Digital Technology to Construct 3D Hydrodynamic Models for Monitoring Environmental Flows

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Abstract To support the implementation of environmental flows (e-flows), we piloted a three-dimensional digital modeling approach to monitor the changes in river ecosystems. A high-resolution 3D model of study sites in the Crocodile River, South Africa, was constructed and used to test its utility and value to monitor changes in river ecosystem structure over time. The initial demonstration of the approach shows highly detailed 3D models of nine tracks across the study sites. The output represents the velocity-depth and bathymetry variability of each site in 3D. The dataset successfully demonstrated the potential value of adopting the approach for e-flow implementation to monitor the habitat dynamism to support the timely management of river health. In the next phase, this assessment will integrate the 3D modeling approach into a hydrodynamic modeling framework to investigate dynamic relationships between flow-ecosystem and ecosystem services.

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Introduction

Phase 1 of the study entails evaluating existing and new innovative methods for the collection of field data to establish a 3D model to support PROBFLO modelling of confident flow-habitat-ecosystem dynamics to support the implementation of e-flows. In this phase existing Acoustic Doppler Current Profiler and LiDAR data will be tested as an innovative addition to existing hydrodynamic modeling 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). A case study site or reach of river on the Crocodile River in the Inkomati Basin has been selected for hydrodynamic modeling for e-flow assessments. The 3D model will describe the hydrological, hydraulic, geomorphological, riparian vegetation and instream ecosystem characteristics so that accurate discharge-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 river above and below 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 implementation of e-flows based on detailed maintenance of habitat structure and water flows.

Ecohydraulics 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). Ecohydraulic modelling is used to predict how hydraulic conditions in a river might change under difference 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 are required and provide 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 are able to 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).
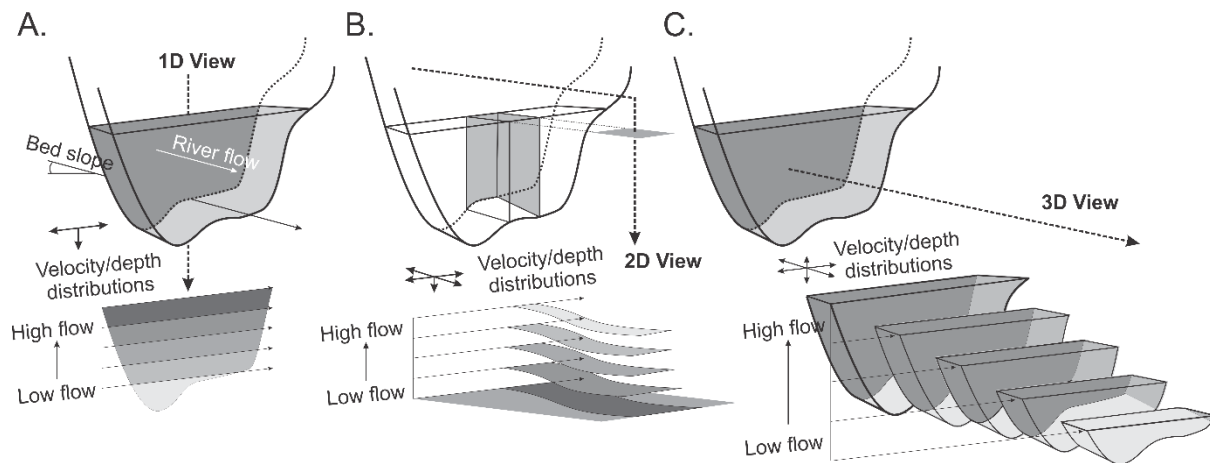
Figure 1 Velocity, water depth and shear stress results in a 1D, 2D and 3D numerical simulation (adapted from Tonina and Jorde, 2013)

The progression in available evidence to describe flow-ecosystem and flow-ecosystem service relationships using 1D, 2D and 3D models includes (consider Figure 1) the following.

- **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 variable and discharge-ecosystem service relationships in e-flow determination processes and implementation. Of great importance to the social and ecological teams who establish flow-ecosystem and flow-ecosystem service relationships is 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/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-sections 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 and or implementation/monitoring processes.

- **2D:** While the amount of data required for 2D modelling increases from requiring 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 information available from 1D approach is available and incorporated, which includes rated cross sections from the 1D approach for accurate discharge determination. But the 2D approach has functionality to model critical habitats within a 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 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 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-ecologically processes. From global reviews (Horne et al., 2017) of e-flow determination studies, 3D hydraulic modelling, which is generally not included in e-flow determination studies due to price 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.

Methods

Hydrodynamic modelling

To set up the 3D hydrodynamic 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 2.

The data collected from the field surveys is being analysed using Hypack Max or Hypack Lite. It will be processed and simulated using OpenFOAM. Lidar data was acquired and processed into a 3D version as shown in Figure 3. Meshing must still be undertaken, which is the process of breaking down the geometry into individual

volumes, and finite volume cells; within each volume critical equations are solved. Once completed it is required to set the boundary conditions which are the observed conditions of the site, like velocity and slope. Simulation can then be run to test the accuracy of the model with the discharge and water level observed.

Figure 2 The location of the cross-section analysis (purple) and bathymetry mapping (red) undertaken at the site on the Crocodile River.
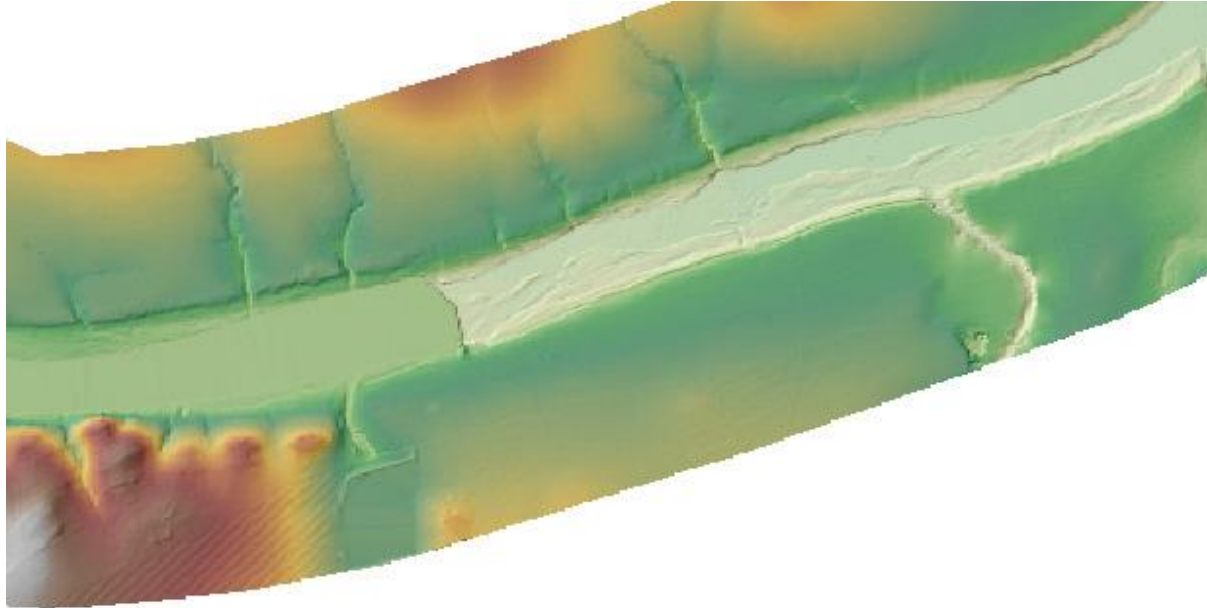

Figure 3 Manipulated Lidar data for the site on the Crocodile River to represent a 3D model

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 pertaining to 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).

Results and Discussion

The results for the four separate tracks surveyed are shown in Figure 4. The first graph in Figure 5A shows the coordinates of the M9 Surveyor for the cross-section. The circles show the last known possession of the M9 Surveyor at the time. The yellow and purple lines are the coordinates produced by the GPS while the blue

lines depict the bottom tracker. This method determines whether the Surveyor is going in a straight line when there is no GPS signal available.

Figure 5 illustrates 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 6). 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 Figure 7 to Figure 13.

Figure 4 Location of the cross-section (purple) and bathymetry (green, red, white) results. Variable direction tracks (zig-zag) are used to generate depth-velocity data for the reach which is used in the modelling process.
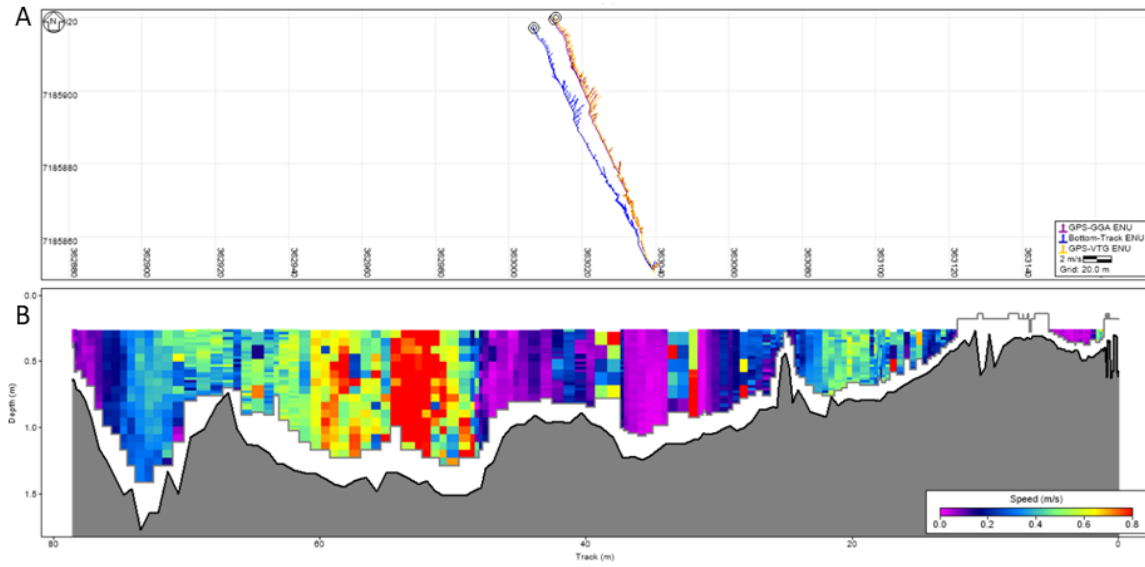
Figure 5 (A) Coordinates of the M9 surveyor and (B) bathymetry over the cross-section to model instream velocity-depth relationships. The total station was used to generate bank bathymetry data for the cross-sections (See Figure 4).
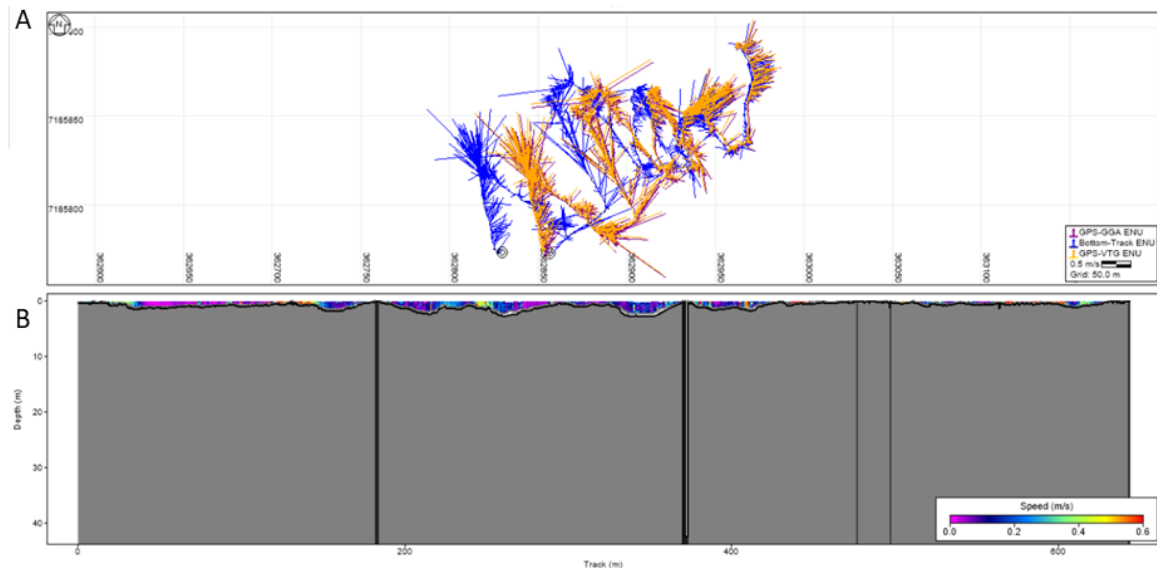

Figure 6 (A) Coordinates of the surveyor and (B) bathymetry over the green track (See Figure 4).
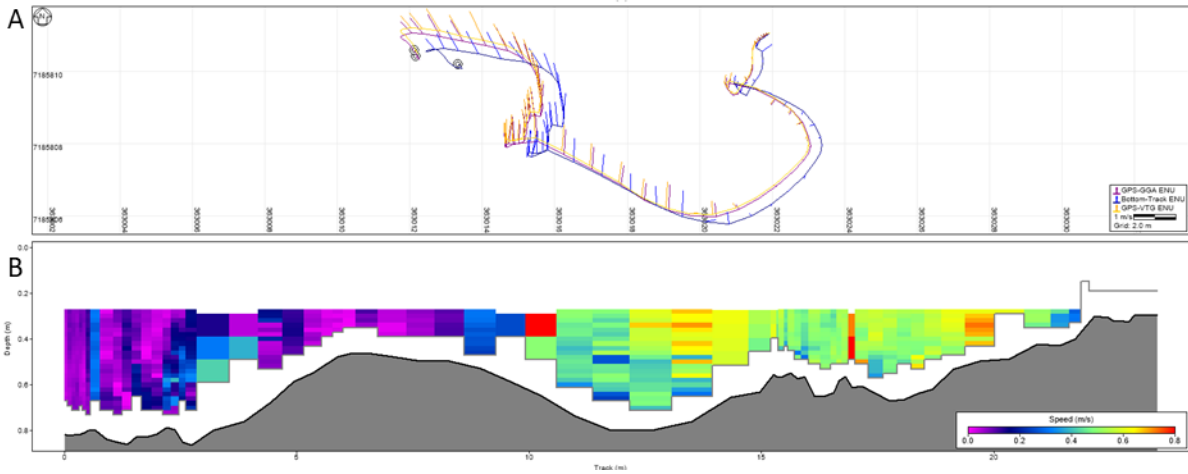
Figure 7 (A) Coordinates of the surveyor and (B) bathymetry over the green track (Fig 4)
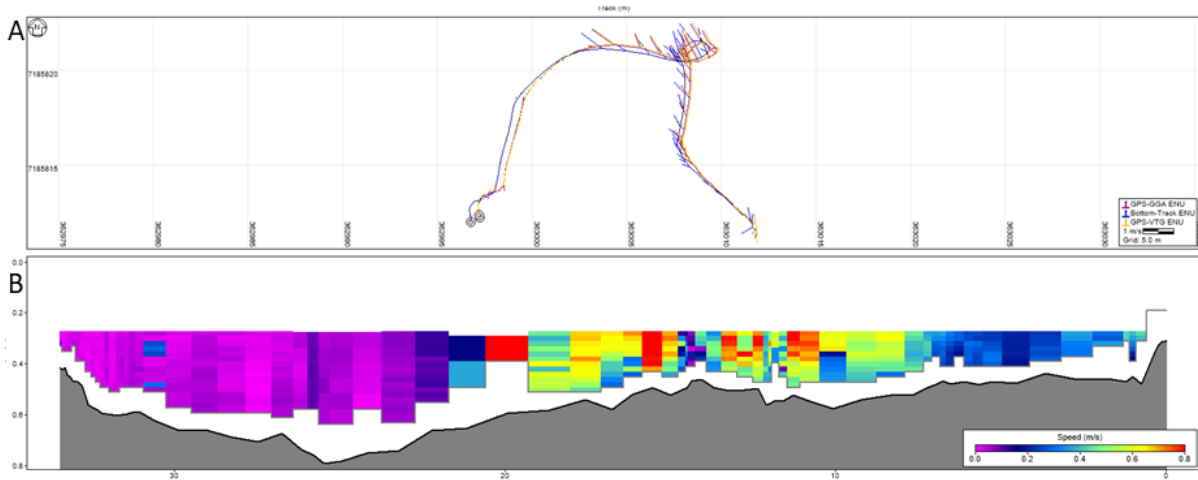

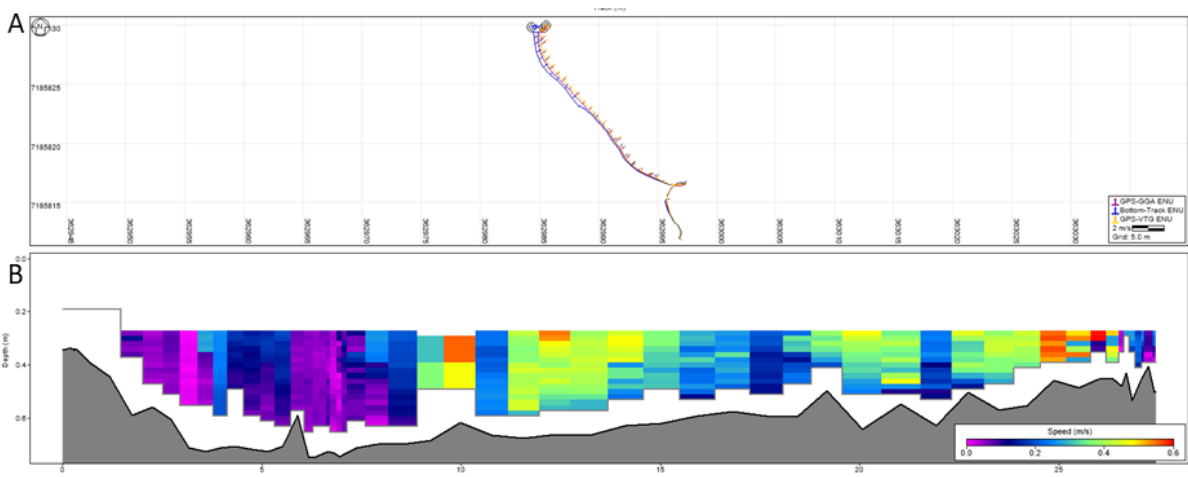*Figure 8 (A) Coordinates of the surveyor and (B) bathymetry over the green track (Fig 4)*

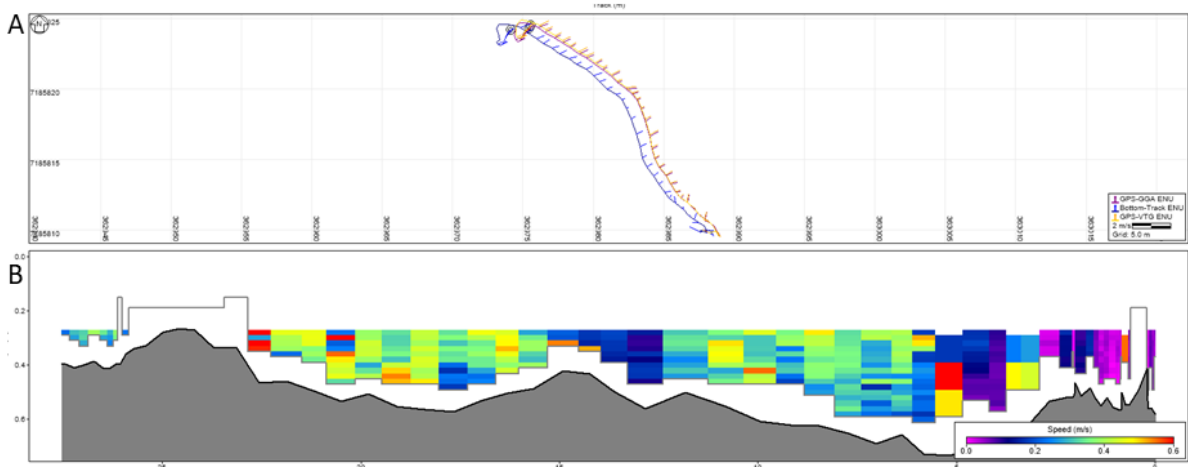*Figure 9 (A) Coordinates of the surveyor and (B) bathymetry over the white track (See Fig 4)*

Figure 10 (A) Coordinates of the surveyor and (B) bathymetry over the white track (Fig 4)
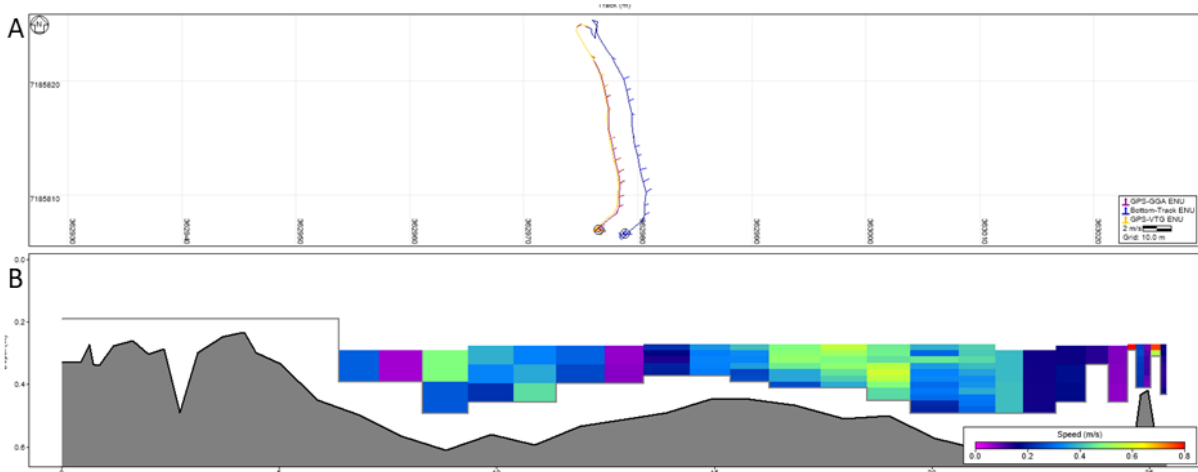

Figure 11 (A) Coordinates of the surveyor and (B) bathymetry over the white track (Fig 4)
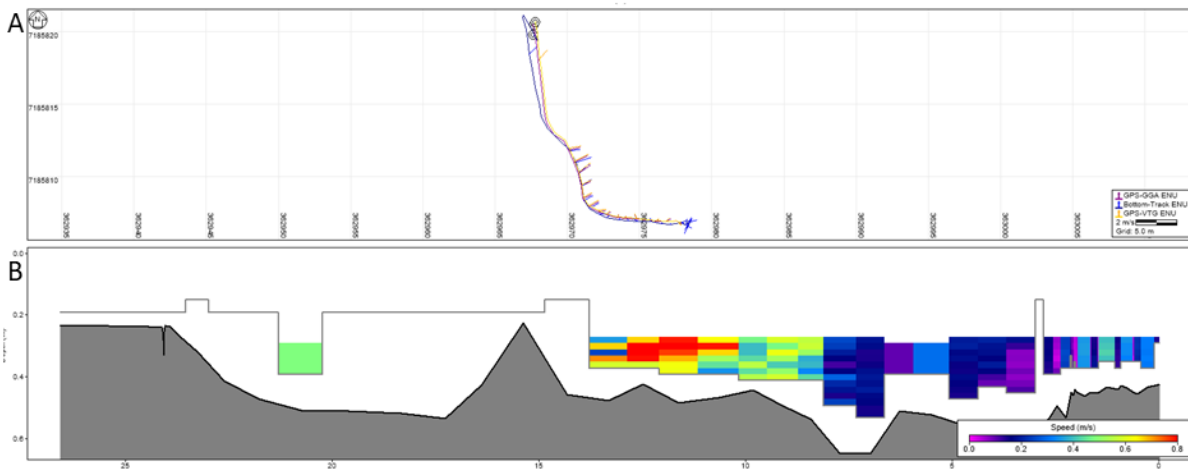

Figure 12 (A) Coordinates of the surveyor and (B) bathymetry over the red track (Fig 4)
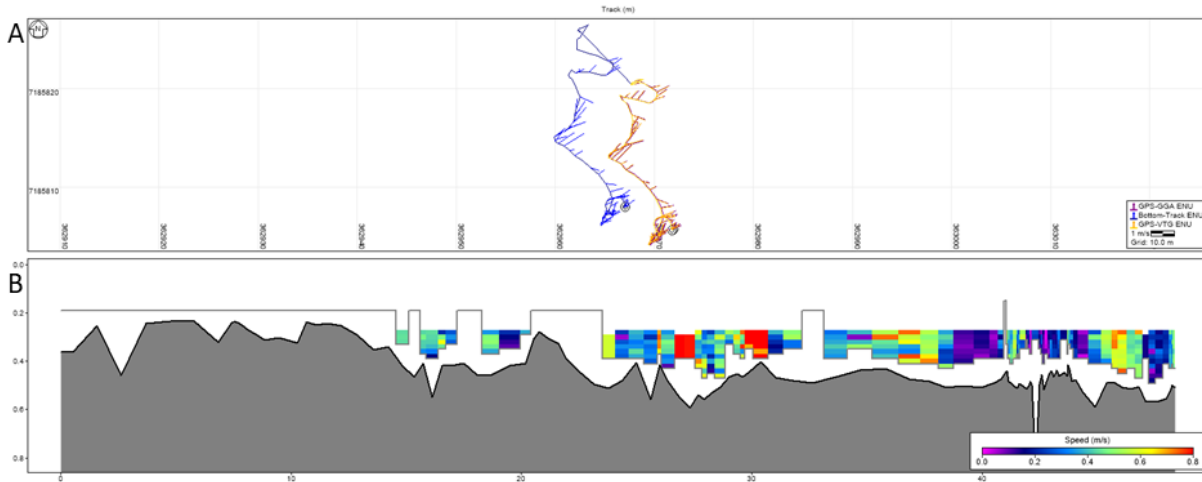
Figure 13 (A) Coordinates of the surveyor and (B) bathymetry over the red track (Figure 4)

The initial demonstration of the approach to establish a 3D model for e-flow implementation in the Crocodile River includes data obtained from a LiDAR survey of the larger reach of the Crocodile River (3km reach selected) with nine initial ADCP tracks (and associated data) to represent velocity-depth and bathymetry variability of the site. This data already demonstrates the value of adopting a 3D approach for e-flow implementation as the habitat dynamism has already been shown as exceptional. The next phase of this assessment is to integrate the data and determine a 3D model generate flow-ecosystem and flow-ecosystem service relationships to demonstrate the value of 3D modelling in e-flow studies.

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