Hydrological assessment to predict velocity-flow classes in the lower Thukela River

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It all starts here ™

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“With man this is impossible, but with God all things are possible.”

~ Matthew 19:26

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ABSTRACT

This study investigates the use of a two-dimensional hydrodynamic model (River2D) to determine environmental flow requirements in the lower Thukela River, KwaZulu-Natal. A digital elevation model (DEM) was developed by combining bathymetric data from field surveys with topographic data in ArcGIS. HECGeo-RAS was used to delineate cross-sections, flow boundaries, river banks and flood plains from the DEM. Data were imported to HEC-RAS were a series of flows were simulated to generate a stage-discharge curve. The predicted stage generated by HEC-RAS was used to set the downstream boundary conditions in River2D. The 2-dimensional modelling techniques used in this study make use of a combination of three different programs namely: BED, MESH and River2D to create a river bed profile that can be used for complex calculations.

To determine the habitat requirements and preferences, 19 freshwater and estuarine fish species relevant to the lower Thukela River were used in the analyses. Multivariate statistical analysis showed that some species community structures changed significantly with a change in substrate and velocity. *Labeobarbus natalensis* and *Eleotris fusca* were the identified indicator species for this study. Preference files were generated for each species as well as habitat suitability according to field data. To determine the environmental flow requirements (EFR) of the lower Thukela River, historic and habitat methods were used and compared. River2D make use of the PHABSIM concept to calculate weighted usable area (WUA) (m^2/m) by combining habitat suitability with velocity and depth preferences. The EFR suggested by the historic methods for the lower Thukela River is too low and does not consider the anthropogenic changes upstream of the study site and therefore the habitat method in the form of WUA was recommended.

Keywords: Velocity-flow classes; River2D; biological indicator; preference files; weighted usable area; environmental flow requirements

SAMEVATTING

Hierdie studie ondersoek die gebruik van 'n twee-dimensionele hidrodinamiese model (River2D) om omgewingsvloeivereistes te bepaal in die laer Thukela-rivier, KwaZulu-Natal. ʼn Digitale elevasie model (DEM) is ontwikkel in ArcGIS deur die kombinasie van velddata en topografiese data. HECGeo-RAS is gebruik om deursnitdata, rivier-oewers, en vloedvlaktes te genereer vanaf die DEM en is dan in HEC-RAS ingevoer. Addisionele vloei is gesimuleer om waterelevasievlakke te skep wat as grenstoestande in River2D gebruik is. Die 2-dimensionele model wat in hierdie studie gebruik is, maak van 'n kombinasie van drie verskillende programme gebruik, naamlik: BED, MESH en River2D om ʼn rivier bodemprofiel te skep wat gebruik kan word vir komplekse berekeninge.

19 varswater- en riviermondings visspesies relevant tot die laer Thukela-rivier is gebruik om habitatvereistes en voorkeure te bepaal. Statistiese analise het getoon dat gemeenskapstrukture van sommige spesies aansienlik verander as gevolg van ʼn verandering van substraat of vloeisnelheid. *Labeobarbus natalensis* en *Eleotris fusca* is as ekologiese aanwyserspesies vir hierdie studie geïdentifiseer. Habitatvereistes en voorkeurlêers vir snelheid, diepte en substraat is gegenereer vir elke spesie. Historiese- en habitatmetodes is gebruik en vergelyk om omgewingsvloeivereistes te bepaal vir die laer Thukela-rivier. River2D maak gebruik van die PHABSIM konsep om geweegde bruikbare area (m^2/m) te bereken deur habitatsgeskiktheid met vloei snelheid en diepte te kombineer. Die omgewingsvloeivereistes voorgestel deur die historiesemetodes is te laag en neem nie menslike verandering stroomop in ag nie en daarom word die habitatmetode voorgestel.

Sleutelwoorde: Habitat-klasse; River2D; ekologiese-aanwyser; voorkeurlêers; geweegde bruikbare area; omgewingsvloeivereistes

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ABBREVIATIONS

1D	One Dimensional
2D	Two Dimensional
ABF	Aquatic Base Flow
ADCP	Acoustic Doppler Current Profiler
ATTZ	Aquatic Terrestrial Transition Zone
BBM	Building Block Method
CSI	Composite Suitability Index
CSI	Combined Suitability Index
DEM	Digital Elevation Model
DTM	Digital Terrain Model
DWS	Department of Water and Sanitation
EFR	Ecological Flow Requirements
FIFHA	Fish Invertebrate Flow Habitat Assessment
FRAI	Fish Response Assessment Index
GIS	Geographic Information System
GUI	Graphical User Interface
HSC	Habitat Suitability Criteria
IFIM	Instream Flow Incremental Methodology
IFR	Instream Flow Requirements
LHDA	Lesotho Highlands Development Authority
LHWP	Lesotho Highlands Water Project
LoEs	Lines of Evidence
MAE	Mean Annual Evaporation
MALF	Mean Annual Low Flow
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
QI	Quality Index
RCC	River Continuum Concept
RDA	Redundancy Analyses
RES	Riverine Ecosystem Synthesis
SI	Suitability Index
TIN	Triangulated Irregular Network
TVHR	Transparent Velocity Head Rod
UTM	Universal Transverse Mercator
WUA	Weighted Useable Area

1. General introduction

Worldwide more than 2.3 billion people live in already water stressed areas where they have an annual per capita water availability of below the world average of 1 700 m^3 (WRI, 2008). South Africa currently has a population of about 53 million people which ranks it at number 24 out of the 25 most populated countries in the world (Statistics, 2013). The uneven distribution of the South African population makes water management challenging as the country mostly consists of an arid to semi-arid landscape and therefore most of the population densities (Figure 1) are concentrated on smaller areas resulting in an increase in environmental impacts.

The current water availability of 1 100 m^3 per capita of South Africans is under serious stress (Johansson, 1993). According to the DWA (2011) “Less than 10% of South Africa’s rainfall is available as surface water, one of the lowest conversion ratios in the world.” By further altering the natural flow system of a river through the construction of dams, weirs and bridges, ecosystems are more threatened today. With an increase in technology, excessive groundwater extraction is further contributing to the deterioration of the natural water resources (Postel, 2000). South Africa’s main rivers face great dangers as only 30% are still preserved and sustainable, while 47% are modified for human benefits and 23% have been transformed to a state where they are irreversible (Nel *et al.*, 2007).

It is impossible for humankind to live in urban agglomerations, producing food and consumer goods, expanding their technological development, without increasing the production of wastes, and especially without having a large part of these wastes reaching the water bodies (Perry & Vanderklein, 2009). Water management is probably the biggest environmental challenge and over the next 30 years the predicted water demand will increase with 52% (Walmsley *et al.*, 1999).

The available fresh surface water on earth only makes up a minuscule portion of 0.01% of the world’s water, yet it contains more than a 100 000 species out of the 1.8 million species described on earth (Dudgeon *et al.*, 2006). Freshwater is considered the most vital resource on earth and its conservation was declared as a priority during the international Decade for Action “Water for Life” 2005-2015 (Dudgeon *et al.*, 2006). The conservation and management of these ecosystems are critical as they provide a valuable natural resource to cultural, scientific, aesthetic and economical progression which is of interest to all humans, nations and governments (Dudgeon *et al.*, 2006). Ecosystems are in great danger because of population growth which results in overexploitation, habitat degradation, water pollution and flow modifications, therefore the conservation of freshwater ecosystems is one of the biggest environmental challenges that our generation faces (Dudgeon *et al.*, 2006).

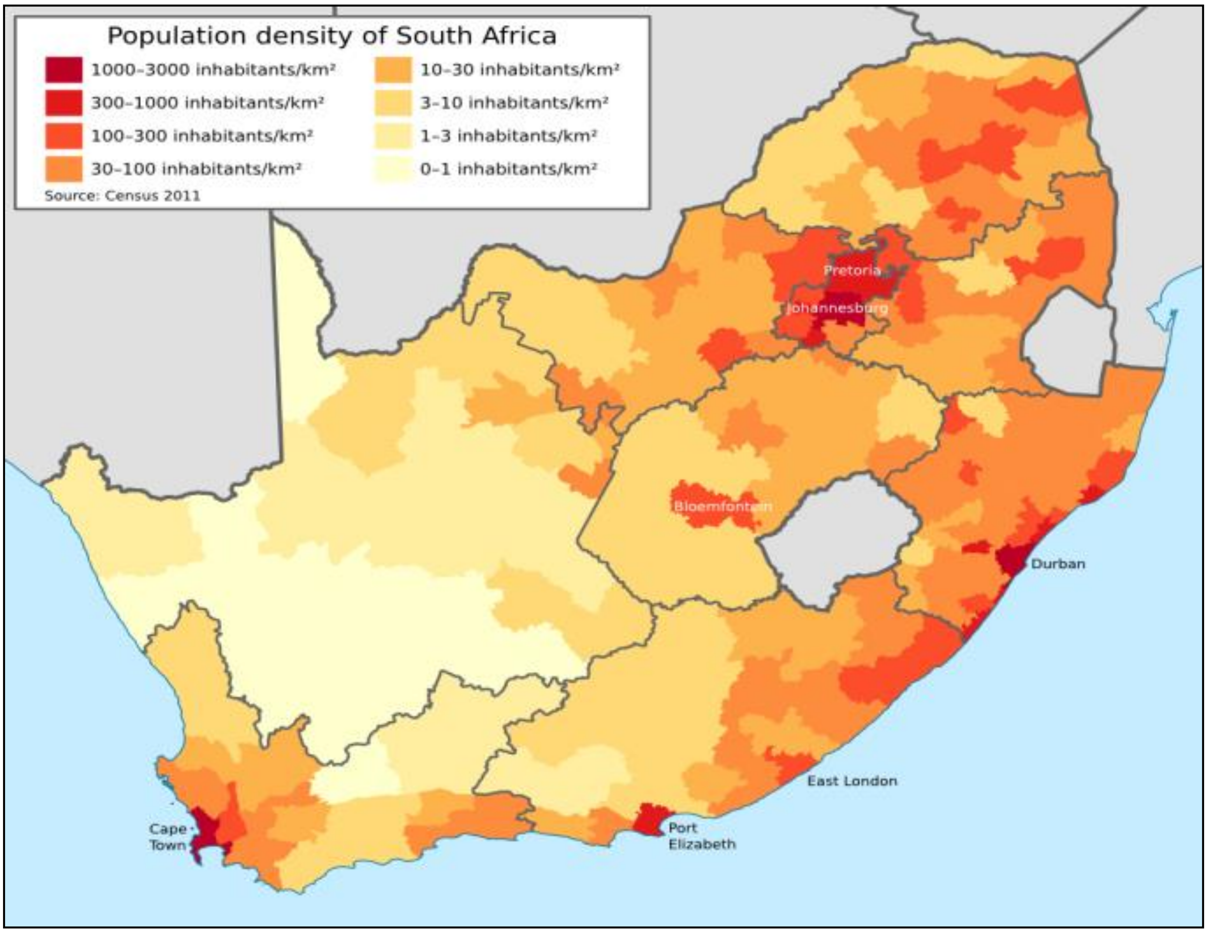

Figure 1: Population density and distribution in South Africa (Statistics, 2013).

1.1. Problem Statement

The Lower Thukela Bulk Water Infrastructure Project in Mandini includes the construction of a new dam on the Thukela River. This will reduce water demand from the Hazelmere Dam which currently provides water for the iLembe District. Construction of the bulk water supply scheme will provide sufficient water for the KwaDukuza and the Mandini local Municipalities in the eThekwini district. The purpose of the project is to supply 55 Ml/d of treated water in phase one and ultimately a total of 110 Ml/d. The new dam in the Lower Thukela River could possibly have a major impact on the flow regime downstream. Ecological flow requirements for the lower Thukela River are not only important on a socio-economic level but also for the ecological state of the river. It is important to protect the aquatic habitat and therefore sustain flows as close to natural flows as possible. Different fish species have different flow requirements to migrate upstream, spawn and feed at different times of the year and for different periods. The regulation of flow will have a direct impact on the natural flow regime and therefore it is important to predict these requirements. The bulk water supply scheme is not the only anthropogenic buffer in the lower Thukela River but Sappi abstract water for industrial use from an artificial barrier established for the mill (Hocking, 1987). Disturbing the natural flow regime will have a negative effect on the aquatic ecology within a river and therefore it is important to understand and evaluate the extend of these impacts on the natural diversity in the ecological ecosystem. Flow alteration affects river hydrology and to link these changes to ecosystem processes eco-hydraulics were used, which links hydrological processes to instream habitat conditions. By modelling the hydraulics of a river it is possible to understand the instream hydraulic habitat that forms the basis of the aquatic ecosystem. As discharge increase so does flow velocity and depth, but this relationship is complex and related to the shape of the river channel as well as the “roughness” of the river’s substrate. Different parts of the river become inundated at different water levels and detailed on-site measurements and numerical modelling are required to determine the hydraulics of a river system.

1.2. Hypotheses

The hypotheses established for this study state:

1. The change in hydrological flow can be linked to habitat using a combination of GIS, HEC-GeoRAS and HEC-RAS.
2. Habitat preferences of fish can be used with hydraulic models to evaluate the environmental flow requirements and consequences of altered flows in the lower Thukela River.

1.3. Aims and objectives

The aims established for this study include the following:

1. Conduct an open water hydrological assessment to predict the different habitat classes for indicator fish species. In order to achieve this aim the following objectives have been established:
    a. Collect bathymetric data of an appropriate reach of the lower Thukela River and create a 2-Dimensional model to predict habitat flow classes.

    b. Collect topographic data for the study area at an acceptable accuracy for the 2D model.
2. Evaluate the flow dependant habitat requirements for indicator fish species in the lower Thukela River and how flow alterations will affect fish preferences for different cover types.
    a. Identify some indicator fish species with a good variability in preferences for different habitats associated with flows.
    b. Create preference relationships for each indicator species.
3. Predict the EFR and determine a baseline flow for the Thukela River not only to maintain the ecological state of the river but also to improve the current state by using fish as ecological indicators.
    a. Use different instream flow assessments to calculate the flow requirements for indicator species by making use of historic methods and habitat methods.

1.4. Dissertation structure

Chapter 1: Introduction

- Emphasise the importance of freshwater ecosystems, the problem statement as well as the aims and objectives set out to complete this study.

Chapter 2: Literature Review

- Discuss the scope of research done prior to field work and provide an outline of physical and ecological aspects that form and take part in a river ecosystem.

Chapter 3: Materials and Methods

- Description of the study area with climate and geology.
- Description of the materials and methods used to complete the study as well as data collection and manipulation techniques.

Chapter 4: Results and Discussion

- Presents an overview of results obtained and a detailed discussion and interpretation of the results obtained throughout the study and a comparison of the different techniques for ecological flow requirements.

Chapter 5: Conclusion and Recommendations

- Summary of the results obtained in the study and the conclusion drawn as well as recommendations for future studies.

Chapter 6: References

- A complete list of references cited in the chapters of this document.

2. Literature Review

2.1. Bioregions and ecoregions

The varying geology and geomorphology in South Africa is because of millions of years of continental movement and erosion as well as the climatic range from semi-arid to arid condition and have resulted in diverse ecosystems, including river ecosystems (Lamouroux *et al.*, 2002). Organisms living in rivers had to adapt over millions of years to cope with their abiotic and biotic environments and therefore the communities of plants and animals tend to be structured rather than random in any given river (Lamouroux *et al.*, 2002). Bio-geographical history of the region like climate, geology and topography will constrain the suite of potential species to the regional species pool. Species with suitable morphological, behavioural and life-history attributes will persist in any given river system (Lamouroux *et al.*, 2002).

Eekhout *et al.* (1997) used three groups of riverine organisms (riparian plants, invertebrates and fish) at a tertiary catchment level delineating bio-geographical regions for South Africa. This with detailed information on physiography was used to produce 18 bioregions for South Africa (Brown *et al.*, 1996).

Allanson *et al.* (2012) used geomorphological, geochemical and climatological features to describe and define five limnological regions within Southern Africa. These regions describe broad suites or typical assemblages of species that form the regional species pools.

More recently the South African landscape and variable geographic data was used to create an ecoregion map for Swaziland, Lesotho and South Africa (Figure 2). The key variables used in the typing were morphological classes and natural vegetation which is considered as an integrated variable of climate, geology, rainfall and soil. Ecoregion classification has become the basis for the grouping of rivers because it provides a broad indication of types of rivers, and types of animal and plant communities, one could expect to find in any part of the country. Information used to classify each of the 31 ecoregions is (Brown *et al.*, 2007):

- Main vegetation types
- Terrain morphology
- Mean annual precipitation
- Coefficient of variation of mean annual precipitation
- Drainage density
- Stream frequency

- Slope
- Median annual simulated runoff
- Mean annual temperature

2.2. River Landscapes

The change in the quantity and quality of water through its passage across the landscape from headwater to sea, annual floods, and the sequences of fast and slow moving water all contribute to the diversity of landscapes found in rivers (James & King, 2010). Water flowing downstream has the ability to do work in the form of turbulence and sound. The interaction of water and sediment during downward flow will shape the river bed and banks of the channel, thus forming distinctive features in the river landscape such as cobble bars, sand bars, islands, floodplains, meanders, deltas and beaches (James & King, 2010). Water flowing through over and around these features will provide physical living space for organisms in the form of habitat. According to Southwood (1988), it is important to understand the physical nature of the riverscape to be able to predict what type of organisms will exist in that river.

Two common features of rivers are:

- They are heterogeneous which means that they provide a variety of different habitats for organisms.
- Temporarily dynamic which allow habitats to change over daily, yearly, decadal and over longer time frames.

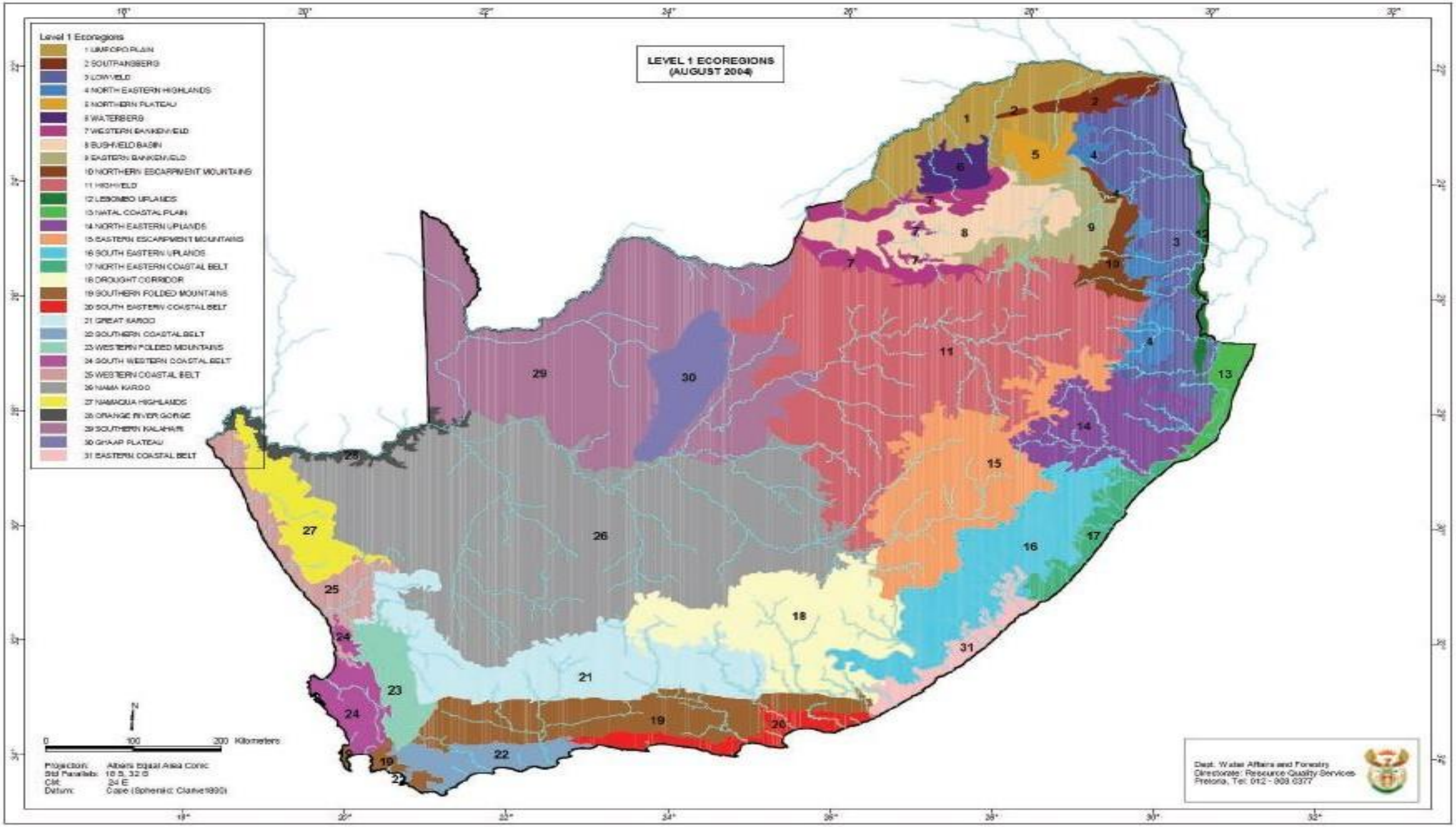

Figure 2: Ecoregion distribution of South Africa (Kleynhans *et al.*, 2005).

River as a longitudinal system

A river system is a longitudinal feature that acts as a conveyer belt transporting materials from the source to the sea. Rivers can be divided into mountain headwaters, mountain streams, foothills, transitional and lowland zones (Rowntree & Wadeson, 1999). Each zone is characterised by its hillslope and gradient which is dependent on topography and geology of the area as shown in Table 1 (Rowntree & Wadeson, 1999). A few variables that can change according to different zones include: channel width, volume of MAR, hydraulic characteristics, substratum particle size, water quality, temperature and more. Most rivers begin in mountain streams were they are fed by seeps and springs from mountain headwater. With a changing topography and geology, the river changes constantly throughout the various reaches.

Table 1: Different longitudinal zones for South African rivers (Rowntree & Wadeson, 1999).

Zone	Definition
Mountain headwater	Steep gradient (>0.1) almost equal vertical and horizontal flow in V-notched canyons, dominated by vertical flow over bedrock and boulders forming waterfalls and plunge pools. First or second order stream with straight channel creating step-pools.
Mountain stream	Steep gradient stream (0.01-0.1) in valleys, dominated by fast flowing water over boulders and cobbles with some coarse gravel in slower water. Second order stream with confined valley floor
Foothill	Moderately steep (0.005-0.001) in gentle gradient valleys, dominated by runs and riffles in a confined valley floor with moderate sinuosity and cobble bed. Second to third order river with narrow sand and gravel floodplains.
Transitional	Lower gradient (0.001-0.005) in wide gentle valley slopes with well-developed floodplains adjacent to river flow. Bed consists of sand and gravel with some bedrock intrusions forming pools that are much longer than riffles/rapids. Middle order river with moderate sinuous channel order.
Lowland	Low gradient (0.0001-0.001) in very broad valleys associated with extensive floodplains and meanders. Sand bed river with a high sinuosity, fully developed meandering stream with large silt deposits.

The River Continuum Concept (RCC) describes linkages between river habitats and the effect of upstream changes on the ecological framework downstream. This is one of the most influential frameworks that emerged from the zonation approach that helped to shape the conceptual thinking of river systems that function for more than a decade (Vannote *et al.*, 1980). The physical stream network must be in a state of dynamic equilibrium with continuous downstream adjustments due to kinetic energy e.g. the relationship between stream width, depth, velocity and sediment load. According to James and King (2010) rivers follow the basic law of conservation of energy, rivers tend to a uniform expenditure of energy along their lengths. The shape of a river is therefore a consequence of this uniform expenditure known as stream power, a product of Slope (S) and Discharge (Q). There is a direct relationship between S and Q, when S is high in the upper reaches the Q is normally low, as the Q increases the S will decline to maintain the constancy of QS (Gordon *et al.*, 2004).

The RCC can be used to predict the changes in catchment topography, hydrology, temperature and water chemistry between the headwater and the lowland which can then be used to predict the longitudinal changes of a rivers production, input, transport, utilisation and food storage (James & King, 2010). These changes will be notable in the river communities.

The Riverine Ecosystem Synthesis (RES) view rivers as longitudinal arrays of large geomorphological conditions that do not consist of a fixed sequence of downstream changes but account for the more sensitive discontinuities in the typical sequence (Thorp *et al.*, 2006). Unlike the RCC their order of occurrence does not follow the downstream continuum. The characteristics that influence the RES are physical and chemical, including tributary confluence, divergence and convergence areas in braided channels and vegetated islands. These characteristics form a template for ecological zonation.

The longitudinal organisation of river ecosystems can be distinguished through the geomorphological classification of river reaches. A hierarchical framework proposed by Frissell *et al.* (1986) has a spatial scale range from the catchment drainage network to a single substratum particle as shown in Table 2. The hierarchical spatial scale is link to a specific time scale: the highest hierarchical level changes over geological time were the lowest hierarchical level is vulnerable to change over a small period of time like a day or even hours and minutes.

Table 2: The hierarchical classification levels (Rowntree & Wadeson, 1999).

Classification	Description
Catchment	The area draining into the stream network
Zone	Areas within the catchment homogeneous in runoff and sediment production
Segment	Section of channel corresponding to each zone through which flow of water and sediment are routed
Reach	The length of channel within which the constraints on channel form are uniform so that a characteristic assemblage of channel forms occurs within identifiable channel patterns
Morphological unit	The basic channel spanning structures comprising channel morphology, such as pools and riffles
Hydraulic biotope	Small patches characterised by specific flow type sand substratum conditions

The hierarchical classification for South African rivers consists of six levels namely catchment, zone, segment, reach, morphological unit and hydraulic biotope each describing a different geomorphological feature of the river as depicted in Figure 3.

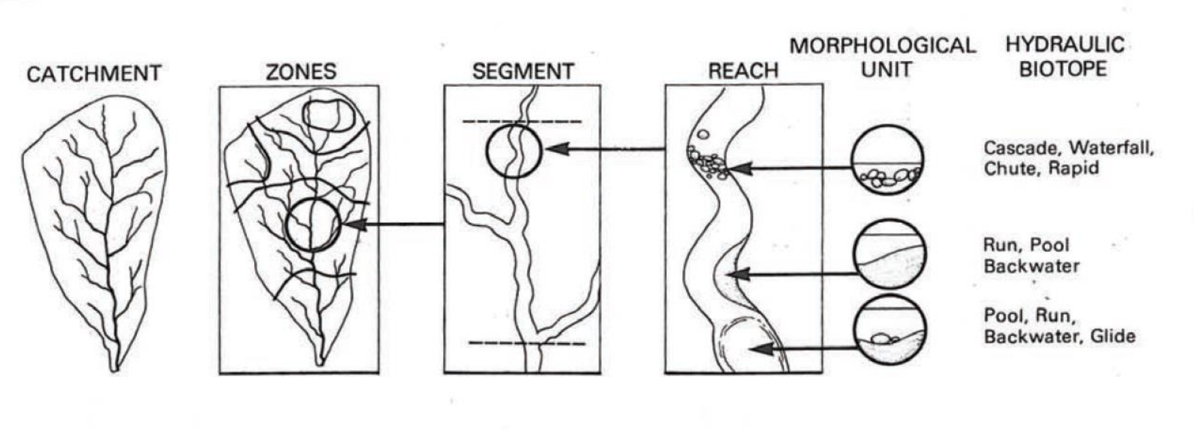

Figure 3: The South African hierarchical system (Rowntree & Wadeson, 1999).

The nature of features at each scale according to this hierarchical classification will be determined by the nature of those units higher in the hierarchy. For example the reach unit characteristics are either bedrock or free-forming in alluvial, this will determine the lower units like the floodplains, sinuosity, substratum size etc. and thus the morphological characteristics present in the next level (Ward, 1998). Rivers does not only consist of a longitudinal dimension but also of vertical and lateral dimension which is temporal in nature.

River as a vertical dimension

Surface and groundwater are hydraulically connected to each other in most areas, and therefore surface water bodies are integral parts of groundwater flow systems. The surface water can seep through unsaturated zones and still act as a recharge boundary for groundwater (James & King, 2010). This interchange between surface and groundwater allow contaminants to be transported from one source to another. The movement of surface and groundwater is directly related to the geology and topography of the specific area, where the climate, precipitation and vegetation affects the distribution of water on the surface.

There are many factors that can influence groundwater flow systems that include the recharge volume from precipitation, geology, watershed characteristics, hydraulic conditions and hydrogeological boundaries such as no-flow boundaries (Fisher *et al.*, 1998). If the piezometric surface are above that of the surface water of the river it can be defined as an effluent system (gaining stream) and the groundwater will contribute and sustain the baseflow, typical in periods of lowflow as shown in the first picture in Figure 4 (Malard *et al.*, 2002). In areas where the piezometric surface is below that of surface water the river can be defined as an influent river and water will discharge from the river into groundwater as shown in the second picture in Figure 4 (Malard *et al.*, 2002).

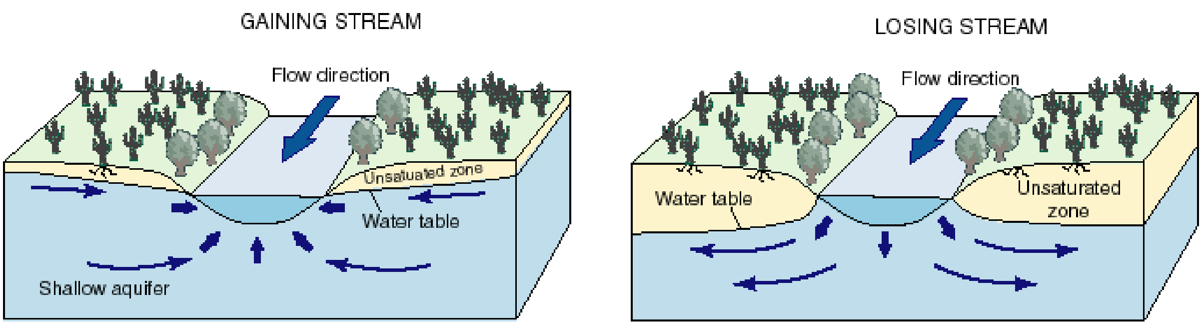

Figure 4: Gaining and losing river systems. Water is either transported from the shallow aquifer into the river system (gaining stream) or water is lost from the river into the shallow aquifer (losing stream) (Stute, 2002).

The vertical exchange of material and energy between surface water and the river bed is just as important as the transport of material longitudinally downstream and laterally between floodplains and the main channel. Therefore it is important to link the groundwater ecology to the traditional ecology of a river system (Malard *et al.*, 2002). The hyporheic zone is immediately below the riverbed at the boundary of surface runoff and groundwater, this flow is called the hyperhoes. Particular organic matter accumulates in the hyporheic zone and are temporarily retained before it is released back into the river system therefore the hyporheic zone plays an important part in the nutrient cycle of a river system. The exchange of water, nutrients and organic matter between groundwater and surface water can have major influences on the temperature, nutrient source and the patchiness of organisms within streambed sediment (Malard *et al.*, 2002).

The lateral dimension within a river

The third component of river ecosystems is the lateral dimension where interaction between terrestrial and aquatic ecosystems takes place when different parts of the river become inundated at different times. These ecotones include backwater, riparian zone, riverine wetlands and floodplains. This process is often referred to as the Aquatic Terrestrial Transition Zone (ATTZ) and is dependent on seasonal fluctuations in flow and the overtopping of river banks during periods of high flow (James & King, 2010). The drowned vegetation creates a new aquatic environment where nutrients are released from terrestrial vegetation. During this period of inundation large quantities of organic carbon and inorganic nutrients are deposited onto floodplains leaving behind fertile soil for terrestrial vegetation. A river system is more complex than just a channel from the source to the sea and in many large rivers in Africa fish synchronise their reproduction to periods of high flow, with adults migrating onto inundated areas to lay eggs. Fish larvae continue to feed and grow in these rich inundated areas until they are strong enough to withstand the velocities of the main channel and therefore it is important not to disturb the natural flows regime of a river system (James & King, 2010).

The temporal nature of a river

The fourth component in river systems is a temporal one and the most important driving factors are flow regime, sediment, chemical and thermal regime. The most important one of these are flow regimes as it has the ability to affect all the others (Wohl *et al.*, 2007). It plays a distinctive role in driving ecosystem processes and is therefore commonly referred to as the ‘master’ or ‘maestro’ physical variable (Walker *et al.*, 1995).

Flow regime can be described as the daily, seasonal and inter-annual variation in flow and its capacity to do work on the channel. Flow regime is largely responsible for the patterns in channel form as well as fluctuations in biological communities including the composition (kind of species present) and structure (proportion of different types of species) (Power *et al.*, 1988). It is also responsible for driving ecosystem processes such as the nutrient cycle as well as evolutionary processes such as a species morphological behaviour and life history adaptations to flood and drought.

2.3. Eco-hydraulics

Water in a river originates from the input of precipitation (P) to a catchment either as runoff or stream recharge from groundwater and in turn produces streamflow and discharge (Q) as output both varying in space and time (James, 2008). Variation of input will result in time-varying hydraulic conditions (H), which can be described as the hydraulic characteristics of riverine biota. Hydraulic conditions are determined by Q, channel form and instream vegetation (flora); the river channel is determined by the geology and sediment supply, hydraulic conditions and by instream flora; the instream flora is dependent on hydraulic conditions and the river channel and the instream fauna depends on the hydraulic conditions and on the river channel (Figure 5). Different inputs will affect the hydraulic conditions and output of a river system.

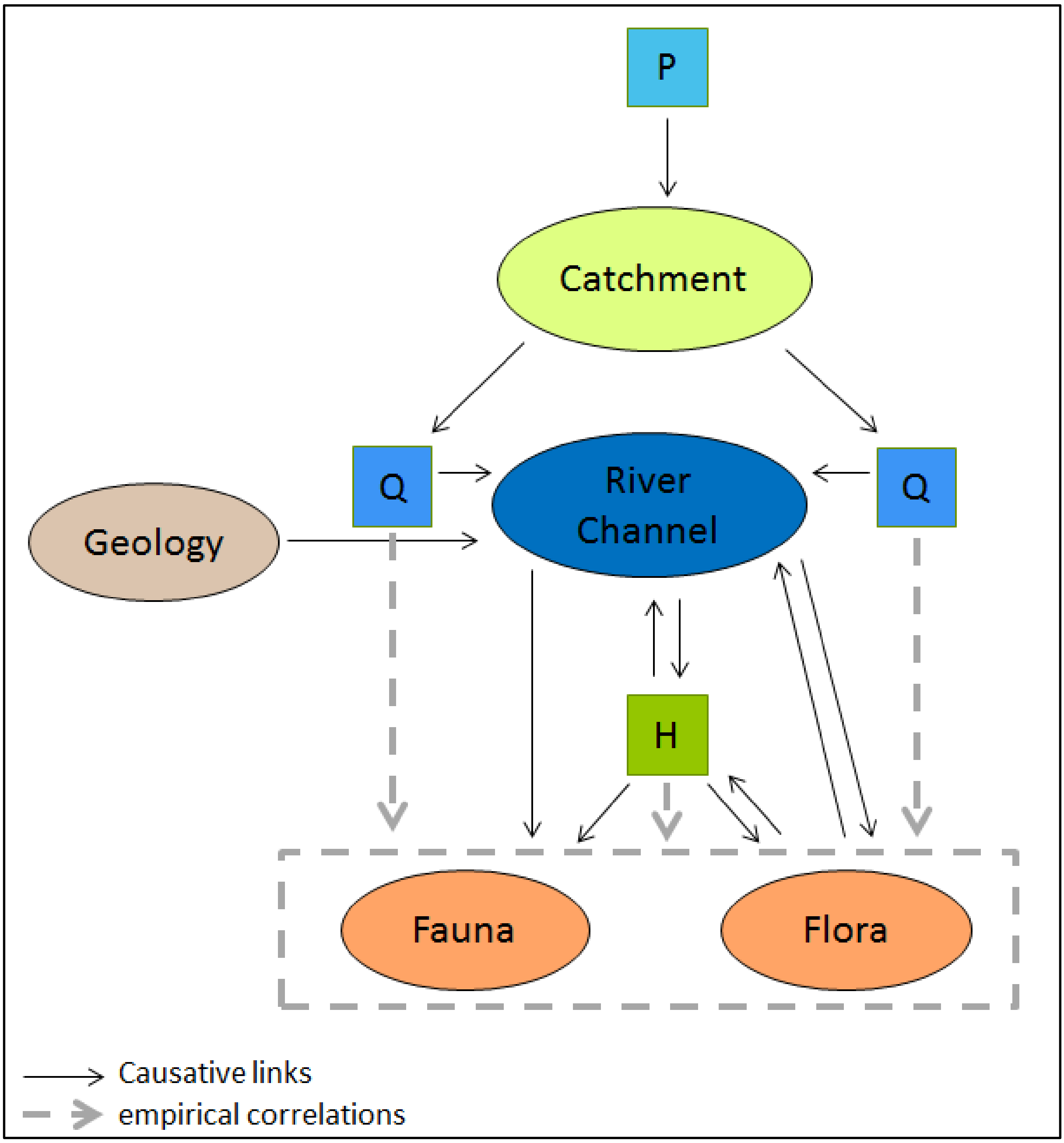

Figure 5: Model of an ecohydrological system (James, 2008).

Different organisms can be linked directly to different flows for instance fish that migrate upstream during periods of floods or spawn during small floods in the dry season. The hydrological data on rivers inform us on discharge, the volume of water moving past a defined point over a period of specified time (James & King, 2010). Hydrological data cannot account for the forces acting on the channel or for the change of conditions at different biotas and therefore hydraulic data is required.

Hydraulic data convert flow data into flow velocity, depth, level of inundation (area where river floods its banks), stream power (ability to transport sediment) and more. The hydraulic conditions of a water column differ, with the slowest flow at the river surface, bed and edges increasing in velocity towards the centre of the column. Different riverine species live in a full range of physical conditions and therefore it is important to understand hydraulic conditions of river ecosystems for ecological studies.

- “Hydrological data detail the magnitude, frequency, duration and timing of each kind of flow over days, seasons, years and decades” (James & King, 2010).
- “Hydraulics transforms this information into descriptors of the water-related conditions experienced by each species over days, seasons, years and decades.” (James & King, 2010).

The collection of hydrological data and the modelling thereof will provide predictions on how many hydraulic habitats are available under various flow regimes for different species specified by ecologists. Key linkages between river ecology and hydraulics are described in the section that follows.

2.4. Flows and channel morphology

According to Heggenes (1996) the presence of a riverine species or community can be compromised by a change in any one of its environmental components, physical, chemical or biological. One of the key physical components is the hydraulic nature of the habitat and to understand why riverine species live in these habitats has to define this aspect of habitat in more detail. Through hydraulic modelling it is possible to predict changes in hydraulic conditions within a river due to flow alterations and how this will affect the habitat of species/communities (Hardy, 1998). Different fish species is dependent on different flow condition for instance, species with a spawning preference for fast turbulent flow could be expected to decline in numbers if flow is altered to consistently slower flow, and river scientists need to be able to predict those conditions (Heggenes, 1996).

It is crucial to develop a database of information on the optimal hydraulic habitat of key riverine species to predict how changing hydraulic conditions could affect the river ecosystems (James & King, 2010).

2.5. River channels

River systems are dynamic and change constantly due to flowing water and sediment load that works the river channel and bed. This work done by a river is responsible for maintaining and eroding channel features such as banks, bars, pools, riffles, secondary channels and islands (Rowntree & Du Plessis, 2003). The hydraulic features such as step-pool formations in headwater and riffle-run sequences in foothill rivers are repeated through its respective zones due to hydraulic conditions created by river flow. Different discharges play different roles in the ecosystems of a river e.g. floods rip out new vegetation invading main channels and wash them downstream to maintain channel width and its ability to transport flood waters (James & King, 2010). Altering flows will move and sort alluvial deposits on the riverbed in different ways and therefore create distinct patches of habitats from sand particles to boulders, contributing to the biodiversity of organisms within a river system.

Riverine species have to adapt to this dynamic geomorphological world to ensure their survival, adult fish use deep pools and meander bends for resting areas where juvenile fish use sandbars, slackwater and side channels to protect them against predators. Altering the flow and sediment regime of a river will change the quantity and quality of available habitats and may threaten the ecological integrity of the river ecosystem itself (Beck & Basson, 2003). The flows required for maintaining the river channel morphology can be referred to as channel maintenance or flushing flows, in this document the term maintenance flow is used since it covers a wider spectrum of features.

To understand the relationship between channel features and flow requires an understanding of the balance between variables such as discharge, sediment size, load and river slope and how they interact through time. To identify the flows responsible for channel maintenance is beyond the scope of this study and requires a combination of expert judgment and examination of major breaks in the cross-sectional channel shape, floodplain height, vegetation zones and flow frequency. To assess the direct influence of hydraulic changes in a river on aquatic organisms three different approaches have been used in South Africa namely: Habitat Suitability Criteria (HSC), Hydraulic Biotopes and Flow Classes.

Sediment movement and sorting

River flow can act directly on organisms through the force of velocity and volume or indirectly through sediment transport, depositing or sorting sediment on river beds which forms an important component of river habitat.

Different flows in a channel perform different types of work such as: eroding, transporting, sorting bed sediment, building sandbars etc. A key aspect of ecohydraulics is to identify which flows perform these functions and how this will change by altering flow regimes. The movement of fines in a channel during floods is natures' way of disturbing invertebrates and algal populations.

Habitat time-series

Rivers are dynamic bodies that change constantly over a period of time and ideally hydraulic studies should integrate some habitat time-series analysis because the well-being of any organism depends on the past and present habitat availability and not only on the immediate availability (Orth, 1987; Capra *et al.*, 1995). To predict the impact that an alteration in flow will have on river ecosystems, duration, frequency, timing of flows and time-series should be components of any assessment of hydraulic studies. This should become a standard part of scenario analysis to support management and sustainable development of river systems.

By combining hydrological data and hydraulic data in models it is possible to predict different scenarios of flows for different discharges.

Habitat suitability criteria (HSC)

HSC is widely used by ecologists worldwide and was the first method to be tested in South Africa (Arthington & Zalucki, 1998). HSC defines the most commonly used hydraulic habitat by any selected species. It includes data of depth, velocity, substratum particle size and the presence of species of interest in the river system.

Deriving HSC is time-consuming due to the fact that it should include the full range of habitat conditions a species will encounter and therefore it is not feasible to derive a HSC for each species within a river. One approach is to group species into habitat guilds and then choose an indicator species for each guild. This is a complex study and different life stages of the same species may have different hydraulic dependencies and therefore have to be treated as different 'ecological species' (Hayes & Jowett, 1994). Very little work of this nature has been done in South Africa and it is a topic that needs further investigation to manage future flows to support the different life cycles of valued species.

Hydraulic biotopes

Hydraulic biotopes can be used to describe hydraulic habitats of different species. Rowntree (1996) defines a biotope as "a set of relatively uniform physical and biological conditions, together with the distinctive biological community associated with it". Thus a biotope defines a group of species (community) where habitat only defines the living condition of a specific species. The hydraulic biotope concept was developed in South Africa by geomorphologists (Rowntree & Wadeson, 1999) describing the physical properties of hydraulic biotopes and ecologists (Rowntree, 1996; King & Schael, 2001; Pollard, 2001) defining their relevance for different aquatic species in the Western Cape headwater streams.

Mapping of hydraulic biotopes can either be done by hand in the field or digitised later or the hand drawn maps can be combined with digitised coordinates taken with a differential GPS on-site. As discharges change the hydraulic conditions change and maps have to be redrawn for hydraulic biotopes and cannot be predicted through modelled drawing (King & Schael, 2001). Maps with measurements of velocity and depth at cross section points can be overlain with hydraulic biotope maps to allow for statistical testing of depth, velocity and hydraulic variables.

Flow Classes

Flow classes were initially developed by Oswood and Barber (1982) and later adapted for fish habitats for South African rivers by Kleynhans (1999). Flow classes are broad categories of hydraulic habitats described by key parameters such as depth and velocity.

Flow classes for fish

Predefined flow classes were determined by a panel of experts based on habitat requirements of 134 indigenous species of freshwater fish. The following four flow classes were pre-defined: slow-shallow (SS), slow-deep (SD), fast-shallow (FS), fast-deep (FD) and include velocity, depth and type of flow (Table 3).

Table 3: Flow classes for fish and method of data collection (Kleynhans, 1999)

Class	Velocity	Depth	Description	Sampling Method
SS	Slow <0.3 m/s	Shallow <0.5 m	Shallow pools and backwaters	Small seine, Electroshocking
SD	Slow <0.3 m/s	Deep >0.5 m	Deep pools and backwater	Large seine, Cast net
FS	Fast >0.3 m/s	Shallow <0.3 m	Shallow runs, riffles and rapids	Electroshocking
FD	Fast >0.3 m/s	Deep >0.3 m	Deep runs, Riffles and rapids	Electroshocking

These flow classes are a very broad description with flow-depths covering only four categories and flow-velocity with only two categories that are important for fish (Figure 6). These flow classes are widely used in assessments of South African Ecological Reserve and Ecological Status. In recent studies Lamouroux *et al.* (1999) described five different velocity classes for fish which lead to more defined flow classes and should be considered in future monitoring.

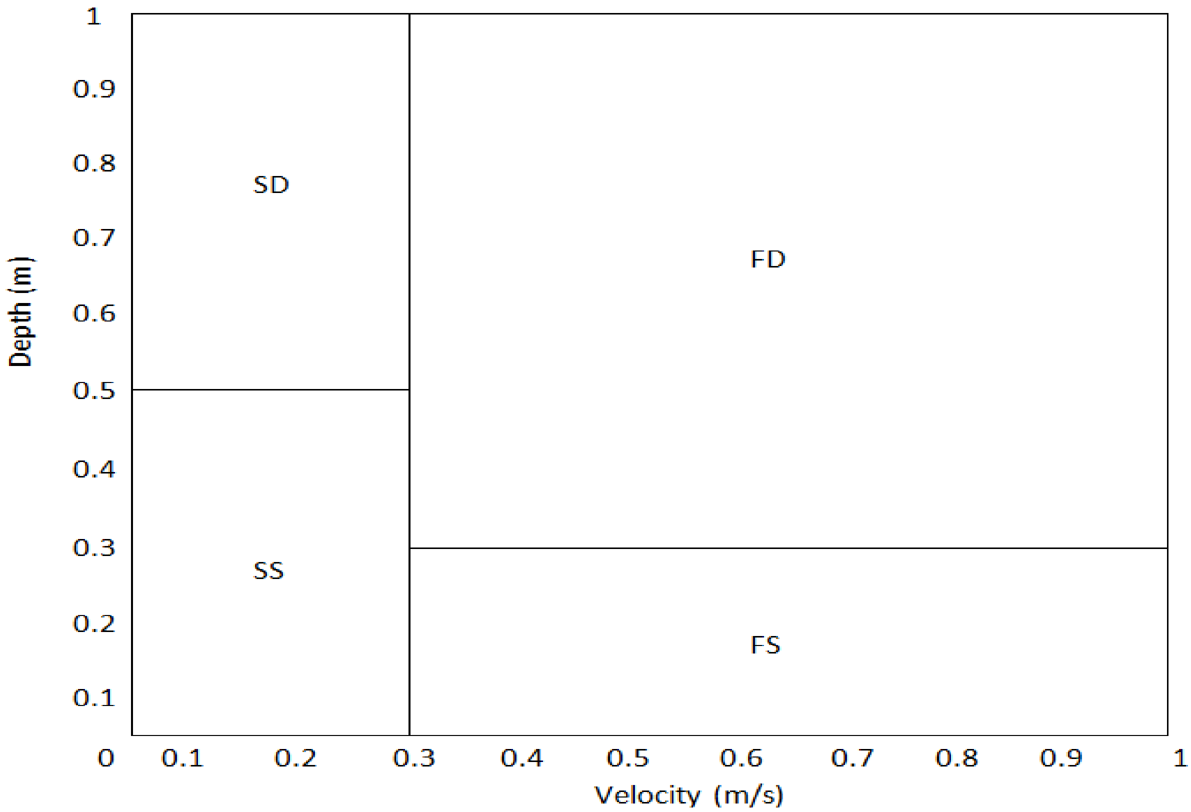

Figure 6: The four velocity-depth flow classes used in this study (Kleynhans, 1999).

The complexity of understanding the biological responses and quantifying these ephemeral phenomena presents considerable challenges for ecologists, geomorphologists and hydrologists. Altering the flow of a river can either act directly on an organism or indirectly by affecting its ecological habitat. Therefore, the relationship between flow and riverine biota are studied by three different approaches: HSC, hydraulic biotopes and flow classes. Hydraulic biotopes are not well understood hydraulically and therefore they are not compatible with hydraulic models. HSC are compatible with hydraulic models and their results are testable and predictive but detailed data collection has to be done over smaller areas to make it cost effective and efficient. Flow classes are semi-quantitative meaning that they can be applied on 'best-available-knowledge' and are compatible with a variety of hydraulic models.

2.6. Eco-hydraulic modelling

The modelling in this study is focused on the linkage of hydraulic conditions with the geomorphological and biological characteristics and the discharges that contributes to the change. The need for modelling is to predict the change in hydraulic conditions, flow depth and velocity and link them to organisms (fish). This is used for short-term description of hydraulic habitat for organisms which are influenced by their environment and does not take into account channel form, hydraulics and vegetation and therefore cannot be used for long-term predictions that include the interaction of geology, sediment supply and vegetation (James & King, 2010).

There are many various modelling approaches and models that can predict these characteristics, with the main difference being the accuracy or resolution of describing hydraulic habitat conditions. The two main types are empirical and deterministic. Empirical models are based on the correlation of measured values of the different variables such as: water level and discharge as opposed to deterministic models that describe the relationship between variables and processes for example: the Saint Venant equation of mass and moment can be described through the relation of depth and velocity (James & King, 2010). Deterministic models will always include some empirical content that can be introduced through equation coefficients and statistical representations to account for processes that influence the relationships between variables which are not fully described. The more detailed the input information, especially topographic survey data in a model, the higher the resolution and the more realistic is the process description. The empirical models require less input or system information but more discharge and flow data is required to provide a basis for correlation between different variables. Therefore an empirical model that is calibrated for a specific site will have greater accuracy, but the deterministic model will be more general and have better transferability between sites (James & King, 2010).

The most basic description for river hydraulics is the relationship between stage and discharge at a specific site. This is modelled by empirical correlation of measured discharges vs. water level at the site and requires no physical site information. With less flow data and more site data deterministic modelling can also be used to determine the relationship between stage and discharge (James & King, 2010). To calculate cross-section average velocities, deterministic modelling is required with the addition of some site surveyed data. At areas where site information is severely limited the simplest approach is to assume uniform flow conditions. By combining the one-dimensional continuity equation with a resistance equation (presented in the next chapter) it is possible to find an appropriate model where information requirements are limited to channel slope, cross-section geometry and a resistance coefficient to account for channel characteristics. To model cross-section average velocities along a reach of the river, a 1-D non-uniform flow model such as HEC-RAS can be used. This is similar to uniform flow models except that it supports a number of cross sections. The depth-average velocities of a river section can only be described as adjacent, non-interacting sub channels and therefore for more accurate modelling other approaches is required.

Depth and velocity distributions over a two dimensional area can be modelled either empirically or deterministically. HABFLO use frequency distributions to describe the occurrence of depth and velocities over cross sections or reaches in a system and requires input information of channel and flow characteristics (James & King, 2010). HABFLO does not show spatial arrangements but only indicates the relative abundance of hydraulic conditions. This method suffers from the same scale limitations as the Froude's and Reynolds numbers in its hydraulic characterization although it is popular with some ecologists, it is difficult to predict biotope arrangements with varying discharges without 2-D deterministic modelling. River2D provides flow depth and velocity data that can be interpreted in terms of spatial arrangement and abundance as necessary (Steffler & Blackburn, 2002b).

Hirschowitz *et al.* (2007) reviewed the different hydraulic models and their application in ecological reserve determination. With the wide variety of models available, considering advantages and disadvantages, requirements, level of accuracy and precision as well as the resources required and available information where taken into account. A high resolution model (e.g. 2-D) is not necessarily better than a lower resolution model (e.g. 1-D). It is of no use describing hydraulic conditions in higher resolutions than the available HSC can use and therefore the review of Hirschowitz *et al.* (2007) shows that HEC-RAS is more than sufficient for 1-D analyses and River2D for 2-D analyses for most eco-hydraulics applications. Both these models are available from the internet free of charge. It is important to note that the quality of a model is directly related to the input data, and the specification of resistance within a system.

The empirical model is statistically derived from measured data at similar sites for frequency distribution of velocity classes. The deterministic model is a simulation of flow by the Saint Venant equations (James & King, 2010). The empirical model only describes the abundance of flow classes and not their spatial distribution where the deterministic model represents high resolution of spatial descriptions of velocity classes from which the abundance can be derived (Figure 7). The empirical model accuracy depends on the representativeness of the data used for compilation and only requires rough data for description of flow and bed characteristics. The deterministic model requires detailed topographic surveyed information for the particular site and allow for a more general output and can accommodate a wider range of discharge inputs (James & King, 2010).

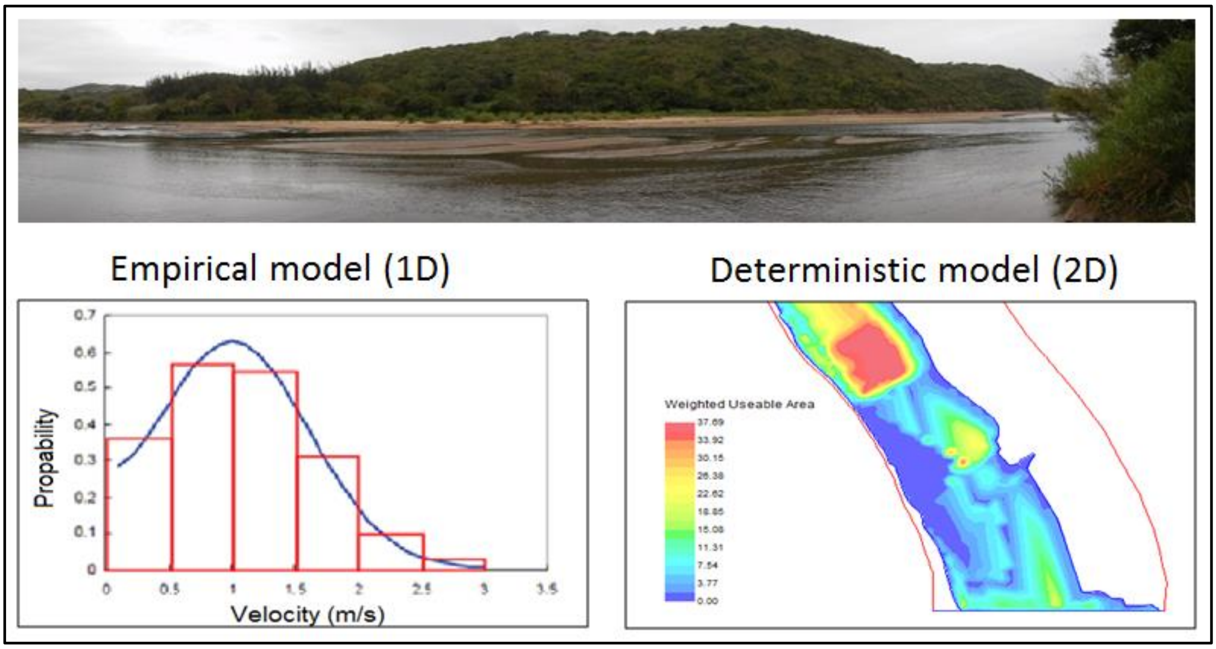

Figure 7: Empirical vs. deterministic modelling of hydraulic conditions.

HEC-RAS description

HEC-RAS was developed by the Hydrologic Engineering Centre of the U.S. Army Corps of Engineers to perform one-dimensional calculations for natural or constructed channels. The model solves the energy equation between cross-sections to calculate/generate water surface profiles for steady and unsteady flows. HEC-RAS is widely used and accepted for flood modelling and flow analyses across the world. The software has a graphic user interface, separate hydraulic components, data storage and management capabilities.

In this study HEC-RAS (version 5.0.1) was used to route flows ranging from $1m^3/s$ to $4000m^3/s$ along the study area in the lower Thukela River. The program can be downloaded from the following website: http://www.hec.usace.army.mil/software/hec-ras/

River2D description

River2D was developed by Professor Steffler at the University of Alberta, Canada and is a public-domain two-dimensional depth average hydrodynamic model. The model consists of four separate modules and is used in succession:

Table 4: Different modules used within the River2D model and their relevance to this study.

Model	Description	Applicability
R2D_Bed	Is the most crucial factor in river flow modelling, representing the physical features of the river channel bed, including bed elevation and bed roughness height. The model is based on the TIN methodology, consisting of nodes and breaklines for spatial interpolation. The process involves the creation of a preliminary bed topography text file from surveyed data, and then editing and refining it in R2D_Bed before it can be used in the R2D_Mesh module.	Yes
R2D_Ice	This module is equipped to model flow under ice cover of known geometry and calculations are done based on ice thickness and ice roughness height.	No
R2D_Mesh	The resulting R2D_Bed file is used in R2D_Mesh for final refining and to develop a computational discretization and to set boundary conditions as input for River2D.	Yes
River2D	River2D is then used to solve water depth and flow velocities and to visualize and interpret the predictions. River2D include colour maps, contour maps and velocity vector fields to aid in visualising the progression and/or final results	Yes

The model is intended for natural streams and rivers and accommodates supercritical and subcritical flow transitions and wetted areas. In this study River2D (version 0.95) was used for depth-velocity predictions and can be downloaded from: http://www.river2d.ca/

2.7. Fish as indicator species

Fish are one of the most commonly used ecological indicators and can be used to measure key elements of complex systems without having to capture the full complexity of a specific system (Whitfield & Elliott, 2002). The primary function of an ecological indicator is to monitor and track changes within an ecosystem. The different indicators that are used in aquatic environments are chemical, physical and biological measures (Whitfield & Elliott, 2002).

Fish are an important component of ecosystems that can contribute to the establishment of the environmental water requirements (EWR) for the Thukela River. Fish is not only an important species for ecological health but they are one of the most important food sources for many communities in Africa (Whitfield & Elliott, 2002). As indicators of ecological health fish has the following advantages as an indicator species:

- Long-lived: therefore good indicators of long-term exposure impacts.
- Ubiquitous: they can live in a wide range of aquatic habitats mostly due to their mobility.
- Extensively studied: a lot of research has already been done regarding their habits, habitats and occurrences.
- Diversity: live across a wide range of feeding habitats, reproductive traits and communities can comprise of a range of species allowing for a greater tolerance to environmental stressors.
- Easily Identified: relative to other groups of aquatic biota, fish are easy to identify to species level and can be done in the field.
- Well-known: fish provide recreational opportunities and many species are familiar to the general public.
- Toxicity trends: data analysis from the presence or absence of certain species and their growth rate can detect sublethal effects.
- Conservation: by establishing sensitive species the conservation of one species can allow for the protection of large diversities of other species.

Fish as indicators of ecological health and flow alterations in a river ecosystem are already being used throughout the world. Fish have been shown as valuable indicators for the evaluation of ecological flow requirements in a river system and in addition provide protection for many other aquatic systems (Karr, 1981; Kleynhans, 1999). Fish can thus be considered as an important component in the establishment of ecological flows for river ecosystems throughout the world.

2.8. Significant elements of the flow regime

Instream flow studies main focus is to determine the low flow conditions required to maintain ecological wellbeing of river ecosystems. The greatest competition between organisms is for the limited amount of available water. The following aspects will influence the flow regime to maintain particular instream values (Jowett *et al.*, 2008):

- Floods will determine the overall form of the channel, floodplain surface and vegetation cover due to its alluvial nature in the Thukela River and can be described as channel maintenance flows. Large floods have a major impact on river channels and cause disturbances to the river ecosystem for a time period due to the displacement of aquatic biota and destroyed habitats.

- Freshes which is smaller floods and are contained within the channel that occur a few times throughout the year with limited effects. They will flush and refresh the river bed by removing silt and algal coatings from riverbed sediments and also mobilise sediment in most parts of the river channel. Freshes are both positive and negative for flushing and cleaning the river bed to disturbing parts of the ecosystem.
- Low flows are one of the most important flow regimes and occur at times when there is the greatest competition for water, the availability of habitat is at its lowest and the ecosystem is under major stress. Low flows can help with the recolonisation of fish and macro invertebrates after floods and the re-establishment of aquatic vegetation.
- Flow variation, the continuous change in flow regime which is a significant hydrological feature and should be maintained within a river ecosystem. Long periods of flat-lining (constant flow) should be avoided.

2.9. Ecological flow assesment methods

To determine ecological flow requirements a lot of different methods can be used from a quick rule-of-thumb assessment to detailed studies over a few years (Jowett *et al.*, 2008). A large number of different methods have been used in different studies and new methods continue to be explored. In this study only the most appropriate method related to the data and study area are described. There is no universally accepted method for all rivers and streams and very little evidence of the success and failures of the different methods (Jowett *et al.*, 2008). The following methods were applied in this study:

Historical Flow Method

The Historical Flow Method is referred to as the standard setting and is based on historical flow records. This is the simplest and easiest method to apply and is a desktop rule-of-thumb method to determine minimum flows (Stalnaker *et al.*, 1995). The historic method make use of statistical analyses to specify a minimum flow, it can be the average flow, a percentile from the flow duration curve or the annual minimum with an exceedance probability. An example of percentiles usage is as follows:

that the flow should never drop below 30% of the mean annual low flow (MALF) or that the average flow should be maintained at a flow above 80% of the MALF and can be referred to as the level of maintenance (Jowett et al., 2008).

This method is used to maintain the flow within the historical flow range, or to avoid the flow regime to deviate largely from natural flows. The assumption made by using the historical flow method is that the ecosystem has adjusted to the natural flow regime and that any reduction in the natural flow regime will cause a reduction in the abundance and diversity of aquatic ecosystems (Jowett *et al.*, 2008). In other words the biological response is related to flow. The most well-known historic flow method is the Tennant 1976 method which specifies 10% of the average flow as the lower limit for aquatic life and that 30% of the average flow will provide a satisfactory stream environment (Jowett *et al.*, 2008). The Tennant method has been adapted to a more recently modified method and its recommended minimum flows are similar to those predicted by the IFIM (Crowe *et al.*, 2004). The Tennant method can be extended by incorporating monthly minimum flows as a percentage of monthly mean flows.

The Building Block Method (BBM) aims to maintain an ecosystem in its existing state and ignores the chance of a system being enhanced by other than the natural flow regime (King *et al.*, 2000). This method considers the duration and frequency of high flows and the degree of low flows and are best used when the linkage between ecosystem integrity and flow requirements are poorly understood.

Habitat Method

The habitat method quantify the loss of habitat caused by changes in the natural flow regime and will assist in the evaluation of alternative flow requirements. The aim of the habitat method is not only to maintain the natural biota but rather to improve the physical habitat for instream requirements of biota (Jowett *et al.*, 2008). This method requires complex hydraulic sampling as well as knowledge of the ecosystem; the method states that if there is no available habitat for a specific species that species cannot exist. However it is not to say that when habitat does exist that the species will be present in the study reach. Species distribution can be influenced by other factors like drought and food sources therefore the habitat method only predicts suitable habitat for species of choice (Jowett *et al.*, 2008). Biological data required for habitat methods is in the form of suitability (preference) curves for each species and different life stages. The main preferences for fish are given in the form of depth, velocity and substrate.

The results of an instream habitat analyses is therefore dependant on the habitat criteria used and can change drastically according to different species (Jowett *et al.*, 2008). If the chosen species has a preference for deep fast flowing water the maximum habitat will only be provided by relatively high flow and if the preferences are for shallow slow flowing water the maximum habitat will be provided by low flows and decrease with an increase in flows. The habitat method does not assume that the natural flow regime is optimal for all species and treats each species preferences individually (Jowett *et al.*, 2008). Environmental changes like an increase in temperature can have different effects on the distribution of fish species within a river but is not incorporated in this study due to the variability of temperature as a parameter.

3. Materials and methods

3.1. Study area

The Thukela River in KwaZulu-Natal is South Africa’s second largest river with a catchment area of 29 000 km^2 that has aptly been named for its ferocity (Whitfield & Harrison, 2003). Increasing demand for water related ecosystem services from the Thukela River catchment have resulted in an increase in pressure on the structure and function of the system (Whitfield & Harrison, 2003). The lower portion of the Thukela River and the associated Thukela estuary have been characterised as an ecologically important region of the Thukela catchment with various social and ecological values associated with the use of ecosystem services (Lamberth *et al.*, 2009). The lower portion of the Thukela River and associated estuary provides habitat for unique species of marine migrant, estuarine and freshwater species and acts as a conduit for many anadromic species that utilise the middle and upper reaches of the Thukela River. According to the FRAI classification system the lower Thukela River and estuary has both recently been established to range between a moderately modified (Class C) and largely modified (Class D) state (Kleynhans, 2007). This suggests that although key ecosystem processes are occurring, some structure and function aspects of the ecosystem may be negatively impacted, as a result of altered water quality, quantity and habitat (Lamberth *et al.*, 2009).

Activities associated with ecosystem service use in the lower Thukela River include water abstraction for domestic use, industries, agriculture, mining, recreation, waste water treatment and road and rail networks. Many of these ecosystem users abstract water directly or indirectly (via municipal abstraction works) from the Thukela, Emandeni, uMsunduze and Amatikulu rivers and some of them release treated or partially treated effluent back into these systems. The region above the Emandeni River outfall supports the Thukela-Mhlathuze Bulk Water Transfer Scheme which is currently under construction (commissioned in 2015). A major industrial activity in the area is the Sappi Tugela Pulp and Paper Mill that has both extraction and discharge points in the same region of the Thukela River. Sappi releases effluent directly into the Thukela River via an underground pipe system, approximately 500m below the confluence of the Thukela and Emandeni Rivers. Risk assessment previously carried out in the Thukela system revealed that the lower Thukela River together with the Emandeni River is the areas at the greatest threat of stressors affecting the ecosystem health.

The Thukela River originates on the slopes of the Drakensberg where it flows eastbound to the Indian Ocean and discharges about 90 km north of Durban. According to De Winnaar and Jewitt (2010) the Thukela River catchment is 29 000 km^2. The study area fall within the quaternary drainage region V50D covers a stretch of 4.6 km on the lower Thukela River (Figure 8). The construction for the new Bulk Water Supply Scheme is on the lower Thukela River and western side of this drainage region about 22 km upstream from the ocean. The Thukela River is 512 km long and flow from the west to the east. The catchment is steeply graded and the major tributaries of the Thukela River include the Buffalo River, Sunday River, Klip River, Little Thukela, Bloukrans River, Bushman River and the Mooi River (Figure 9). The estimated mean annual runoff (MAR) of the catchment ranges between 3850 and 4600 MCM/a (De Winnaar *et al.*, 2007) with 4 300 MCM/a appearing to be a reasonable average. Peak flows occur during summer months and baseflows during dryer winter months of July, August and September. The baseflow of the Thukela River accounts for about 19.3% of total flow (Vegter *et al.*, 2003) which is equal to 3.2% of MAP.

Major dams in the catchment include Woodstock Dam (Thukela River), Chelmsford Dam (Buffalo River), Spioenkop Dam (Thukela River) and Wagendrift Dam (Bushmans River). The DWS have permitted small farm dams in the catchment which are mostly situated in the upper reaches (Figure 9). According to Matete and Hassan (2005) these dams have an estimated storage capacity of 338 MCM. Dams in the catchment will have a massive impact on flow regimes downstream. The study site is below the bulk water supply scheme that is being built and expected to be in full operation in April 2016.

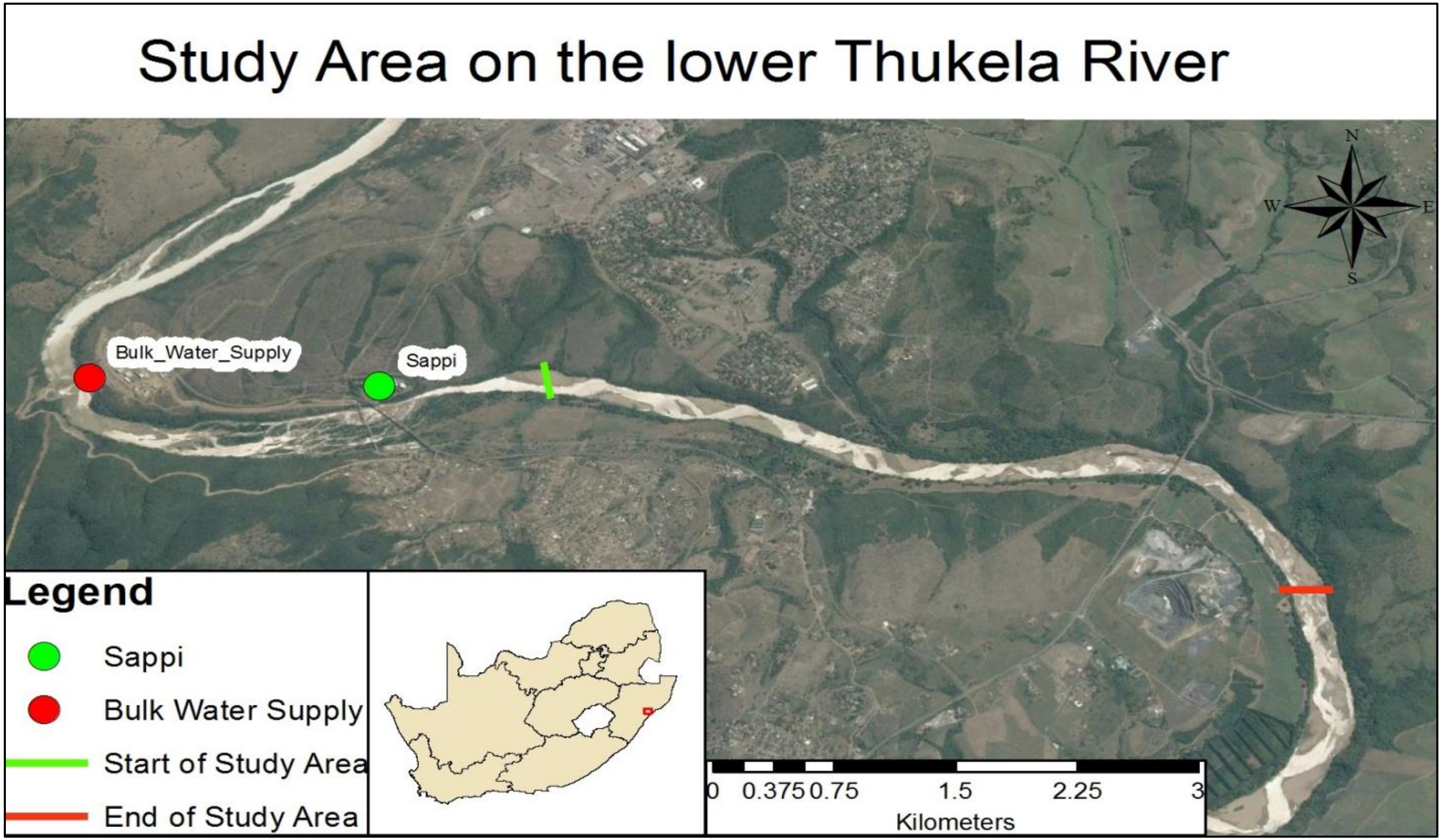

Figure 8: The study area on the lower Thukela River.

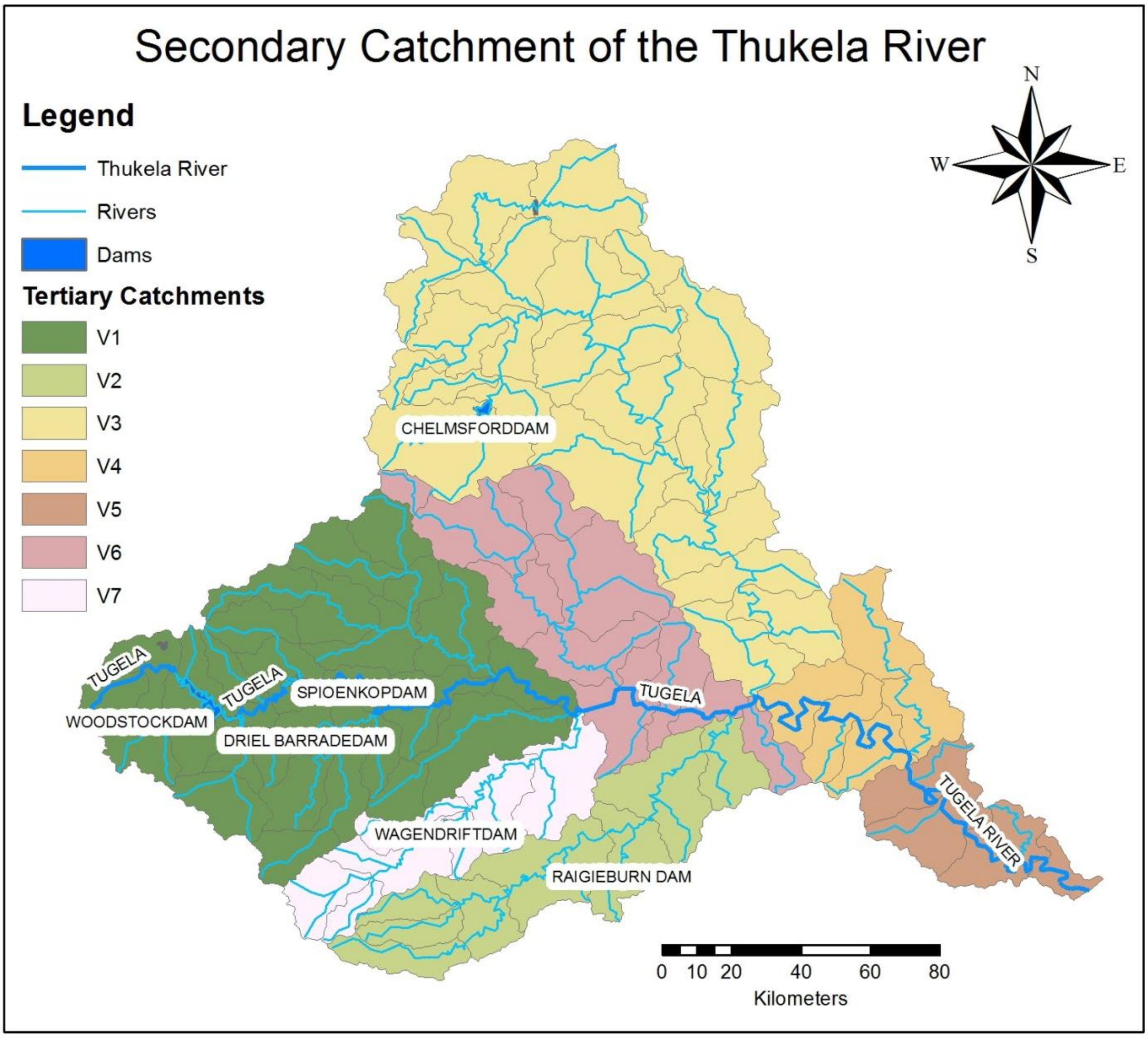

Figure 9: Secondary and tertiary catchments of the Thukela system.

3.2. Climate

The range of climatic conditions is due to the vast area of the catchment. In the north and west where winters are cold temperatures often fall below zero and frost occur regularly. Summers are warm and temperatures often reach more than 35 °C. Along the cost and relative to our study site temperatures are generally more moderate with smaller fluctuations between winter and summer.

The mean annual precipitation (MAP) in the Thukela River catchment is 830 mm/a (Vegter *et al.*, 2003). With rainfall exceeding 1 000 mm/a along the escarpment and dropping down to less than 600 mm/a east of Weenen. The central parts of the catchment receive between 600-800 mm/a where the coastal areas receive considerably more, in excess of 1 000 mm/a.

The proposed study area fall within the area and have a MAP of 1018 mm/a (Vegter *et al.*, 2003). With most rainfall occurring in the summer months between December and March and little rain during cold winter months. Some snowfall occurs on the higher lying Drakensberg peaks near the origin of the river but this snow melts fairly quickly. Rainfall in the catchment is fairly unpredictable and extended years of drought can be followed by very wet periods (Vegter *et al.*, 2003). Mean annual evaporation (MAE) along the escarpment range between 1 300 mm/a and 1 400 mm/a where evaporation in the central parts of the catchment can increase up to 1 500 mm/a. The evaporation decreases to the coastal areas to 1 250 mm/a in the quaternary catchment of the study area (Vegter *et al.*, 2003).

3.3. Geology

Lithostratigraphy

The rock formations in the Thukela River catchment represents a good geological sequence as the oldest rocks are in the South-Eastern sides of the catchment and follow a younging sequence North-Westwards (Source-to-Sea, 2003). Some granites of the Barberton group outcrops west of Tugela Ferry and are the oldest rock formation known and dates back more than 3 000 Ma. The Natal Metamorphic and Natal group is limited to the South-Eastern side of the catchment. The Natal Metamorphic rocks are found between Kranskop and Mandini where the Natal group is limited to the areas south-east of Kranskop. These formations are more than 1 000 Ma old (Source-to-Sea, 2003).

Most of the Thukela River catchment is comprised of the Karoo Supergroup which was deposited 180 Ma to 280 Ma ago. The older Dwyka group was deposited under cold polar conditions while the younger Clarens formation was deposited in dry arid conditions. Volcanic activities during the Jurassic period marked the end of this supergroup about 180 Ma ago (Table 5).

Tillite outcrop in the area of Kranskop and forms part of the Dwyka group. Sediments from the Ecca group are found in the eastern parts of the catchment and form the basis of the Sunday and Buffalo Rivers. The underlying geology is rock from the Vryheid formation and is mainly comprised of sandstone which is relatively resistant to erosion and therefore resulting in narrow deep river channels. The western part of the catchment is dominated by the Beaufort group which is mostly shales and mudstones. They are comprised of finer grained material and are less resistant to erosion therefore the valleys will be shallower wide sections (Source-to-Sea, 2003). These sections are characterised by alluvial deposits and large alluvial floodplains. The fine grained minerals will be transported in suspension and deposited in lower slow flowing sections like the study area section (Source-to-Sea, 2003).

Along the western edge of the Thukela River catchment post Beaufort sedimentary rocks are found and are capped by Karoo-aged basalts. Dolerite dykes and sills of the Jurassic age are found west of Kranskop (Figure 10). These features play an important role in the geohydrology and help to understand the water properties in the study area.

Young unconsolidated sands are found only in the coastal area and are in the vicinity of the lower Thukela River and estuary (King, 1997). This indicates the transport of alluvial sands from upstream and then deposited in the lower sections. Some of these deposits can reach a thickness of up to 40 m.

Table 5: Stratigraphy of the Thukela catchment (King, 1997)

Age (Ma)	System	Supergroup	Group	Formation	Liothology
65	Quaternary Tertiary		Maputaland		Calcereous sands
	Cretaceous		Zululand		Marine siltstones, sandstones and some conglomerates
140	Jurassic		Drakensberg		Basalt
195			Lebombo	Jozini Letaba	Rhyodactite and rhyolite basalt
		Karoo		Clarens Eliot Nyoka Ntabene Molteno	Sandstone, Sandstone and mudstone, Mudstone interbedded with sandstone, Sandstone with subordinate mudstone, Sandstone, mudstone and shale
	Triassic		Beaufort	Tarkastad Adelaide Emakwenzini Normandien	Sandstone with mudstone, Mudstone alternating with sandstone, Sandstone alternating with shale and mudstone, Sandstone interbedded with shale
			Ecca	Volsrust Vryheid Pietermaritzburg	Shale and siltstone, Sandstone with some shale, Shale
345	Permian Carboniferous		Dwyka		Tillite, Diamictite
	Devonian Silurian Ordovician		Natal		Conglomerates, arkostic sandstone, Quarts-arenite and subordinate shale
570	Cambriam	Natal Metamorphic Province			Mafic metavolcanic rocks with subordinate metasediments
3100		Pongola	Nsuze		Tuffs, Black sandstone, Dactites and rhyolites, quartzites and shales, basalts and andesite, greywackes, conglomerates and shales
3200		Baberton Sequence	Swazian granites		Granite and granit gneiss

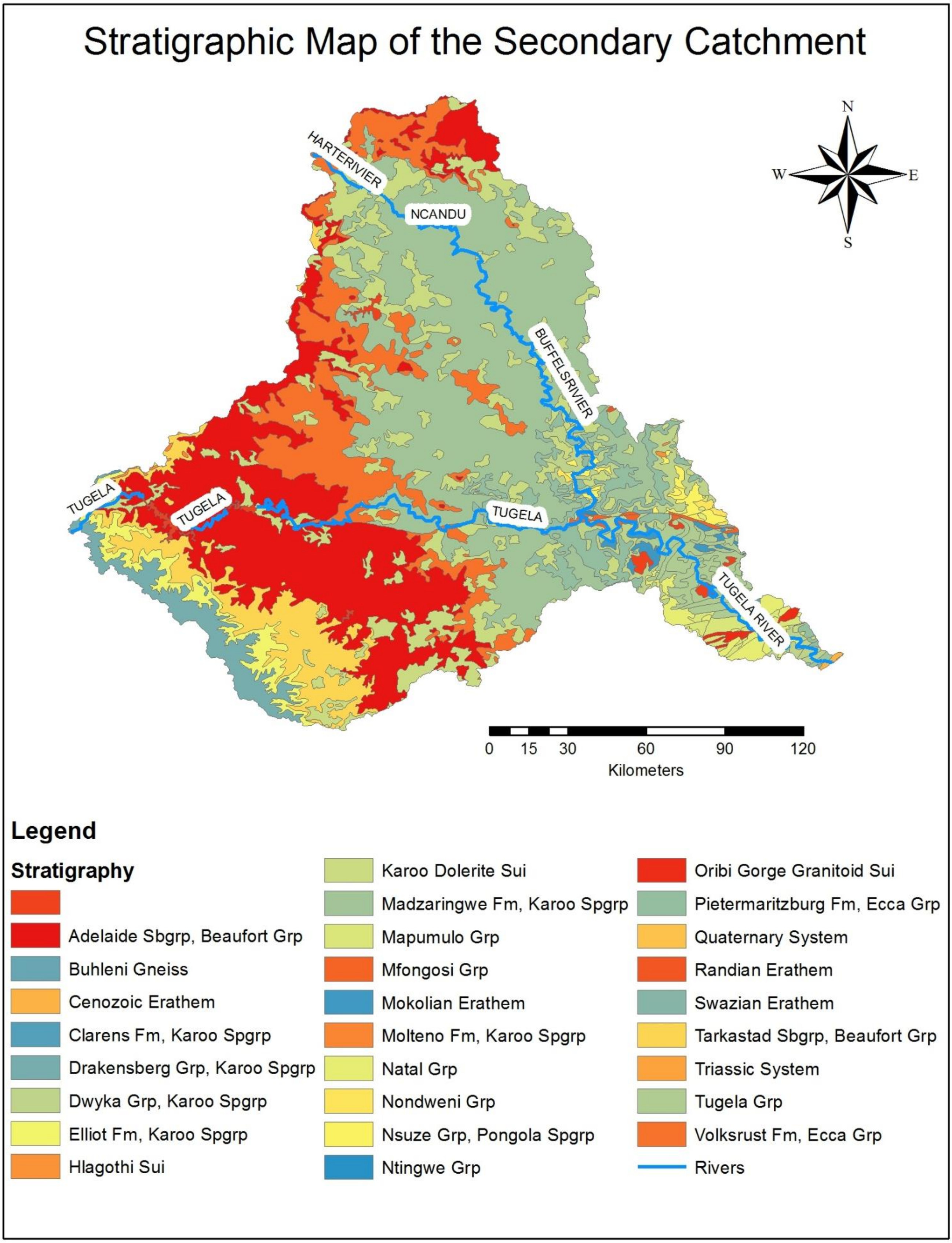

Figure 10: Simplified geological map of the Thukela River catchment

Tectonics

Parallel to the coast some 70 km inland a well-defined area has been faulted which led to the development of tilted block faults, horst and garben structures in the study area south-east of Kranskop (Source-to-Sea, 2003). These structures are of the post Karoo age and are limited to the lower Thukela River. The Southern Thukela fault plays an important role in defining the morphology and position of the river. The fault was caused by the break-up of Gondwanaland and there are a few more throughout the primary catchment, they play an important role in the water bearing properties of prevailing aquifers (King, 1997).

Population

The total population for the Thukela River catchment is approximately 1 570 000 and dominated by rural areas. The population of the quaternary catchment V50D of the study area is approximately 39 000 (Statistics, 2013). Most of the population live in Mandini and are poor with a GDP well below the provincial average (BKS, 2001). The other towns in the close vicinity are the Thukela and Thukela mouth.

Land use

The agricultural sector in the quaternary catchment includes sugar cane and stock farming. Sappi manufacture paper in the immediate vicinity and have a discharge point at the higher part of the study area (Source-to-Sea, 2003). Sappi and other manufacturing companies discharge in the Mandini River which is a tributary of the lower Thukela River and fall within the study area.

3.4. Hydrological Data collection

Prior to the field trip site 1, 2, 3, 4 and 5 were selected by using aerial and satellite photographs (Figure 11) as well as some alternative sites in case one of the sites were not suitable. Preferred sites from a hydraulics perspective consisted of a single channel, located on a reach with constant gradient and channel cross-section shape (Figure 12D). There was no hydraulic control downwards of the selected sites and the sites contained suitable habitat for the biota of interest. The desktop site selection saved a lot of time searching for sites. Some of the major issues on the Lower Thukela River are accessibility and safety (crocodiles) (Figure 12C).

It is critical to obtain a detailed representation of bed topography for 1-D and 2-D hydraulic modelling. Site benchmarks (Figure 12A) were established in August 2015 and an open water hydraulic survey was conducted on the 15th of August when water levels were constant. A total of 6 cross-sections were surveyed with a Total Station (Nikon D-50) (Figure 12B, F, G) in the study area as well as a longitudinal transect with a level logger and Aquameter from the upstream boundary to the downstream boundary taking both location and depth measurements (Figure 11). A supplemented bathymetric survey was conducted in April 2016 which was supposed to be the high flow period, but due to the drought the stage of the river was lower than the previous survey.

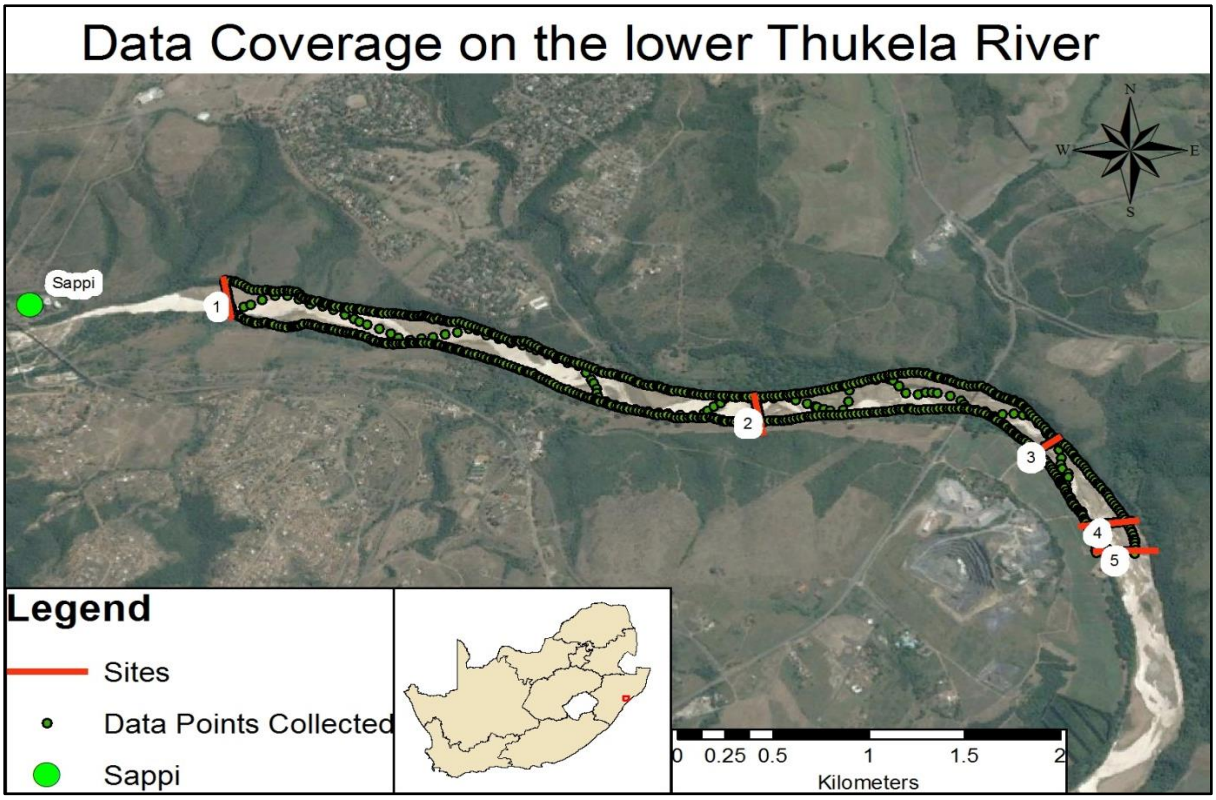

Figure 11: Data coverage on the lower Thukela River during this study.

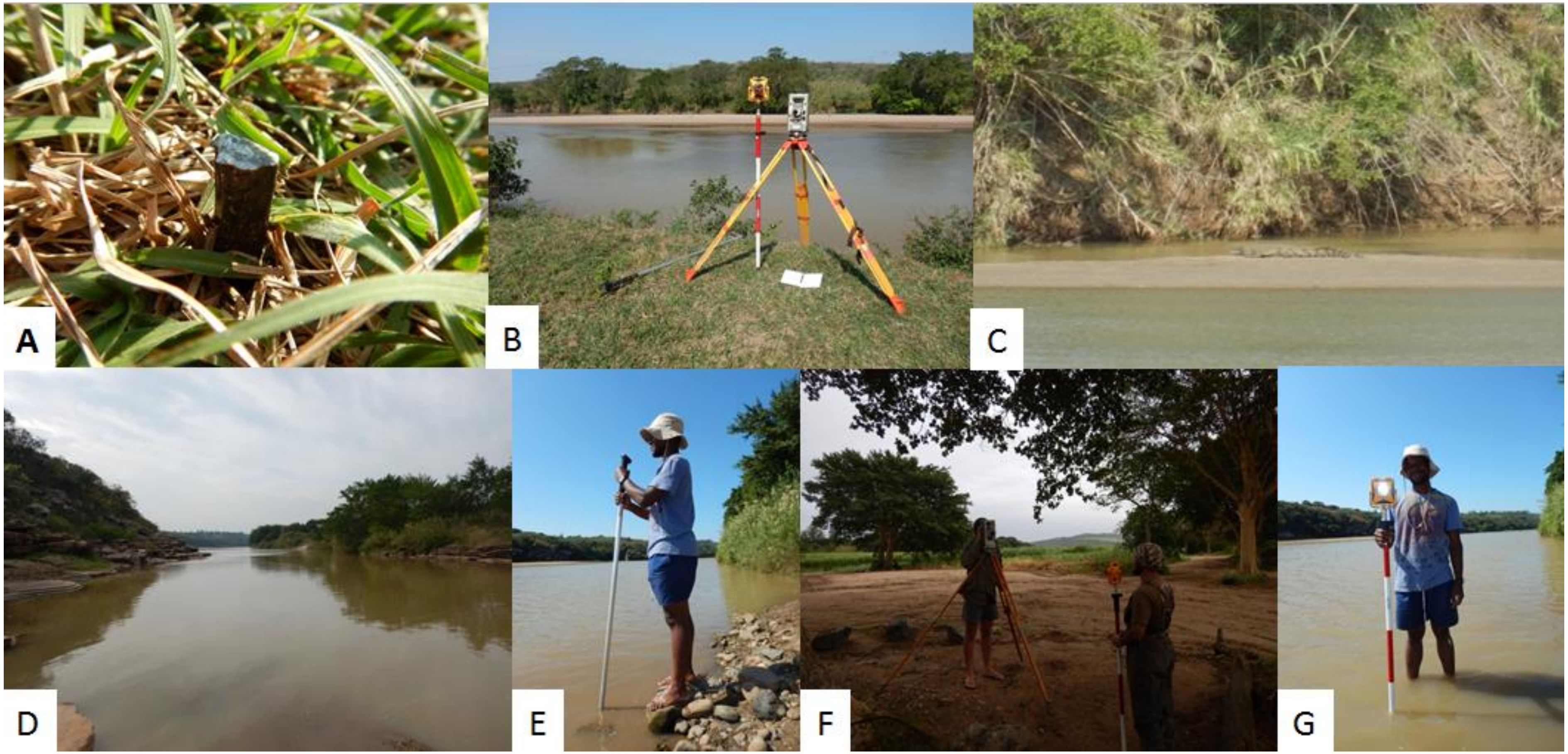

Figure 12: A) One of the benchmarks installed in April 2015 on the first survey for a cross-section to get a stage discharge profile, B) Setting up the Total station to complete the cross section. C) One of the crocodile encounters at a cross-section profile, D) Showing a single channel for one of the cross-sections, E) Ntaki measuring flow velocities with the flow meter, F) Starting a cross-section close and working the way back, G) Testing the prism to make sure it works before starting the cross-sections.

3.5. Fish collection

Fish collection surveys were carried out to the lower Thukela River in variable flow period including low flow (August 2015) and high flow (April 2016). Multiple fish sampling techniques were used for the different habitat types available during each survey with some precautions taken for safety against crocodiles. Different netting methods that were used during the surveys included kick nets, seine nets, casting nets and fyke nets (Figure 13). Other methods that were used were electrofishing and angling depending on the characteristics of the river system (Figure 13). The seine nets were used in shallow pools and backwaters sampling vegetated overbanks were the cast nets were mostly used in faster flowing water like rapids and riffle habitats. In areas with sand as the main substrate a medium size seine net 35 m long with a 1.2 m deep bag in the middle with 8 mm mesh size were used for sampling larger specimens and a smaller seine of 7 m long with a 1 m deep bag with 1 mm mesh size were used for capturing small specimens in vegetation and along banks and backwaters. The electrofishing were used in wadable habitats and stunned fish were collected with fine-meshed hand-held scoop-nets. Sampled fish were placed into buckets of water until identification and measurements (SL and TL) were taken. Fish were described and counted in the field to determine community structures for each species. For each effort different habitat variables were described including depth (mm), velocities (m/s), substrate distribution (Figure 14) and cover types and were then compared to fish community structures for each sampling type. The velocities were measured with a Global Water Meter (model FP211) that can only take readings in increments of 0.1 m/s, thus velocity curves are not smooth and differ from velocities simulated.

Figure 13: Sampiling methods used for fish collection during surveys included: A) Seine nets, B) Casting net, C) Electrofishing and D) Scoop net

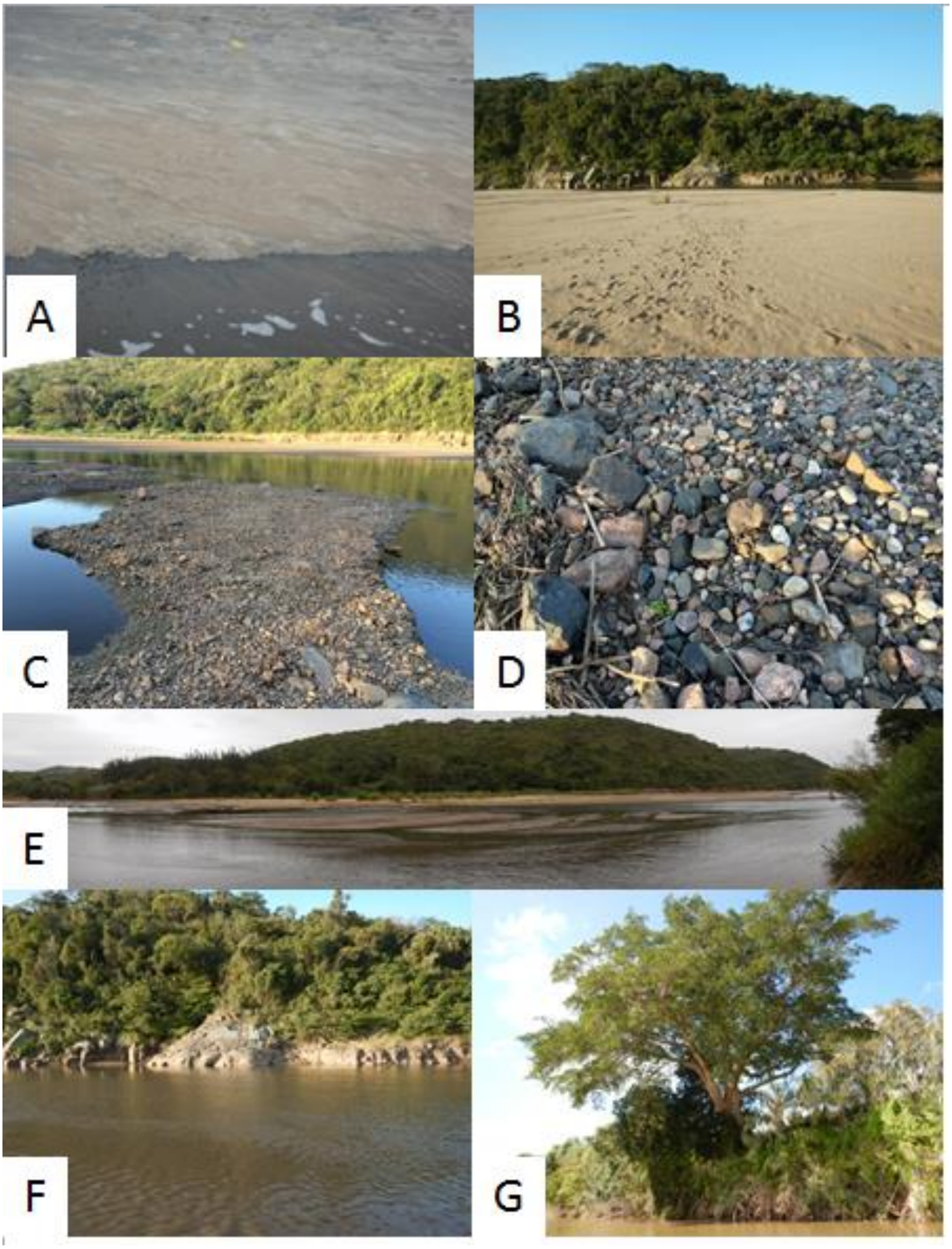

Figure 14: The different habitats used for the channel index substrate in the WUA calculations. A) Silt, B) Sand, C and D) Gravel, E) Sand cover area, F) Bedrock, G) Vegetated overbanks

3.6. Data analyses

3.6.1. Field Measurements

Discharge was calculated by using the velocity-area measurement method based on the velocity at 60% of the depth (James & King, 2010). At site 1 the depth was measured every meter and for site 2, 3, 4 and 5 the depth was measured in 2 m intervals for practical reasons. At each point where depth was measured a velocity reading was recorded (Figure 15). Cross sections are then divided into different sections each with their own velocity, and discharge for each section are calculated and then added to obtain a total discharge (James & King, 2010).

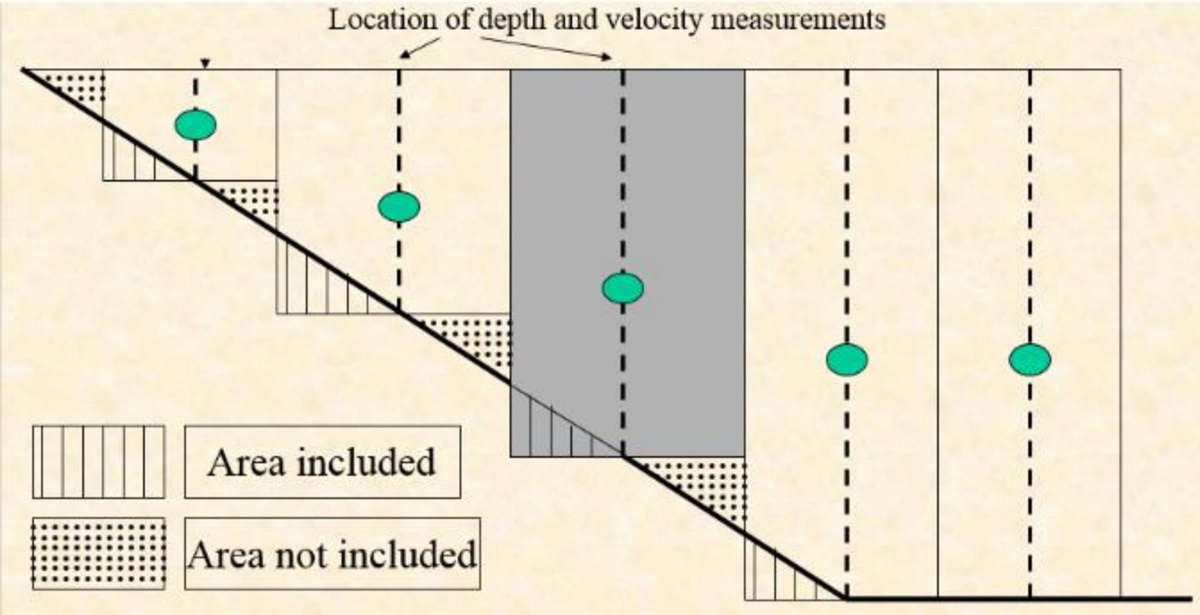

Figure 15: Velocity-area method based on the velocity at 60% of the depth (John, 2001).

To calculate discharge with the velocity-area method the following equation were used:

$$Q = AV$$

Where Q is equal to the discharge (volume/unit time e.g. m^3/second), A is the cross sectional area as governed by the stage of the river in (m^2) and V is the average velocity of flow (m/s).

Two ropes where strung across the river at the sites, one to hold the boat in place and the other to survey in a straight line. The rope that was strung for the cross-section had markings on every meter and by using a total station the cross sections where mapped out. The points, cross-section gradient and water stage where recorded manually and processed afterwards.

3.6.2. DEM and cross sections generated

Elevation data in the form of 5 m contour lines, spot heights and bathymetric data from surveys where merged to create the most accurate DEM (Digital Elevation Model) in ArcGIS.

The following steps were followed as a quality control to ensure data accuracy:

- All data sets were inspected and suspect values were removed.
- Bathymetric data were sorted by depth and those outside reasonable bounds were removed.
- Unrealistic velocity data were removed.

The data where projected to UTM zone 36S (Universal Transverse Mercator) and a TIN (Triangulated irregular network) where then created to get the most suitable 3D model of the topography as suggested by the Hydrological Engineering Centre. LIDAR elevation data were not available for the study. HEC-GeoRas with a series of tool was used to develop geometric data for HEC-RAS which included stream centreline, main banks, flow paths and cross sectional cut lines perpendicular to flow direction.

Cross sections generated by HECGeo-RAS from the DEM in GIS were imported into HEC-RAS. The cross-sections were extracted from HEC-RAS at the same coordinates as cross sections done with the total station and compared to estimate the accuracy of the newly generated cross sections.

3.6.3. Model selection

The study area is 4.6 km long and for this study two hydraulic models were chosen (HEC-RAS and River2D) to conduct the analyses and stimulate flow predictions.

- HEC-RAS is a 1-D model and was used to generate estimate water levels for selected flow modelling scenarios at the downstream boundary of the River2D model. The reasons for selected HEC-RAS to assist in modelling are:
  - By using HEC-RAS to predict downstream boundary water levels for River2D will eliminate/minimize any boundary effects in River2D (Payne *et al.*, 2011).
  - HEC-RAS will assist in the calibration process of River2D based on the relationship between Manning's roughness and the roughness height.
- River2D can accommodate dry elements under a wide range of flows under open water conditions. River2D also have a fish habitat component, based on the Weighted Useable Area (WUA) which is an important aspect of the study conducted.

The model will be used to simulate flows ranging from low flow (1 m^3/s) to high flows in excess of (1000 m^3/s).

3.6.4. HEC-RAS analyses

Historical data from gauging station V5H002 (Mandini) were used to select 23 simulated flows for various possible discharges of the Thukela River including drought, normal and high flow periods. This is the closest gauging station to the study area and is situated 4.6 km upstream from the first cross-section.

HEC-RAS was developed by the Hydrological Engineering Centre of the U.S. Army Corps of Engineers (Brunner, 2001) to calculate water surface elevation by solving the energy equation between cross-sections along a river section. The HEC-RAS model was set up using surveyed river cross-sections and cross-sections generated from the DEM. The model was then calibrated based on the measured open-water stage and discharge (4.3 m^3/s) data from the survey in April 2016. HEC-RAS was used to conduct the 23 model runs for various selected discharges ranging from 1 m^3/s to 4000 m^3/s under open water conditions. The water levels predicted by HEC-RAS were used as the downstream boundary conditions of the River2D model (Payne *et al.*, 2011).

3.6.5. River2D data analyses

The existing DEM created in GIS were used for topographic data in River2D. The bathymetric data from the survey in August 2015 and April 2016 were used and integrated as accurately as possible with the limited funding and equipment. Site information (e.g. vegetation, geology, soil and bed material) were collected on the various surveys.

The river bed topographic data from the integrated DEM and the bathymetric data from surveys as well as additional cross-section data generated with HEC-GeoRAS were used to produce the bed file required by the River2D model.

Mesh generation

An appropriate mesh system is required to ensure numerical stability and accuracy in the River2D model. One mesh profile was generated for flows in the study area, due to the nature of the river which include high banks and minimum floodplains along the study reach. A mesh system was generated using triangular finite elements for the River2D model. The following features are present:

- A computational domain was defined by exterior boundaries for the study area of interest.

- Breaklines were assigned at areas with significant topographic changes for example: top and bottom of river banks.
- The mesh grid size was set to 8 m for the main channel and refined to 5 m along the river banks.
- Areas of the mesh system were optimized by editing nodes and grid connections to improve the quality index (QI) until a satisfactory value of greater than 0.15 was obtained. A QI of 0.15 is considered to be acceptable for River2D modelling (Steffler & Blackburn, 2002a).
- The final mesh profile consisted of approximately 18258 nodes and 34625 finite elements with an optimized QI value of 0.224.

Roughness height selection

The bed roughness height K_s (m) is an important aspect for River2D modelling. The observation of bed material, land formation and vegetation provided a physical basis for selecting reasonable initial values of bed roughness. The river bed consisted mostly of fines (sand and some silt) with very little cobbles. The particle size of bed material D_{50} is 0.2 mm (for sand and silt) with a typical K_s value ranging between 0.006 to 0.1 m according to the (hydraulic and geomorphic characteristics of rivers in Alberta (Kellerhals *et al.*, 1972)). Final adjustments of K_s values were made during model calibration.

Boundaries

For this study discharge was assigned as the upstream hydraulic boundary and water level was assigned for the downstream boundary. A total of 23 simulated flow scenarios were identified and used for discharges ranging between 1 m^3/s to 4000 m^3/s, the same value set used in HEC-RAS simulations. The corresponding water levels generated by HEC-RAS were set as the downstream boundary for the River2D model.

Model Calibration

The River2D model was calibrated for open-water low flow conditions. A measured discharge of 4.3 m^3/s and water levels from the April 2016 survey were used for initial model calibration. The primary model parameter for River2D is the roughness height. To select suitable K_s, site information, bank and bed material, vegetation cover and literature reviews of similar river systems have to be considered. The K_s was then adjusted until a satisfactory match was obtained between the measured and simulated water levels, and were then further adjusted based on the comparison between simulated and measured velocity profiles along the study reach.

Calculating fish habitats

After calibration the River2D model can be used to calculate fish habitat index or availability by making use of WUA using the same concept as in the Physical Habitat Simulation System (PHABSIM) (Paxton, 2008). A composite suitability index (CSI) is used in the calculation of WUA at each node in a specific domain and the area associated with that node (CSI x surface area), CSI is dimensionless and therefore the unit of WUA will stay m^2 (Paxton, 2008). To calculate WUA in River2D, data such as habitat Suitability Index (SI), channel index, depth and velocity is required. SI is in the form of fish preference files containing SI curves in table form for channel index, depth and velocity. River2D calculates the product of these indices to obtain a CSI (Paxton, 2008).

Composite SI = depth SI x velocity SI x Channel Index

This file is then imported into River2D and combined with the channel index to calculate WUA. Channel index can be described as a constant assigned for each computational node that does not change with a change in flow such as the different substrates found in river channels (Table 6) (Paxton, 2008). The bed topography editor, in River2D can be used to build the computational mesh used for the channel index file by replacing the bed roughness values with channel index values and later renaming them to the specific substrate and changing the file extension from (.bed) to (.chi). Once the solution has converged to steady state, with a goal solution change of less than 0.00001 and a reasonable inflow and outflow value within 1% of each other the model will provide depth and velocity suitability indices for each node over the entire computational mesh (Steffler & Blackburn, 2002a)

Table 6: Numbers assigned for different substrates on the computational mesh.

Channel Index	Substrate
1	Silt
2	Sand
3	Small Gr.
4	Lg. Gravel
5	Cobble
6	Cobble 2
7	Boulder
8	Boulder 2
9	Bed Rock
10	Vegetated overbank

3.7. Ecological wellbeing of fish in the Thukela River

The following Lines of Evidence (LoEs) were used to characterise the ecological wellbeing (or state) of the fish component of the riverine ecosystem in the study area:

- Statistical evaluation of shifts in community structure (Van den Brink *et al.*, 2003; O'Brien *et al.*, 2009). The state evaluation were carried out using a multivariate statistical procedure for fish community structures in relation to changes in community structures (using a Redundancy Analysis ordination technique based on Canoco version 4.5 software (Ter Braak & Šmilauer, 2002)). The direct correlation of changes in fish community structures in terms of taxa obtained during surveys can be interpreted and combined with Monte Carlo permutation testing to see if there are a statistical significance between the relationship of community structures and environmental variables (Van den Brink *et al.*, 2003; O'Brien *et al.*, 2009). With this approach fish sample data and species ordination can be overlain with environmental variables (such as habitat and velocity-depth) to acquire the drivers of shifts in fish community structures in the lower Thukela River.
- Fish Response Assessment Index (FRAI) classification system and an adapted method of FRAI was used in this study as shown in Figure 16 (Kleynhans, 2007). Data that were required for fish habitats for addition to our database were used including:
    - Velocity-depth preference data
    - Flow preferences
    - Substrate preferences
    - Importance and distance of fish migration

The FRAI approach incorporates the motivation for specific selections of, and use of preference conditions. The FRAI results in two scores, an automated score and an adjusted score (Kleynhans, 2007). The automated scores are largely based on the automated evaluation of the state of the driver variables (FRAI metric variables) based on the differences in expected and observed species in the assessment. FRAI allows operators to manually evaluate the state of driver variables (selected physical environmental variables), therefore the FRAI scores can be adjusted for the state of fish communities in response to selected driver variables. The FRAI scores can be compared with the ecological classification system, a continuum of six classes used in the Ecostatus methodology (Kleynhans *et al.*, 2008).

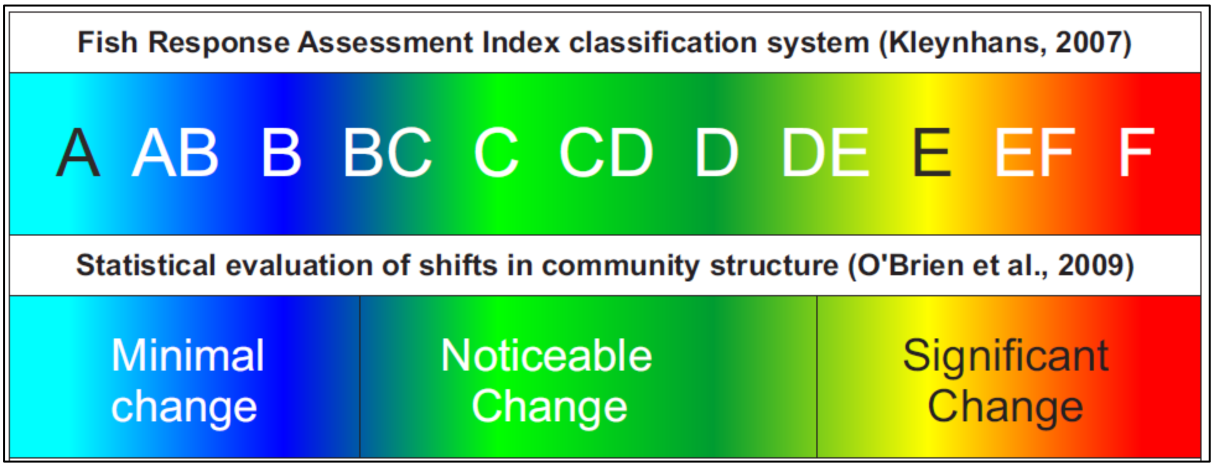

Figure 16: Comparisons/overlaps in scoring systems of the Lines of Evidence used in the study to represent fish health (FRAI), community structures and community wellbeing.

3.7.1. Response of communities to habitat variable condition alterations

The following Line of Evidence (LoEs) was used to characterise the ecological flow requirements of fishes in the study area:

- Indicator species recruitment information (Paxton *et al.*, 2013).
- Fish Invertebrate Flow Habitat Assessment Index (FIFHA).

FIFHA was developed to evaluate the effects of flow dependant habitat type alterations on an ecological indicator fish species and/or guild. FIFHA is an excel based evaluation tool developed by Kleynhans (2007). The FIFHA integrates historical hydraulic data from weirs with those collected during field surveys. The evaluation process includes:

- Practitioner must have a thorough understanding of the species/guild and their range of habitat preferences for velocity, depth and available habitat. The specific use of rheophillic or semi rheophillic species should be identified for different flow periods (high or low flow). The assessment can be based on habitat suitability of species and/or guild and the operator can modify the preference information to generate a hypothetical flow-habitat preference which can be imported into River2D. For the Thukela River two different species will be used to calculate a combined EWR to maintain critical baseflow and still maintain the necessary diversity. *Labeobarbus natalensis* will be used as a rheophillic species, they have a high preference for flows and will mostly be used for velocity-depth classes, *E. fusca* is a lowland river species that needs estuarine habitats for survival and can be considered an important species to maintain diversity within the ecosystem. There is a relatively good understanding of the biology and ecology of both species.

3.7.2. Habitat preference assessment

Velocity readings were taken 3 times at the different places with a transparent velocity head rod (TVHR) for each effort where fish have been caught. The TVHR were inserted with the flat side perpendicular to the flow and data were recorded in centimetres with the first reading on the upstream side were water push up against the TVHR and the second reading at the downstream side (Fonstad *et al.*, 2005). The head difference between the two readings were used to calculate the velocity for each reading and then divided by three to get an average for that area. This was done three times and an average of the three times was then used as the velocity for the effort. The TVHR has a highly significant correlation of 0.94 when compared to a traditional AA current meter making it precise to almost 5% (Fonstad *et al.*, 2005). The following equation were used to convert head differences to velocities (Fonstad *et al.*, 2005):

$$V = 0.728 * ((2gh)^{0.5}) - 0.1126 \text{ m/s}$$

Where g is the gravitational velocity which is a constant at 9.8 m/s and h is the difference in head from the reading facing upstream and downstream on the TVHR in metres (Fonstad *et al.*, 2005).

The depth of each effort where fish have been caught were measured with the TVHR thin side turned into flow and depth would be unaffected by the TVHR. Measurements were taken three times for each effort and the average of these readings was used in data analyses.

For each effort where fish have been caught the substrate type was recorded in percentage covering the bed. If channel bed was covered by more than one substrate type the combined percentages of covered area were estimated and recorded out of 100%.

Velocity, depth and substrate were recorded for each effort and each species separately on data sheets in the field. A box and whisker plot was created for velocity and depth using average velocity and depth for each species. The percentile function was then used to calculate the 5^{th}, 25^{th}, 50^{th}, 7^{th} and 95^{th} percentiles for velocity and depth. The 5^{th} percentile shows the lower end of the data of which only 5% of the population was caught in including slower velocities and shallower depths. The 50^{th} percentile represents the velocity and depth of which 50% of the population preferred making this the biggest and most preferred habitat. The 95^{th} percentiles represent the higher end of data of which only 5% of the population preferred, including the higher velocities and depths. For substrate a stack column graph was used to demonstrate the preferred substrate for each species out of 100%. These graphs were used to create a preference file for indicator species that were used in River2D to calculate the WUA. For velocity the 25th, 50th and 75th percentile were assigned a value of 1 which is the most preferred velocity for the specific species. For faster velocities an 85th percentile were calculated and assigned a value of 0.5, for the 95th percentile a value of 0.25 was assigned. For slower velocities a 15th percentile was calculated and given a value of 0.25 and for the 5th percentile a value of 0.1 was given which is the least preferred habitat type for velocities.

A preference file for depth for each species were created using the same techniques but it was assumed that an increase in depth would relate to an increase in preference for any given species and that the maximum depth is not the limiting factor but rather the minimum depth and therefore the 50th, 75th, 95th percentile were all given a value of 1 and the 25th and 5th percentiles were assigned 0.5 and 0.1 respectively.

The stack column graph already calculated the preference for each species as a percentage and these values were converted to a value out of 1 and assigned to each substrate type. The preference files were saved as text delimited from excel and then changed to a (.prf) file extension to be imported to River2D for calculations.

3.8. Historic method for calculating ecological flow requirements

The flow-duration curve were calculated on daily average flow data from 1963 to 2016, with some data removed or edited according to missing information in data received from the Department of Water and Sanitation. The indices used for flow duration curves are referred to using a Qx notation when the x indicates the percentile that was used. Q50 is the median monthly flow and represent the flow which exceeded 50% of the time, this method was developed by the New England U.S. Fish and Wildlife service for catchments with good historic hydrological records (Caissie & El-Jabi, 1995). The method is now slightly adapted and used on a more seasonal basis to describe the median flow for 6 different seasonal periods and is referred to as the New England Aquatic Base Flow method (ABF). The different time periods are (Linnansaari *et al.*, 2012):

- Summer (January 1 to march 15) = to the February Q50
- Autumn (March 16 to May 15) = to the April Q50
- Early winter (May 16 to June 30) = to the June Q50
- Winter (July 1 to September 15) = to August Q50
- Spring (September 16 to November 15) = to October Q50
- Early summer (November 16 to December 31) = to December Q50

The Q50 do not describe the environmental flow that needs to be maintained but indicates the level of flow were no further abstraction of water is allowed and the actual minimum environmental flow is determined by using a percentage of the natural flows where 70% of the median flows as recommended by Fisheries and Oceans in Canada (Caissie & El-Jabi, 1995).

The Tennant method has also been used which specifies 10% of the average flow as the lower limit for aquatic life (critical base flow) and that 30% of the average flow will provide a satisfactory stream environment (base flow) for ecological survival. To increase the ecological state of the river a flow of 50% (median) monthly flow is described and for freshes 70% were used, this is the flow that will flush bed sediment (Tennant, 1976).

3.9. Instream flow incremental methodology

There is no clear point at which instream conditions turn good or bad, but rather a general assumption that habitat gets worse as flows decrease below optimal value. The rate of habitat change vary with flow and therefore when habitat modelling results are available the rate of change is used as the basis for setting a minimum flow. The point of greatest change in the rate (the breakpoint) is used as the minimum flow requirement for the lower Thukela River. This is set based on the criteria that higher flows will have a diminishing effect on habitat availability although the effect of higher than optimum flows will be less significant to those of decreasing the flow and any habitat loss may be balanced by the amount of cover and food production (Jowett *et al.*, 2008).

Instream flow incremental methodology (IFIM) can be described as hydraulic habitat modelling and is a combination between habitat suitability and hydraulic modelling of the river flow, also known as instream habitat modelling or physical habitat modelling. The river uses physical habitat velocity, depth and substrate and in this study River2D was used to predict the physical habitat based on the PHABSIM concept of WUA (m^2/m) (Jowett *et al.*, 2008). The purpose of predicting the minimum flows are to maintain, or even improve the physical habitat by retaining adequate water depth and velocities.

4. Results and Discussion

4.1. Digital elevation model (DEM) creation, predicting water levels and velocity-flow classes

During the different surveys bathymetric data were collected by means of cross-sections and random sections that were mapped with a Total Station. These data were combined with 5 m contours and spot heights in ArcGIS to create an accurate DEM (Figure 17).

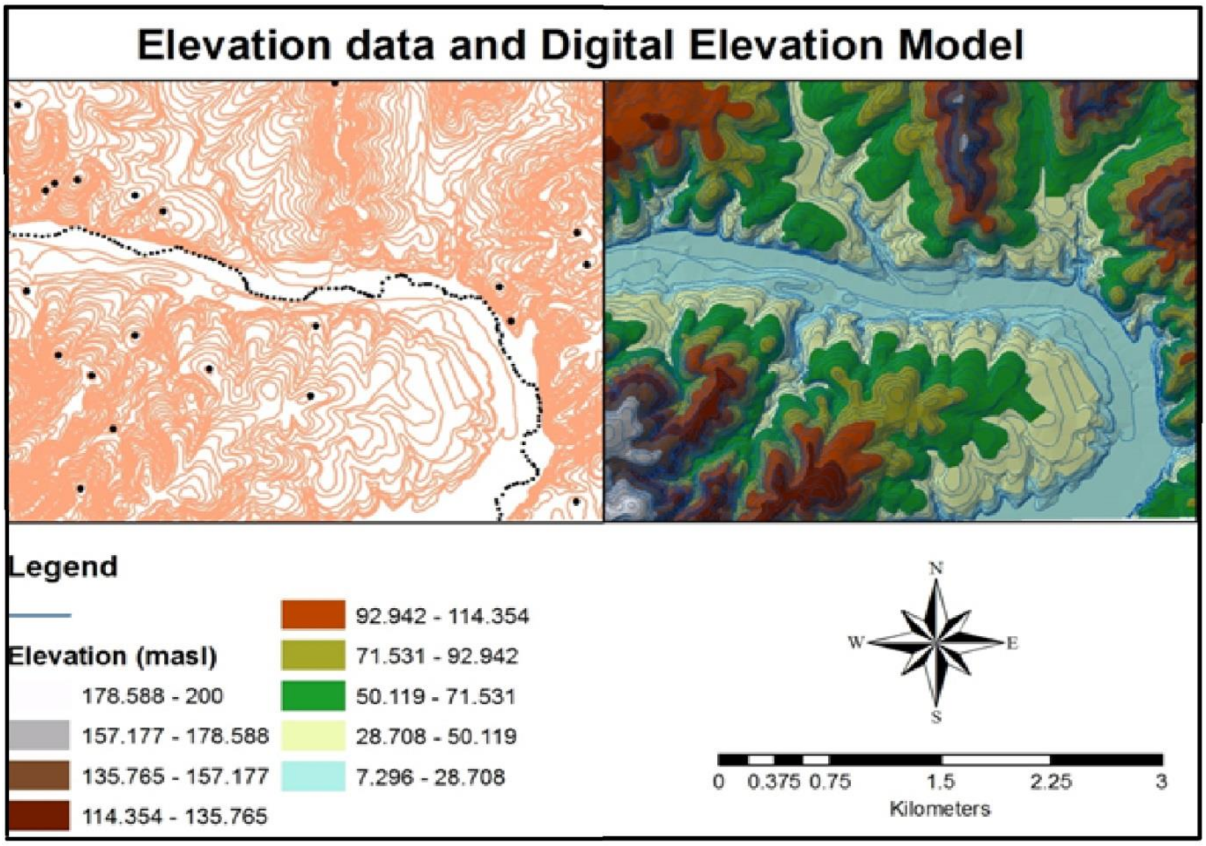

Figure 17: Topographic data used to generate a DEM.

Additional data were needed for the bed topography and therefore HEC-GeoRAS were used to generate extra cross sections through the study area. The DEM created in GIS with 5 m contours and spot heights were used as a topography map to delineate flow boundaries, river banks and flood plains (Figure 18).

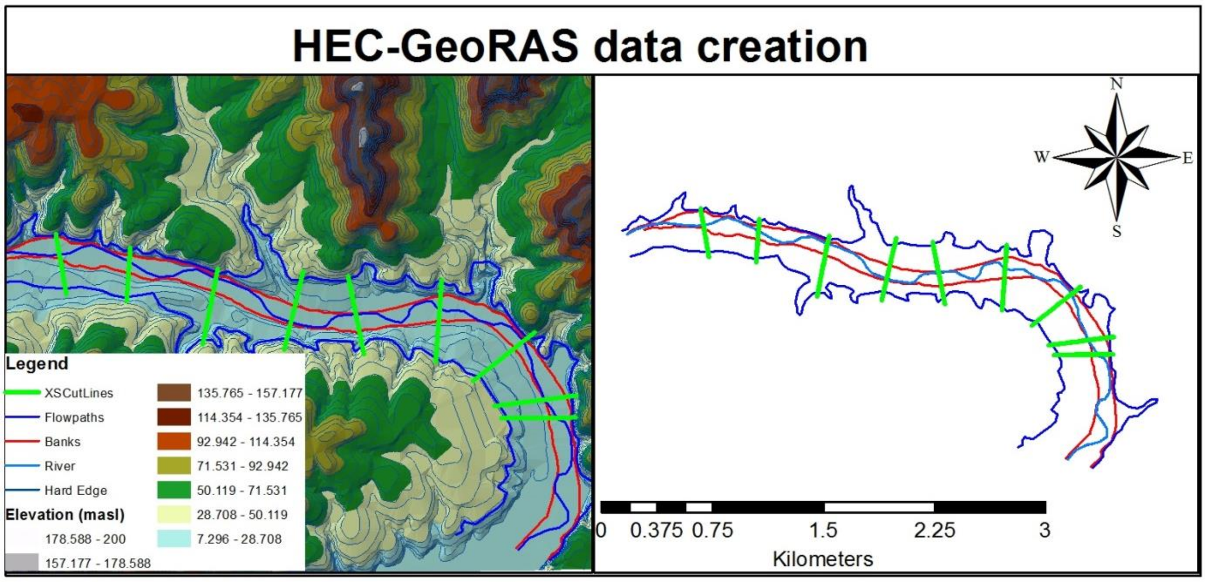

Figure 18: Additional bathymetric data created with HEC-GeoRAS before exporting it into HEC-RAS.

Data exported from HEC-GeoRAS into HEC-RAS were first tested with a steady state analysis with a discharge of 4.3 m^3/s as measured on the survey in April 2016. The simulated water levels were compared to those measured during the survey and by changing the roughness coefficient the water levels were adjusted slightly until a best fit were achieved. The simulated and observed water levels fell within a reasonable calibration with the largest difference between water levels of 0.03 m as shown in Table 7. Calibrated Manning's n values ranged between 0.015 and 0.025 along the study area.

Table 7: Comparison between surveyed water levels and those calibrated by HEC-RAS

Distance from inflow Boundary (m)	Measured Water Elevation (mamsl)	Simulated Water Elevation (mamsl)	Water Level Difference (m)	Notes
0	10.4	10.37	-0.03	1st Cross-Section
1959	9.77	9.76	-0.01	2nd Cross-Section
3171	9.7	9.69	-0.01	3rd Cross-Section
4454	9.61	9.63	0.02	4th Cross-Section
4625	9.58	9.58	0	5th Cross-Section

The results are presented in Figure 19 displaying measured vs. simulated water levels over the measured thalweg.

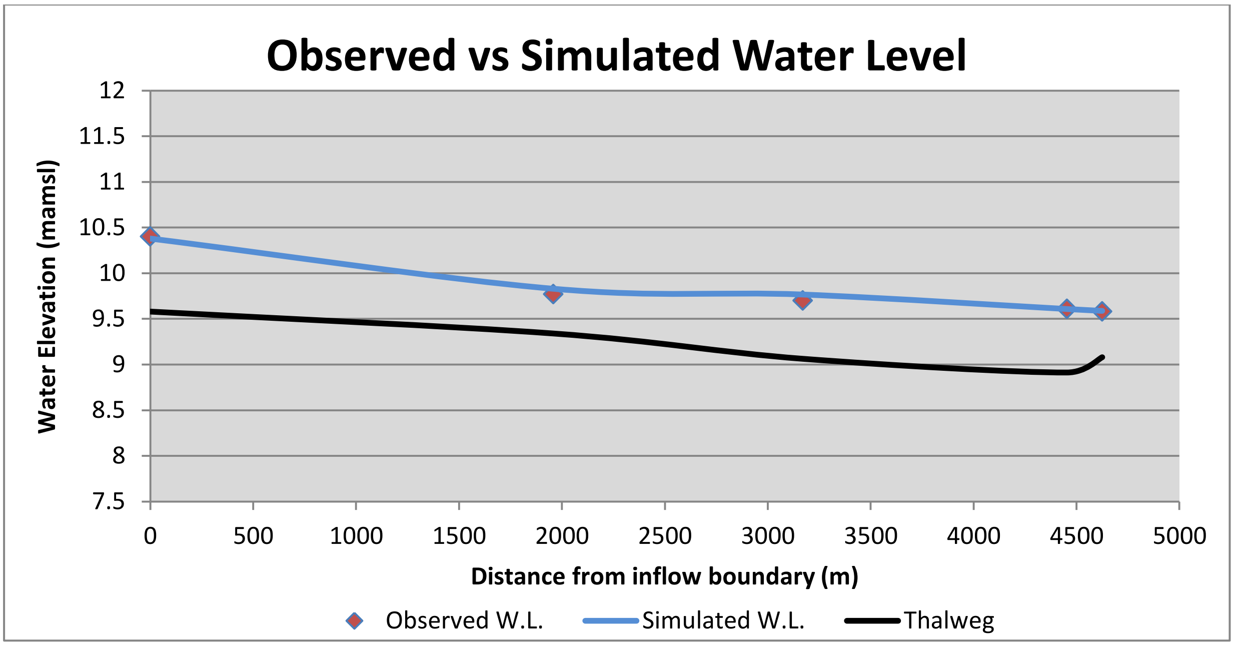

Figure 19: The comparison between HEC-RAS simulated water levels and measured water levels along the thalweg after calibration with a discharge of 4.3 m^3/s.

The correlation between measured and simulated water levels was determined for the calibration in HEC-RAS to illustrate the relationship and accuracy of the model (Figure 20). This is important as it proves that the model is truly calibrated and that the data used for further analyses is trustworthy. The correlation coefficient for measured vs. simulated water levels is 0.99 showing a strong linear relationship between the measured and observed values.

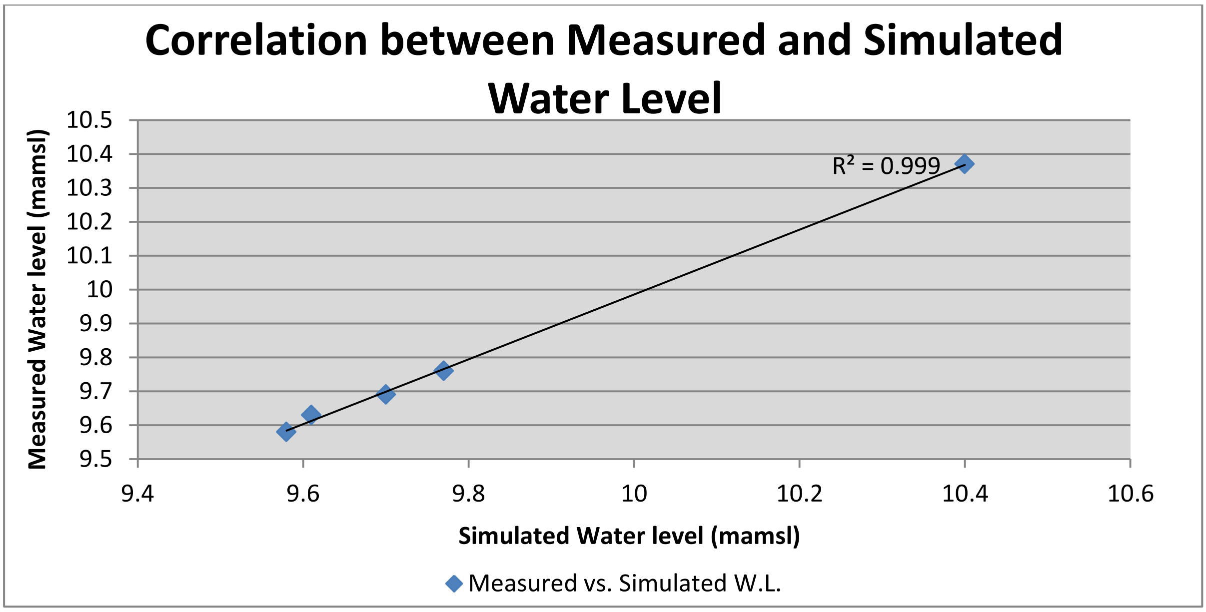

Figure 20: Correlation between measured and simulated water levels at different cross-sections using HEC-RAS after model calibration.

After HEC-RAS were calibrated with a 4.3 m^3/s discharge, peak flow data were collected from gauging station V5H002 (Mandini) and different discharges were selected ranging from low flow to extreme floods for steady flow analyses. The model was then used to predict water surface elevations at each cross-section according to the selected flows (Table 8). The discharge ranges were selected to present the best stage-discharge curve. Only water levels from the outflow boundary (end of study reach) were recorded to predict outflow conditions in River2D.

Table 8: Predicted Water Levels by HEC-RAS for the River2D Model Downstream Boundary.

Model Run (I.D.)	River Flow (m^3/s)	Predicted water levels by HEC-RAS model (mamsl)
1	1	9.57
2	4.3(model calibration)	9.58
3	15	9.60
4	30	9.63
5	45	9.68
6	60	9.78
7	100	9.94
8	200	10.14
9	300	10.32
10	400	10.47
11	500	10.61
12	600	10.74
13	700	10.87
14	800	10.98
15	900	11.1
16	1000	11.21
17	1250	11.46
18	1500	11.7
19	1750	11.93
20	2000	12.13
21	2500	12.52
22	3000	12.86
23	4000	13.69

Figure 21 shows the stage-discharge curve simulated for the downstream boundary by HEC-RAS for River2D. A linear interpretation between predicted water levels represents the relationship between stage and discharge and can be used to extract any water level at any given discharge for the downstream boundary of the study area (Figure 21). Water surface elevations (mamsl) from the stage-discharge curve simulated by the calibrated HEC-RAS model were used as a downstream boundary condition for the River2D model.

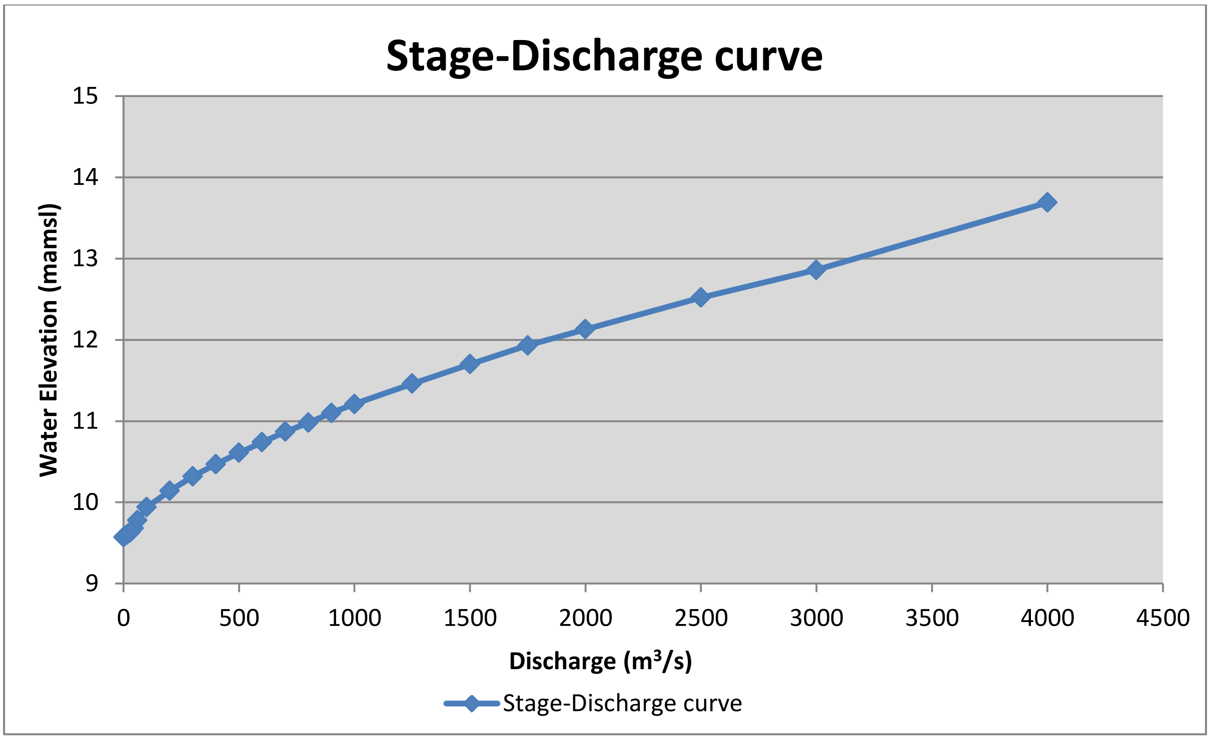

Figure 21: Stage vs. Discharge simulated from HEC-RAS model for the lower boundary conditions in River2D.

4.2. River 2D

Bathymetric data collected from the two surveys, HEC-GeoRAS data from GIS and topographic data from the DEM were used in the bed creation file for River2D. Breaklines were assigned for areas of significance topographic change including upper and lower banks and drop-offs. The thalweg (deepest section of a river channel) were defined as a breakline. No-flow boundaries were delineated in an anti-clockwise direction and instream boundaries in a clockwise direction. Everything to the left of assigned boundaries fall within the domain and everything to the right fall outside the domain and does not form part of the channel and act as a no flow boundary. The model were triangulated and exported as a mesh file and could then be refined in the mesh section of River2D. A mesh grid was generated with regional fill of 8 m in channel and 5 m along the banks. Nodes and bad triangles were identified and edited until a satisfactory QI of 0.224 were obtained. The inflow boundary was set at a discharge of 4.3 m^3/s and the outflow boundary to 9.58 mamsl before the Mesh file were exported as a .cdg file and imported into River2D were a steady flow analysis were performed. Due to some irregularities in data the model did not merge. By filtering the data in the bed program two points with unrealistic elevation heights were discovered in the river channel and after they were removed from the data the new model merged with a goal solution change of 0.00000024 and an inflow-outflow difference of less than 1%. To calibrate the model steady state conditions were considered and surface water elevation data were extracted at each cross-section. The surface water elevation between measured data and those simulated in River2D were compared. In areas were simulated water elevations were too high a lower roughness coefficient were assigned and in areas were simulated water elevation were too low the roughness coefficient were increased. This process was repeated until a satisfactory fit were obtained with the largest differences between simulated and measured water levels reaching as low as 0.07 m (Table 9).

Table 9: Comparison between surveyed water levels and those calibrated by River2D at a discharge of 4.3 m/s.

Distance from inflow Boundary (m)	Measured Water Elevation (mamsl)	Simulated Water Elevation (mamsl)	Water Level Difference (m)	Notes
0	10.40	10.38	0.02	1st Cross-Section
1959	9.77	9.83	-0.06	2nd Cross-Section
3171	9.70	9.76	-0.07	3rd Cross-Section
4454	9.61	9.60	0.00	4th Cross-Section
4625	9.58	9.58	-0.01	5th Cross-Section

Observed and simulated water levels were plotted against each other over the thalweg to provide a graphical image of how well the model is calibrated (Figure 22).

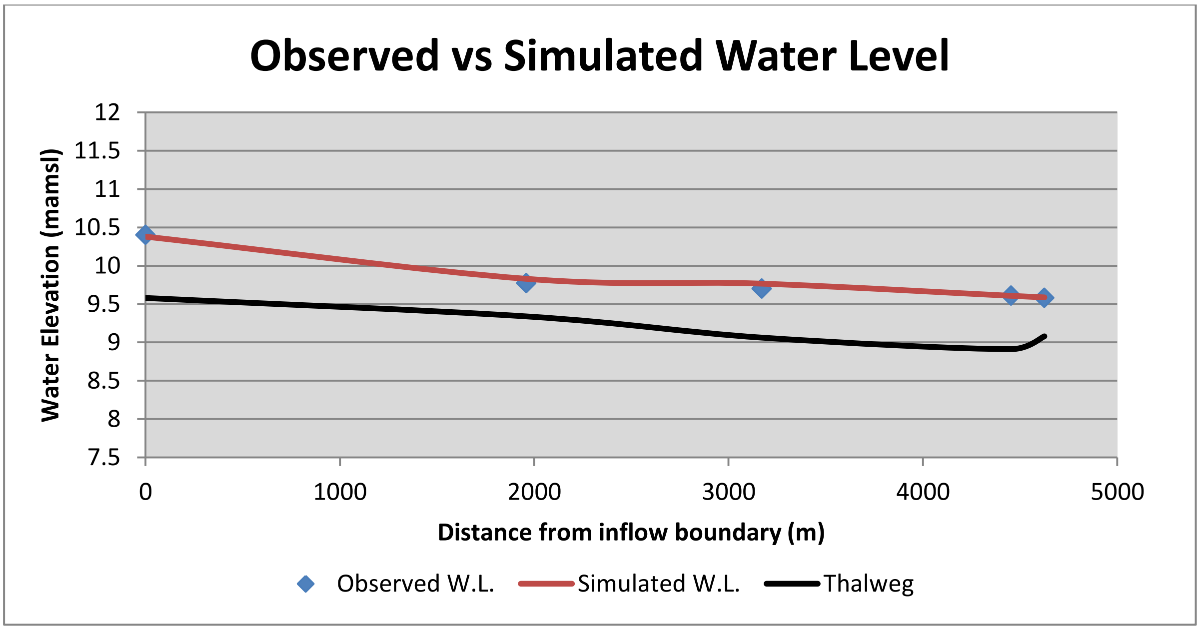

Figure 22: The comparison between River2D simulated water levels and measured water levels along the thalweg after calibration with a discharge of 4.3 m^3/s.

The correlation co-efficient between measured and simulated water levels were determined for the calibration in River2D to illustrate the relationship and accuracy of the model (Figure 23). This is important as it proves that the model is truly calibrated and that the data used for further analyses is trustworthy. The correlation coefficient for measured vs. simulated water levels is 0.98 showing a strong linear relationship between the two variables.

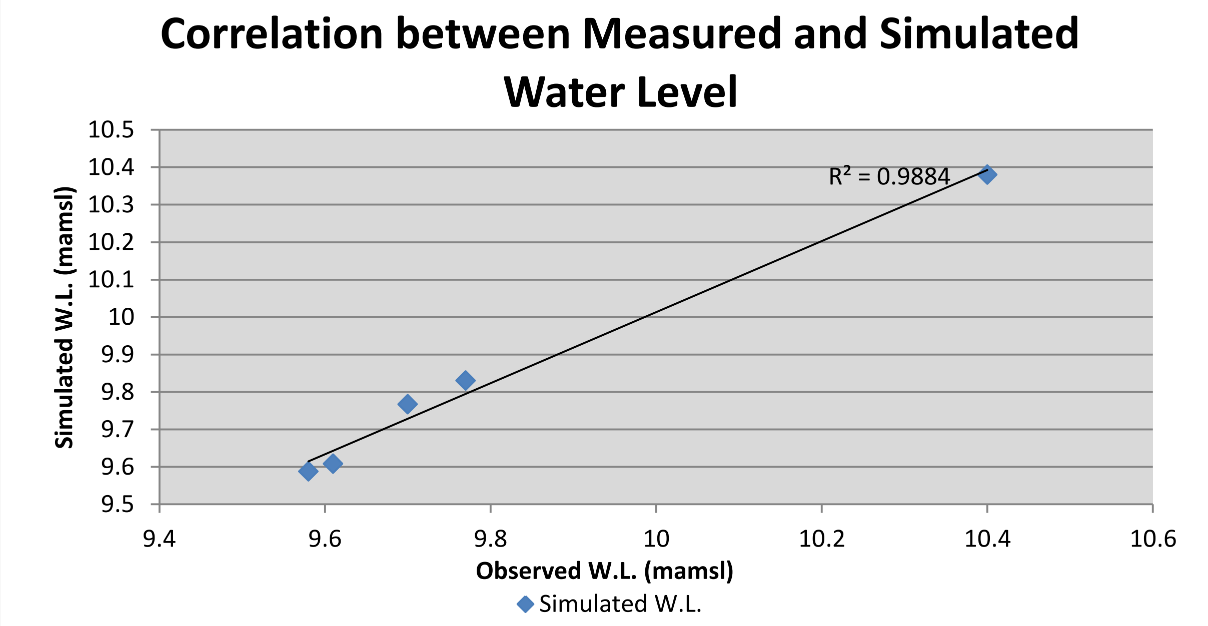

Figure 23: Correlation between measured and simulated water levels at cross-sections using River2D after model calibration.

Simulated velocities were compared to those measured on surveys to assess the similarity in magnitude and distribution on the cross-sections. The simulated velocities match closely with the measured velocities along all cross-sections at the calibrated discharge and therefore no further adjustments were required. In the section that follows banks are described as left and right, looking downstream. The Global Flow meter can only measure velocities in increments of 0.1 m/s and thus resulted in a difference between measured and simulated velocity predictions. Discharge at each cross-section was calculated to get an average discharge over the study area (Table 10).

Table 10: Discharges of sites using velocity-area method (Coordinates is in UTM 35s).

	X	Y	Distance from inflow boundary (m)	Discharge
Site 1	344716.484	6772217.231	0	4.29
Site 2	347112.980	6771781.484	1959	4.41
Site 3	348404.309	6771485.329	3171	4.22
Site 4	348645.591	6771073.928	4454	4.35
Site 5	348683.746	6770930.132	4625	4.24

Site 1: Cross-section

Site 1 was selected to be the inflow boundary and therefore marking the beginning of the study area. The benchmark for the total station was placed on the right bank on higher ground (Figure 21A). Beyond the benchmark the bank flattened and sugarcane plantations are dominant. Habitat/substrate consists of very course gravels and small boulders (Figure 24D) on the right bank and changed into sand substrate from about 4 to 5 m all the way to the other bank. This is a single channel with an isolated pool close to the left bank as shown in Figure 25. The left bank is steep and consists mainly of solid rock. The area-velocity method was used to calculate discharge and a Total Station was used to get elevation data as accurately as possible (Figure 24A).

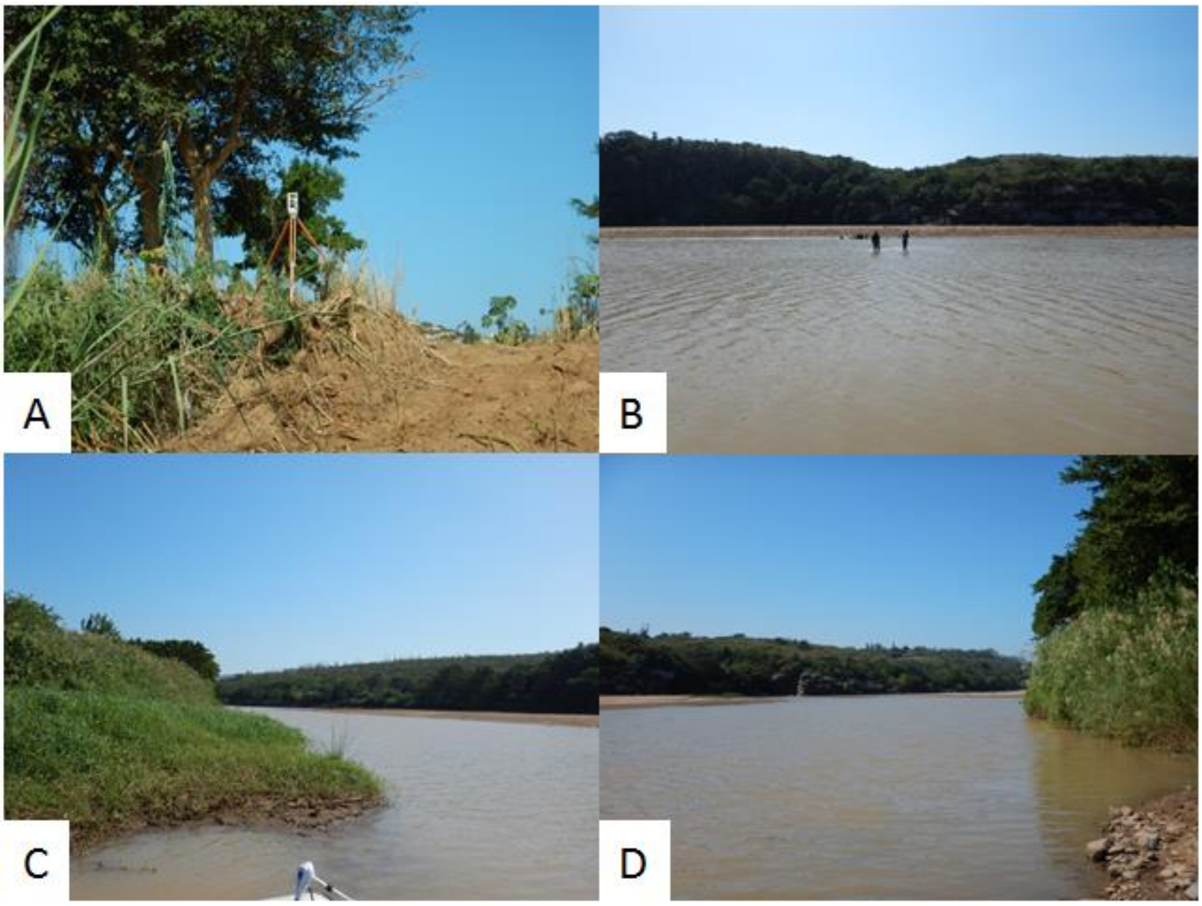

Figure 24: Site 1: cross-section, the inflow boundary for River2D A) Total station setup, B) View across river, C) View upstream, D) View downstream.

Cross-section 1 is shallow with depths reaching a maximum of 0.95 m and velocities stayed constant at about 0.1 m/s (Figure 25). After the River2D model was calibrated velocity values were extracted for each point where velocities were measured with the global flow meter along the cross-section. By comparing the simulated velocities to those measured (Figure 25) it is possible to see a good correlation between the two with only slight alterations closer to the river banks.

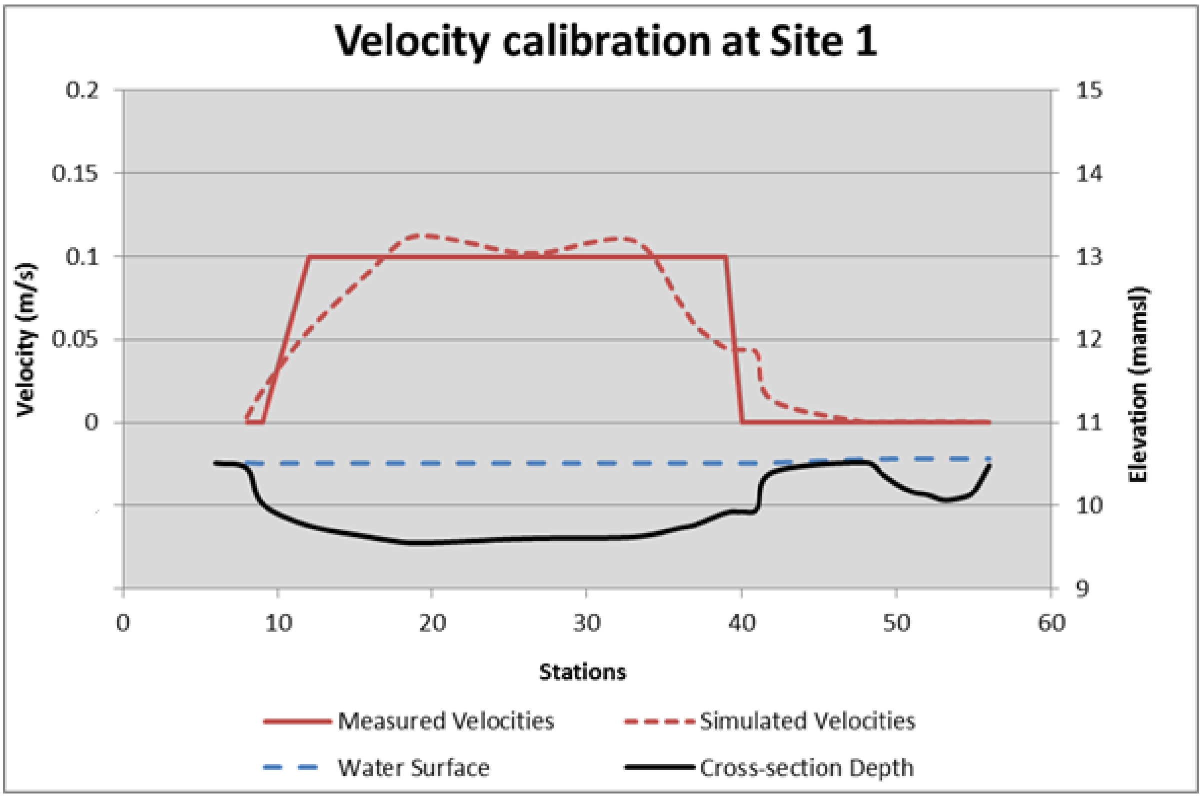

Figure 25: Simulated vs. Measured velocities for cross section 1 over bed topography and depth.

Site 2: Cross-section

Site 2 is situated below SAPPI Water Works and a small discharge from the water works flowed into the Thukela River downstream of the cross section. The inflow from the water works are very variable and on the survey of April 2016 no water was released into the river over that time period and therefore discharge from the water works were completely ignored. Due to accessibility it was impossible to add additional cross sections between site 1 and site 2. Crocodile were spotted at this cross section more than once and posed a threat while doing the elevation measurements and velocity measurements. The benchmark was set on the left bank quite high up and substrate for the channel is dominated by sand throughout (Figure 26). The main stream flowed in the middle of the channel with sand banks on either side. Some small channels formed over sand banks and were modelled as accurately as possible. The right bank is steep and elevated and for this cross-section no flood plains were visible.

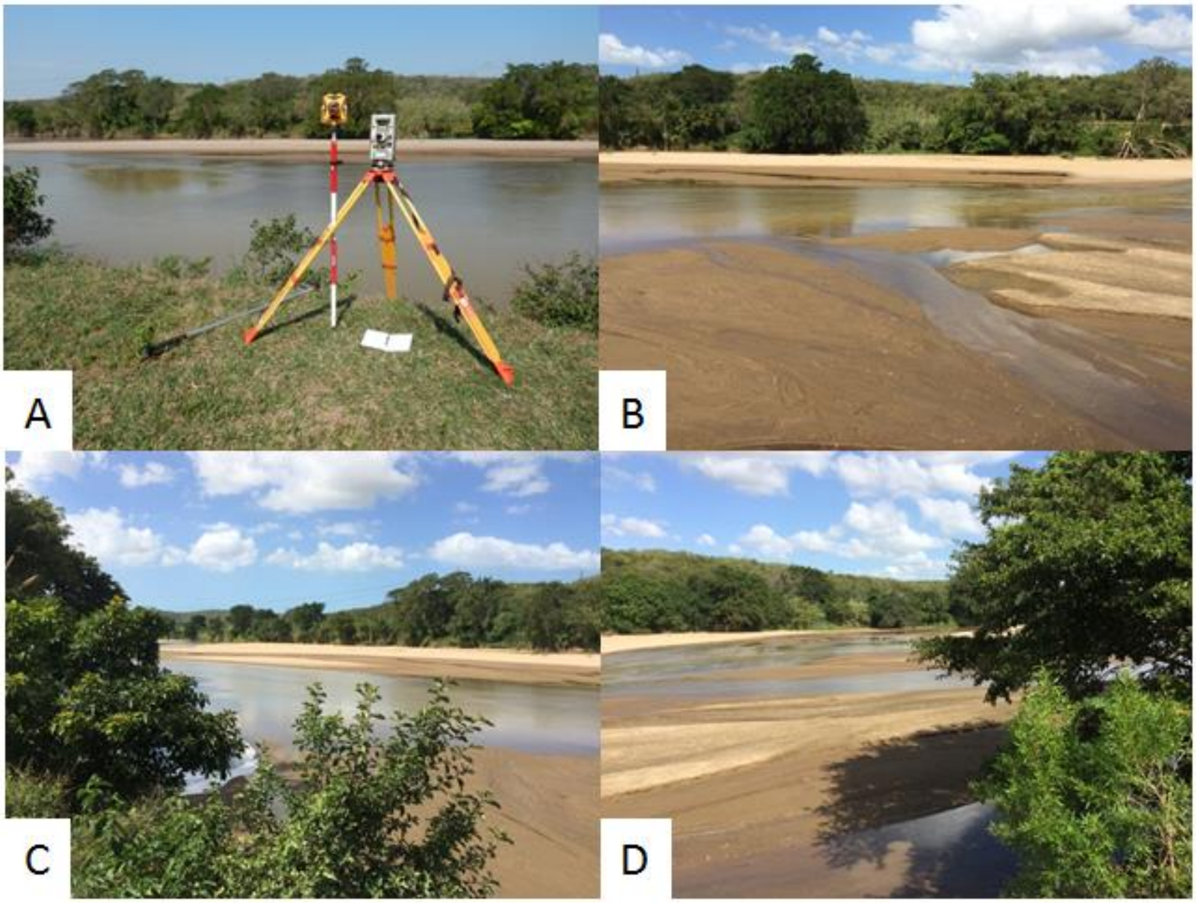

Figure 26: Site 2 A) Total station setup, B) View across river, C) View upstream, D) View downstream

Cross-section 2 is shallow with depths reaching a maximum of 0.80 m (Figure 27) and measured velocities increased up to 0.2 m/s (Figure 27). The stream was narrower than at cross-section 1 and therefore the velocity were higher. After the River2D model was calibrated the velocity values were extracted for each point where velocities were measured with the global flow meter along the cross-section. There is a strong correlation between simulated and measured velocities at site 2 as shown in Figure 27 with only slight alterations of less than 0.03 m/s in channel flow.

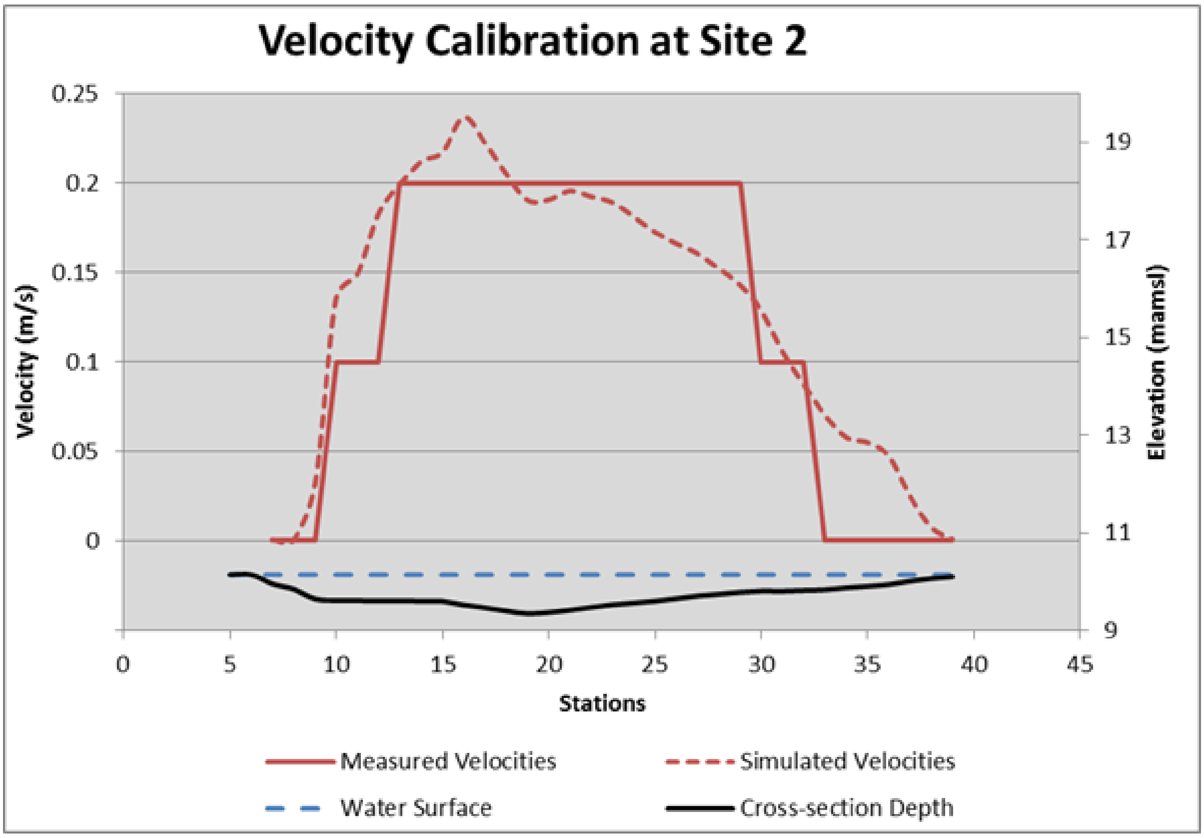

Figure 27: Simulated vs. Measured velocity for cross section 2 over bed topography and depth.

Site 3: Cross-section

Site 3 is situated 400 m downstream of the John-Ross Bridge to avoid any flow disturbance that could have been caused by the bridge structures in the water. This site is one of the main sites for fish collection and some historical data for the site were available from the University of KwaZulu-Natal. The benchmark was set high up the right bank for a detailed cross-section. To the back of this benchmark sugarcane plantations are common. Channel substrate is mostly sand from the right bank until about 2 to 3 m from the left bank where it turned to solid bedrock. The left bank is steep and consists mainly of solid rock.

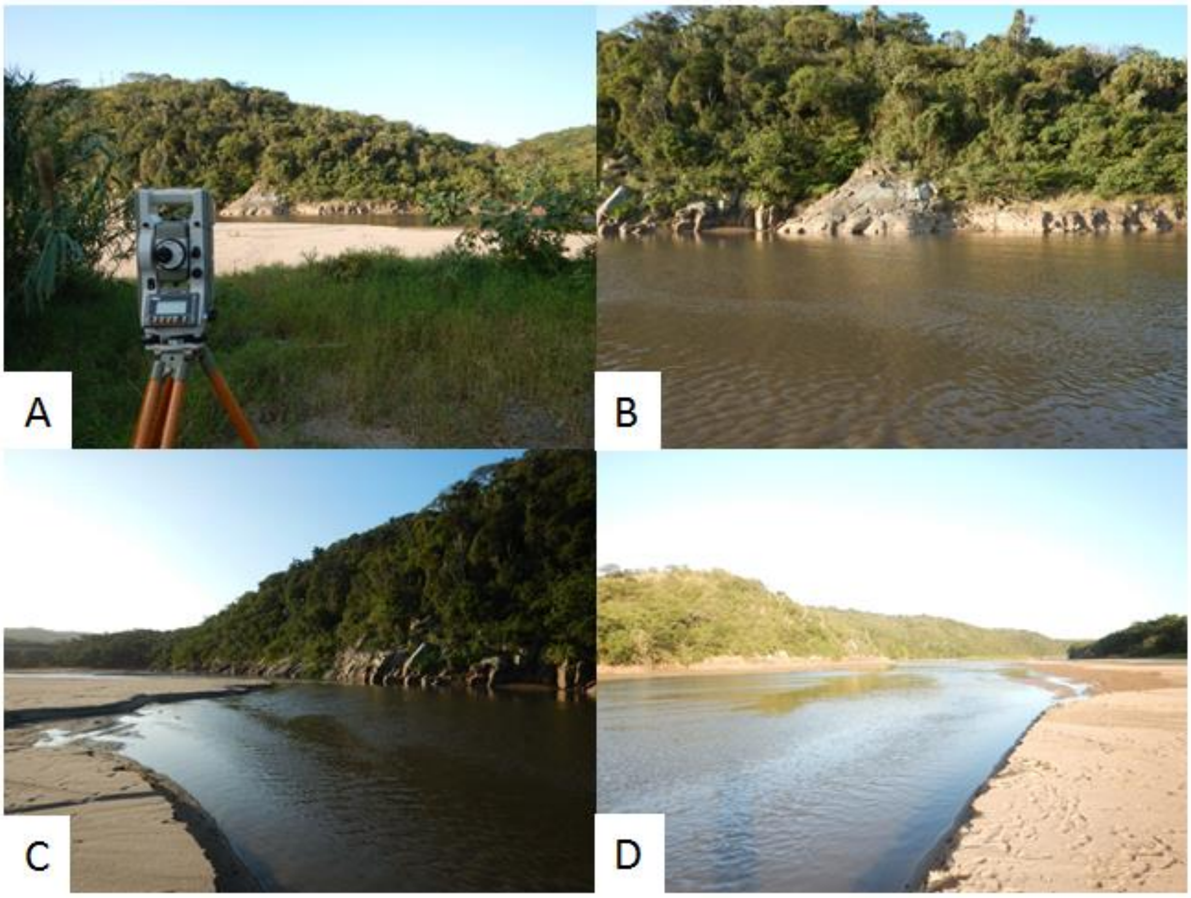

Figure 28: Site 3 with steep bedrock on the opposite bank A) Total station setup, B) View across river, C) View upstream, D) View downstream

Cross-section 3 is shallow with depths reaching a maximum of 0.84 m (Figure 29) and velocities increased up to 0.4 m/s in deeper sections (Figure 29). After the River2D model was calibrated the velocity values were extracted for each point where velocities were measured with the global flow meter along the cross-section. The comparison between measured and simulated velocities over the cross-sections illustrate a strong correlation with slight difference of 0.1 m/s and less in the middle of the stream and closer to the left bank (Figure 29).

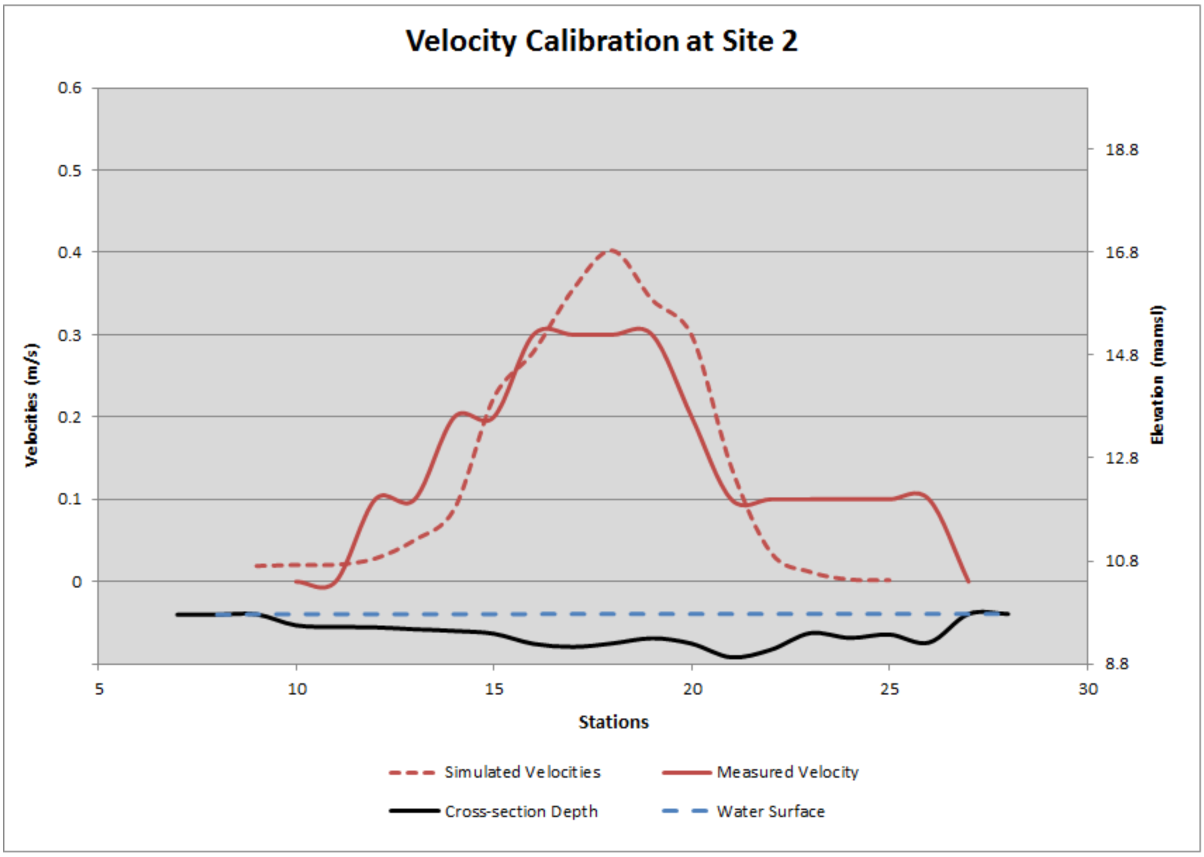

Figure 29: Simulated vs. Measured velocity for cross section 3 over bed topography and depth.

Site 4: Cross-section

Site 4 is situated 4454 m downstream of the inflow boundary in a straight single flow channel. The site is easily accessible from the right bank and is close to an old sand mining pit on the bank of the Thukela River. The benchmark was placed high on the right bank. Substrate for this section is again dominated by sand from the right bank all the way to the left bank (Figure 30). Stream flow close to the right bank with big sand banks dominating to the left bank. This was a single channel 200 m upstream of the outflow boundary and marked the beginning of a meander in the channel.

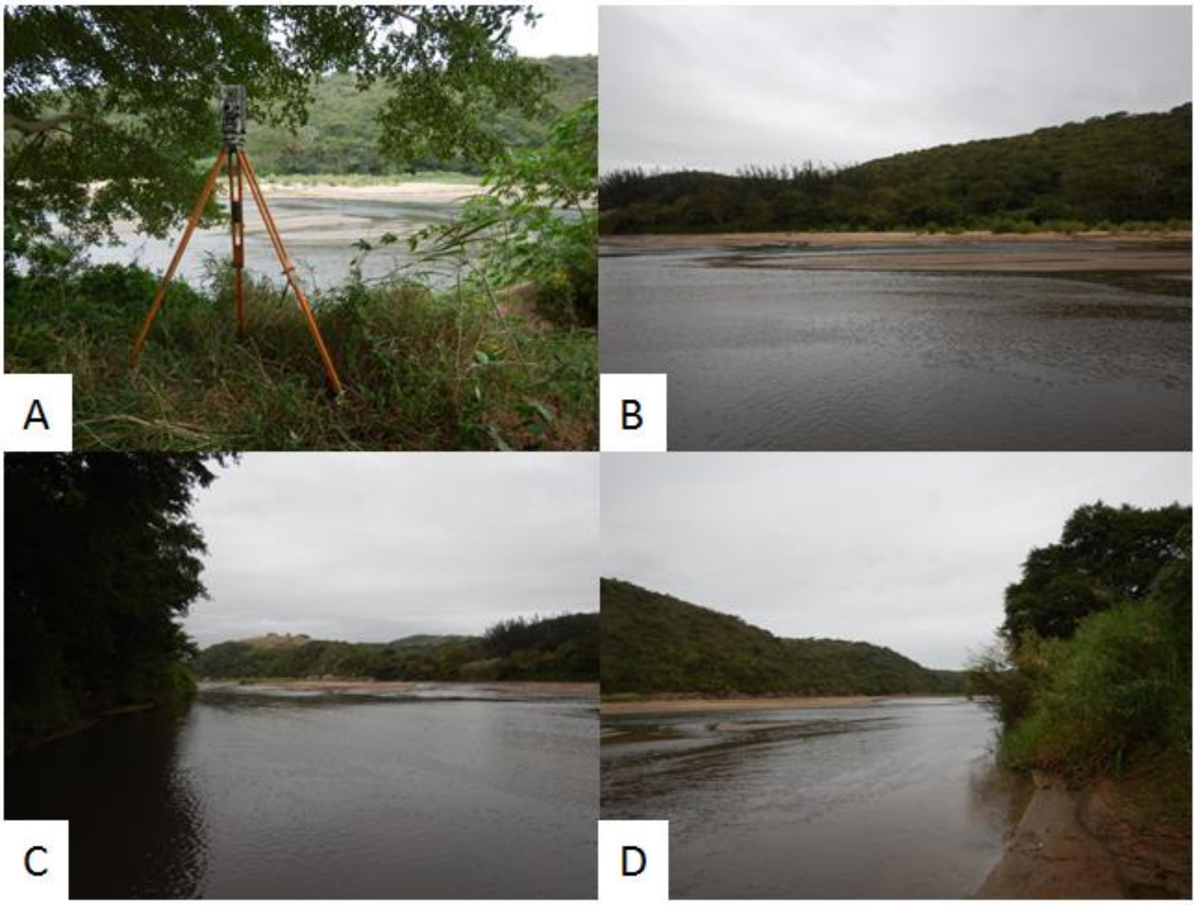

Figure 30: Site 4 A) Total station setup, B) View across river, C) View upstream, D) View downstream.

Cross-section 4 is shallow with depths averaging below 0.3 m but reaches a maximum of 0.69 m (Figure 31) close to the right bank. Velocities ranged between 0.1 up to 1.3 m/s (Figure 31) due to this shallow section. After the River2D model was calibrated the velocity values were extracted for each point where velocities were measured with the global flow meter along the cross-section. At site 4 the model predicted flow velocities of up to 0.3 m/s higher than those measure close to the right bank, this is due to the sudden depth increase in the river. The rest of the cross-section has a strong correlation between the measured and simulated velocities.

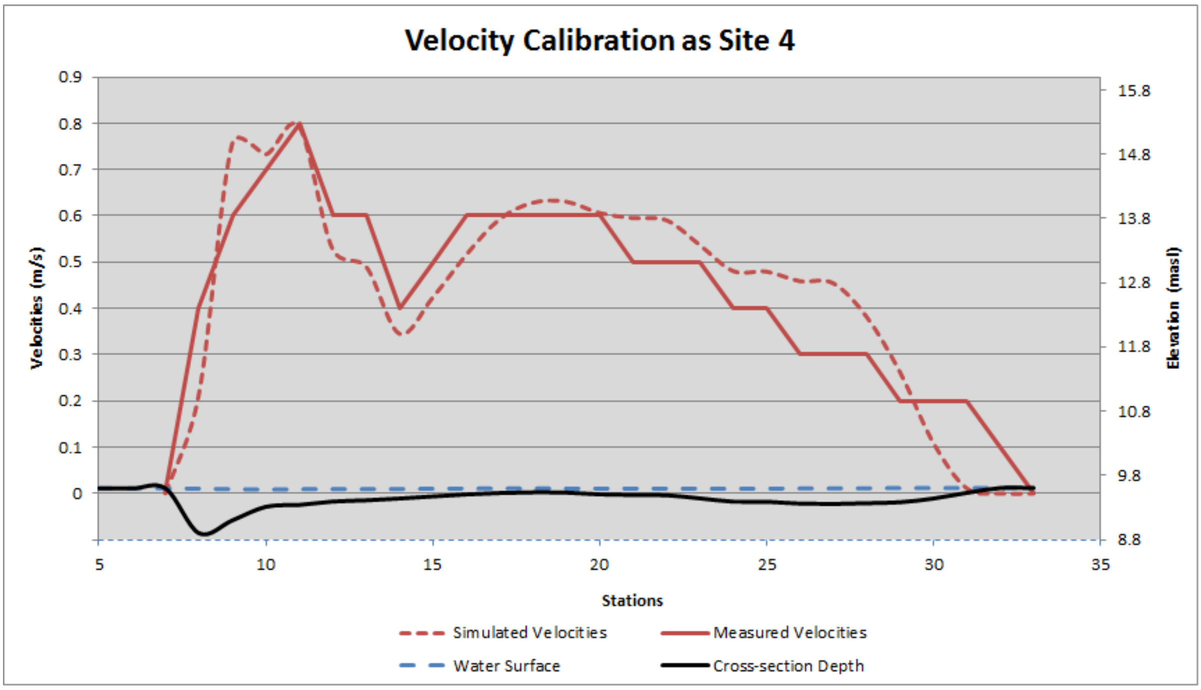

Figure 31: Simulated vs. Measured velocity for cross section 4 over bed topography and depth.

Site 5: Cross-section

Site 5 is the downstream boundary for the River2D model and is situated 4625 m from the inflow boundary. The benchmark for the cross-section was placed high on the right hand bank. The substrate consists of small cobbles to course gravels close to the right bank and changes to sand from about 5 m instream. Sand dominate the rest of the site, the site have two channels close to the right bank that are separated by a shallow sand streak (Figure 32). The left bank is steep and consists mainly of degraded rock formations.

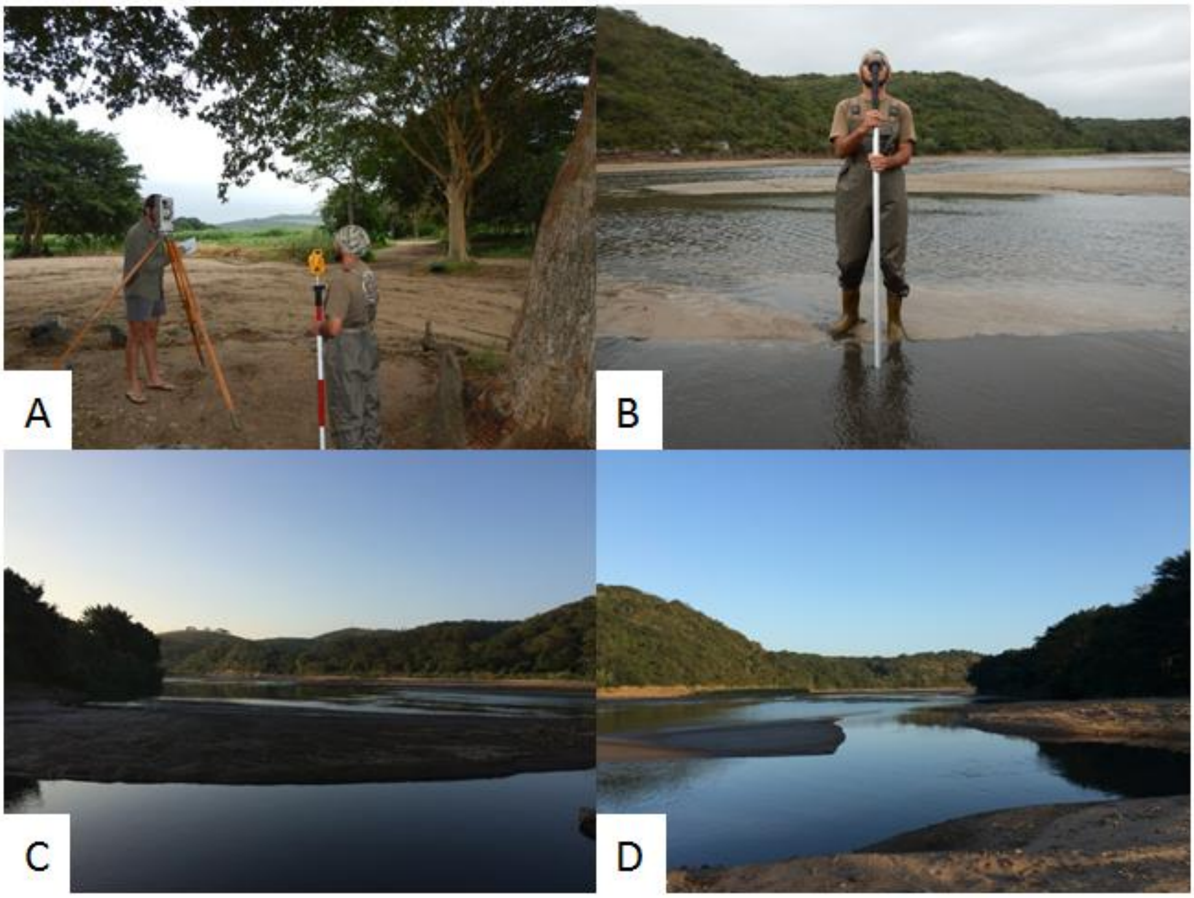

Figure 32: Cross-section 5 (Sand mining two) with cobbles and silt as substrate A) Total station setup, B) View across river, C) View upstream, D) View downstream

Cross-section 5 is shallow with depths reaching a maximum of 0.58 m (Figure 33) and velocities ranging from an average of 0.2 m/s up to 0.5 m/s (Figure 33). After the River2D model was calibrated the velocity values were extracted for each point where velocities were measured with the global flow meter along the cross-section. By comparing the simulated velocities to those measured (Figure 33) it is possible to see a good correlation between the two with only slight alterations closer to the river banks. The velocity is fastest in the deeper channel closest to the right bank and then drops to zero on the sand bank and increases again in the second channel. The largest difference in velocity between measured and simulated values for cross-section 5 is 0.1 m/s (Figure 33) and can be explained by the resistance which the sand bank generates in the middle of the stream.

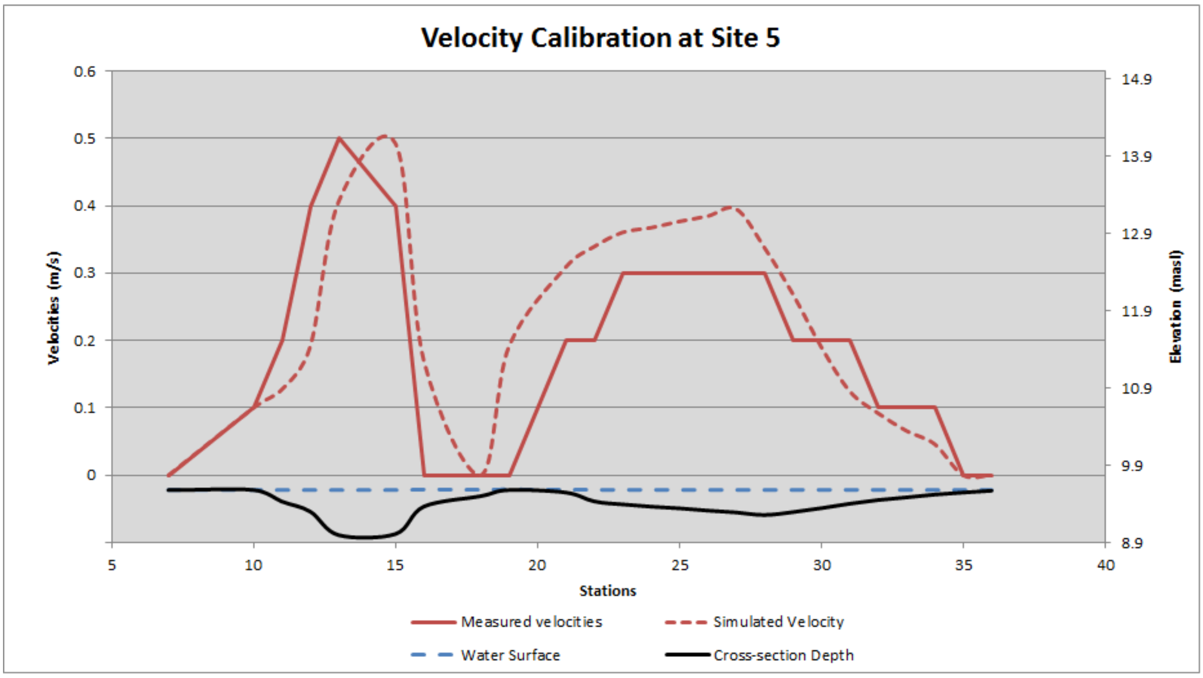

Figure 33: Simulated vs. Measured velocity for cross section 5 over bed topography and depth.

4.3. Fish collection and preferences

During the fish collection surveys 29 freshwater and estuarine species of fish were collected and a total of 1810 specimens. The Species were compared to those in FRAI and it was decided to use only 19 species (n = 1221) of which all are found in the lower Thukela River for the fish analyses and preferences (Table 11).

Table 11: Species sampled in the study area and their abundances.

Abbreviation	Scientific name	Common name	Abundance
AAEN	*Awaous aeneofuscus*	Freshwater goby	10
ANAT	*Ambassis natalensis*	Slender glassy	1
ANG	*Anguilla spp.*	Eel	3
CCAR	*Cyprinus carpio*	Common carp	1
CGAR	*Clarias gariepinus*	Sharptooth catfish	48
CREN	*Coptodon rendalli*	Redbreast tilapia	8
EEUT	*Enteromius eutaenia*	Orangefin barb	13
EFUS	*Eleotris fusca*	Dusky sleeper	16
EPAU	*Enteromius paludinosus*	Straightfin barb	13
ETRI	*Enteromius trimaculatus*	Threespot barb	42
EVIV	*Enteromius viviparus*	Bowstripe barb	3
GCAL	*Glossogobius callidus*	River goby	21
LCYL	*Labeo cylindricus*	Redeye labeo	3
LMOL	*Labeo molybdinus*	Leaden labeo	4
LNAT	*Labeobarbus natalensis*	KwaZulu-Natal Yellowfish	299
MCAP	*Myxus capensis*	Freshwater mullet	5
OMOS	*Oreochromis Mossambicus*	Mozambique tilapia	119
PPHI	*Pseudocrenilabrus Philander*	Southern mouth-brooder	45
TSPA	*Tilapia sparrmanii*	Banded tilapia	550

The most specimens collected from one species were *Tilapia sparrmanii* (n = 550) of which most were juveniles and collected in big shoals with small seine nets. The most abundant and widely distributed species were KwaZulu-Natal yellowfish *Labeobarbus natalensis* (n = 299) as shown in Table 11. *Eleotris fusca* are only found in lowland rivers and need salt content for juvenile stage and therefore they are considered as an important indicator species for monitoring natural biodiversity within the ecosystem. The Golden sleeper *Hypseleotris cyprinoides* is a near threatened species which has been observed in the study area and have the same habitat preference as *E. fusca* and therefore habitat preference of *E. fusca* is important not only for a specific species but rather for a group of species with the same preferences (umbrella species). Figure 34 show some of the different fish species sampled in the lower Thukela River during surveys.

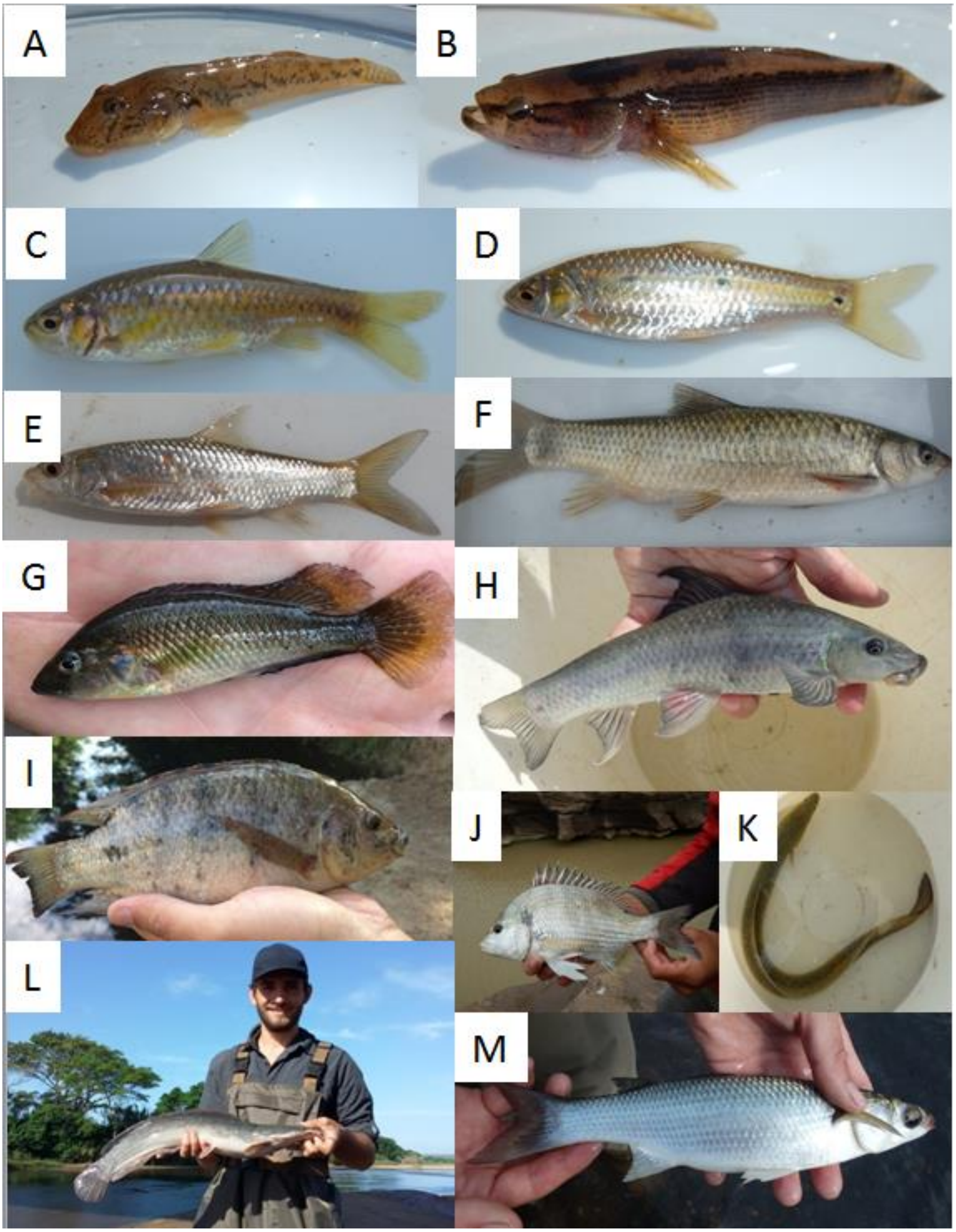

Figure 34: Fish species sampled during surveys in the Lower Thukela River included A) *Glossogobius callidus*, B) *Eleotris fusca*, C) *Enteromius eutaenia*, D) *Enteromius trimaculatus*, E) *Labeobarbus natalensis* (juvenile), F) *Labeobarbus natalensis* (adult), G) *Pseudocrenilabrus philander*, H) *Labeo molybdinus*, I) *Oreochromis mossambicus*, J) *Acanthopagrus berda*, K) *Anguilla marmorata*, L) *Clarias gariepinus* and M) *Myxus capensis*

4.3.1. Response of fish community structures to habitat variable conditions

These analyses consist of a high diversity of fish species collected throughout the KwaZulu-Natal province during different surveys. Due to the adaptiveness of fish data over a range of rivers and habitats were combined to obtain the most accurate habitat preference for each species. A multivariate statistical analysis where performed with Canoco in the form of a Redundancy Analysis (RDA) plot (Figure 35) shows the fish communities and the variance in the substrate types. It is possible to identify three different groups of species associated with a change in substrate. The Monte Carlo permutation procedure on the RDA plot shows how fish community structures change significantly ($p < 0.05$) with boulders, gravel, sand and silt (Table 12). *Labeobarbus natalensis* shows a strong correlation with boulders where *P. philander* and *O. mossambicus* communities are correlated with gravels and sands. *Tilapia sparrmanii* has a high correlation with silt and their community structures change significantly with a change in substrate. The significance of the proportion of mud were marginal ($p = 0.174$) and cobbles had no significant impacts on fish community structures (Table 12). These results demonstrate how different fish species have different preferences in substrate and the importance of maintaining a variety of these substrates within a riverine ecosystem.

Table 12: Statistical change in fish communities of rivers in KZN per effort where substrate types differ.

Variable	Var.N	LambdaA	P	F
Sub. Boulders	8	0.080	0.001	10.540
Sub. Sand	5	0.030	0.003	3.670
Sub. Gravel	6	0.020	0.027	2.740
Sub. Silt	3	0.020	0.042	2.400
Sub. Mud	4	0.010	0.174	1.470
Sub. Cobbles	7	0.000	0.619	0.680

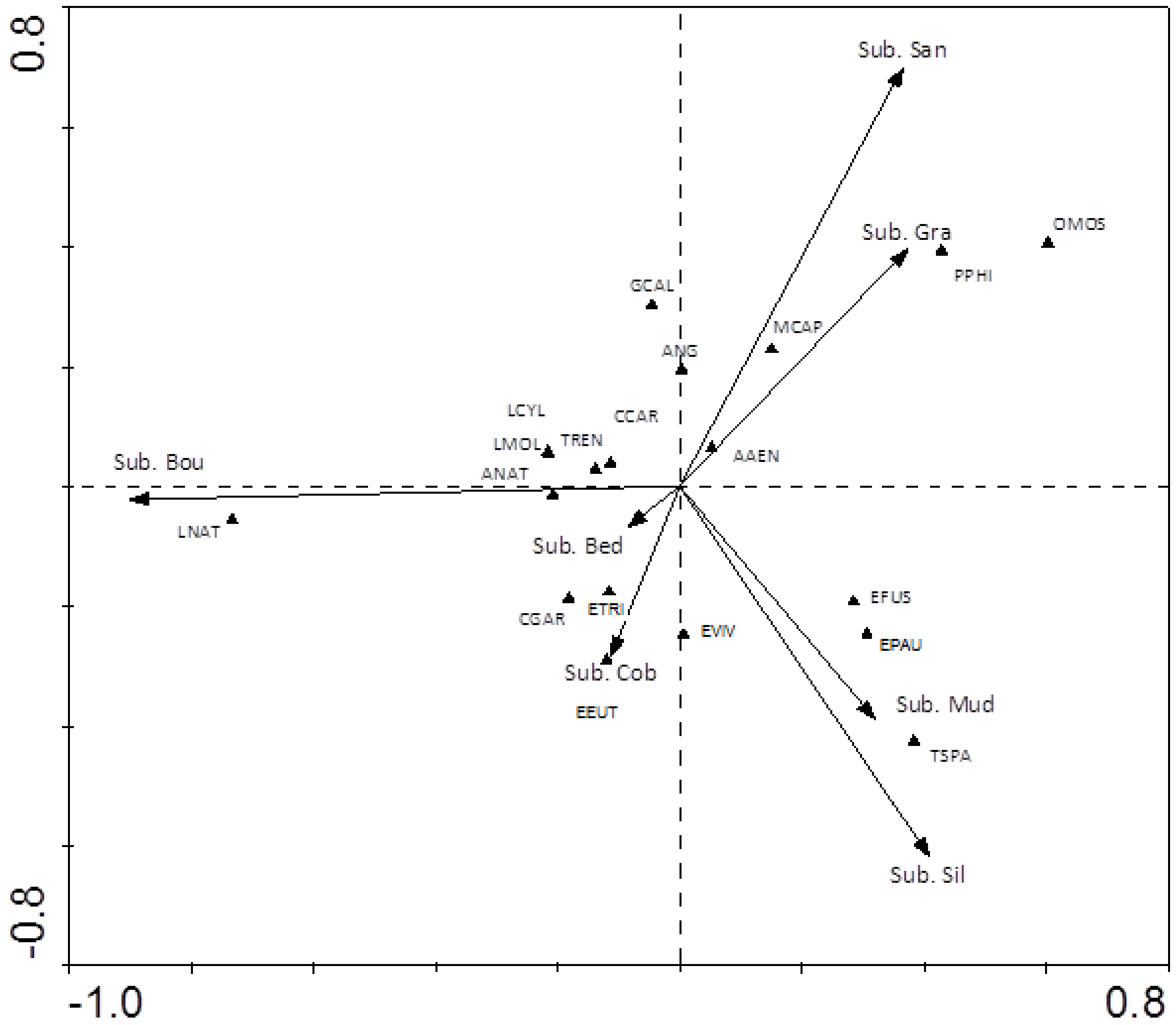

Figure 35: Redundancy analyses plot showing correlation between fish species and substrate types. With a variance in fish community structures for axis 1 = 60.7% and additional 26.5% and on axis 2 = 87.2% of variability displayed on graph**.**

The Monte Carlo permutation procedure on the RDA plot resulted in significant differences in fish community structures to a change in velocity as shown in Table 13. There is a strong correlation between changes in community structures and a change in depth but it was not significant. A RDA plot (Figure 36) shows the fish communities and the variance in the velocity and depth. The different fish species that reacted significantly to a change in velocity are *L. natalensis* particularly with *L. molybdinus* and *A. natalensis* also having a high correlation with velocity. A change in community structures was not significant with depth but have a high correlation with *C. gariepinus* and *E. fusca*. These results demonstrate how different fish species have different preferences for velocity-depth classes and the importance of maintaining these conditions within a riverine ecosystem for these indicator species.

Table 13: Statistical change in fish communities of rivers in KZN per effort where velocity-depth classes differ

Variable	P	F
Velocity	0.001	7.99
Depth	0.058	2.07

Most species did not show any correlation with depth and velocities and therefore they were not considered as indicator species to determine the EFR (Figure 36).

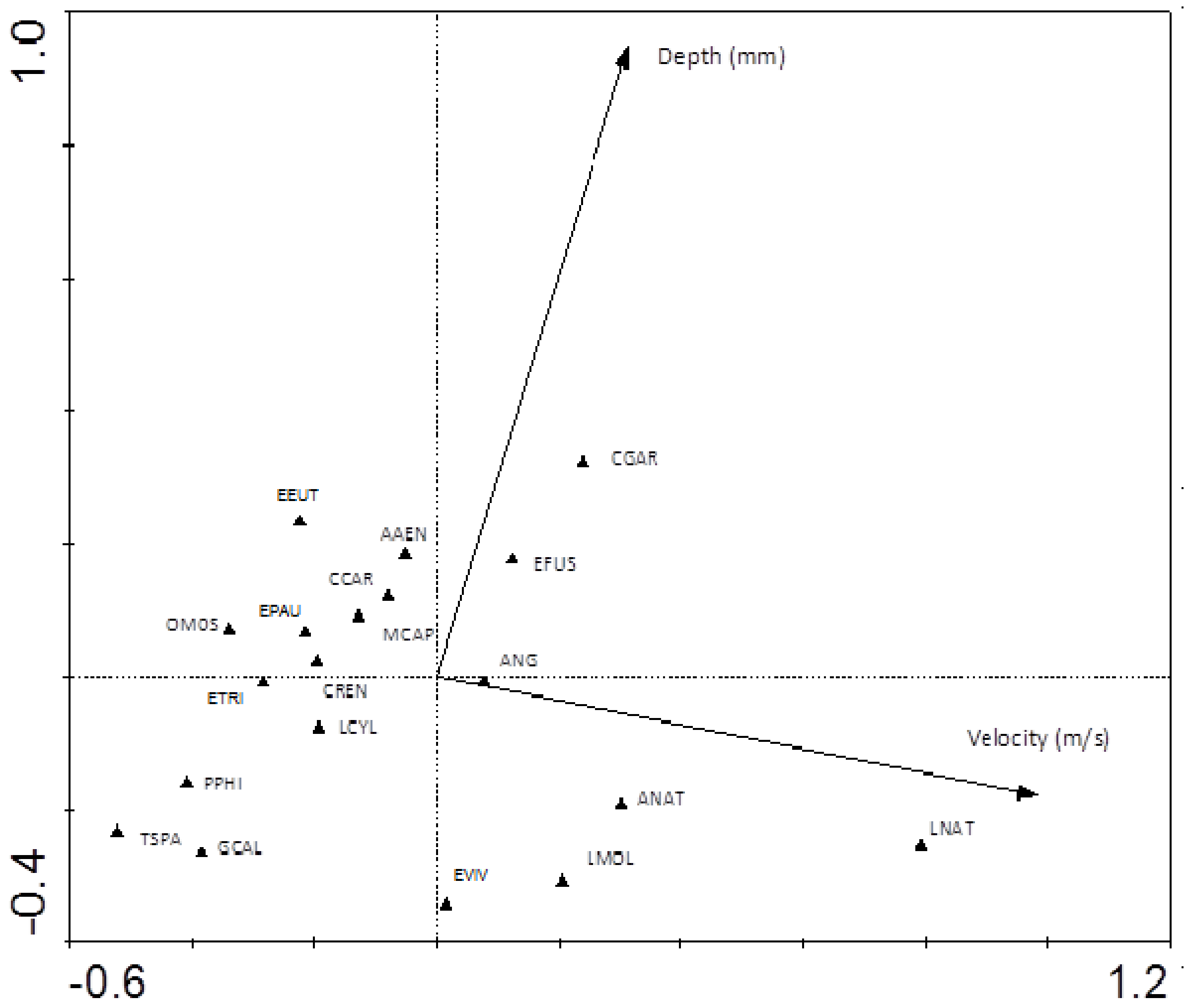

Figure 36: Redundancy analyses plot showing correlation between fish species and velocity-depth classes. With a variance in fish community structures for axis 1 = 84.5% and additional 15.5% and on axis 2 = 100% of variability displayed on graph.

4.3.2. Habitat preference assessment

Velocity and depth were collected for each effort and 19 different fish species caught during surveys in KZN. Species observed in the study area make use of a wide variety of flows (Figure 37). Species like *L. natalensis and L. molybdinus* have a preference for flow velocities ranging from 0.25 m/s to 0.63 m/s and some were found in velocities as high as 0.86 m/s. Sharptooth catfish (*C. gariepinus*) have the widest preference from no flow up to 0.51 m/s with some specimens found in 0.74 m/s, these species make use of a range of different habitats and flow conditions which suggests that these fish are adapted and relatively tolerant to habitat change. Other species that had a preference for low velocities were *A. aeneofuscus, E. fusca and G. callidus* ranging between 0 m/s (pools) to 0.34 m/s with *A. aeneofuscus* and *E. fusca* rarely found in velocities higher that 0.5 m/s. The confidence of *A. natalensis* and *C. carpio* were too low to describe preference for these species due to low abundances. The *Enteromius* species *E. eutaenia, E. paludinosus* and *E. trimaculatus* as well as other species including *O. mossambicus, C. rendalli* and *T. sparrmanii* had very low preferences for velocities and was found between 0 m/s and 0.27 m/s. The only barb species that had a preference for faster velocities were *E. viviparus* and was found between 0.22 m/s and 0.56 m/s.

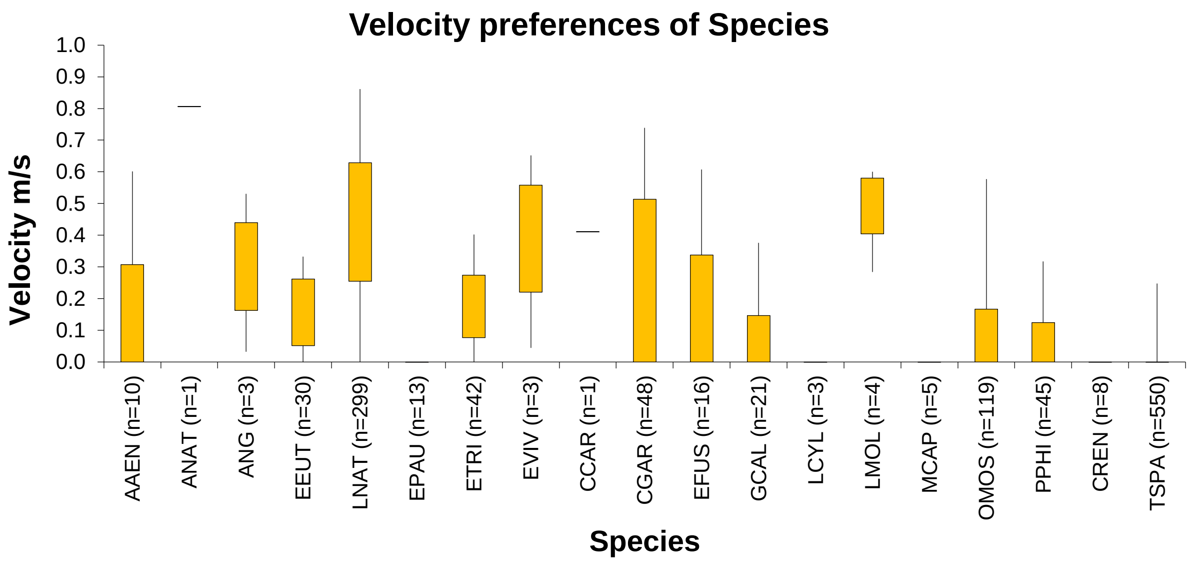

Figure 37: Box (25th to 75th percentile) and whisker (max and min value) for water velocity habitats associated with species observations in KZN.

Sampling deeper than 1.2 m is difficult with the techniques used and due to available depth during surveyed times therefore it is difficult to predict the higher percentile for preference depth and it was assumed that preference will increase with depth. The maximum depth will not determine or have an effect on the EFR and the minimum depth requirement only indicates that the fish are able to survive and not thrive in these habitats. Therefore the median value for depth was used to create a depth preference file (Figure 38). No fish were caught in areas shallower than 150 mm with most species caught in a depth of more than 300 mm. *Labeobarbus natalensis* and *L. molybdinus* preferred depths between 300 mm and 440 mm, where *C. gariepinus* had a preferred depth of approximately 500 mm. *A. aeneofuscus* and *Eleotris fusca* showed preference for deep water >550 mm. All species were collected in an average depth of 400 mm which is considered to represent suitable cover for fish.

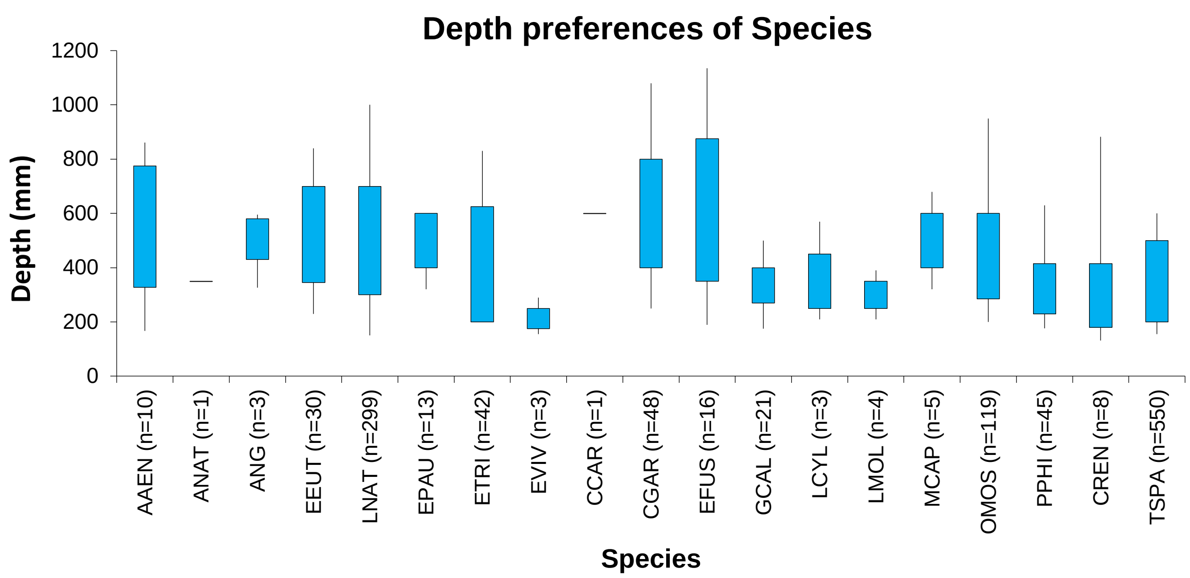

Figure 38: Box (25th to 75th %tile) and whisker (max and min value) for water depth habitats associated with species observations.

Two indicator species were selected one representing high velocities and deep habitats and another representing slow velocities and deep habitats typical of lowland rivers. *Labeobarbus natalensis* were used as an indicator species to characterise fast-deep habitats that cover a range of preferred habitats by other species as well and therefore can be considered an important criteria for the lowland river. Upstream of the study area steep rocks are present, this acts as a natural boundary to fish which makes it impossible for communities in the lower Thukela River to migrate upstream for feeding and breeding during low flows, fish can only migrate upstream under severe high flows and therefore it is important to protect the Yellowfish communities in the lower Thukela River. *E. fusca* was selected as the second indicator species with a preference for slow-deep habitats and is important mostly for their high depth preference which will be a good indicator to sustain the diversity of all other fish species with a lower depth preference. Following the identification of indicator species a review of the relationship between depth and velocity preferences for *L. natalensis* and *E. fusca* is provided in Figure 39 and Figure 40.

Figure 39 show that *Labeobarbus natalensis* have the highest preference for fast-deep flowing water with velocities more than 0.3 m/s and depths more than 300 mm. With only some specimens found in no flowing water, this could be a result of habitat availability due to the low flows.

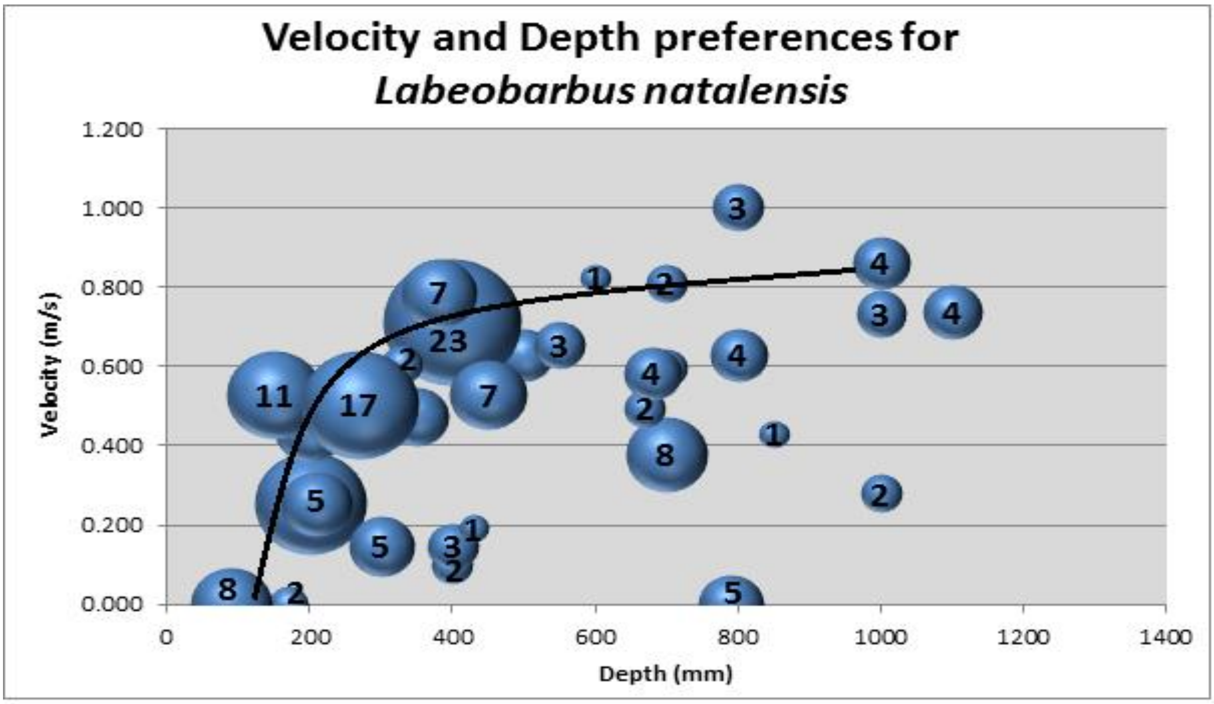

Figure 39: Velocity (m/s) and depth (mm) preference relationship for *Labeobarbus natalensis* with abundances displayed as bubbles.

The shape for *Eleotris fusca* is opposite that of *L. natalensis* due to their preference for deep slow flowing water. It will take a lot of energy for *E. fusca* to move into faster flowing water therefore they will only move into higher velocities for a purpose or if they are forced. Figure 40 show that they will only move in shallow water when the velocity is higher, mainly for feeding purposes.

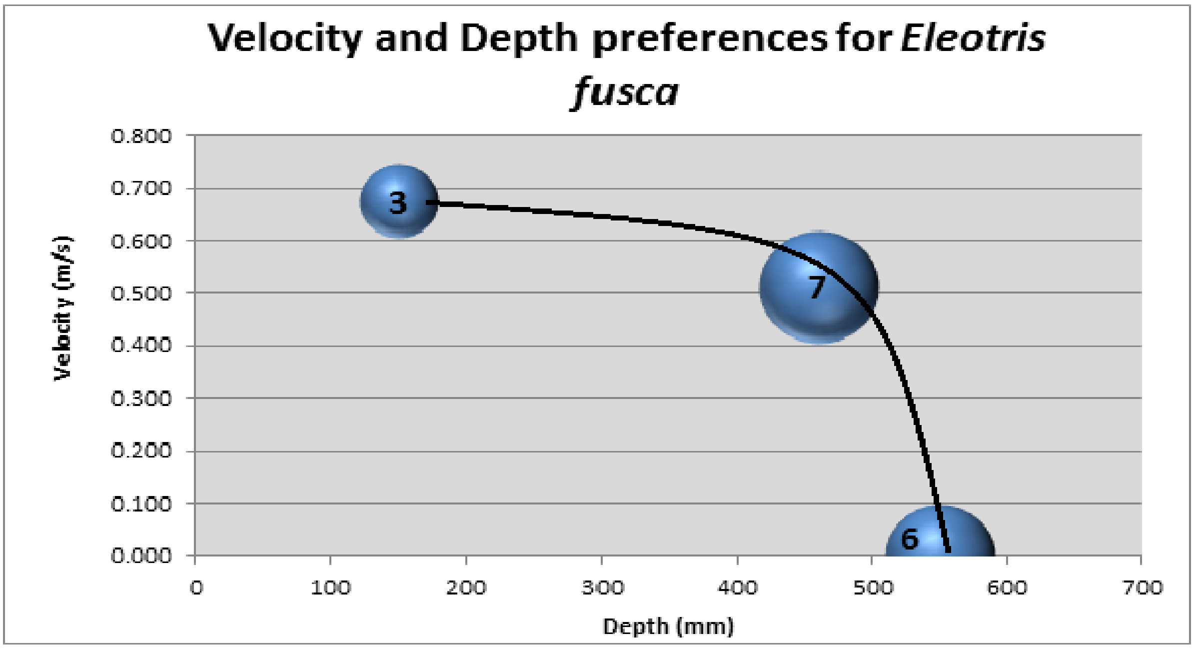

Figure 40: Velocity (m/s) and depth (mm) preference relationship for *Eleotris fusca* with abundances displayed as bubbles.

Substrate preferences of species were evaluated and results showed that most species were observed in a wide variety of different substrates but preference to one or more substrate types dominated (Figure 41). Species like *L. natalensis and L. molybdinus* have a high preference for boulders although they are found in sand, bedrock, cobbles and gravel. Most of the species have a high preference for boulders including *C. gariepinus*, *Awaous aeneofuscus*, *Enteromius eutaenia*, *Enteromius trimaculatus*, and *Enteromius viviparus*. Species with a higher preference for sand included *Glossogobius callidus* and *Myxus capensis*. *Eleotris fusca* are found in many substrates with silt dominating and are followed by sand, boulders and solid bedrock.

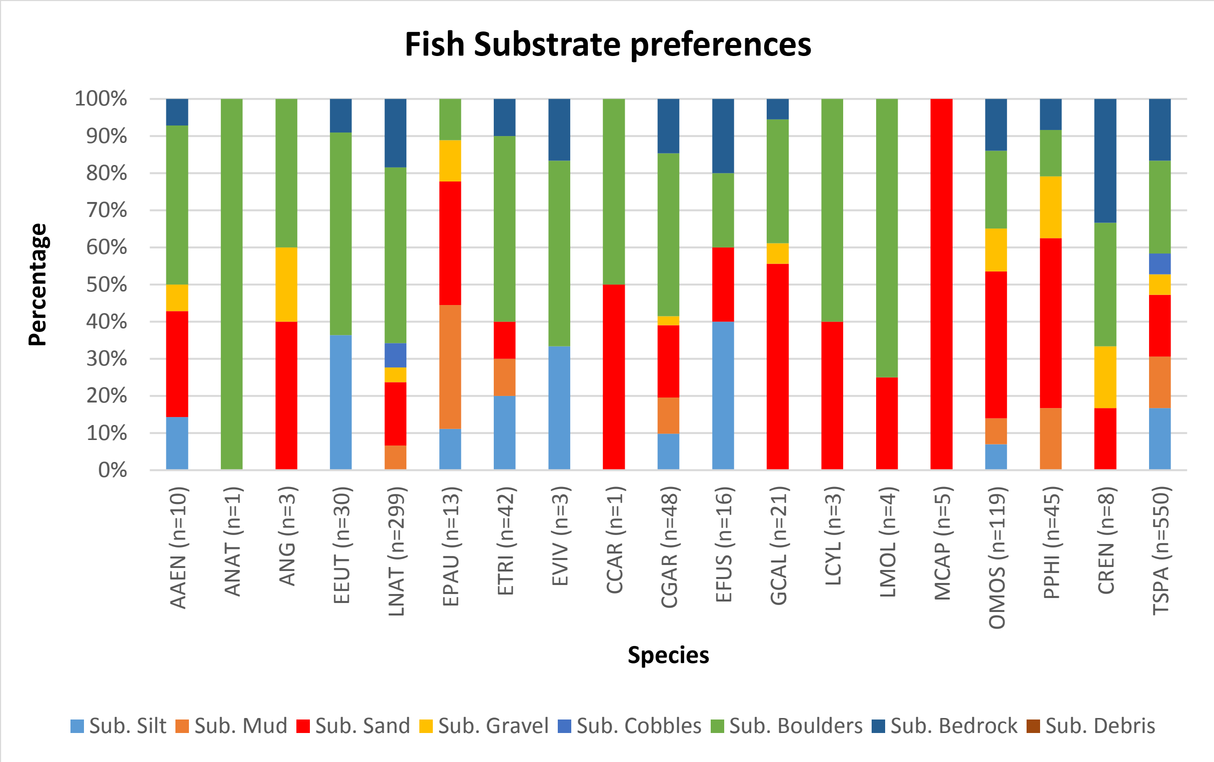

Figure 41: Fish preferences in relationship with substrate types

Indicator fish species were identified by making use of multivariate statistical analyses that showed the significance between different variables and fish community structures. Box and Whisker plots with a combination of bubble charts and a stack bar graph were used to create preference files for depth, velocity and substrate for indicator species (Appendix A).

4.3.3. The effects that altered flows will have on the lower Thukela River

Altering the natural flow regime of a river poses a great threat to the ecological sustainability and aquatic biodiversity of that system (Bunn & Arthington, 2002). The shape and size of a river channel, the distribution of habitats, and the distribution of substrate is all determine by the interaction between the flow regime and the physical landform and geology of the area (Frissell *et al.*, 1986). Fish community structures are strongly related to habitat structure and therefore fish species display a preference for particular types of habitats such as velocity, depth and cover types (Schlosser, 1982). The regulation of lowland rivers by weirs and embankments along the Great Ouse River (UK) has converted the river into a series of relatively deep slow flowing channels separated by short lotic stretches. The impact of the altered flows caused for the absence of local salmonids and a steep decrease in rheophilic *cyprinids* throughout most of the system (Copp, 1990). The lives of fish and their critical life events (spawning, growth and recruitment) are evolved to correspond with the natural flow regime. Temperature, length of day and the flow regime are synchronised so that if one of these natural factors are not in harmony it will cause a disturbance in fish behaviour (Copp, 1990; Sparks, 1995). Spawning of certain species are triggered with a rise in flow as for Colorado River squawfish (*Ptychocheilus lucius*) in the Yampa River and Clanwilliam yellowfish (*Labeobarbus capensis*) in the Western Cape (King *et al.*, 1998).

Construction of barriers even small in-stream barriers, such as v-notch gauging weirs can lead to isolation of populations and local extinction for e.g. the Western minnows (*Galaxias occidentalis*) in south-western Australian forest streams (Pusey *et al.*, 1989). Invading fish species are more successful in rivers that are permanently altered by humans. The regulation or reduction in flows will favour species that are adapted to the modified flow regime like carp (*Cyprinus carpio*) and mosquitofish (*Gambusia affinis*) (Edwards, 1978; Faragher & Harris, 1994; Walker *et al.*, 1995). Flow alteration is a serious threat in the lower Thukela River with the new weir that has been build upstream of the study area, water extraction of SAPPI and other water use activities e.g. agriculture and irrigation. The following biotic responses are a direct result of altered flows and some of them are already visible in the lower Thukela River:

- Loss of fishes adapted to turbid river habitats.
- Delayed spawning in fish.
- Loss of cues for fish spawning and migration.
- Favourable populations of exotic fish species (carp, mosquitofish).
- Loss of migratory fish species.
- Reduced spawning areas and/or recruitment success of lowland river fish.

4.4. Ecological flow requirements

Ecological flow requirements are highly variable depending on the purpose of the study as well as the methods used. In this study both the historic method and the habitat method were done and compared. The historic data were processed by making use of the ABF method as well as the Tennants (1976) method. The ABF method (Figure 42) predicts the median flow and the base flow which is 70% of the median monthly flow. Data were collected from the Department of Water and Sanitation website from 1963 to 2016. The data were collected in daily average flows and converted into average monthly flows for each year. The data were then edited into percentiles of flow including the 10^{th}, 30^{th}, 50^{th} and 70^{th} percentile showing natural flows which exceeded for that specific percentages of the time (Table 14).

Table 14: The different flows according to the historic method for predicting critical, base, median and freshes flows for the lower Thukela River

Month	10 percentile (critical base)	30 percentile (base)	50 percentile (median) Discharge	70 percentile Freshes	70% of Median Discharge
February	50.6	149.6	208	287.5	145.6
April	17.6	31	65.2	130.7	45.64
June	5.1	8.3	15.9	23.1	11.13
August	2.7	7.4	8.8	13.8	6.16
October	5.7	9.9	20.7	44.5	14.49
December	34.1	69	115.4	161.9	80.78

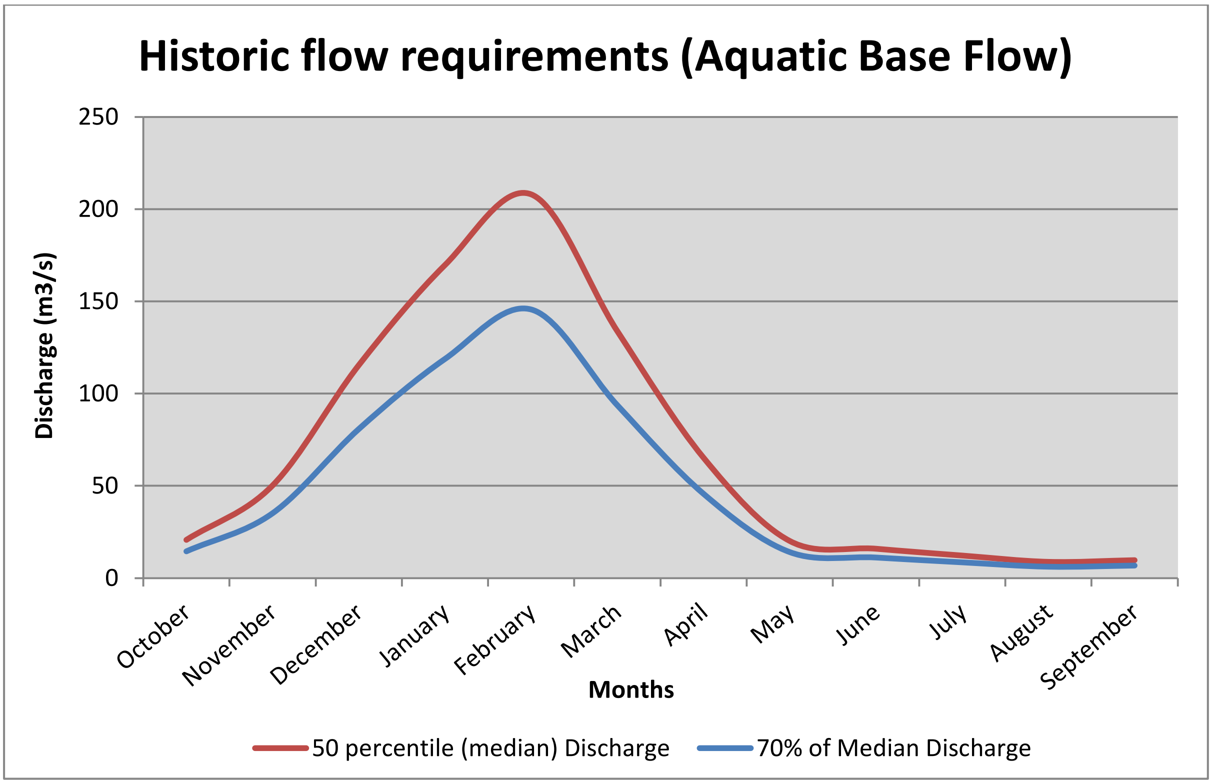

Figure 42: Flow duration curve for the median flow and the base flow for the lower Thukela River based on historic data

The Tennant method is more descriptive and gives a wider range of flows, predicting the critical base flow which is the 10th percentile for flows exceeding the lower limits for only a period of 10% of natural flow. This method predicts the base flow, median flow as well as freshes (Figure 43) that flush and clean the river bed. It is important to get these different flows at different times of the year and prevent flat lining conditions.

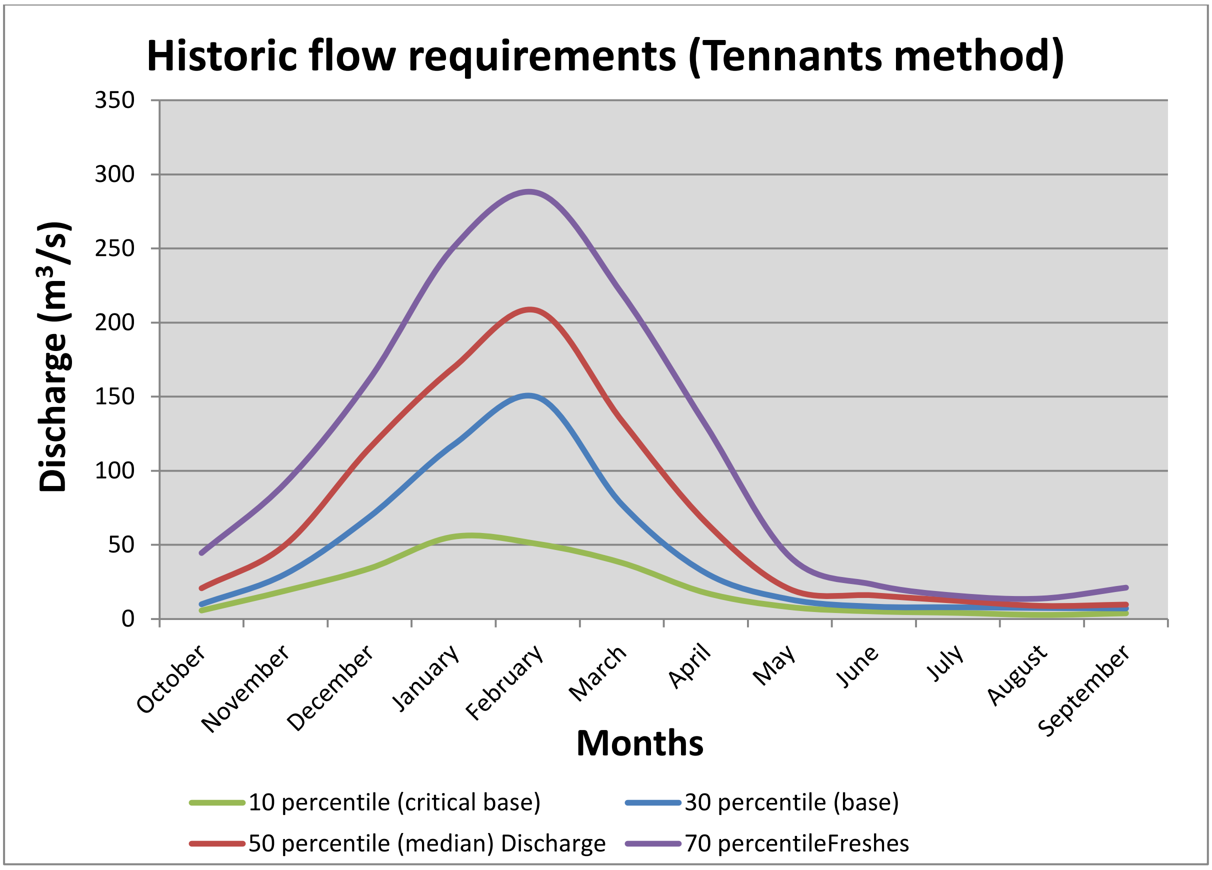

Figure 43: Flows for different months using the Tennants (1976) method to predict critical base, base, median and freshes flows for the lower Thukela River

The critical base is determined by the 10^{th} percentile of the month with the lowest average monthly flow which is 2.7 m^3/s for the lower Thukela River and occurs in the month of August. According to Jowett (1997) velocity and depth are degraded at critical base flow and it would only provide short-term survival for aquatic life, fish will not be able to breed or feed in this habitat and will use all their energy for survival. They are under greatest stress and the aquatic ecosystem cannot be exposed to these conditions for extended periods of time and therefore it is important to avoid these conditions at all costs, sometimes impossible due to droughts. The role of temperature changes in drought conditions should be considered as it can lead to oxygen depletion and cause physiological stress which lower spawning ability and have negative impacts on fish populations.

Base flow at 30% of the average flow as predicted by the Tennants method is 7.4 m^3/s during low flow months and is considered to provide satisfactory stream width, depth and velocity for a baseflow regime (Jowett, 1997). The base flow for wet periods (summer) is 149.6 m^3/s and can be described as the minimum flow requirements for fish populations during high flows to maintain population structures. This flow will allow fish to migrate upstream for spawning and feeding and is of critical importance.

By using the historic method in calculating environmental flow requirements for the Thukela River fish populations will only be maintained in the current state. For the lower Thukela River it is important to set a flow requirement that is higher than the current natural base flow, due to the decrease in available habitat and fish preferences that are influenced by human activities upstream of the study area. *Labeobarbus natalensis* highest substrate preference is boulders and with the current state of sand in the lower Thukela River boulders will be completely covered with sand in the near future. This would not have been a problem if fish could migrate freely upstream, but due to the barrier created by SAPPI for their extraction fish are unable to migrate over the rocky areas to better spawning habitat except for times of very high flow and therefore the median natural flow will be a more suitable flow requirement at 8.8 m^3/s in winter and 208 m^3/s in summer. The higher flow in winter will allow better cover and more habitats for different fish species and will have a lower stress factor on population structures, where the high flow in summer will allow fish species to migrate upstream to spawn and feed.

A comparison between the ABF method and the Tennant's (1976) method for base flows were done in Figure 44. The difference between these two methods for predicting the base flows are very close with a difference of less than 1.3 m^3/s for the dry period in august and as little as 4 m^3/s for wet period.

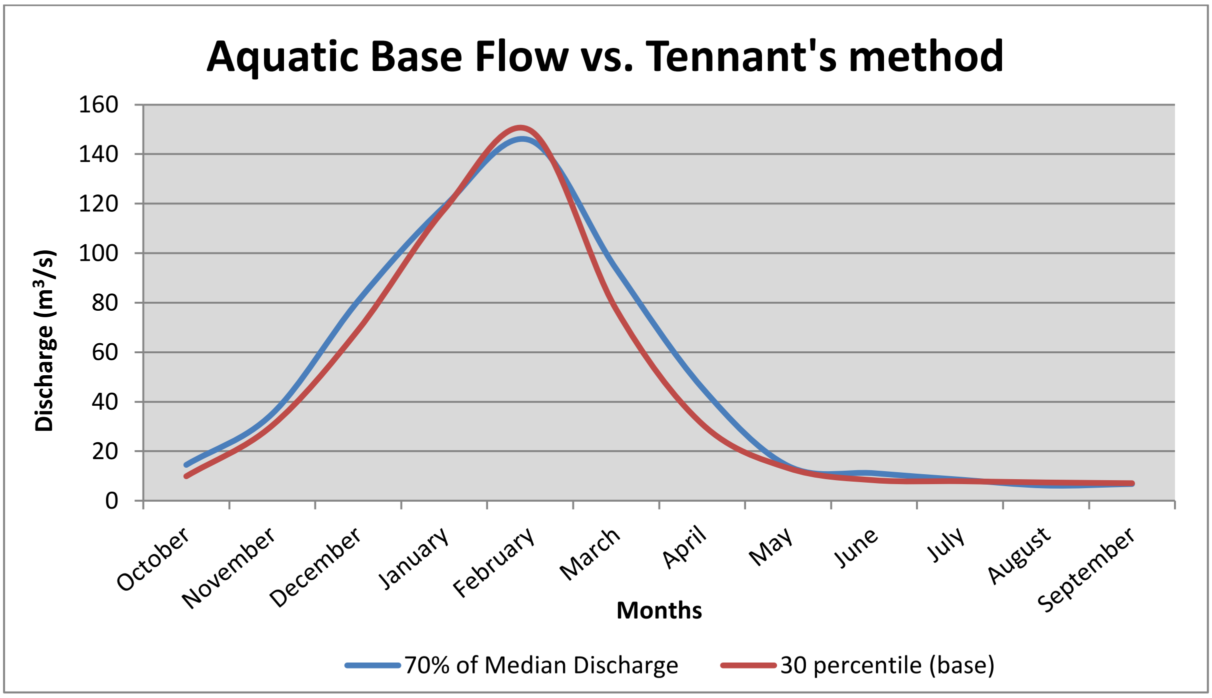

Figure 44: Aquatic Base Flow method vs. Tennant (1976) method for base flows

Habitat data were collected during field surveys by making use of different techniques, the bathymetric data for the Thukela River were done with a total station and a level logger while topographic data were edited and processed in ArcGIS. River2D was used to calculate the WUA on the same concept used by PHABSIM. River2D is a 2-dimensional model which gives a good spatial coverage of the study area. The study area is 4.6 km long and the river bed is on average more than 100 meters wide. The unit for WUA is m^2/m and represent the available habitat as an index of habitat rather than an area. The WUA have to be calculated for each indicator species within River2D by making use of the same index file but different preference files. Preference files should be loaded for each individual species and for this study two species were used, *L. natalensis* with a high preference for deep fast flowing water and *E. fusca* which had a higher preference for deep slow flowing water. The result for each species was calculated in River2D with different flows (Table 15).

Table 15: WUA in the lower Thukela River for LNAT and EFUS with an increase in discharge

Discharge m^3/s	LNAT	WUA m^2/m	EFUS	m^2/m	Total units
2.7	6590.7	0.94	60222.8	8.58	701546.7
4.3	9449.5	1.35	63429.3	9.04	701546.7
8.8	14010.5	2.00	69353.9	9.89	701546.7
13.8	20887.4	2.98	70077.8	9.99	701546.7
21.1	25267.3	3.60	71819.8	10.24	701546.7
50.6	27947.9	3.98	74604.7	10.63	701546.7
208	16929.5	2.41	90324.7	12.88	701546.7
509.5	16055.1	2.29	100866	14.38	701546.7

The rate of habitat change varies with flow and therefore habitat modelling results of WUA against discharge can be plotted on a graph for each species (Figure 45 and Figure 46). The rate of change is used as the basis for setting a minimum flow for each indicator species. The point of greatest change in the rate (the breakpoint) is used as the minimum flow requirement for the lower Thukela River. The total unit of available WUA is not that important rather the point of greatest change, this is because the graphs shape will remain the same even though the value will increase or decrease at different sites. The minimum flow requirement for *L. natalensis* is 15 m^3/s, this does not mean that the species will require this minimum flow for survival but rather to thrive in an environment with favourable habitat.

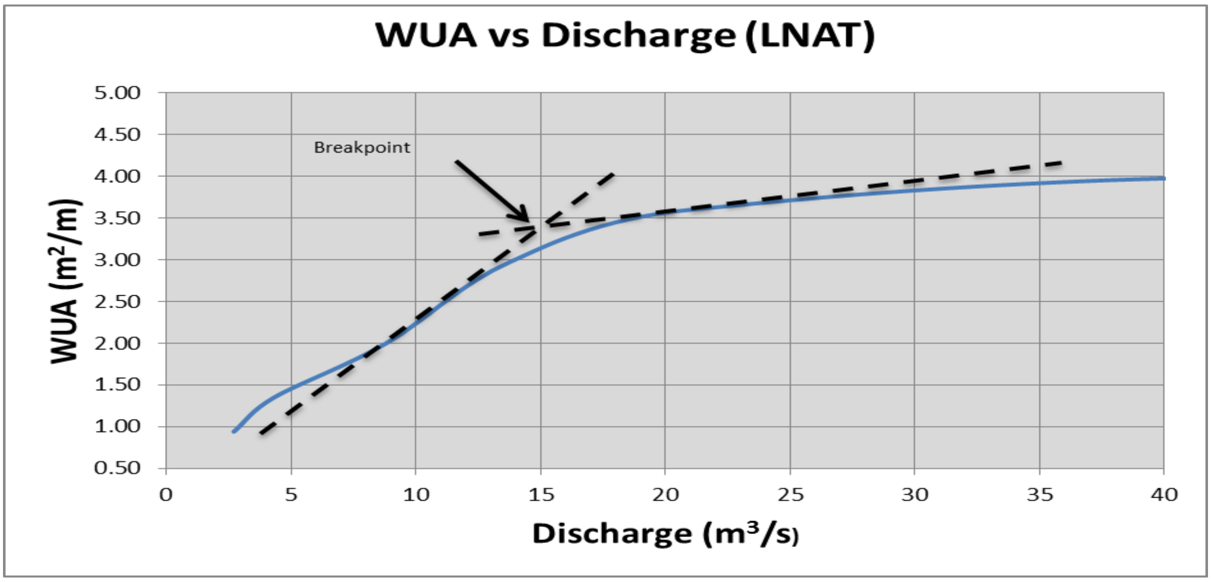

Figure 45: Selection of minimum flow for *L. natalensis* at the breakpoint: point where habitat begins to degrade sharply with a decrease in flow

The minimum flow requirements for *E. fusca* is 8 m^3/s (Figure 46), they will be able to survive in lower flow conditions but to reach their full potential and to benefit their ecological state these minimum requirements needs to be maintained.

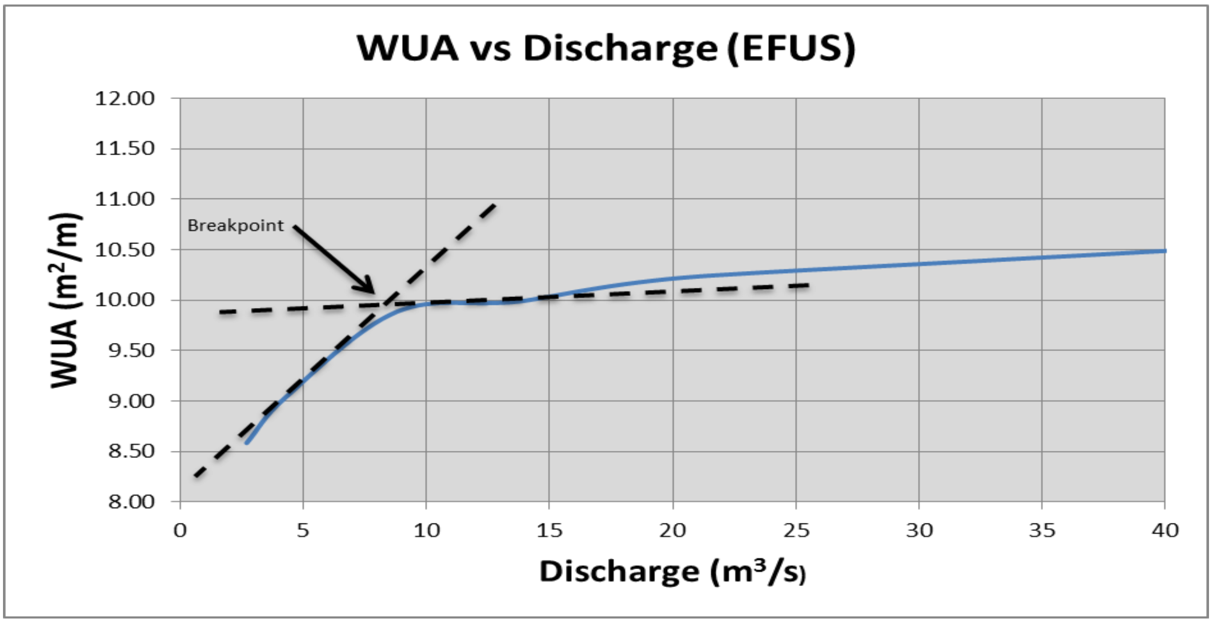

Figure 46: Selection of minimum flow for *E. fusca* at the breakpoint: point where habitat begins to degrade sharply with a decrease in flow

According to a reserve determination study of the Department of Water Affairs and Forestry done in 2003 the minimum flow requirements for the lower Thukela River is 7.7 m^3/s (DWAF, 2004). This is relatively low and was calculated based on historic flow data only and not in combination with other methods. A higher reserve for environmental flow requirements are suggested by the results of this study.

Habitat methods are quantitative and incorporate biological principles and therefore have been considered more reliable than assessments made by means of other methods (Annear & Conder, 1984). In this study two separate species were used as indicator species *L. natalensis* and *E. fusca*. *Labeobarbus natalensis* were used to determine the upper limit of ecological flow requirements as it is a rheophillic species with preferences for fast-deep flows (Pander *et al.*, 2013) and *E. fusca* as a non-rheophillic species with higher preferences for slow-deep flowing habitats (Linnansaari & Cunjak, 2007). It is important to use different species with different preferences and importance to the ecological state of the Thukela River to determine flows that will optimise the ecological state of the river. *Labeobarbus natalensis* is more important on a socio-economic scale for recreational and subsistence fisheries where *E. fusca* is more important from a conservation perspective and represents the flow requirements that needs to be maintained to protect species like *H. cyprinoides.* The flow requirements as determined by the habitat method for *L. natalensis* are 15 m^3/s and for *E. fusca* is 8 m^3/s. It is difficult to determine environmental flow requirements for a specific species and therefore it was assumed that higher flow requirements would maintain and benefit species with lower requirements (Jowett *et al.*, 2008) and to enhance the ecological state of the Thukela River, flows that would benefit all species needs to be maintained as closely as possible. The whole life cycle of different fish species should be considered and sustainable flows are required for fry to complete its growth in inundated areas for optimal food, habitat and temperature conditions.

It is assumed that minimum flows set for rheophillic species like *L. natalensis* will be adequate to maintain native fish populations in the lower Thukela River (Jowett *et al.*, 2008). The reason for this is due to their large size and feeding habits of the natal Yellowfish giving them a higher preference for fast-deep flowing water than that of most native species. Smaller native fish species have preferences for slow-deep flowing water and are most abundant at the margins of the Thukela River with habitat availability at its maximum with low flows. The margins of the river will still provide suitable habitats for these species even with an increase in flow velocity and depth (Jowett *et al.*, 2008). Nevertheless it is still inappropriate to set flows with these high requirements as it would be impossible for the natural flow regime to sustain these requirements, flow requirements if determined only by maximum habitat for rheophillic species is higher than median low flows. The conservation status of some species like the *H. cyprinoides* warrants special attention (Vrdoljak & Hart, 2007). This specific species could not be sampled during the time of the study and therefore *E. fusca* a species with the same preferences were also considered for minimum flow requirements. These species occur only in lowland rivers with estuarine conditions and are just as important to keep the aquatic diversity in the ecosystem.

There are many different fish species and life stages in the Thukela River at any given time and thus cause for a conflict in flow requirements. Certain species juveniles may be found in low velocities and prefer an increase in velocities as their size and ability to swim increases. In rivers with small habitat variability the different species will benefit with different flows, where some species may find a reduction in depth and velocity as beneficial other species habitat will decrease (Jowett, 1997). Compromises like adjusting the flow requirements to different seasonal life stages are possible by increasing the flow requirements for spawning, rearing and adult habitats. Another method is to adjust the flow requirements based on seasons, the biological habitat requirements for fish species may be less in winter as food requirements and their metabolic rate decreases with a decrease in temperature (Caissie & El-Jabi, 1995). The flow requirements of individual species vary and therefore it is important to find a neutral flow requirement that will suit all species habitat requirements or by defining flow requirements for aquatic communities.

Instream habitat will decrease as flows fall below the optimum value and therefore there is no clear point at which instream habitat can be identified as good or bad although the rate of decrease may vary with flows (Jowett *et al.*, 2008). The rate of change is therefore often used as the basis for describing a minimum flow requirement by selecting the point of greatest change (the breakpoint). This concept is based on the principle that higher flows will lessen optimum habitat conditions although the diminishing effect of a greater than optimum flow is less than that of a lower than optimum flow (Jowett *et al.*, 2008). Habitat loss associated with higher flows can be balanced due to the increase of food availability, cover or the ability to migrate and spawn. In wide rivers like the Thukela River habitats like shallow-slow flowing water will always be available near river banks as the water level rises and bank flow will only be reached in times of flood.

To estimate the minimum flow requirements in a river a habitat suitability curve is required, this is obtained by modelling instream habitat for a range of flows for each indicator species. In this study River2D was used to calculate the habitat suitability for *Labeobarbus natalensis* (Figure 47) and *Eleotris fusca* (Figure 48) . The valuation of an appropriate minimum flow for a river is complex and there are no computers that can assist with this step. River2D make use of the PHABSIM concept WUA, and can be seen as an index of usable habitat rather than a physical area although WUA has units of m^2/m (Paxton, 2008). When binary habitat criteria is used as for this study (0 is unsuitable and 1 is most suitable) the WUA can be used as a physical area (m^2). The PHABSIM concept is criticised due to the posibility that a large area of sub-optimal habitat or a small area of optimum habitat will both result in a high WUA. By examining the habitat suitability index (HSI) (habitat index score at each node averaged over the reach) and how it changes with flow can be a solution to this problem (Jowett *et al.*, 2008). It is equal to WUA (m^2/m) divided by the average water surface width of the river, by interpretation of these results it is possible to identify flows with most suitable habitats.

Substrate size can be taken into consideration when evaluating habitat suitability where particle size is determined by velocities and depths at channel forming flows. Habitat analyses to determining base flows is normally lower than that of channel forming flows and it can be assumed that substrate size will not change. In the lower Thukela River the substrate consists mainly of coarse sand particles causing the river bed to be very dynamic and channel forming flows to be very low. It was assumed that even though the channel shape might change the habitats (velocity-depth) in relation to stretch area will stay the same and therefore the 2D model is relevant. It was possible to calculate flows and habitat availability over substrate and to predict flows that would provide the most suitable habitat for different species at different flows. Substrate composition and distribution does not influence the shape of habitat-flow relationships and this was tested by calculating the relationship with and without substrate suitability, giving a higher total WUA without substrate suitability but the shape of the curve remained the same and therefore the flow requirements.

The biological interpretation of the results is the most uncertain and difficult part of an instream habitat analysis. The key elements are to calculate WUA with habitat suitability and the linkage between available habitat and the abundance of aquatic populations (Paxton, 2008). No given aquatic species can be maintained in a river or stream without some form of suitable habitat and therefore the importance of habitat analyses cannot be undermined. The relationship between species abundance and habitat availability is not directly linked or flow related and there are many other factors that can influence species abundance like food, migration patterns and spawning periods (Jowett *et al.*, 2008). Therefore habitat suitability would not indicate the abundance of any given species for any given time but rather set the lower limited of possible population size of a species in an area.

The only way to ensure relief for fish under times of high stress is by means of freshes, this is a natural high flow for short periods of time (flash flood) and is the limit at which 80% of bed material covered by water gets mobile (King *et al.*, 1998). The timing and frequency of freshes is important for the sustainability of fish populations and it is recommended that freshes takes place as many as 2 times during low flow periods (May – September) and 6 times during high flow periods (October - April). Freshes flow can be calculated by using the historic method with the 70th percentile which is 13.8 m^3/s for low flow and 287.5 m^3/s for high flows (King *et al.*, 2000). These flows will allow periodical stress relief in terms of some spawning and feeding for fish in winter months and more specifically in summer month with fish migration to spawning grounds and new habitat availability at overbanks for feeding.

Habitat suitability in the form of WUA for different flows is attached in Appendix B.

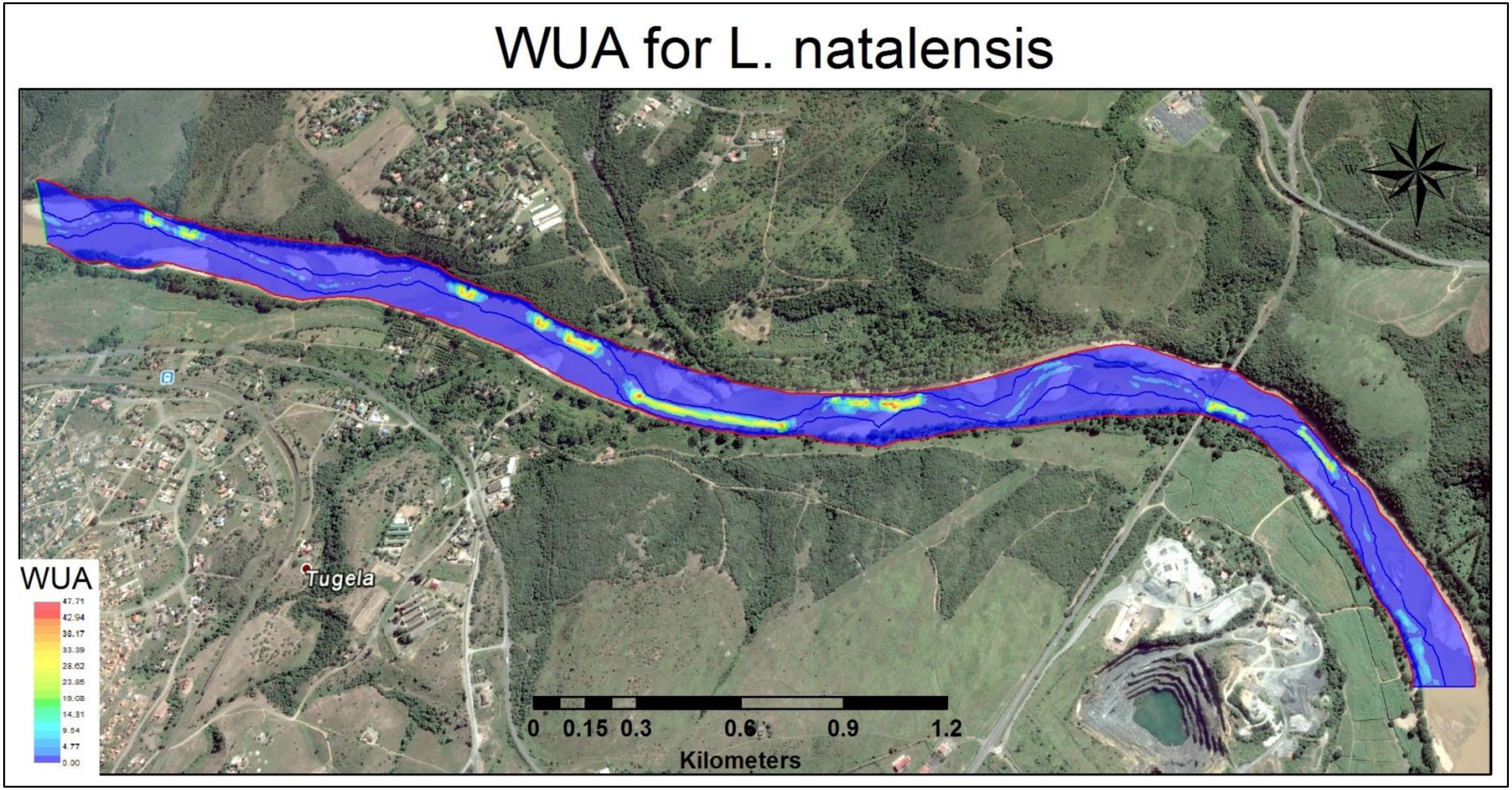

Figure 47: WUA for *L. natalensis* at their minimum flow requirement of 15 m^3/s for the 4.6 km study area in the lower Thukela River as predicted by the IFIM methodology.

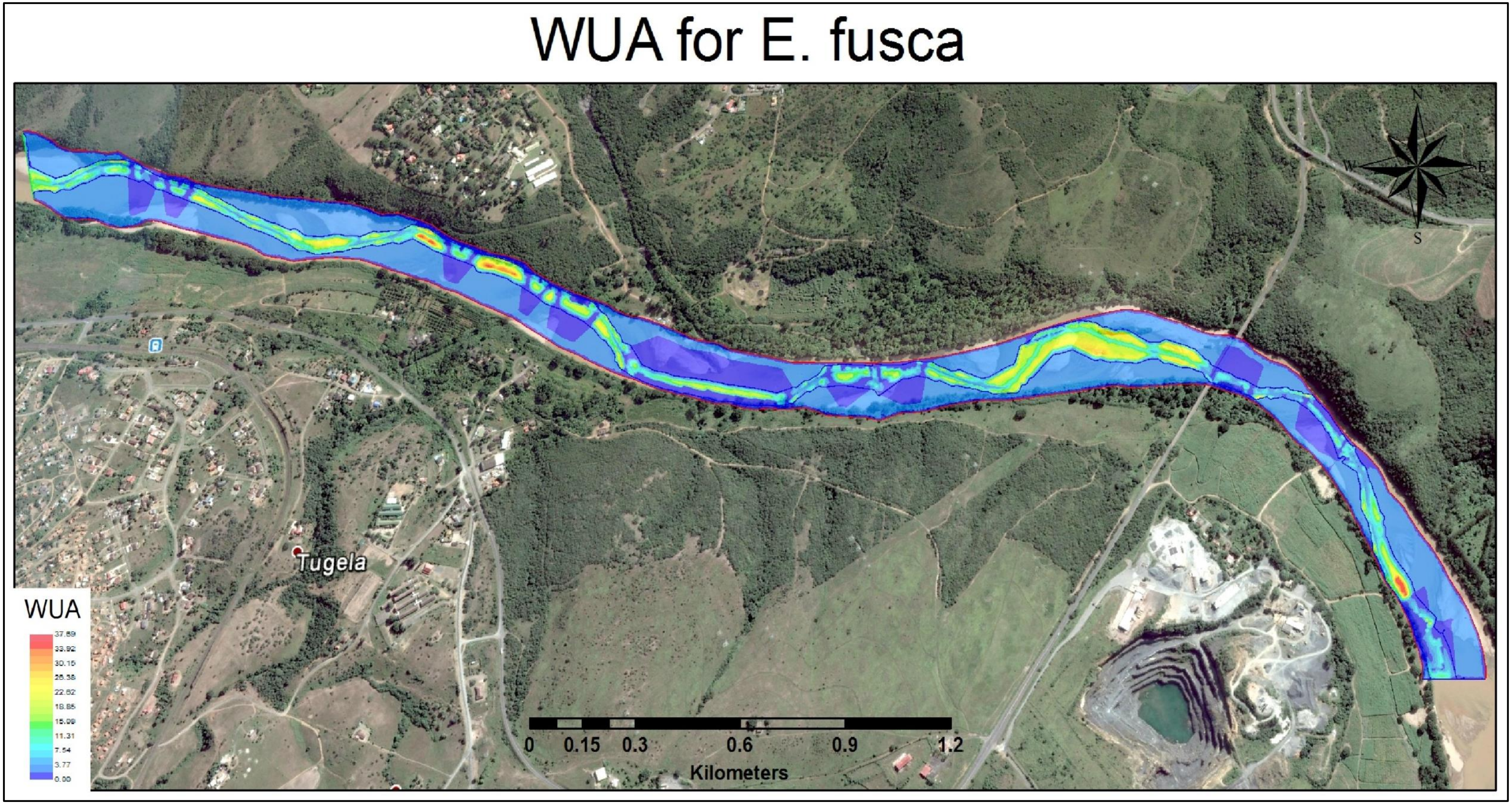

Figure 48: WUA for *E. fusca* at their minimum flow requirement of 8 m^3/s for the 4.6 km study area in the lower Thukela River as predicted by the IFIM methodology.

5. Conclusion

Bathymetric data collected with a Total Station and an Aquameter were combined with topographic data in ArcGIS to create a Digital Elevation Model. By using HECGeo-RAS to generate additional bathymetric data in combination with the DEM created in GIS, it was possible to delineate cross-sections, flow boundaries, river banks and flood plains for the lower Thukela River in areas which was inaccessible to reach. Data created were exported from HECGeo-RAS to HEC-RAS and bathymetric data were refined within the program to ensure accurate modelling. The model was calibrated for steady flow analysis at a discharge of 4.3 m^3/s as measured on the survey of April 2016 and a satisfactory correlation between measured and simulated water elevations were obtained. In addition another 22 different flows were simulated for the lower Thukela River ranging from 1 m^3/s to 4000 m^3/s to generate a stage-discharge curve. This played an important part in the study to generate water levels for different discharges as there were only two points from surveyed data available.

Topographic and bathymetric data used in GIS and HEC-RAS were used to create a bed profile for River2D, a 2-Dimensional hydraulic model. The model data were triangulated and exported as a mesh file and could then be refined in the MESH section of River2D where boundary conditions are set before final exportation to River2D for flow simulations. Water elevation data generated by HEC-RAS were used as the downstream boundary for River2D. After model calibration for steady state analysis measured and simulated velocities, surface water elevation and cross-section depth were compared and showed a good correlation.

To determine the habitat requirements and preferences, 19 freshwater and estuarine fish species (n = 1221) relevant to the lower Thukela River were used in the analyses. Multivariate statistical analyses were performed in the form of a Redundancy Analysis plot to determine the groups of species associated with a change in substrate, velocity and depth. The Monte Carlo permutation procedure on the RDA plot indicated that fish community structures change significantly with a change in substrate. Velocity had a significant effect on fish community structures while depth showed a strong correlation for some species but not significant.

Habitat preference assessments were done for all fish species in the form of velocity, depth and substrate. Box and Whisker plots were used to generate preferences for velocity and depth and a stack bar graph was used to identify preferred substrate types for different species. KwaZulu-Natal yellowfish (*Labeobarbus natalensis*) was the most abundant and widely distributed species and showed a strong correlation between substrate and velocities, and therefore was used as an indicator species for fast-deep habitat conditions. The Dusky sleeper (*Eleotris fusca*) was identified as the other indicator species as it is endemic to lowland rivers and its velocity and flow preferences can act as a double for the Golden Sleeper (*Hypseleotris cyprinoides)* that is near threatened. The preference values for indicator species were converted to binary units with 0 being the least preferred habitat and 1 the most preferred habitat to get unit area in square meters. River2D make use of the PHABSIM concept to calculate WUA (m^2/m) by combining habitat suitability (substrate) with velocity and depth preferences.

Flow alteration is a serious threat in the lower Thukela River due to anthropogenic changes upstream that disturb the natural flow-regime. The reduction in flow will have many negative effects on the endemic fish populations including the loss of rheophillic species, and delayed or loss of spawning and migration of different species. The reductions in flows will also benefit exotic species like carp and mosquitofish that are already present in the lower Thukela River. These effects pose a great threat to the existence of the natural aquatic biodiversity and therefore it is important to determine environmental flows that will improve the current ecological state of the river.

Different historic methods have been used as well as a habitat method to determine the environmental flow for the lower Thukela River. The historic methods that were used and compared are the Tennants method (1976) and the Aquatic Base Flow method. The flow requirements determined through the historic methods were both lower than that of the habitat method used in River2D. By using the historic methods it is assumed that by maintaining the natural flow regime the ecological state of the river will be maintained, but does not make provision for anthropogenic changes within the system. The lower Thukela River have been altered by the bulk water supply scheme and the abstraction at the SAPPI mill and therefore the habitat method to determine environmental flow requirements are more relevant to the study area. The habitat method provides a flow requirement for each individual species and their life stages and therefore conflict between flow requirements do exist. It is an accepted practice to use species with higher flow requirements, rheophillic species like *L. natalensis*, to determine the environmental flow requirement as this will maintain and benefit all species with lower flow requirements. The margins of the river channel will still provide sufficient habitat suitability for smaller native fish species. The environmental flow requirement determined by this study is higher than the flow requirement determined by the DWAF (2004) and therefore suggests that the environmental flow requirements for the lower Thukela River is increased to avoid the negative impact associated with a reduction in flow.

Environmental flows describe the quantity, quality and timing of water flows required to sustain freshwater ecosystems. The flow regime consist of different components like low flows, freshes, channel maintenance and floods and even though the importance of these flows are known, the degree to which the frequency and durations of these flows affect the biota are unknown and there are no clear method for assigning values to these components other than mimicking natural flows. Low flow requirements can be considered as the most important flow requirement for a river and with flows lower than the minimum requirements aquatic life will decrease drastically. By only maintaining base flow conditions for a river ecosystem the ecological state of the river may stay the same or degrade and therefore it is important to have variable flows..

No model exists that can be globalised and for that reason it is important not to use habitat analysis as a decision making process itself but rather as a tool to assist in the process of establishing flow requirements. This is achieved when the goals for flow requirements are clear and target objectives for the effect of flow on the ecological state are identified, to maintain or improve the ecological state of a river.

6. Recommendations

By doing this study a few shortcomings were identified both in data collection and that of natural conditions. The greatest limitation was the collection of bathymetric data due to inaccessibility and the dangers of crocodiles in the river. The use of a total station provided limited data and for future studies sampling bathymetric data with an Acoustic Doppler Current Profiler (ADCP) over larger areas is recommended. This will allow higher detail of river bed profiles. It is recommended that if possible LIDAR data should be used for the topography data rather than 5 m contours to improve accuracy of high flow predictions that will flood river banks. Due to the dynamic nature of the lower Thukela River the model will need to be updated for new studies to ensure accurate distribution of habitat classes as they will change after high flows and floods. The fish preference file can be used again and additional fish data collected can be added to existing files to increase reliability.

Additional studies that are required to determine true instream requirements and their timing for the lower Thukela River includes the stage/flow requirement for fish to migrate actively over the rocky barrier of SAPPI's extraction point. The impact altered flows will have on the chemical properties of the lower Thukela River and to what extend the concentration of harmful chemicals will increase must be considered in combination with the physical properties for a better understanding in timing and extend of freshes and flood requirements. An increase in sediment due to human activities upstream will decrease habitat suitability downstream and therefore studies incorporating sediment transport will proof of great value for decision making.

Temperature plays an important role in the distribution of different fish species and should be considered as a parameter in future studies.

It is important to conduct a groundwater-surface water interaction study on the lower Thukela River to determine the magnitude of groundwater contribution to the baseflow conditions. Groundwater-surface water interaction will have a significant contribution to available ecological habitat within a river and therefore groundwater-dependant ecosystems needs more research in terms of understanding the contribution and linkages between groundwater and surface water. This will require intrusive work along the river banks.

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Appendix A – All fish species collected during field surveys

	Site nr	Site		AAEN	ANAT	ANG	EEUT	LNAT	EPAU	ETRI	EVIV	CCAR	CGAR	EFUS	GCAL	LCYL	LMOL	MCAP	OMOS	PPHI	TREN	TSPA	Velocity (m/s)	Depth (mm)	Sub. Silt	Sub. Mud	Sub. Sand	Sub. Grav	Sub. Cobb	Sub. Boul
1	RHP1	W4BIVN-NTLSP	RHP1-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.474	200	0	0	0	0	50	50
2	RHP1	W4BIVN-NTLSP	RHP1-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.718	800	0	0	30	0	0	0
3	RHP1	W4BIVN-NTLSP	RHP1-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.039	200	0	0	100	0	0	0
4	RHP1	W4BIVN-NTLSP	RHP1-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	500	0	0	70	0	30	0
5	RHP1	W4BIVN-NTLSP	RHP1-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	600	0	0	100	0	0	0
6	RHP1	W4BIVN-NTLSP	RHP1-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	1000	0	0	50	0	0	50
7	RHP1	W4BIVN-NTLSP	RHP1-E7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.500	700	0	0	0	0	0	80
8	RHP1	W4BIVN-NTLSP	RHP1-E8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.757	1300	0	0	30	0	0	70
9	RHP1	W4BIVN-NTLSP	RHP1-E9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.887	1100	0	0	70	0	0	30
10	RHP2	W4PONG-N2PON	RHP2-E1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	3	0	0.000	1000	0	0	50	0	0	50
11	RHP2	W4PONG-N2PON	RHP2-E2	0	0	0	0	0	0	0	0	0	0	0	4	1	0	0	0	0	3	11	0.000	200	0	0	0	0	0	100
12	RHP2	W4PONG-N2PON	RHP2-E3	0	0	0	0	0	0	0	0	0	0	0	4	1	0	0	0	0	0	0	0.000	300	0	0	50	0	0	50
13	RHP2	W4PONG-N2PON	RHP2-E4	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0.000	150	0	0	50	0	0	50
14	RHP2	W4PONG-N2PON	RHP2-E5	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0.000	600	0	0	30	0	0	70
15	RHP2	W4PONG-N2PON	RHP2-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	800	100	0	0	0	0	0
16	RHP2	W4PONG-N2PON	RHP2-E7	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0.000	400	0	0	40	0	0	60
17	RHP3	W4NGWV-D1840	RHP3-EDRY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0	0	0	0
18	RHP4	W4PONG-NDUMO	RHP4-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	320	0	0	0	30	0	0
19	RHP4	W4PONG-NDUMO	RHP4-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.254	1200	0	0	0	0	0	0
20	RHP4	W4PONG-NDUMO	RHP4-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	1000	0	0	0	0	0	0
21	RHP4	W4PONG-NDUMO	RHP4-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	600	0	0	0	0	0	20
22	RHP4	W4PONG-NDUMO	RHP4-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	210	0	0	0	30	0	30
23	RHP5	W3MKZE-D0230	RHP5-E1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0.000	600	100	0	0	0	0	0
24	RHP5	W3MKZE-D0231	RHP5-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	47	0.000	500	100	0	0	0	0	0
25	RHP5	W3MKZE-D0232	RHP5-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	0.000	200	60	0	0	0	40	0
26	RHP5	W3MKZE-D0233	RHP5-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	0.000	300	0	0	70	0	0	30
27	RHP5	W3MKZE-D0234	RHP5-E5	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	94	0.000	400	100	0	0	0	0	0
28	RHP5	W3MKZE-D0235	RHP5-E6	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	6	0.000	500	80	0	0	0	0	20
29	RHP7	W3HLHW-HLWGR	RHP7-E1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	200	0	30	70	0	0	0
30	RHP7	W3HLHW-HLWGR	RHP7-E2	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	350	0	30	70	0	0	0
31	RHP7	W3HLHW-HLWGR	RHP7-E3	0	0	0	0	2	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0.000	600	0	40	60	0	0	0
32	RHP6	W3MKZE-DNYDR	RHP6-EDRY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0	0	0	0
33	RHP8	W2SKWB-GRTGL	RHP8-E1	0	0	0	10	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	0.333	600	40	0	0	0	0	60
34	RHP8	W2SKWB-GRTGL	RHP8-E2	0	0	0	4	0	0	20	0	0	0	0	0	0	0	0	0	0	0	25	0.191	200	0	0	0	0	0	80
35	RHP8	W2SKWB-GRTGL	RHP8-E3	1	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	700	40	0	0	0	0	60
36	RHP8	W2SKWB-GRTGL	RHP8-E4	1	0	0	5	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0.000	900	0	0	0	0	0	100
37	RHP8	W2SKWB-GRTGL	RHP8-E5	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.147	300	70	0	0	0	0	30
38	RHP8	W2SKWB-GRTGL	RHP8-E6	0	0	0	2	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0.102	700	100	0	0	0	0	0
39	RHP9	W2BMFO-NGOLO	RHP9-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	160	0	60	40	0	0	0
40	RHP9	W2BMFO-NGOLO	RHP9-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	300	0	100	0	0	0	0
41	RHP9	W2BMFO-NGOLO	RHP9-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0.000	540	0	80	0	0	0	0
42	RHP9	W2BMFO-NGOLO	RHP9-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.254	220	0	60	40	0	0	0
43	RHP9	W2BMFO-NGOLO	RHP9-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.367	150	0	0	30	70	0	0
44	RHP10	W2MVNY-P0016	RHP10-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.147	200	0	0	100	0	0	0
45	RHP10	W2MVNY-P0017	RHP10-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.147	300	0	0	100	0	0	0
46	RHP10	W2MVNY-P0018	RHP10-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.333	200	0	0	90	0	10	0

Continued

	Site nr	Site		AAEN	ANAT	ANG	EEUT	LNAT	EPAU	ETRI	EVIV	CCAR	CGAR	EFUS	GCAL	LCYL	LMOL	MCAP	OMOS	PPHI	TREN	TSPA	Velocity (m/s)	Depth (mm)	Sub. Silt	Sub. Mud	Sub. Sand	Sub. Grav	Sub. Cobb	Sub. Boul
47	RHP11	W2WMFO-DINDI	RHP11-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0.850	300	0	0	80	0	0	20
48	RHP11	W2WMFO-DINDI	RHP11-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.440	500	0	0	100	0	0	0
49	RHP11	W2WMFO-DINDI	RHP11-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0.606	400	0	0	90	0	0	10
50	RHP11	W2WMFO-DINDI	RHP11-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0.474	500	0	0	90	0	0	10
51	RHP11	W2WMFO-DINDI	RHP11-E5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.466	600	0	0	100	0	0	0
52	RHP11	W2WMFO-DINDI	RHP11-E6	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.931	300	0	0	70	0	0	30
53	RHP12	W2MFOL-CONFL	RHP12-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	840	0	50	50	0	0	0
54	RHP12	W2MFOL-CONFL	RHP12-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.798	550	0	50	50	0	0	0
55	RHP12	W2MFOL-CONFL	RHP12-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.494	350	0	50	50	0	0	0
56	RHP12	W2MFOL-CONFL	RHP12-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.333	200	0	50	50	0	0	0
57	RHP12	W2MFOL-CONFL	RHP12-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	130	0	50	50	0	0	0
58	RHP12	W2MFOL-CONFL	RHP12-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	280	0	50	50	0	0	0
59	RHP13	W1MFLE-ELIZB	RHP13-E1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0.000	400	0	100	0	0	0	0
60	RHP13	W1MFLE-ELIZB	RHP13-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.147	220	0	0	0	0	0	0
61	RHP13	W1MFLE-ELIZB	RHP13-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.411	150	0	0	0	50	0	0
62	RHP13	W1MFLE-ELIZB	RHP13-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0.000	550	0	80	0	0	0	20
63	RHP13	W1MFLE-ELIZB	RHP13-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0.000	650	0	0	0	0	0	30
64	RHP13	W1MFLE-ELIZB	RHP13-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	800	70	0	0	0	0	0
65	RHP14	W1MHLA-GWEIR	RHP14-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0.038	430	0	0	100	0	0	0
66	RHP14	W1MHLA-GWEIR	RHP14-E2	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0.376	500	0	0	50	0	0	50
67	RHP14	W1MHLA-GWEIR	RHP14-E3	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0	0.376	280	0	0	40	0	0	30
68	RHP14	W1MHLA-GWEIR	RHP14-E4	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	3	0	0	0.038	260	0	0	100	0	0	0
69	RHP14	W1MHLA-GWEIR	RHP14-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0.254	200	0	0	40	0	0	60
70	RHP14	W1MHLA-GWEIR	RHP14-E6	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0.254	360	0	0	100	0	0	0
71	RHP14	W1MHLA-GWEIR	RHP14-E7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0.466	200	0	0	100	0	0	0
72	RHP14	W1MHLA-GWEIR	RHP14-E8	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0.000	400	0	0	100	0	0	0
73	RHP14	W1MHLA-GWEIR	RHP14-E9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0.000	1100	0	0	90	0	0	10
74	RHP15	W1NWKU-MTGLU	RHP15-E1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	35	18	0	0	0.000	600	0	0	50	50	0	0
75	RHP15	W1NWKU-MTGLU	RHP15-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	7	0	0	0.000	200	0	0	50	50	0	0
76	RHP15	W1NWKU-MTGLU	RHP15-E3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.326	560	0	0	60	0	0	40
77	RHP15	W1NWKU-MTGLU	RHP15-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.297	500	0	0	30	0	0	70
78	RHP15	W1NWKU-MTGLU	RHP15-E5	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0.513	700	0	0	20	0	0	80
79	RHP16	W1EVTH-GINNE	RHP16-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	500	0	50	50	0	0	0
80	RHP16	W1EVTH-GINNE	RHP16-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	400	0	50	50	0	0	0
81	RHP16	W1EVTH-GINNE	RHP16-E3	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	4	0.000	400	0	100	0	0	0	0
82	RHP16	W1EVTH-GINNE	RHP16-E4	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	1	0	32	0.000	600	0	70	30	0	0	0
83	RHP16	W1EVTH-GINNE	RHP16-E5	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	1	0	62	0.000	400	0	100	0	0	0	0
84	RHP16	W1EVTH-GINNE	RHP16-E6	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	7	0.000	500	0	70	30	0	0	0
85	RHP17	W1MATI-NYEZA	RHP17-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	0.000	200	0	0	100	0	0	0
86	RHP17	W1MATI-NYEZA	RHP17-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	0.000	400	0	0	30	70	0	0
87	RHP17	W1MATI-NYEZA	RHP17-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	800	0	0	20	50	30	0
88	RHP17	W1MATI-NYEZA	RHP17-E4	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0.000	1200	0	0	100	0	0	0
89	RHP17	W1MATI-NYEZA	RHP17-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	1	0	0	0.000	700	0	0	100	0	0	0
90	RHP17	W1MATI-NYEZA	RHP17-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0.000	150	0	0	0	0	100	0
91	RHP17	W1MATI-NYEZA	RHP17-E7	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0	0	0	0	0.000	300	0	0	100	0	0	0
92	RHP17	W1MATI-NYEZA	RHP17-E8	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0.000	500	0	0	70	30	0	0
93	RHP18	V3SLNG NCHTW	RHP18-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.675	400	0	0	0	0	0	100
94	RHP18	V3SLNG NCHTW	RHP18-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.815	200	0	0	0	0	0	40
95	RHP18	V3SLNG NCHTW	RHP18-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.713	500	0	0	0	0	0	100

Continued

	Site nr	Site	0	AAEN	ANAT	ANG	EEUT	LNAT	EPAU	ETRI	EVIV	CCAR	CGAR	EFUS	GCAL	LCYL	LMOL	MCAP	OMOS	PPHI	TREN	TSPA	Velocity (m/s)	Depth (mm)	Sub. Silt	Sub. Mud	Sub. Sand	Sub. Grav	Sub. Cobb	Sub. Boul
96	RHP18	V3SLNG NCHTW	RHP18-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.580	1200	0	0	0	0	30	0
97	RHP18	V3SLNG NCHTW	RHP18-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.598	600	0	0	0	0	0	0
98	RHP19	V3NCND-LEYDN	RHP19-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.621	200	0	0	0	0	0	100
99	RHP19	V3NCND-LEYDN	RHP19-E2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.806	350	0	0	0	0	0	100
100	RHP19	V3NCND-LEYDN	RHP19-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.469	800	0	0	0	0	0	30
101	RHP19	V3NCND-LEYDN	RHP19-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.695	600	0	0	0	0	0	0
102	RHP19	V3NCND-LEYDN	RHP19-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.708	400	0	0	0	0	0	100
103	RHP19	V3NCND-LEYDN	RHP19-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.716	800	0	0	0	0	0	70
104	RHP20	V3BUFF-CONFL	RHP20-E1	0	0	0	0	2	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0.411	600	0	0	30	0	0	70
105	RHP20	V3BUFF-CONFL	RHP20-E2	0	0	0	0	4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0.629	500	0	0	0	0	0	100
106	RHP20	V3BUFF-CONFL	RHP20-E3	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0.695	250	0	0	0	0	0	100
107	RHP20	V3BUFF-CONFL	RHP20-E4	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0.000	1200	0	0	0	0	0	100
108	RHP20	V3BUFF-CONFL	RHP20-E5	0	0	0	0	4	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0.552	250	0	0	0	0	0	100
109	RHP20	V3BUFF-CONFL	RHP20-E6	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0.299	700	0	0	0	0	0	70
110	RHP20	V3BUFF-CONFL	RHP20-E7	0	0	0	0	4	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0.739	1100	0	0	0	0	0	80
111	RHP20	V3BUFF-CONFL	RHP20-E8	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0.739	800	0	0	0	0	0	60
112	RHP20	V3BUFF-CONFL	RHP20-E9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0.000	400	0	0	50	0	0	50
113	RHP21	V3SAND-COTSW	RHP21-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	100	0	0	0	0	0	20
114	RHP21	V3SAND-COTSW	RHP21-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.474	150	0	0	0	0	20	40
115	RHP21	V3SAND-COTSW	RHP21-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.147	200	0	0	0	0	0	50
116	RHP21	V3SAND-COTSW	RHP21-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	500	0	0	0	0	20	40
117	RHP21	V3SAND-COTSW	RHP21-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.299	500	0	0	0	0	20	40
118	RHP22	V1THUK-TUGEL	RHP22-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	500	0	30	0	0	0	70
119	RHP22	V1THUK-TUGEL	RHP22-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.529	300	0	0	0	0	0	100
120	RHP22	V1THUK-TUGEL	RHP22-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.396	400	0	50	0	0	0	50
121	RHP22	V1THUK-TUGEL	RHP22-E4	0	0	0	0	15	0	1	0	0	0	0	0	0	2	0	0	0	0	0	0.254	200	0	0	0	0	0	100
122	RHP22	V1THUK-TUGEL	RHP22-E5	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0.554	300	0	0	0	0	0	100
123	RHP22	V1THUK-TUGEL	RHP22-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.317	600	0	0	0	0	0	100
124	RHP22	V1THUK-TUGEL	RHP22-E7	0	0	0	0	6	0	3	1	0	4	0	0	0	0	0	0	0	0	0	0.440	200	0	0	0	0	0	100
125	RHP22	V1THUK-TUGEL	RHP22-E8	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0.102	400	0	50	0	0	0	50
126	RHP22	V1THUK-TUGEL	RHP22-E9	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0.147	400	0	50	0	0	0	50
127	RHP23	V7BUSH-MOORP	RHP23-E1	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.377	700	0	0	0	0	0	100
128	RHP23	V7BUSH-MOORP	RHP23-E2	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.629	800	0	0	0	0	0	100
129	RHP23	V7BUSH-MOORP	RHP23-E3	0	0	0	0	113	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.147	300	0	0	30	0	0	70
130	RHP23	V7BUSH-MOORP	RHP23-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.554	600	0	0	100	0	0	0
131	RHP23	V7BUSH-MOORP	RHP23-E5	0	0	0	0	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.713	400	0	0	0	0	0	100
132	RHP23	V7BUSH-MOORP	RHP23-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.758	800	0	0	20	0	0	80
133	RHP23	V7BUSH-MOORP	RHP23-E7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	1200	0	0	80	0	0	20
134	RHP24	V2UNSP-KMBRG	RHP24-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.671	350	0	0	0	0	50	50
135	RHP24	V2UNSP-KMBRG	RHP24-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.299	120	0	0	0	0	0	30
136	RHP24	V2UNSP-KMBRG	RHP24-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.474	250	0	0	0	20	0	60
137	RHP25	V1THUK-RAILB	RHP25-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.440	300	0	0	0	0	0	0
138	RHP25	V1THUK-RAILB	RHP25-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.698	600	0	0	0	0	0	0
139	RHP25	V1THUK-RAILB	RHP25-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.778	400	0	0	0	0	0	0
140	RHP26	U4MVOT-SHANK	RHP26-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	270	0	0	0	0	0	0
141	RHP26	U4MVOT-SHANK	RHP26-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	310	0	0	0	0	0	50
142	RHP26	U4MVOT-SHANK	RHP26-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0.102	240	0	0	0	0	0	0
143	RHP26	U4MVOT-SHANK	RHP26-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	240	0	0	0	0	0	50
144	RHP26	U4MVOT-SHANK	RHP26-E5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.333	390	0	0	0	0	0	100

Continued

	Site nr	Site	0	0	AAEN	ANAT	ANG	EEUT	LNAT	EPAU	ETRI	EVIV	CCAR	CGAR	EFUS	GCAL	LCYL	LMOL	MCAP	OMOS	PPHI	TREN	TSPA	Velocity (m/s)	Depth (mm)	Sub. Silt	Sub. Mud	Sub. Sand	Sub. Grav	Sub. Cobb	Sub. Boul
145	RHP26	U4MVOT-SHANK	RHP26-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.454	260	0	0	0	0	0	20
146	RHP26	U4MVOT-SHANK	RHP26-E7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	560	0	0	0	0	0	20
147	RHP27	U4MVOT-N2BRI	RHP27-E1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0.000	910	0	0	100	0	0	0
148	RHP27	U4MVOT-N2BRI	RHP27-E2	12	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	8	0	0	0	0.210	200	0	0	100	0	0	0
149	RHP27	U4MVOT-N2BRI	RHP27-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.440	650	0	0	100	0	0	0
150	RHP27	U4MVOT-N2BRI	RHP27-E4	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0.000	600	0	0	100	0	0	0
151	RHP27	U4MVOT-N2BRI	RHP27-E5	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0.000	770	0	0	100	0	0	0
152	RHP27	U4MVOT-N2BRI	RHP27-E6	5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	4	0	0	0	0.000	450	0	0	100	0	0	0
153	RHP28	U2TONG-ROADB	RHP28-E1	9	2	0	0	0	0	0	0	1	0	0	6	0	0	0	0	0	0	0	0	0.675	150	80	0	0	0	0	10
154	RHP28	U2TONG-ROADB	RHP28-E2	4	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0.000	550	100	0	0	0	0	0
155	RHP28	U2TONG-ROADB	RHP28-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	200	100	0	0	0	0	0
156	RHP28	U2TONG-ROADB	RHP28-E4	4	0	0	0	0	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0.000	300	60	0	0	0	0	40
157	RHP28	U2TONG-ROADB	RHP28-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.362	600	60	0	0	0	0	20
158	RHP28	U2TONG-ROADB	RHP28-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	200	70	30	0	0	0	0
159	RHP29	U3MDLO-HAZIN	RHP29-E1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0.000	200	0	0	0	60	0	20
160	RHP29	U3MDLO-HAZIN	RHP29-E2	3	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0.598	700	0	0	0	0	0	60
161	RHP29	U3MDLO-HAZIN	RHP29-E3	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0.254	300	0	0	30	0	0	40
162	RHP29	U3MDLO-HAZIN	RHP29-E4	3	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0.000	500	40	0	0	0	0	60
163	RHP29	U3MDLO-HAZIN	RHP29-E5	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.466	150	0	0	0	0	20	80
164	RHP29	U3MDLO-HAZIN	RHP29-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.362	300	0	0	0	20	0	40
165	RHP30	U2MGNI-DRGLE	RHP30-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	370	0	0	0	0	0	100
166	RHP30	U2MGNI-DRGLE	RHP30-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	400	0	0	0	0	20	80
167	RHP30	U2MGNI-DRGLE	RHP30-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	800	0	0	0	0	70	30
168	RHP30	U2MGNI-DRGLE	RHP30-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.672	290	0	0	0	0	10	90
169	RHP30	U2MGNI-DRGLE	RHP30-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.446	230	0	0	0	0	20	80
170	RHP31	U2MGEN-MIDMA	RHP31-E1	7	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.529	450	0	0	0	0	0	70
171	RHP31	U2MGEN-MIDMA	RHP31-E2	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.494	670	0	0	0	0	0	70
172	RHP31	U2MGEN-MIDMA	RHP31-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.406	500	0	0	0	0	0	0
173	RHP31	U2MGEN-MIDMA	RHP31-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	300	0	0	0	0	70	30
174	RHP31	U2MGEN-MIDMA	RHP31-E5	11	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.529	150	0	0	0	0	50	30
175	RHP31	U2MGEN-MIDMA	RHP31-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	950	0	50	0	0	0	50
176	RHP32	U2MGEN-MPOLW	RHP32-E1	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.608	330	0	0	0	0	0	0
177	RHP32	U2MGEN-MPOLW	RHP32-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.999	150	0	0	0	0	0	0
178	RHP32	U2MGEN-MPOLW	RHP32-E3	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.191	430	0	0	0	10	10	20
179	RHP32	U2MGEN-MPOLW	RHP32-E4	4	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.583	680	0	0	0	0	0	50
180	RHP32	U2MGEN-MPOLW	RHP32-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.606	630	0	0	0	10	0	30
181	RHP32	U2MGEN-MPOLW	RHP32-E6	4	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.863	1000	0	0	0	0	0	70
182	RHP32	U2MGEN-MPOLW	RHP32-E7	3	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.654	550	0	0	0	0	0	80
183	RHP32	U2MGEN-MPOLW	RHP32-E8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	540	0	0	0	0	0	30
184	RHP32	U2MGEN-MPOLW	RHP32-E9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	260	0	0	0	0	0	0
185	RHP32	U2MGEN-MPOLW	RHP32-E10	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	3	0.000	120	0	0	0	10	0	0
186	RHP32	U2MGEN-MPOLW	RHP32-E11	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0.000	300	0	0	30	30	0	0
187	RHP32	U2MGEN-MPOLW	RHP32-E12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.542	240	0	0	0	40	0	0
188	RHP32	U2MGEN-MPOLW	RHP32-E13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.343	500	0	0	0	0	0	0
189	RHP32	U2MGEN-MPOLW	RHP32-E14	5	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.474	350	0	0	0	30	0	40
190	RHP32	U2MGEN-MPOLW	RHP32-E15	7	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.786	380	0	0	0	20	0	80
191	RHP32	U2MGEN-MPOLW	RHP32-E16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.090	500	0	0	0	0	0	50
192	RHP32	U2MGEN-MPOLW	RHP32-E17	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0.972	840	0	0	0	0	0	50
193	RHP32	U2MGEN-MPOLW	RHP32-E18	2	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0.431	850	0	0	0	0	0	30

Continued

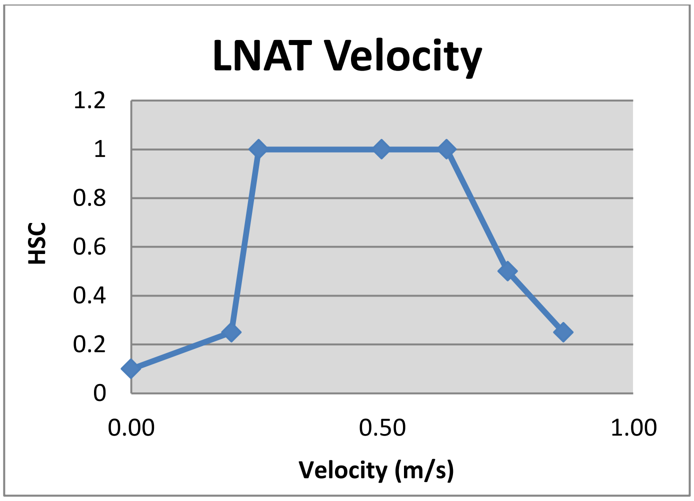
	Site nr	Site	0	AAEN	ANAT	ANG	EEUT	LNAT	EPAU	ETRI	EVIV	CCAR	CGAR	EFUS	GCAL	LCYL	LMOL	MCAP	OMOS	PPHI	TREN	TSPA	Velocity (m/s)	Depth (mm)	Sub. Silt	Sub. Mud	Sub. Sand	Sub. Grav	Sub. Cobb	Sub. Boul
194	RHP32	U2MGEN-MPOLW	RHP32-E19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	0.000	220	0	0	0	0	0	0
195	RHP32	U2MGEN-MPOLW	RHP32-E20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	500	0	0	0	0	0	0
196	RHP32	U2MGEN-MPOLW	RHP32-E21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	400	0	0	0	0	0	0
197	RHP32	U2MGEN-MPOLW	RHP32-E22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	1000	0	0	0	0	0	30
198	RHP32	U2MGEN-MPOLW	RHP32-E23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	1000	0	0	0	0	0	100
199	RHP32	U2MGEN-MPOLW	RHP32-E24	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.812	700	0	0	0	0	0	100
200	RHP32	U2MGEN-MPOLW	RHP32-E25	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.824	600	0	0	30	0	0	70
201	RHP32	U2MGEN-MPOLW	RHP32-E26	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.280	1000	0	0	40	0	0	60
202	RHP32	U2MGEN-MPOLW	RHP32-E27	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.003	800	0	0	0	0	0	100
203	RHP32	U2MGEN-MPOLW	RHP32-E28	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.734	1000	0	0	50	0	0	50
204	RHP33	U2MGEN-NINAW	RHP33-E1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	370	0	0	0	50	0	50
205	RHP33	U2MGEN-NINAW	RHP33-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.377	440	0	0	0	0	0	100
206	RHP33	U2MGEN-NINAW	RHP33-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.377	340	0	0	0	40	0	60
207	RHP33	U2MGEN-NINAW	RHP33-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	720	0	0	50	0	0	50
208	RHP33	U2MGEN-NINAW	RHP33-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.000	300	0	0	0	0	0	60
209	RHP33	U2MGEN-NINAW	RHP33-E6	2	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	790	0	0	50	0	0	50
210	RHP33	U2MGEN-NINAW	RHP33-E7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0.254	200	0	0	50	0	0	50
211	RHP35	U6MLAZ-USBAY	RHP35-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	350	0	0	0	0	0	0
212	RHP35	U6MLAZ-USBAY	RHP35-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	680	100	0	0	0	0	0
213	RHP35	U6MLAZ-USBAY	RHP35-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	950	100	0	0	0	0	0
214	RHP35	U6MLAZ-USBAY	RHP35-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	270	100	0	0	0	0	0
215	RHP35	U6MLAZ-USBAY	RHP35-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	500	100	0	0	0	0	0
216	RHP35	U6MLAZ-USBAY	RHP35-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.406	160	0	0	0	0	50	50
217	RHP36	U6MLAZ-P0502	RHP36-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.377	200	0	0	0	0	0	100
218	RHP36	U6MLAZ-P0503	RHP36-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.147	600	30	0	0	0	0	70
219	RHP36	U6MLAZ-P0504	RHP36-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	600	40	0	0	0	0	60
220	RHP36	U6MLAZ-P0505	RHP36-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.631	250	0	0	0	0	0	100
221	RHP36	U6MLAZ-P0506	RHP36-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.102	700	40	0	0	0	0	60
222	RHP36	U6MLAZ-P0507	RHP36-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.466	400	40	0	0	0	0	60
223	RHP36	U6MLAZ-P0508	RHP36-E7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	400	20	0	0	0	0	80
224	RHP37	U6MLAZ-SHONG	RHP37-EDNF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0	0	0	0
225	RHP38	U6LOVU-RICHM	RHP38-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	160	0	0	0	0	90	10
226	RHP38	U6LOVU-RICHM	RHP38-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	310	70	0	0	0	0	30
227	RHP38	U6LOVU-RICHM	RHP38-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.288	100	100	0	0	0	0	0
228	RHP39	U6LOVU-MIDIL	RHP39-EDNF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0	0	0	0
229	RHP40	U6LOVU-KAMPU	RHP40-EDNF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0	0	0	0
230	RHP41	U6LOVU-R0197	RHP41-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	1200	0	0	100	0	0	0
231	RHP41	U6LOVU-R0198	RHP41-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0.000	800	0	0	100	0	0	0
232	RHP42	U1MKMZ-SANIP	RHP42-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.557	200	0	0	0	0	0	100
233	RHP42	U1MKMZ-SANIP	RHP42-E2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.606	480	0	0	0	0	0	50
234	RHP42	U1MKMZ-SANIP	RHP42-E3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	140	0	0	0	50	0	0
235	RHP43	T5MZIM-NYAMA	RHP43-E1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0.000	350	0	100	0	0	0	0
236	RHP43	T5MZIM-NYAMA	RHP43-E2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	0.000	400	0	50	0	50	0	0
237	RHP43	T5MZIM-NYAMA	RHP43-E3	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	170	0	0	0	0	0	0
238	RHP43	T5MZIM-NYAMA	RHP43-E4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	960	0	0	0	100	0	0
239	RHP43	T5MZIM-NYAMA	RHP43-E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.387	680	0	0	0	90	0	10
240	RHP43	T5MZIM-NYAMA	RHP43-E6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.650	450	0	0	0	0	0	50
241	RHP43	T5MZIM-NYAMA	RHP43-E7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.754	280	0	0	0	0	0	90
242	RHP43	T5MZIM-NYAMA	RHP43-E8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.652	650	0	0	0	0	0	0

Continued

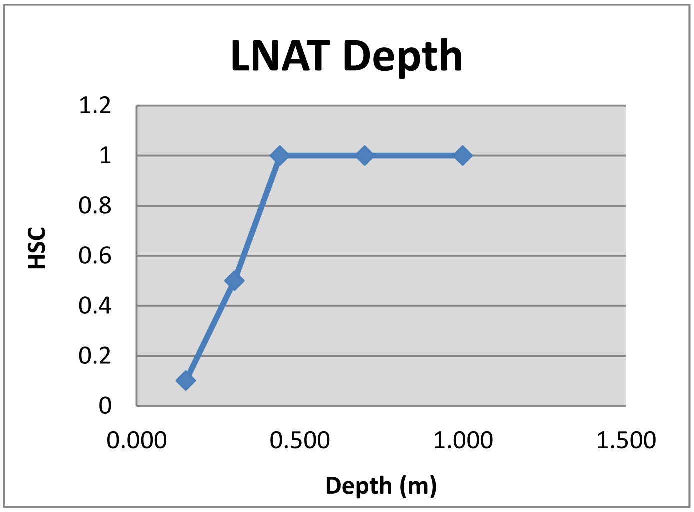
	Site nr	Site		0	AAEN	ANAT	ANG	EEUT	LNAT	EPAU	ETRI	EVIV	CCAR	CGAR	EFUS	GCAL	LCYL	LMOL	MCAP	OMOS	PPHI	TREN	TSPA	Velocity (m/s)	Depth (mm)	Sub. Silt	Sub. Mud	Sub. Sand	Sub. Grav	Sub. Cobb	Sub. Boul
243	RHP43	T5MZIM-NYAMA	RHP43-E9		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.147	640	0	0	0	60	0	40
244	RHP44	T4MTAM-MADIK	RHP44-E1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	210	0	0	50	0	0	50
245	RHP44	T4MTAM-MADIK	RHP44-E2		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	450	0	0	50	0	0	50
246	RHP44	T4MTAM-MADIK	RHP44-E3		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	360	0	0	20	0	0	80
247	RHP44	T4MTAM-MADIK	RHP44-E4		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	1000	0	0	80	0	0	20
248	RHP44	T4MTAM-MADIK	RHP44-E5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.696	300	0	0	0	0	0	100
249	RHP44	T4MTAM-MADIK	RHP44-E6		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	560	0	0	0	0	0	30
250	RHP44	T4MTAM-MADIK	RHP44-E7		0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.503	270	0	0	50	0	0	50
251	RHP44	T4MTAM-MADIK	RHP44-E8		0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.254	210	0	0	0	0	80	20
252	RHP44	T4MTAM-MADIK	RHP44-E9		0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	90	0	0	0	0	30	0
253	RHP44	T4MTAM-MADIK	RHP44-E10		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.618	450	0	0	0	0	20	80

Habitat suitability and preference files for KwaZulu-Natal yellowfish (L. natalensis)

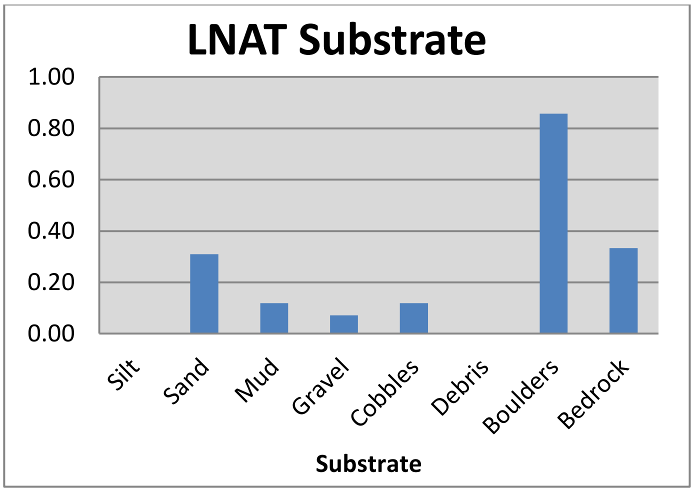
Velocity	m/s	hsc
5%tile	0.00	0.1
	0.20	0.25
25%tile	0.25	1
Median	0.50	1
75%tile	0.63	1
	0.75	0.5
95%tile	0.86	0.25



Depth	m	
5%tile	0.151	0.1
25%tile	0.300	0.5
Median	0.440	1
75%tile	0.700	1
95%tile	1.000	1

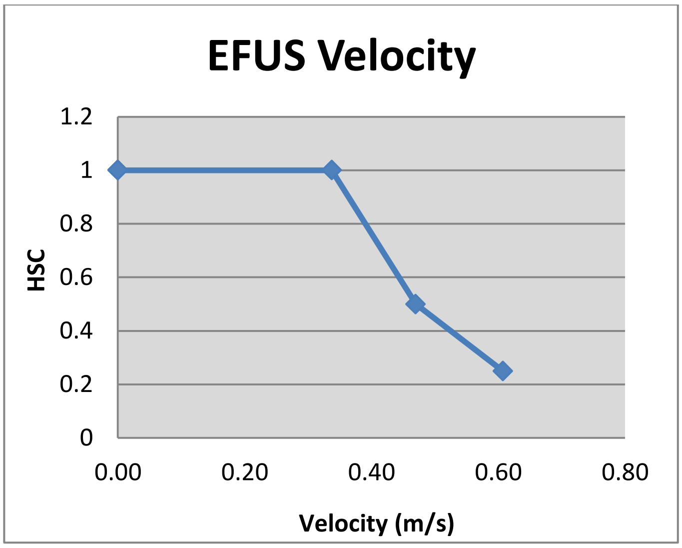


Substrate	
Silt	0.00
Sand	0.31
Mud	0.12
Gravel	0.07
Cobbles	0.12
Debris	0.00
Boulders	0.86
Bedrock	0.33

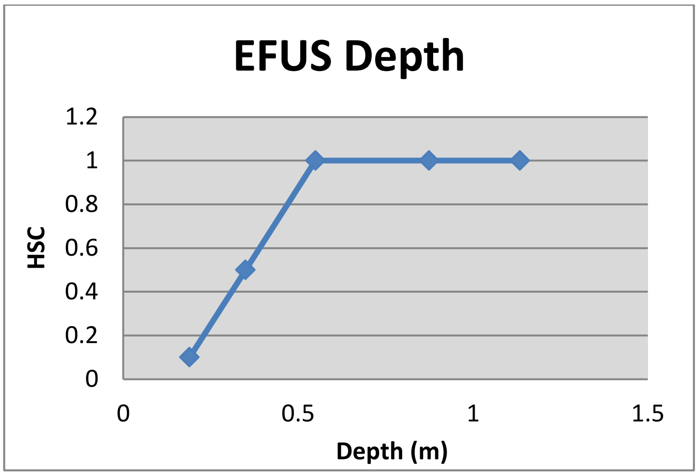


Habitat suitability and preference files for Dusky sleeper (E. fusca)

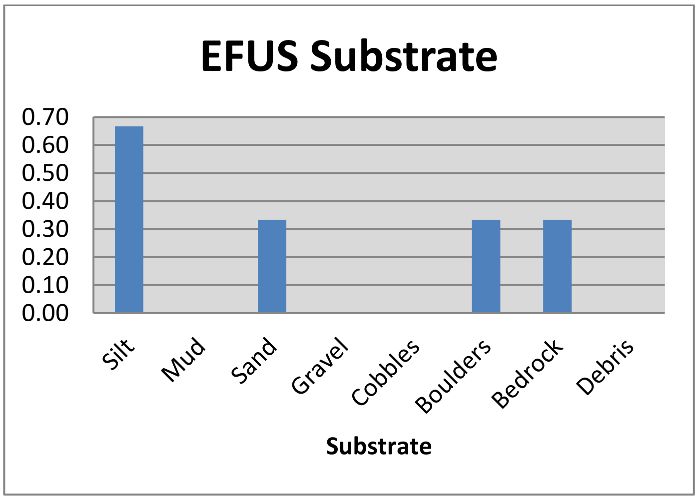
Velocity	m/s	hsc
5%tile	0.00	1
	0.00	1
25%tile	0.00	1
Median	0.00	1
75%tile	0.34	1
	0.47	0.5
95%tile	0.61	0.25



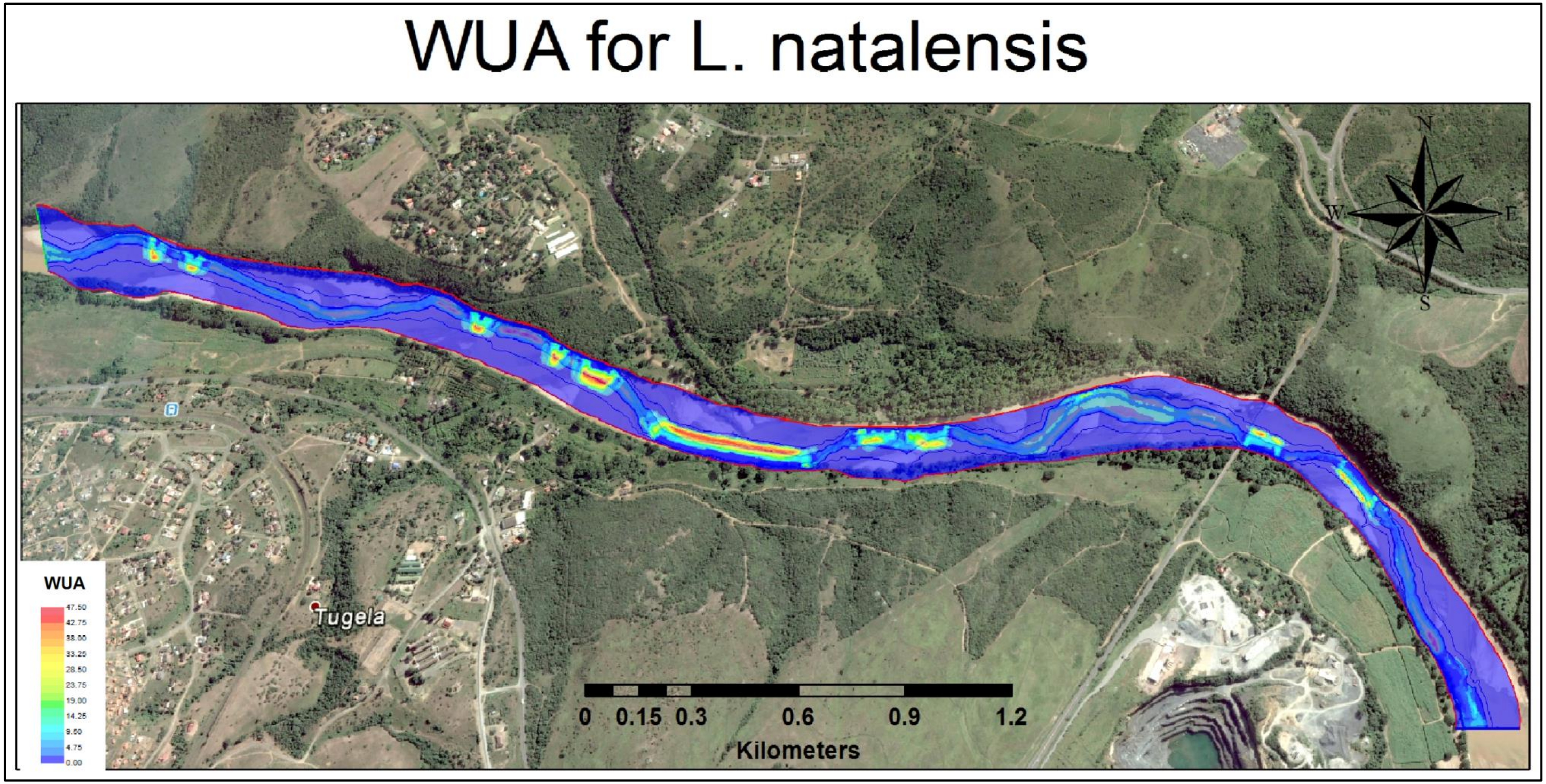
Depth	m	
5%tile	0.19	0.1
25%tile	0.35	0.5
Median	0.55	1
75%tile	0.875	1
95%tile	1.135	1



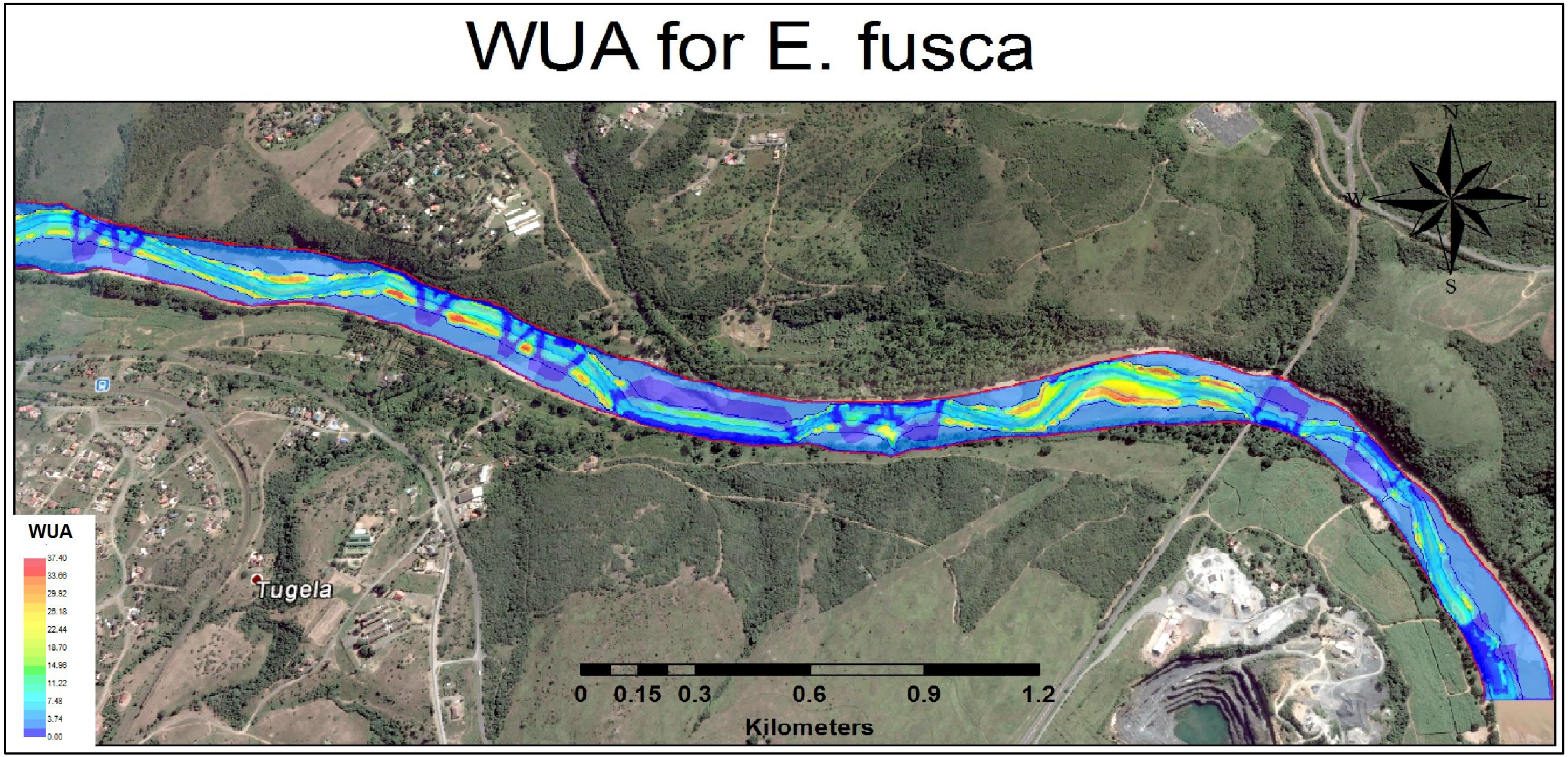
Substrate	
Silt	0.67
Mud	0.00
Sand	0.33
Gravel	0.00
Cobbles	0.00
Boulder	0.33
Bedrock	0.33
Debris	0.00



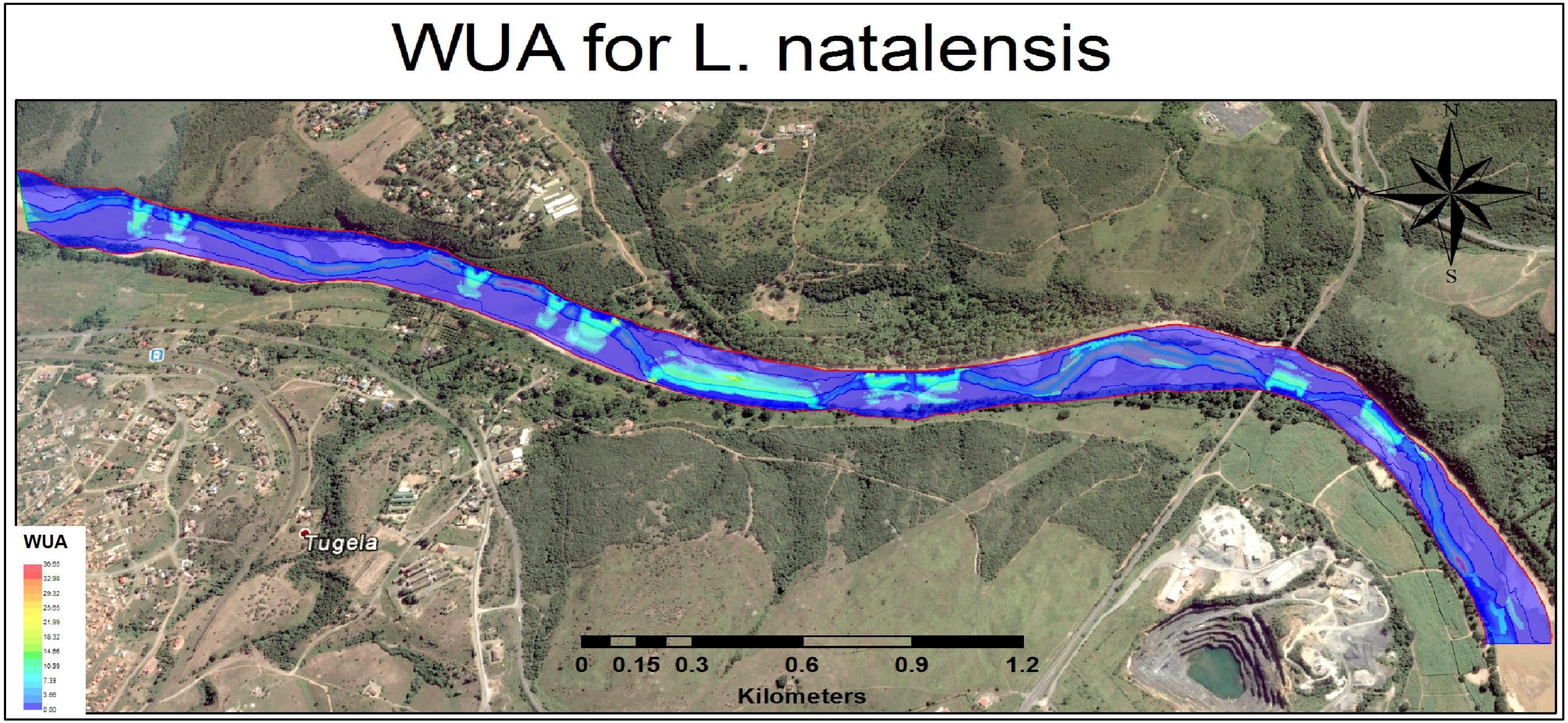
Appendix B – Additional maps for indicator species



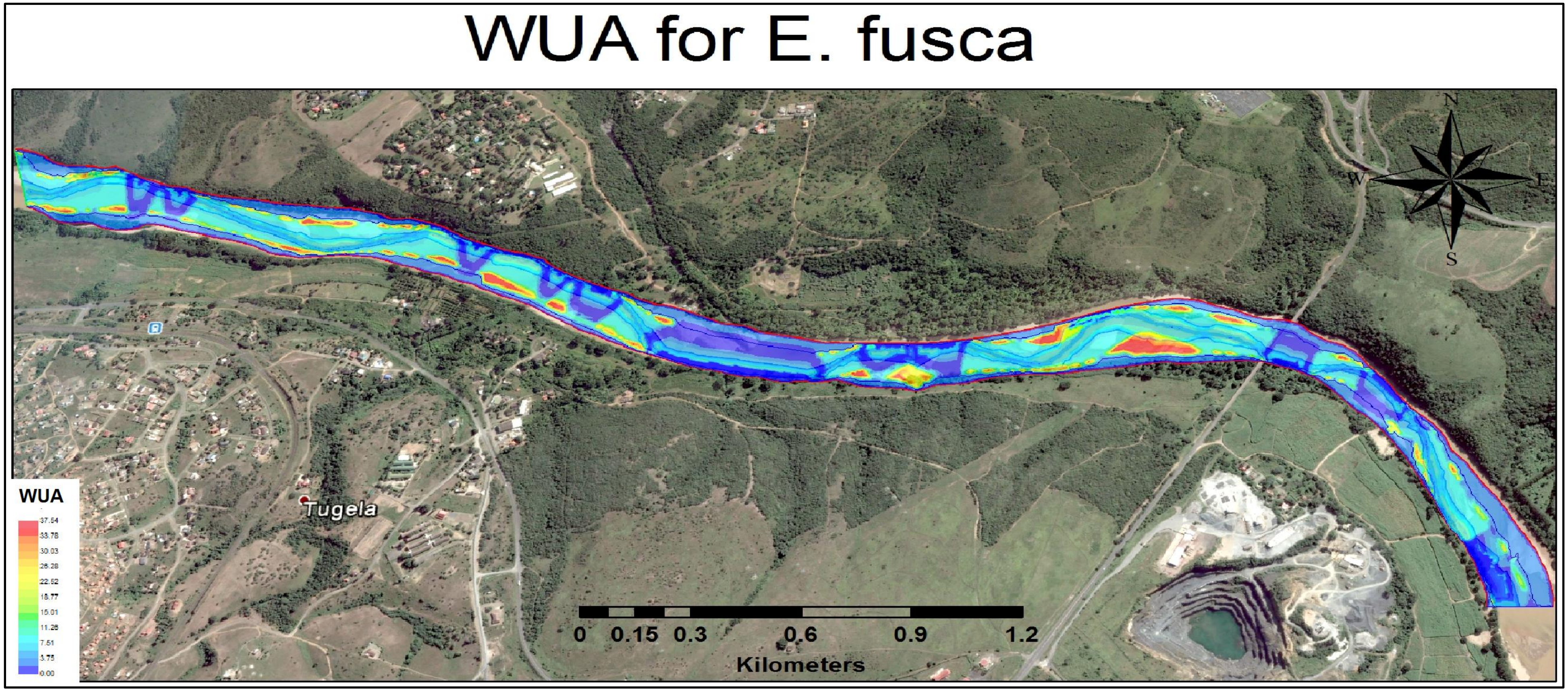
WUA for *L. natalensis* at 50.6 m^3/s for the 4.6 km study area in the lower Thukela River.



WUA for *E. fusca* at 50.6 m^3/s for the 4.6 km study area in the lower Thukela River.



WUA for *L. natalensis* at 208 m^3/s for the 4.6 km study area in the lower Thukela River.



WUA for *E. fusca* at 208 m^3/s for the 4.6 km study area in the lower Thukela River.