bathymetry of the Sabie is very complex and for the Hydraulic model, a 2D flexi mesh will be used to account for the complexity. Delft3D from Deltares will be used for the modelling work. The Upper Sabie modelling will be done first and then the Lower Sabie.

2.3. Olifants River

GroundTruth has been appointed by the International Water Management Institute (IWMI) to develop a 2D hydraulic model for a portion of the Olifants River, located in the Limpopo province, 30 kilometres upstream of the Massingir Dam in Mozambique. The objective of developing this 2D hydraulic model is to update the e-flows generated from the Limpopo PROBFLO study. The software being used for this particular river is the HEC-RAS (Hydraulic Engineering Centre – River Analysis System) 2D. The model was selected due to its ability to produce suitable velocity and flow depth data for a range of discharges which can be used to inform the e-flow study and update.

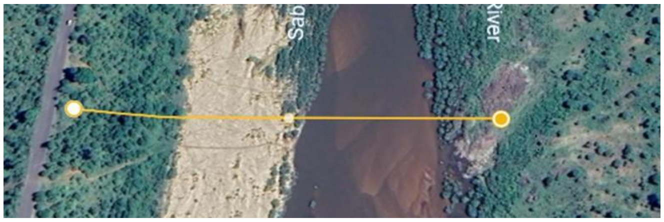

Figure 24 A visual representation of the transect situated at Lower Sabie utilizing Google Maps.

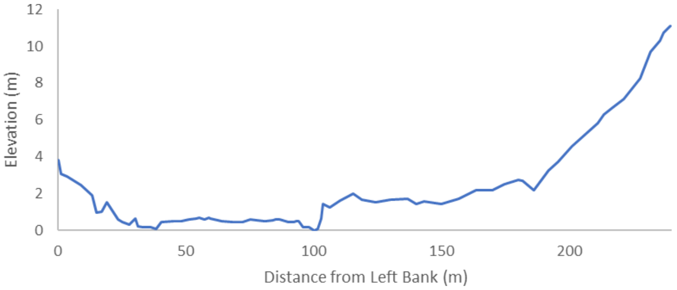

Figure 25 One dimensional representation of lower Sabie (X33B) developed in excel to showcase the length and heigh of the transect.

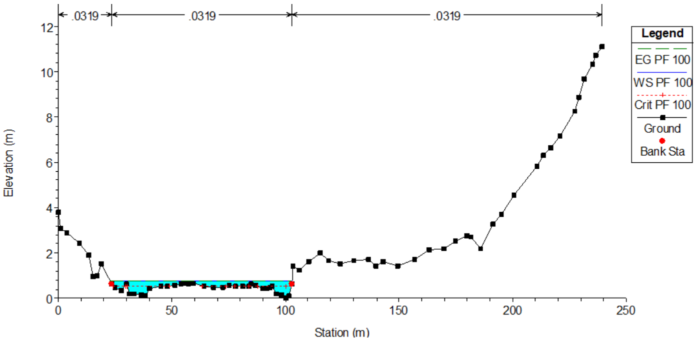

Figure 26 Simulation of flow on the one dimensional transect ran in HEC-RAS 6.4.1 to illustrate how the rating curves are generated.

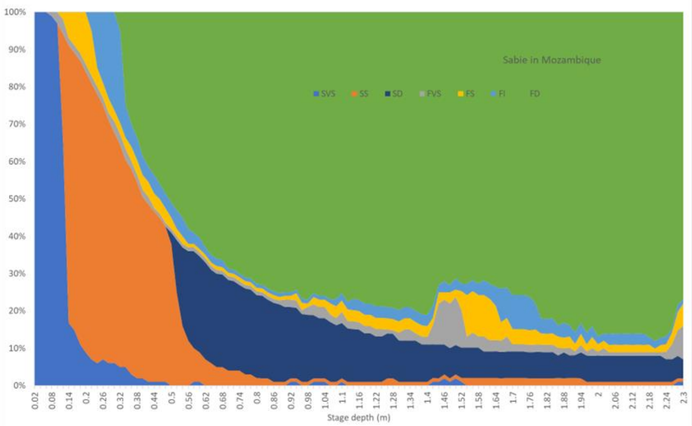

Figure 27 Modelled velocity depth frequency distributions for various maximum depth levels for Lower Sabie (X33B).

Figure 28 The survey extent for the Digital Terrain Models (DTMs) and Red, Green, Blue (RGB) Orthomosaic and multispectral imagery of the Upper and Lower Reach of the Sabie River.

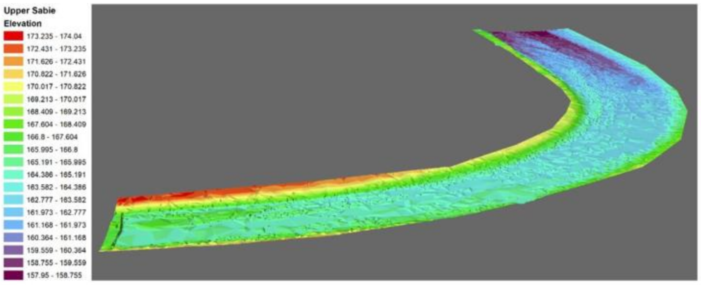

Figure 29 The elevation model of the upper Sabie River.

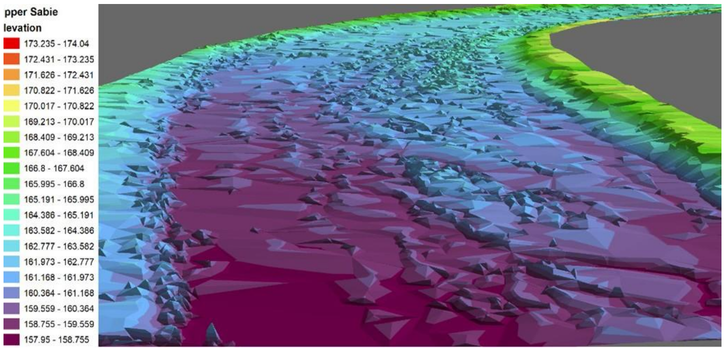

Figure 30 The elevation model of the upper Sabie River looking downstream.

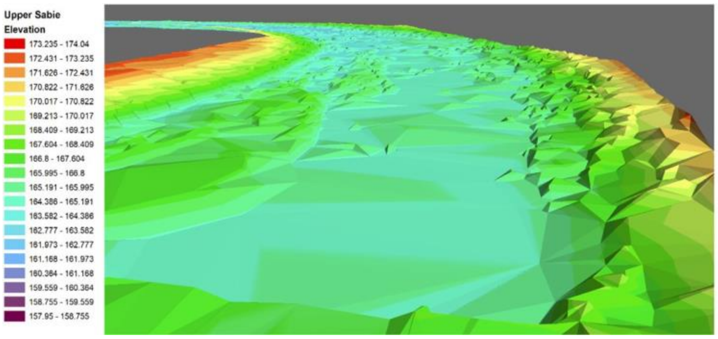

Figure 31 The elevation model of the upper Sabie River looking from the bottom of the reach upstream.

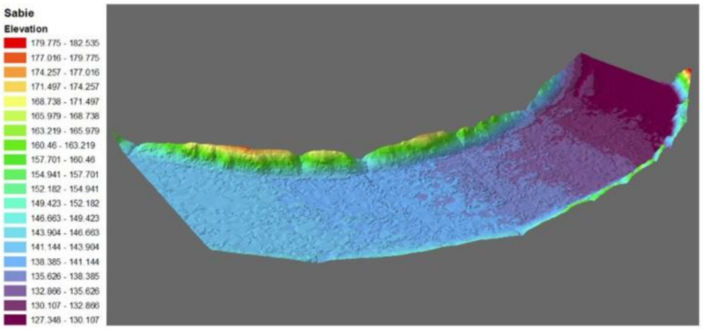

Figure 32 The elevation model of the lower Sabie River.

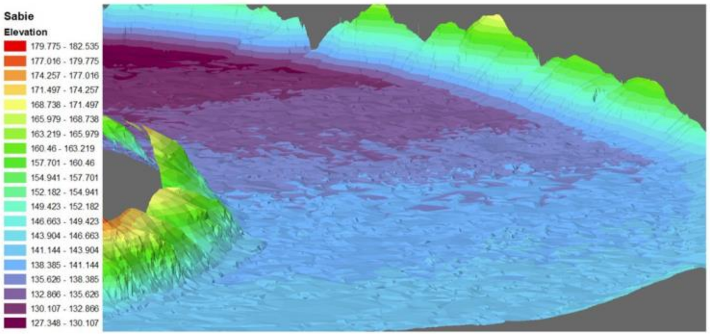

Figure 33 The elevation model of the lower Sabie River looking downstream.

To form part of the digital innovation of the study, an Unmanned Aerial Unmanned (UAV) survey of the area of interest was conducted in September 2023. Elevation data derived from the surveys were thereafter used to develop a 3D terrain model to incorporate into the hydraulic model.

This report details the progress of the generation of this model as well as what is still required to finalise the results.

The progress associated with the hydraulic model of the Olifants River is highlighted below:

A LiDAR survey to capture elevation and RGB imagery was undertaken in September 2023. The elevation and imagery datasets have been processed and delivered.

- The HEC-RAS 2D model has been partially set up with a few trial runs to check model stability.
- A Habitat-Flow (HABFLO) simulation model has been undertaken using the 1D cross-section surveyed on-site, which will be compared to the 2D model and the modelling results.
- The combined elevation model of the LiDAR data and the SONAR data is yet to be processed and established, and therefore no further work on the model has been undertaken.
- The bathymetric data from the Rivers of Life Aquatic Health Services (ROL) has been received and could be used to verify/calibrate the SONAR survey.
- The HEC-RAS model will be refined once all the datasets are processed. A range of flows will be simulated through the model to generate both a depth and velocity result layer. These will then be processed to create a depth-velocity relationship to be used to verify the PROBFLO e -flows study.

The discharge, 1D hydraulic models have been developed and the rating curves have been tested for the Olifants River. Additional comprehensive sub-surface bathymetric mapping for the Olifants River reach using the SonTek Hydrosurvayor-M9 has been collected. The GroundTruth team used a Bluerobotics Ping echosounder and an ultrasonic sensor to obtain the underwater depths for points along the Olifants River to generate a complete terrestrial and riverbed profile for a portion of this River. In addition, an MF pro and a Global Water flow probe were used to collect depth and flow velocities for points along the Olifants river. The GroundTruth team have completed their field surveys to collect data to generate Digital Terrain Models (DTMs) and Red, Green, and Blue (RGB) Orthomosaic and multispectral imagery for the Olifants River (Figure 34). Ground Truth will use this data to generate a draft 3D digital twin river model and 2D hydraulic model for the Olifants River at Balule for the study.

Balule is a bedrock-controlled site at a dolerite dyke (Figure 35 to Figure 37). The river follows an anastomosing flow pattern along the steeper bedrock sections and a wandering channel or braided low flow channel for the gentle gradient sections between bedrock sections. Several of the

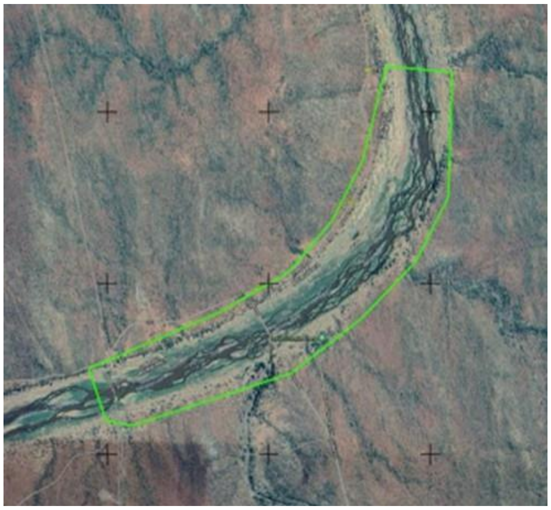

Figure 34 The survey extent for the Digital Terrain Models (DTMs) and Red, Green, Blue (RGB) Orthomosaic and multispectral imagery of Olifants River reach.

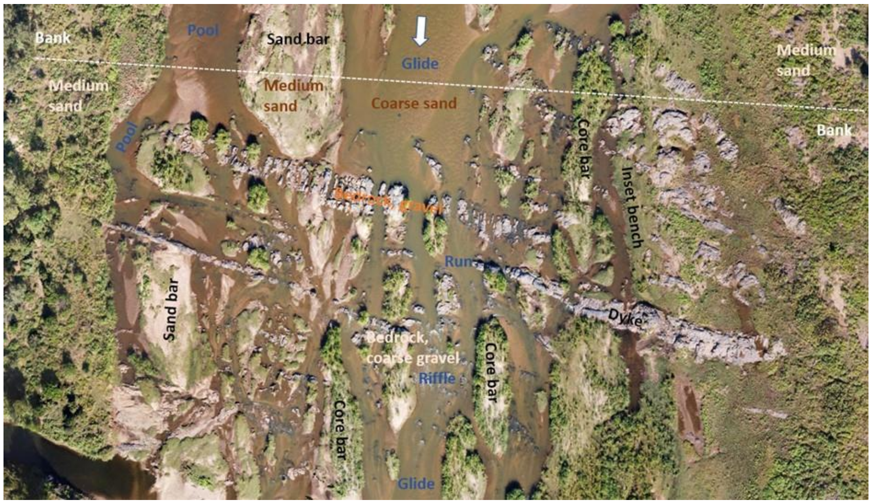

Figure 35 Orthophoto showing morphological features and sediment composition of OLIF-B73H-BALUL (Olifants River at Balule).

Figure 36 Site images showing a) a view from the right bank of the anastomosing bedrock channels; b) Silt drapes over sandy bed material; c) vegetated bars and stagnant high flow channels; d) gravel deposits in and around bedrock chutes.

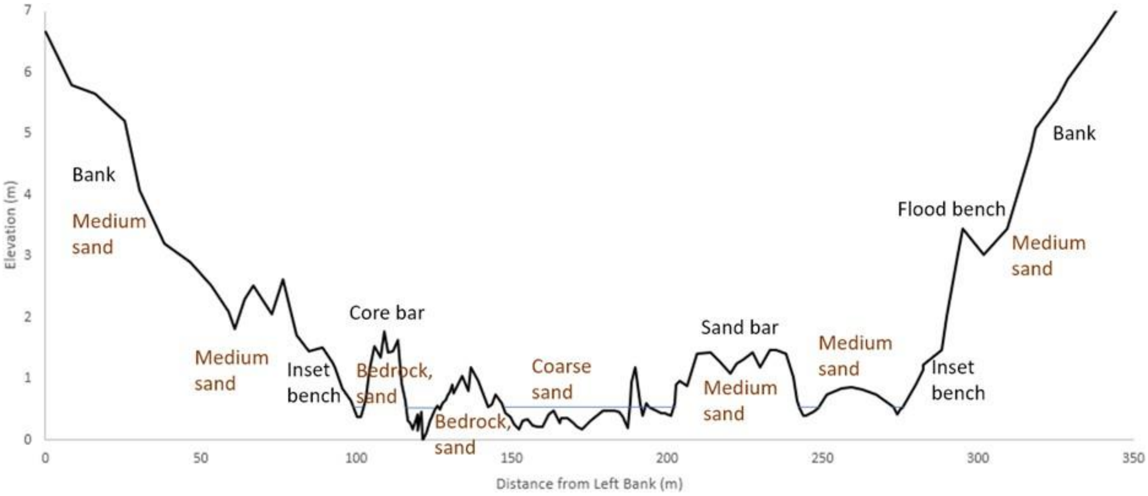

Figure 37 Cross section of OLIF-B73H-BALUL (Olifants River at Balule) showing morphological features and sediment composition.

high-flow channels become stagnant pool-type habitats under low-flow conditions. Silt deposits in these stagnant water during lower flows. Rapids, riffles, runs, glides and pools are associated with the bedrock sections, with glides and pools associated with the sandy sections. Bedrock core bars are common and are well-vegetated with reeds, forbs and grasses. Inset benches are narrow and poorly defined and composed of fine to medium sand. A flood bench is located along the right bank. The river is incised into the surrounding plain, with no active floodplain.

There is downstream fining of sediment from the rapids (boulder), riffle (cobble and gravel) to pools (sand and silt). Sand is largely stored as sand bars along the gentler gradient sections. The sand is moving in a single layer in water as shallow as 20cm. Flood debris was observed at 3 to 3.9m above the channel bed for 2021.

The upper and middle catchment has moderate to low densities of natural grassland and woodland that is used for grazing, with moderate densities of dryland agriculture, fallow fields, subsistence agriculture and urban development and low densities of mining. The lower catchment is largely natural grassland and woodland used for grazing purposes in conservation areas, with low to moderate densities of dryland agriculture, fallow fields, subsistence agriculture, urban

Table 4 Observed and modelled data used to derive the rating curve.

Date	Depth (m)	Mannings n	Energy gradient	Discharge (m3/s)	Velocity (m/s)	Comment
Zero flow	0.001	0.1000	0.002	0.000	0.001	Modelled
30 Feb 2020	0.53	0.031	0.002	4.47	0.410	Observed
3 May 2021	0.7	0.0338	0.0011	10.67	0.410	Observed
Flood 1	4.5	0.0300	0.003	3439.268	3.860	Modelled

development and mining. High to moderate sediment yield was predicted for most of the catchment, with lower values along the fringes of the catchment.

The observed and modelled hydraulic parameters are presented in Table 4. The rating equation and curve are presented in Table 5 and Figure 38 respectively. Figure 39 shows the modelled velocity depth frequency distributions for various water levels.

Utilizing advanced hydrographic surveying technology, specifically the Hydrosurveyor-M9, we successfully conducted bathymetric mapping throughout approximately 3 kilometres. The acquired data underwent thorough processing, enabling the generation of comprehensive 3D visualizations, as illustrated in Figure 40 to Figure 42. This technological approach not only facilitated precise and extensive bathymetric data collection but also empowered the creation of detailed representations essential for a comprehensive understanding of the surveyed area.

Subsequently, the collected data undergoes further analysis and modelling conducted by professionals. This comprehensive process aims to generate a 3D simulation of the catchment area. By employing advanced analytical techniques and modelling tools, these professionals integrate the acquired field data to create a sophisticated and accurate representation of the catchment's three-dimensional characteristics. This 3D simulation serves as a valuable tool for in-depth exploration, allowing for a nuanced understanding of the catchment's topography, hydraulic dynamics, and environmental features. The collaboration with experts in the field ensures the precision and reliability of the simulation, contributing to a comprehensive assessment of the studied catchment.

2.4. Sediment Mapping and Trapping

Crocodile River

The Crocodile River is bedrock-controlled with multiple channels. Boulder and cobble deposits are localized along the channel, with bars of cobble and gravel along the macro channel (Table 6). Sand deposits are widespread along the flood benches, with dense grazed grass covering the sand.

Table 5 Equation for the rating curve.

Power Fit: y=axb + c	
Coefficient Data	
a =	0.327
b =	0.322
c =	0

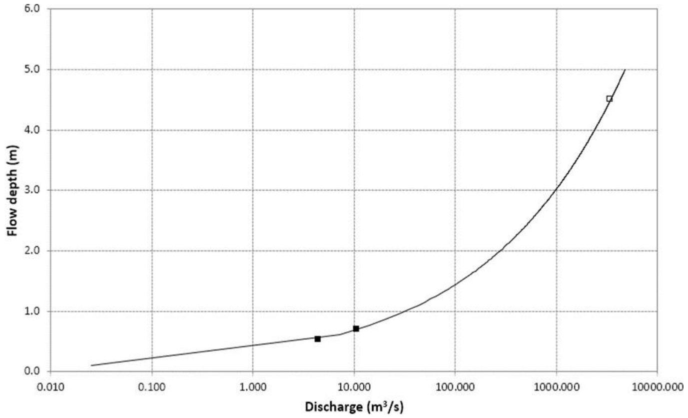

Figure 38 Rating curve for OLIF-B73H-BALUL (Olifants River at Balule).

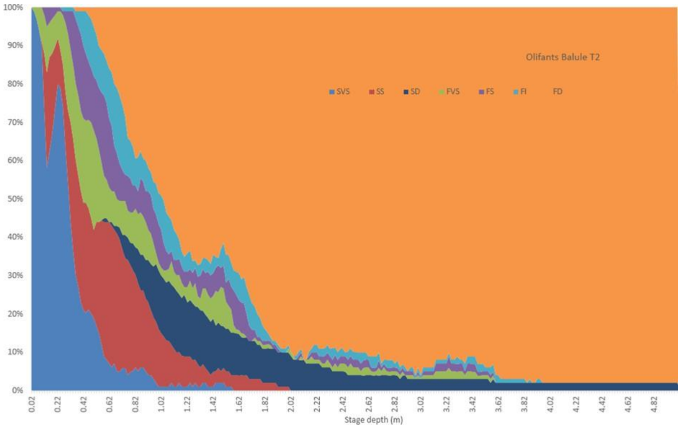

Figure 39 Modelled velocity depth frequency distributions for various maximum depth levels for OLIF-B73H-BALUL (Olifants River at Balule).

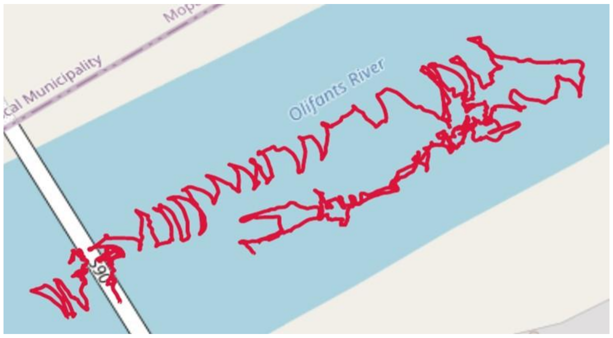

Figure 40 Map view of Bathymetric track covered with HydroSurveyor software.

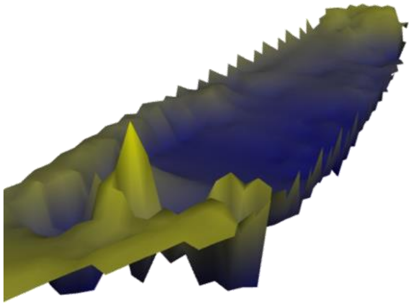

Figure 41 3D map of bathymetry collected on the Olifants River processed using HydroSurveyor.

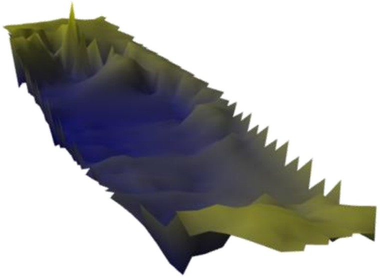

Figure 42 3D map of bathymetry collected on the Olifants river processed.

Sabie River

The Sabie River downstream of the weir is dominated by multiple bedrock channels, with localised sand and fine gravel deposits (Figure 43). Larger gravel and cobble substrates were largely absent outside the inundated channel, but localised deposits could be present within the channels.

The lower end of the gorge reach is impacted by siltation associated with the hydraulic backwater effect caused by the Corumana Dam (Figure 44). Due to the steep gradient of the reach, evidence of the siltation is only observed within the first ~400m upstream of the border with Mozambique and the high-water mark of the Corumana Reservoir. The area upstream of the impact zone is dominated by bedrock, with multiple reed-lined anastomosing channels (Figure 45). Sand deposits are common lee deposits outside the high-flow channel or within larger pools. Gravel and cobble are locally deposited in association with bedrock outcrops.

The deposited sediment ranged from silt and clay near the Corumana Reservoir to coarse sand to small cobbles over bedrock (Table 7).

Olifants River

The Olifant's reach at Balule is a bedrock-dominated reach with a widespread sand cover (Figure 46 and 47).
Localised deposits of gravel, cobble and boulders are associated with exposed bedrock sections (Figure 48 to 50). Reeds grow on the sandy and gravelly substrates. The sand sections are largely shallow with flows ranging from slow to fast. Deeper water is associated with bedrock runs along dissected anastomosing sections.

Sediment samples ranged from fine sand to large cobbles (Table 8), with the ground-truthing showing good agreement with observations from the orthophotos.

3. Way Forward

The ongoing work on the Crocodile River encompasses several key phases. Currently, the focus is on advancing the 2D model, involving the analysis of field data, its calibration, and validation. This extensive dataset is pivotal in mapping both fish occurrence and the prevailing flow characteristics. Subsequently, the model will undergo simulation using typical river flows, culminating in a comprehensive two-dimensional profile of the river, which will be integrated into PROBFLO.

In an innovative stride towards establishing a 3D model for e-flow implementation in the Crocodile River, a LiDAR survey covering a substantial stretch (3km reach selected) has been conducted. This survey, accompanied by nine initial ADCP tracks, provides valuable insights into velocity-depth relationships and bathymetry variability at the site. The initial data already showcases the significance of adopting a 3D approach, particularly evident in the exceptional dynamism of the river habitat. Moving forward, the next phase involves integrating this data to construct a 3D model, aiming to reveal flow-ecosystem and flow-ecosystem service relationships, thereby underlining the value of 3D modelling in e-flow studies (example model in Figure 52).

The GroundTruth team has completed field surveys employing drone-based red LiDAR, amassing approximately 2-4km of bathymetric data for the Van Graan, Lower Sabie, and Balule sites (Figure 51). This extensive dataset is slated to be utilized by Justin Pringle, Smrithi Singh, and Linda Cronje in developing hydraulic models. Additional contributions are expected from Benjamin van der Waal, who is planning a geomorphology survey, incorporating additional ADCP river bathymetric data collection (consider Annexure Figure 53 to 58) crucial for completing the Digital Twin.

While the targeted completion date for all bathymetric data for digital twin modelling is set for November 30, 2023, the updated 2D hydraulics may extend beyond this deadline.

Sediment mapping field data play a critical role in refining substrate mapping accuracy along macro channels. Despite challenges in sediment classification, efforts are underway to extract dominant sediment types, with an upcoming focus on collecting and analysing sediment trapped by time-integrated samplers. These insights will serve as valuable input for the hydraulic models.

In addressing challenges and prioritizing safety, alternative methodologies for capturing cross-sections and bathymetry at the Sabie site are actively being explored. Among the technologies under consideration is the YSI rQPOD Remote Surface Water Vehicle. This deployment aligns with our commitment to team safety, maintaining data integrity, and ensuring accuracy in the face of unique conditions at the Lower Sabie site. This commitment is further underscored by our exploration of advanced technologies, emphasizing the comprehensive and meticulous nature of our study.

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Figure 43 Bedrock dominated anastomosing channels of the Sabie River.

Figure 44 Silted habitat near the Mozambique border.

Figure 45 Upstream view of the bedrock anastomosing section of the Sabie showing no siltation due to the backup effect of Corumana Dam.

Figure 46 Bedrock with sand and gravel deposits.

Figure 47 Shallow sandy habitat with limited vegetation cover.

Figure 48 Cobble and gravel bar with sand lee deposit.

Figure 49 Gravel and cobble deposit with sand and reed fringes.

Table 6 Particle size for selected substrates along the Crocodile River.

Sample location	D16 (mm)	D50 (mm)	D84 (mm)	Classification
Cob 01	90	130	180	Large cobble
Med sand 02	0.2	0.3	1	Medium sand
Cob grav 03	80	140	180	Large cobble

Table 7 Particle size for selected substrates along the Sabie River.

Sample location	D16 (mm)	D50 (mm)	D84 (mm)	Classification
Sabie Sand 01	0.25	0.5	0.9	Coarse sand
Coarse sand fine gravel	0.4	1.5	6	Coarse sand
Coarse sand fine grav 02	1	2	5	Fine gravel
Coarse sand fine grav 03	0.2	2	6	Fine gravel
Coarse sand fine grav 04	0.3	1.8	5	Coarse sand
Large grav small cob 05	80	110	186	Small cobble
Large Grav 06	41	61	84	Very coarse gravels

Table 8 Particle size for selected substrates along the Olifants River.

Sample location	D16 (mm)	D50 (mm)	D84 (mm)	Classification
Balule Med Sand 01	0.15	0.4	0.8	Medium sand
Balule Med Sand 02	0.1	0.3	0.5	Medium sand
Balule Med Sand 03	0.2	0.4	0.9	Medium sand
Balule Fine Sand 01	0.1	0.18	0.4	Fine sand
Balule Med sand 04	0.18	0.28	1	Medium sand
Balule Large Gravel bar 01	36	54	83	Very coarse gravels
Balule Med gravel bar and riffle	12	32	52	Coarse gravel
Gorge Cobble bar	130	190	380	Large cobbles

Figure 50 Example of ground-truthed locations of a range of sediment types (grav is gravel and br is bedrock).

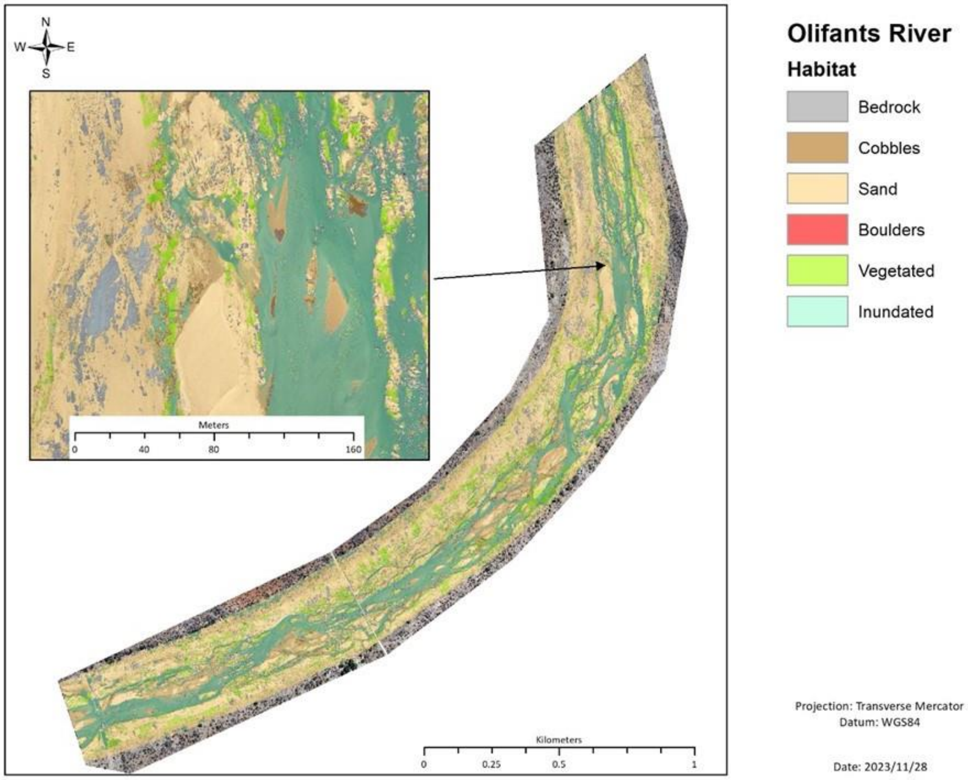

Figure 51 Example of the basic sediment types present along the Olifants River following an interactive supervised classification.

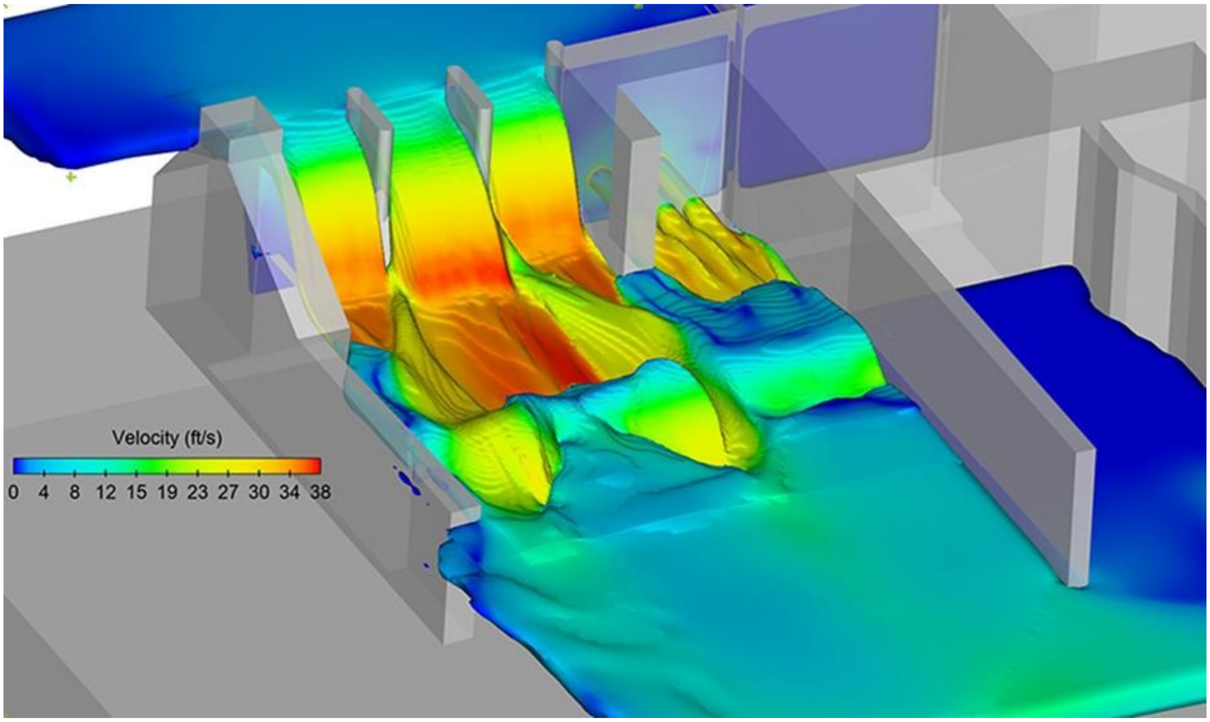

Figure 52 An example of a 3D OPENFOAM model of a dam flow release. This study will result in the model and associated hydrodynamic model.

Appendix. Evidence of cross section and bathymetric sections of the Crocodile River

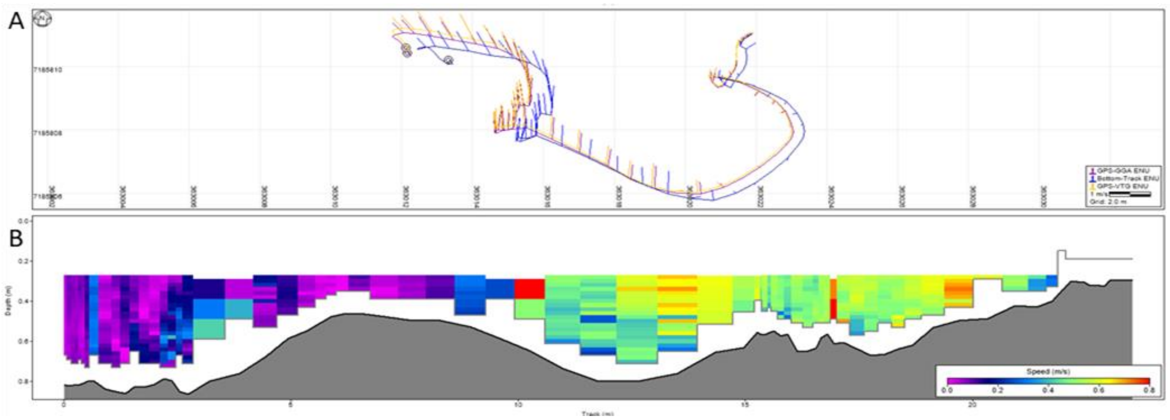

Figure 53 Example of a bathymetric river modelling track generated for the Crocodile River in the study using the ADCP M9 with coordinates for the tracks (A) and velocity depth profiles (B).

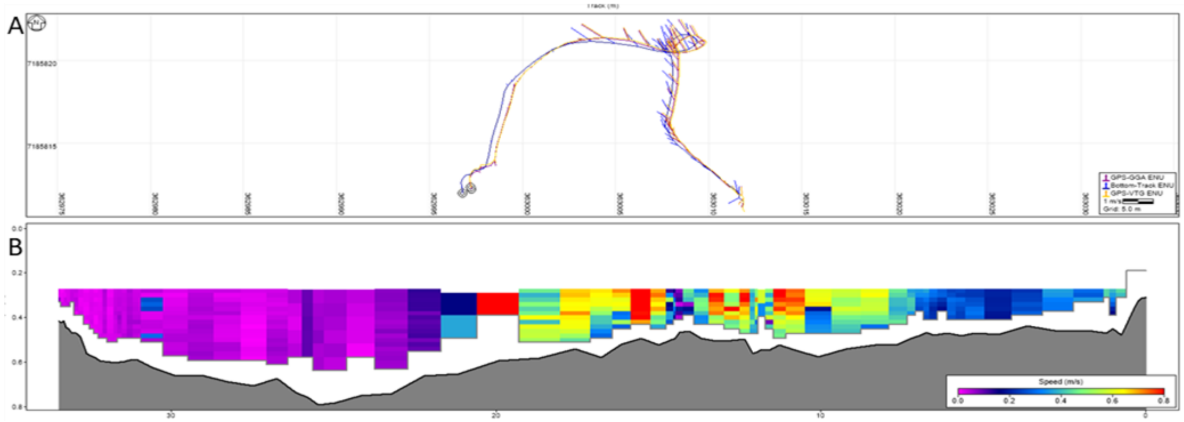

Figure 54 Example of a bathymetric river modelling track generated for the Crocodile River in the study using the ADCP M9 with coordinates for the tracks (A) and velocity depth profiles (B).

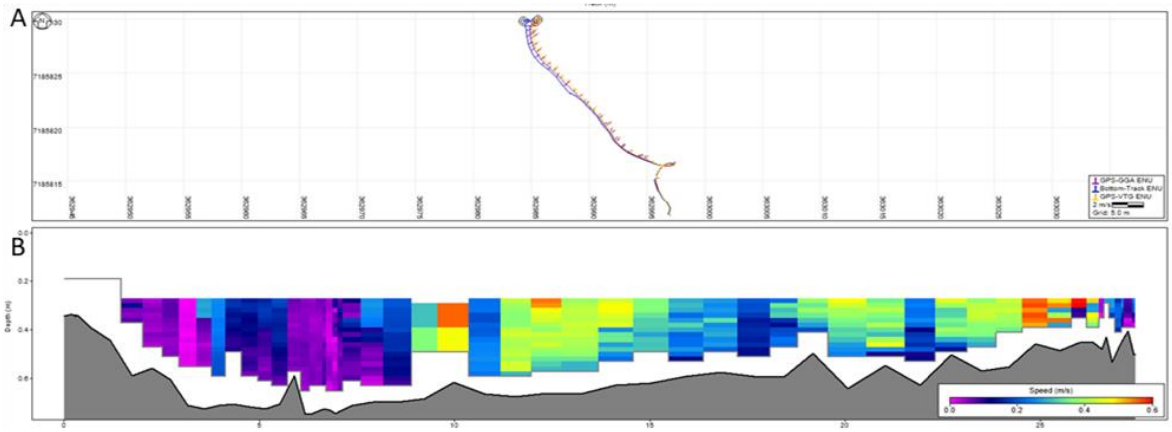

Figure 55 Example of a bathymetric river modelling track generated for the Crocodile River in the study using the ADCP M9 with coordinates for the tracks (A) and velocity depth profiles (B).

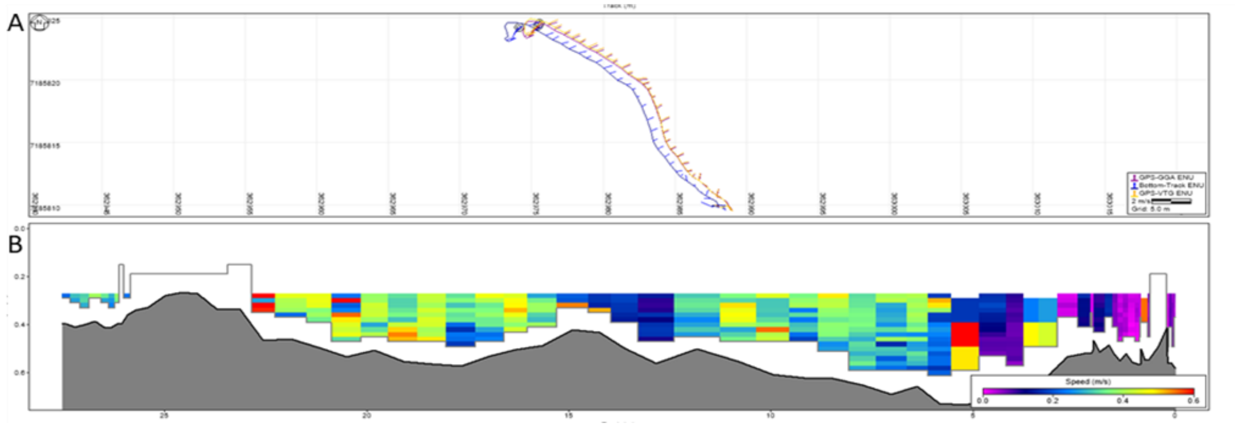

Figure 56 Example of a bathymetric river modelling track generated for the Crocodile River in the study using the ADCP M9 with coordinates for the tracks (A) and velocity depth profiles (B).

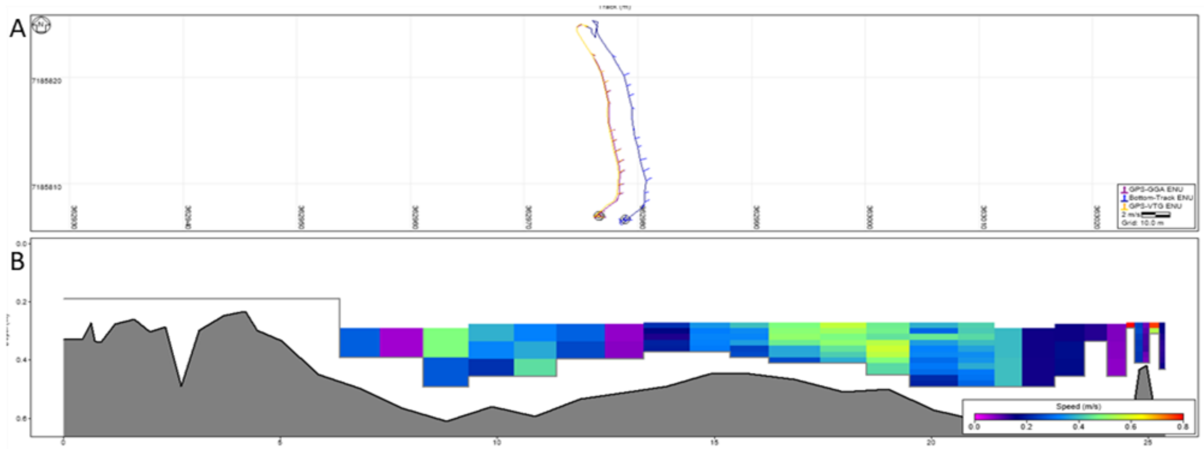

Figure 57 Example of a bathymetric river modelling track generated for the Crocodile River in the study using the ADCP M9 with coordinates for the tracks (A) and velocity depth profiles (B).

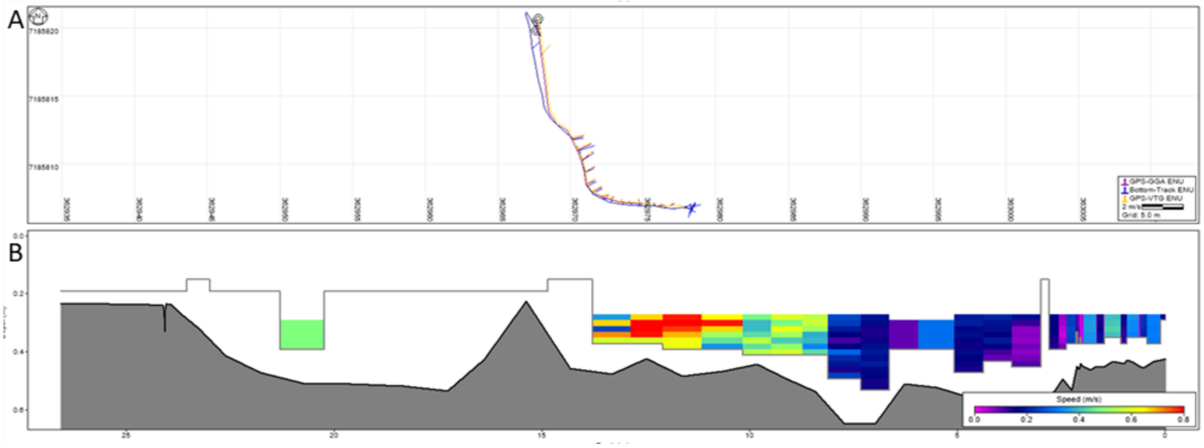

Figure 58 Example of a bathymetric river modelling track generated for the Crocodile River in the study using the ADCP M9 with coordinates for the tracks (A) and velocity depth profiles (B).