

The effect of flow variability on riparian vegetation in the lower Olifants River

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PREFACE

The data described in this dissertation were collected within the Republic of South Africa from September 2020 to May 2021. The data collection, analysis and write-up for this dissertation was compiled while registered at the North-West University, Potchefstroom campus, while under the supervision of Professor Victor Wepener, co-supervisor Dr. Gordon O'Brien and assistant supervisor Mr. James MacKenzie.

This dissertation was submitted for the degree of Master of science in environmental sciences, natural and agricultural sciences, University of North-West, Potchefstroom campus. This dissertation represents the work by the author and has not been submitted in any form for any degree or diploma to any University. Where the work of others was used, it was duly acknowledged within this document.



Stacey Gerber

March 2022

I certify that the above statement is correct, and as the candidate's supervisor, I have approved this dissertation for submission.

A handwritten signature in black ink, appearing to read 'V. Wepener', with a long horizontal stroke extending to the right.

Professor Victor Wepener

Supervisor

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ABSTRACT

This study investigated the drivers of vegetation composition and the hydraulic niche requirements of riparian plants at two sites along the lower Olifants River within the Kruger National Park. Drivers assessed included substrate, water quality and hydraulic associations. The VEGRAI tool was applied as a supplementary assessment for the determination of the present ecological state. Hydraulic niche requirements of riparian vegetation communities were identified for their use as biological indicators of environmental flow determination. This was achieved through surveyed cross-sections with superimposed riparian plants and associated biological, substrate and hydraulic data. Hydraulic rating curves designed for individual cross-sections provided activation discharge (AD) values for individual plants. Activation discharge translates to the amount of discharge required to activate a plant at root level. These values were found to be useful for hydraulic niche determination on local scales as values were specific to site characteristics. In order to remove site-specific variation, AD values were applied to hydrological exceedance tables which provided values relating to the percentage of time that individual plants, populations and communities experienced hydraulic activation. This information was found to be transferrable across sites and therefore could be effectively used in the application of environmental flow determination.

Keywords: biological indicator; riparian vegetation; hydraulics; hydrology; environmental flow requirements.

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ABBREVIATIONS

AD	Activation Discharge
CSIR	Council for Scientific and Industrial Research
CWE	Centre for Water in the Environment
DFFE	Department of Forestry, Fisheries and the Environment
DRIFT	Downstream Response to Imposed Flow Transformations
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
E-flows	Environmental flows
FAO	Food and Agriculture Organization
FDC	Flow Duration Curves
GIS	Geographic Information System
HEC-RAS	Hydrologic Engineering Centre River Analysis System
IEADB	International Environmental Agreements Database
KNP	Kruger National Park
LID	Large, infrequent disturbances
LUT	Look-up table (also known as hydrological flow exceedance table)
PES	Present Ecological State
SADC	South African Development Community
SDC	Serial discontinuity concept
Stats SA	Statistics South Africa
TPCs	Thresholds of Probable Concern
VEGRAI	Riparian Vegetation Response Assessment Index
WRC	Water Research Commission

1 General introduction

Water security for current and future generations has become a major global concern as freshwater ecosystems and biodiversity are declining (Dudgeon et al., 2006; Vörösmarty et al., 2010; Dudgeon, 2014). Freshwater ecosystems are responsible for supporting most humans as well as over 100,000 different species (Dudgeon et al., 2006; Dudgeon, 2014). As human populations increase, so does our need to address the challenge to sustainably manage the natural resources associated with inland freshwater ecosystem as well as the rehabilitation and/or maintenance of the associated ecological processes (Horne et al., 2017).

South Africa has an annual average rainfall of 450 mm compared to the global average of 850 mm (King and Pienaar, 2011). Some of the greatest challenges of South Africa's below average rainfall is that the rainfall is not evenly distributed on both a spatial or temporal scale. In addition to the above, the country experiences an annual mean temperature above 17°C, which results in evaporation that could far exceed annual rainfall in most areas (King and Pienaar, 2011). South Africa also experiences regular drought events as a result of the natural conditions and landscapes (DWS, 2019a). Past drought events have resulted in substantial reductions in available water resources for South Africa with dam levels continuing to decrease. As a result of extensive and intensive droughts and the associated reduction in water and food security, South Africa has progressively increased the number of water impoundment infrastructures. There are more than 4,395 registered dams in South Africa (DWAF, 2013).

Water storage infrastructure such as dams and weirs are essential for the economic growth and development of a country (DWAF, 2013), however, when incorrectly managed they result in reduced ecosystem functioning and the associated processes in freshwater aquatic ecosystems (Vörösmarty et al., 2010). The disruption of freshwater ecosystems as a result of dams and weirs was described by Stanford and Ward (1983) and referred to as the Serial Discontinuity Concept (SDC). The concept predicts ecosystem responses within rivers with reference to the rate of recovery with distance from the dam. The distance from a dam or physical barrier was referred to as the discontinuity distance. The concept stated that dams and weirs disrupt ecosystem processes by restricting natural flows regimes and sediment transportation potential, thereby disrupting biotic and abiotic components of freshwater ecosystems (Stanford and Ward, 1983; Stanford and Ward, 1995; Stanford and Ward, 2001; Naiman et al., 2005, 2008).

Riparian vegetation relies upon these natural processes as they have adapted their life histories to coincide with the natural flow regimes (Reinecke et al., 2013). They provide a plethora of functions and services to freshwater habitat, including the trapping and absorption of potentially harmful pollutants, absorption of excessive nutrients, improved soil stability, flood attenuation and habitat provision for aquatic and terrestrial biota (Prosser, 1999; Terrill, 1999; Reinecke et

al., 2015). Some species of riparian vegetation even have the ability to process toxic chemicals and convert them into less harmful compounds (Schachtschneider et al., 2017; Rowiński et al., 2018). Alterations of flow regimes, flood alleviation and sediment distributions have negative impacts on riparian vegetation habitat and the services rendered (Gleick, 2003; Poff et al., 2007; Naiman et al., 2008; Jager et al., 2012; DWAF, 2013).

The effective management of riparian vegetation ecosystems in modified rivers and catchment basins in a manner that maintains the integrity and functioning of the ecosystem services is essential for its sustainable utilization (Naiman et al., 2008; Vörösmarty et al., 2010; Reinecke et al., 2013, 2015). In order to achieve this, one must be able to replicate the important driving factors that influence riparian vegetation functionality, namely; flow regimes (seasonal and intensive infrequent discharge events) with the correct timing, frequency and duration and the geomorphological nature of a river through substrate distribution potential (Poff et al., 1997; Richter et al., 1997; Naiman et al., 2005, 2008; Reinecke et al., 2015; Horne et al., 2017).

The links between riparian vegetation and flow have been identified through their responses to altered flow regimes (Reinecke et al., 2013, 2015) however there is a need to establish a generic method that can be utilized to predict the flow requirements of an ecosystem through sound, replicable methodology (Kleynhans et al., 2007; Naiman et al., 2005, 2008; Reinecke et al., 2013, 2015). Existing research suggests that rivers possess various zones arranged laterally along a river (Naiman et al., 2005; Kleynhans et al., 2007; James and King, 2010; Reinecke et al., 2015). They state that riparian vegetation species can be assigned to associated zones with each of the zones based on their hydraulic and other ecological requirements. Their research aimed to use defined riparian vegetation zones as a means to predict the flow requirements of river systems and found that there was still much speculation regarding the number of zones within a river and that not all zones were always present in different catchment basins. In addition to this, the identification and delineation of zones was biased depending on different sampling methodology utilized and observer exposure.

The Riparian Vegetation Response Assessment Index (VEGRAI) tool was developed in order to determine the Present Ecological State (PES) of a river reach or site (Kleynhans et al., 2007). The resultant objective of the tool is to determine a PES category based on observed disturbances and the degree of deviation from a defined 'reference condition'. The reference condition refers to the natural state one would expect to observe at a site devoid of anthropogenic influences (Kleynhans et al., 2007).

Brown et al. (2005) designed an environmental flow (e-flow) assessment process commonly referred to as DRIFT (Downstream Response to Imposed Flow Transformations). The process aims to advise management on the determination of e-flows based on various specialist

recommendations. DRIFT also utilizes river zonation and the associated plants one would expect to locate at each of the zones to classify species into categories arranged laterally along rivers. This process adds an additional component by assigning positions of lateral zones along surveyed cross-section in order superimpose associated vegetation to various flooding events. Flow Duration Curves (FDC) are constructed through modelling processes with the use of hydrological data and then applied to cross-sections and the related vegetation zonation. This in-turn would provide information pertaining to the proportion of time that the various zones would experience periods of inundation throughout the year (Brown et al., 2005).

1.1 Problem Statement

Riparian vegetation plays an essential role in healthy riverine ecosystem functioning through erosion control, flood mitigation, contribution to biodiversity and water-quality improvement through the retention of pollutants and mitigation of nitrification from upstream anthropogenic sources (Prosser, 1999; Terrill, 1999; Reinecke et al., 2013). Riparian plants also provide shaded areas that regulate water temperature and nutrient input into nearby water bodies from the primary production. These nutrients are used by aquatic micro-invertebrates and other animals that make use of the river systems (Prosser, 1999; Terrill, 1999; Reinecke et al., 2013). Furthermore, riparian vegetation (including aquatic plants) provides habitat for breeding fishes, invertebrates as well as other terrestrial water-dependant species that rely almost exclusively upon riparian riverine habitat for their survival, such as the Pel's Fishing owl (*Scotopelia peli*), African Fish Eagle (*Haliaeetus vocifer*) and African Crowned Eagle (*Stephanoaetus coronatus*) (Prosser, 1999; Terrill, 1999; Sinclair and Ryan, 2003;).

Vegetation found within riparian zones possesses specific compositions and physical structures that are distinct from those found outside of the riparian zone (Naiman et al., 2008). An important evolutionary adaption exclusive to riparian vegetation is the coinciding of life history events (phenology) with inundation intervals provided by natural flow regimes (Reinecke et al., 2015). As previously mentioned, existing research (Tabacchi et al., 1998; Naiman et al., 2005; Kleynhans et al., 2007; James and King, 2010; Reinecke et al., 2015) has identified the links between riparian vegetation position, laterally along a river relative to the present-day flow regime. One of the accepted explanations for this is understood by the fact that the quantity of available water generally decreases laterally as the distance from surface water increases and as the depth of the groundwater increases from the surface (Kleynhans et al., 2007; Reinecke et al., 2015). Riparian obligate vegetation therefore shifts depending on the stability of the historical hydrology and other environmental conditions in order for germination and establishment to take place (Hupp and Osterkamp, 1996; Kleynhans et al., 2007; Naiman et al., 2008; Reinecke et al., 2015). The stability of riparian vegetation ecosystems is under threat

from flow regulation by water impoundment structures (e.g., water abstractions and damming) and the resultant disruption of natural processes (Naiman et al., 2005, 2008; DWAF, 2013).

Water storage infrastructure is necessary for economic growth and stability, however if improperly managed could result in downstream losses of habitat, biodiversity and ecosystem services (Naiman et al., 2008). The physical complexity in the form of habitat heterogeneity in natural river systems is driven by natural flow variability and geomorphological processes through sediment distribution (Naiman et al., 2008; Navarro-Llácer et al., 2010). According to Naiman et al. (2008), “Natural flows are characterized by temporal and spatial heterogeneity in the magnitude, frequency, duration, timing, rate of change, and predictability of discharge”. When natural flow variability is threatened by anthropogenic modifications, it changes geomorphological processes which threatens the integrity and stability of the biotic components (Navarro-Llácer et al., 2010; Reinecke et al., 2015).

The Olifants River is a tributary of the Limpopo River, which falls within the Limpopo Catchment Basin (Seibert et al., 2017). The catchment basin spans approximately 408,000 km² and encompasses four countries, namely; South Africa, Botswana, Zimbabwe and Mozambique (Seibert et al., 2017). In 2003 the riparian countries entered into an agreement known as “The Limpopo Watercourse Commission agreement” or LIMCOM (IEADB, 2003). The agreement recognized that the basin was an important resource to the affected countries and those directly affected by the resources. The agreement also recognized that the sustainable management and use of the resources was important for the “mutual benefit, peace, security, welfare and prosperity” of the affected regions. It is therefore our responsibility as a nation to uphold this agreement in ensuring the sustainable use and management of the catchment basin.

The Limpopo catchment is considered one of the most water-stressed river basins on the African continent (McCartney et al., 2004; Trambauer et al., 2014). This is mainly due to intensive and extensive agricultural and industrial practices that take place along the catchment. It was suggested that by the late 1990's irrigation demands for agriculture had already exceeded supply (FAO, 1997). McCartney et al. (2004) reported that the catchment generates approximately 6% of the annual Gross domestic product (GDP) in South Africa. In addition to anthropogenic influences, the catchment is also strongly affected by drought events (Love et al., 2010; Trambauer et al., 2014). One such event took place in the 1980s and 1990's where the country was severely impacted by losses through agriculture which in turn resulted in economic losses and reduced food security (Love et al., 2010). High water demands and historical drought events have resulted in the establishment of multiple water impoundment structures to improve yield (DWAF, 2013; Trambauer et al., 2014; Seibert et al., 2017).

The Olifants River originates east of Johannesburg within the province of Gauteng and continues through Mpumalanga, Limpopo and into Mozambique (McCartney et al., 2004). Despite intense agricultural and industrial pressures, it is also one of the six prominent rivers flowing through the Kruger National Park (KNP) and therefore an essential contributor towards tourism in South Africa (McCartney et al., 2004).

There is an international movement towards improved water management policies that sustainably utilize natural water resources and consider the e-flow requirements of catchment basins (Horne et al., 2017). Catchment basins experience unique pressures from the various sectors; therefore, they should be managed on an individual basis (Kleynhans et al., 2007; Naiman et al., 2008; Reinecke et al., 2013, 2015). There are two main aspects to consider when determining environmental water regimes in catchment basins; firstly, identifying the objectives and values for both humans and ecosystem requirements and secondly, understanding the links between river flow regimes and ecosystem health at a scientific level (Horne et al., 2017).

The links between riparian vegetation and e-flows have been identified in previous literature (Brown et al., 2005; Naiman et al., 2005; Kleynhans et al., 2007; James and King, 2010; Reinecke et al., 2015). They achieved this through the use of multiple tools, vegetation descriptions and with the use of surveyed cross-section profiles and/or the determination of activation discharge (AD) values for lateral zones and associated vegetation groups. Activation discharge can be defined as the discharge value that species (datum) becomes activated at rooting level (Mackenzie, 2020). Previous studies mentioned above grouped species into lateral vegetation zones, based on where the species was most frequently observed.

The aims of this dissertation were to determine the hydraulic niches of riparian plant communities at the Mamba and Balule EWR sites along the Olifants River in the KNP to allow for their use as biological components of ecological water requirement. This was achieved through the application of AD to hydrological FDC's, also known as hydrological exceedance tables. The combined FDC data were applied to present day, natural and base flow hydrological scenarios. FDC values were determined through the application of AD values of riparian plant communities to FDC's which indicated the percentage of time that plant communities experienced AD on a monthly and annual basis.

1.2 Hypotheses

The hypotheses established for this study state:

- 1** The setting of environmental flow requirements for riparian vegetation as part of water resources management can be achieved through the development of activation discharge and hydrological exceedance values for indicator riparian plant communities.

The identification of the hydrological niche requirements of riparian vegetation can be applied at a community level in order to set the environmental flows with the aims of maintaining and/or rehabilitating ecological processes.

- 2** Environmental flow requirements for riparian plant communities are useful for water resource management.

Flow requirements identified for riparian vegetation can be applied to water management practices along the Olifants River for improved replication of natural flow regimes.

1.3 Aims and objectives

The main aim for this study was to:

Determine the hydraulic niches of riparian plant communities at the Mamba and Balule EWR sites along the Olifants River in the KNP to allow for their use as biological components of ecological water requirements.

Specific objectives in order to achieve this aim include:

- a) Assess the riparian vegetation community structure at two sites along the lower Olifants River within the Kruger National Park.
 - a. Statistical evaluation of community structures and environmental drivers at two sites along the lower Olifants River in the Kruger National Park
 - b. Determine the present ecological state of riparian vegetation with the use of the Riparian Vegetation Response Assessment Index (VEGRAI) at two sites along the lower Olifants River in the Kruger National Park.
- b) Identify the hydraulic niche requirements of the plant species, population and communities at two sites along the lower Olifants River within the Kruger National Park with the application of activation discharge values to flow duration curves to allow for site comparisons.

1.4 Dissertation structure

Chapter 1: General Introduction

- I. Identify the importance of inland freshwater ecosystems and the stressors threatening the wellbeing of riparian vegetation habitats
- II. Problem statement
- III. Hypotheses
- IV. Aims and objectives
- V. Dissertation structure

Chapter 2: Literature Review

- I. Review the current state of sustainable water resource management
- II. Review the social and ecological importance of water resources and their sustainable management.
- III. Review the role of ecological indicators and the role of riparian vegetation as indicators of the wellbeing of socio-ecological ecosystems.
- IV. Review the use of riparian plants as ecological indicators in the Limpopo Catchment
- V. Review environmental flows
- VI. Review water resources of the Limpopo Catchment
- VII. Review current literature using riparian plants in environmental flow assessments.

Chapter 3: Riparian vegetation of the lower Olifants River, Kruger National Park (KNP).

- I. Introduction consisting of a brief discussion emphasizing the importance of freshwater ecosystems for social and ecological wellbeing as well as an introduction to the contents of the chapter.
- II. Description of the study area and methodology.
- III. Description of riparian vegetation community structure relative to environmental drivers along cross-section profiles.
- IV. Description of VEGRAI for the determination of the PES.
- V. Presents results pertaining to community structure along cross-section profiles and related drivers.
- VI. Presents results pertaining to riparian VEGRAI and the determination of the PES.
- VII. A summary discussion of findings relating to riparian plant community structure and drivers.
- VIII. A conclusion of the findings in chapter 3.

Chapter 4: Riparian vegetation as indicators of flows in the lower Olifants River, Kruger National Park (KNP).

- I. An introduction to the contents of the chapter as well as an overview of the importance of freshwater ecosystems, the current methods regarding environmental flows and an overview of the current state of the Olifants and lower Olifants River.
- II. Description of the study area and methodology.
- III. The identification of hydraulic and hydrological preferences of the riparian plant communities
- IV. The identification of hydraulic niches of riparian plants along the lower Olifants River with the use of hydrological flow exceedance tables.
- V. A summary discussion of the findings in chapter 4.

VI. A conclusion of the findings in chapter 4.

Chapter 5: Conclusions and recommendations

- I. Final conclusion summary discussion relating to the findings in Chapter 3 and 4 as well as recommendations for future studies relating to this topic.

Chapter 6: References of papers used in this dissertation.

2 Literature Review

2.1 Sustainable water resources management

There is a global trend, a recognition that the future of water resource utilization depends upon healthy freshwater ecosystem functioning. This movement requires the establishment of new balances between human use and the needs of the environment and the associated ecosystems (Richter, 2014). Altered flow regimes are considered the driving disturbance factor to freshwater ecosystem degradation, however there are many other impacts that must also be considered when managing water resources (Poff et al., 1997; Horne et al., 2017). Some of these disturbances include; land use activities which result in altered sediment distributions, removal of riparian vegetation, the introduction of extralimital and alien species and compromised water quality (Horne et al., 2017).

According to Horne et al. (2017) there are typically four steps that must be taken in order to successfully achieve sustainable freshwater utilization. It is important to note that the outcomes for each of the steps are unique for each catchment basin. The first step is led by an initiative or concern for the future wellbeing of the resource, the services provided by the resources and the biodiversity. This is usually initiated as a response to observed disturbances or reduced resource availability (Horne et al., 2017).

The second step involves the establishment of environmental objectives and/or visions in order to re-establish balance between human use and ecosystem requirements. The third step is to physically determine the e-flow requirements of an ecosystem through the spatial and temporal “timing, frequency and duration” of flow regimes (Richter et al., 1997; Naiman et al., 2008; Horne et al., 2017). Naiman et al. (2008) stated that in addition to frequency, duration and timing, natural flows are also characterized by the magnitude, rate of change and the predictability of the discharge. A crucial objective during this step is to understand the amount of water available in the catchment basin and to identify the relevant parties that directly and indirectly depend upon the resource (Horne et al., 2017).

The fourth step is to integrate the planning and management of the water requirements of an ecosystem into a broader framework in which the environment is offered appropriate protection against further degradation and that human use and requirements are also considered. This phase usually incorporates a degree of compromise from various water allocation groups and the requirements of the ecosystem (Horne et al., 2017). These four steps are usually followed by active monitoring and evaluation in order to optimize on the benefits to the environment and therefore the ecosystem services derived from healthy ecosystem functioning.

Multiple studies have shown that managing freshwater ecosystems with the objective of optimizing ecosystem service functionality has a plethora of benefits to both direct and indirect users (Prosser, 1999; Terrill, 1999; Gleick, 2003; Naiman et al., 2005, 2008; Dudgeon et al., 2006; Poff et al., 2007; Vörösmarty et al., 2010; Jager et al., 2012; DWAF, 2013; Reinecke et al., 2015, 2013; Horne et al., 2017). Throughout the process of establishing the e-flow requirements, one must remember that the human uses of different river system are unique and diverse. In order to ensure the success of the initiative, the process should be built on educating stakeholders and affected parties with the goal of informing them that the process is in their best interest and the interest of future generations that will also rely upon the natural resources for their livelihoods (Horne et al., 2017).

In conclusion, one must consider that ecosystems are dynamic and are constantly shifting. Species distributions, community structures, food webs and interactions are constantly changing, therefore ecosystems may change even if they are not influenced by anthropogenic sources of disturbance (Naiman et al., 2008; Horne et al., 2017).

2.2 Social and ecological importance of resources and their sustainable management

Donnenfeld et al. (2018) reported that current statistics suggest that approximately 60% of all of South Africa's rivers are being overexploited and only one third of the country's main rivers are in a good condition. Climate change models that predict that South Africa will receive less rainfall and the country will experience increased frequency of drought and flooding events (Mpofu and Botha, 2021). In 2015 the Western Cape documented the lowest total rainfall recorded in history since 1904, the Eastern and Northern Cape were declared disaster areas in late 2019 due to ongoing droughts and in March 2020 the national government declared drought as a natural state of disaster alongside COVID-19 pandemic (Mpofu and Botha, 2021).

South Africa is classified as a water scarce, semi-arid to arid country (Donnenfeld et al., 2018). Recent drought events have not only initiated conversations relating to the sustainable and responsible management of the countries water resources, but it has also highlighted both the shortfalls and the magnitude of the challenge. There is a need to establish affordable technologies and updated research policies to ensure water security for South Africa's future generations (Donnenfeld et al., 2018).

Access to freshwater resources is essential for economic growth and community upliftment (Horne et al., 2017). Water is required for food production, industrial processes such as paper production and industrial cooling mechanisms, mining, forestry and household use.

The Department of Water and Sanitation (DWS) (2017) reported that South Africa sourced approximately 68% of all utilized water from surface water sources. Surface water includes all

inland freshwater sources including rivers and dams (Figure 2.1). Additional sources included; 13% ground water, 13% return flows (recycled water) and 6% were classified as other sources which included sea or brackish water (DWS, 2017).

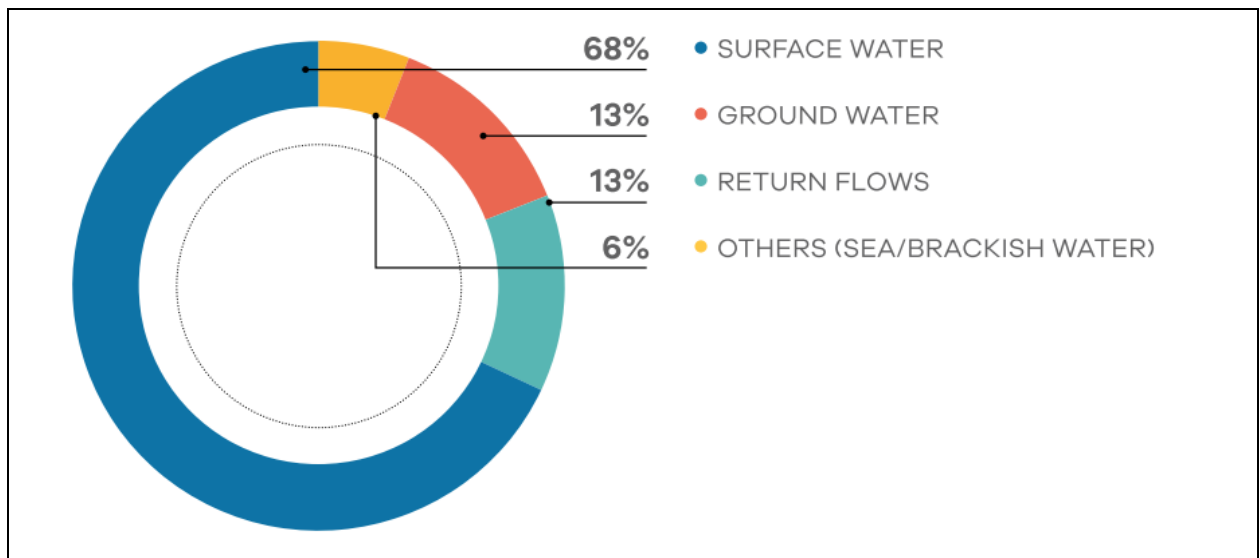


Figure 2.1: Various water sources for utilization, South Africa (DWS, 2017).

During the second quarter of 2021, mining and manufacturing industries contributed a combined GDP of 22%, with agriculture contributing a total of 3% (StatsSA, 2021). Of the total water usage allocation for South Africa, 61% of all water resources were allocated to agriculture, 3% was allocated to industry, 2% was allocated to mining and finally, a mere 2% was allocated to livestock watering and nature conservation combined (Figure 2.2) (DWS, 2019b).

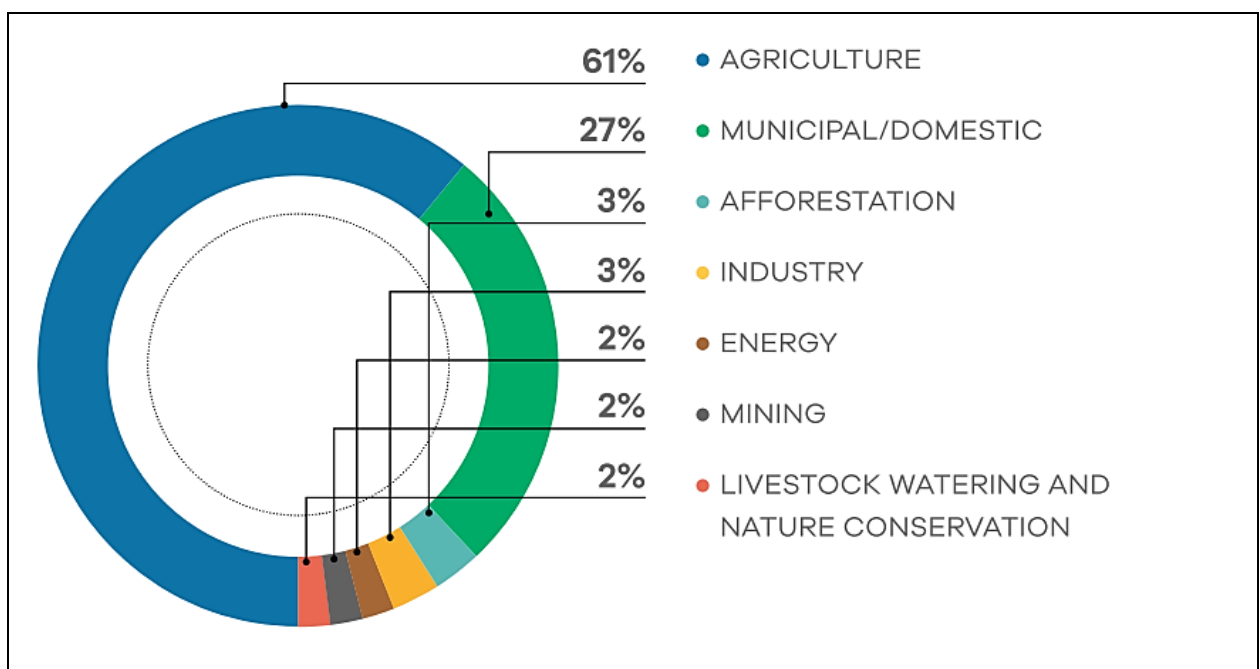


Figure 2.2: Water use in South Africa (DWS, 2019b).

Water demands in South Africa are projected to increase, resulting in increasing pressure on water allocations to the various sectors. Projections indicating increased demands have resulted in South African government departments implementing strategies for increased water usage efficiency, however sources indicate that the proposed implementations will be insufficient to curb the increasing demands (GreenCape, 2017; Mpofu and Botha, 2021). The DWS (2019) reported that even if “critical interventions” are implemented, by the year 2030 South Africa will still be short 10% of the required water resources for the various sectors.

Mpofu and Botha (2021) stated in the Water Market Intelligence Report 2021 that there is a need to reduce our reliance on surface water sources. They continue to suggest that groundwater, return flows (recycled water) and desalination should increase in contribution towards the total water usage in South Africa. Reports indicate that waste water treatment plants within South Africa are operating at 69% of their designed capacity (Green Drop, 2022). Statistics indicate that there is a general downward trend regarding the condition of wastewater treatment stations. Reports from 2011 and 2021 show that stations in critical condition have increased from 317 to 334 and those in poor condition increased from 143 to 208 stations (Green Drop, 2022). It is clear that this general downward trend is a cause for concern.

For reasons unrelated to financial gain, South Africa is a land that is proud of their cultural diversity, uniquely attractive natural landscapes and diverse array of wildlife (Horne et al., 2017). Freshwater ecosystems are an essential aspect for the future wellbeing of the country's many diversities and natural beauties, whether in the form of local cultures conducting their ceremonies in riverside environments or a typical African sunset scene with a breeding herd of elephants drinking from a flowing river. Inland freshwater environments are worth protecting and we have a responsibility to ensure that future generations can experience the same benefits that we have access to today.

2.3 The Kruger National Park Rivers Research Programme

The purpose of the programme was to address the water quality and quantity requirements of the major river ecosystems that flow through the KNP. The programme was divided into three separate phases; (1) the scientific research phase, (2) the focused phase for enhancing prediction capabilities and (3) the corrective action phase (Breen et al. 2000).

Phase I directed the studies at improving their understanding of the “physical template” was formed and the time line at which this took place. Phase II focused on predictive capabilities, focusing on bedrock-dominated freshwater ecosystems. Phase III included the application of the above to determine the Thresholds of Probable Concern (TPCs) to the Sabie River. They concluded that if extensive efforts were not applied to reduce sediment loading into the Sabie River, then it would be impossible for the KNP to achieve the management objectives set out by

the programme (Breen et al. 2000). An additional aspect that was added to both Phase II and III included the improved development of riparian vegetation studies by the organizations Centre for Water in the Environment (CWE) and the Council for Scientific and Industrial Research (CSIR). The woody riparian species *Breonadia salicina* was selected as the riparian indicator for the *Breonadia* model. This species was selected as they are typically located within environments sensitive to sediment loading. The purpose of the model was to provide biotic TPCs that expressed the interactions between “fluvial geomorphology and vegetation” (Breen et al. 2000).

Important recognitions that were identified included the acknowledgement that although compromises are necessary, there is “no absolute amount for water quality and quantity to sustain the natural environment indefinitely”. The programme highlighted the importance of adaptive and flexible management strategies. The recognition of the above statement allowed for researchers to focus on the enhancement of predictive capabilities which focused geographically on the Sabi River within the KNP (Breen et al. 2000).

One of the weaknesses identified at the conclusion of the programme was that rivers had never been formally managed in South Africa prior to the programme. The consequent application of the knowledge gained through the programme therefore was not effectively implemented (Breen et al. 2000). Further weaknesses identified included the lack of collaboration between scientists, stakeholders and managers.

2.4 The River Continuum Concept

The River Continuum Concept (RCC) states that “from headwater to mouth, the physical variables within a river system present a continuous gradient of physical conditions” (Vannote et al., 1980). The concept further states that this elicits a predictable response by the ecosystem in a “continuum of biotic adjustments and consistent patterns of loading, transport, utilization, and storage of organic matter” along a river. As physical parameters of a river change longitudinally, the associated biotic components adjust according to the variable physical characteristics to produce harmonious balances between producers and consumers. In natural systems the biotic communities are constantly adjusting to the ever-changing physical parameters with species compositions constantly adjusting to maintain the state of harmony. The biological components of freshwater ecosystems are therefore constantly adjusting according to energy input and expenditure where efficient energy expenditure is prioritized (Vannote et al., 1980). There is a relationship between upstream energy “leakage” or “wastage” to downstream capitalization of wasted nutrients. This process is proposed as “predictable” under natural conditions. When alterations are made to freshwater ecosystems, the ability to observe and predict the above-stated interactions is no longer possible (Vannote et al., 1980).

2.5 Ecological indicators and the role of riparian vegetation as indicators of the wellbeing of socio-ecological systems

The use of biological responses as predictors and indicators of the wellbeing of the environment and associated aspects has existed since early man (Niemi and McDonald, 2004). Humans have long used ecological and environmental indicators to gain insight into changes to environment conditions through many observations, such as migrating animals, the lengthening of days through the development of flowers and fruits or the times at which trees lose their leaves, indicating the approaching winter. Use of ecological and environmental indicators in the field of formal research and environmental management has progressed rapidly over the past 40 years (Niemi and McDonald, 2004).

The focus on indicators for environmental responses stems from a need to determine the ecological condition of natural systems in order to improve management policies for the sustainable utilization of resources, improved biodiversity and stewardship responsibilities (Niemi and McDonald, 2004). If applied with precise, unbiased and accurate methodology, the use of ecological indicators provides researchers and environmentalists the ability to detect changes in nature, predict responses to potential change and inform of historical events (Niemi and McDonald, 2004). The key to the utilization of ecological indicators for improved management of natural resources is through the identification of the linkages with specific stressors and the selected indicator group.

Indicators were initially used to predict environmental conditions, and as a result, were termed environmental indicators. The differences between the terms ecological indicators and environmental indicators are often misunderstood (Smeets and Weterings, 1999; Niemi and McDonald, 2004). Environmental indicators refer to indicators that reflect all of the elements that linking anthropogenic activities to the environmental and social-economic responses. Ecological indicators refer to a sub-set of environmental responses, specific to particular processes (NRC, 2000).

Herbert (1977) was awarded a Nobel Prize in the field of physics due to the discovery of the particle commonly known as a pimeson or pion. One aspect of his studies focused on the bonds of communication between physics and biology regarding the various levels of biological organisation. He observed that when the environment experiences random variations of disturbance, the higher levels of biological organisation, the lower the disturbance factor as a result of the degree of variation within the levels below the level in question. This is because the disturbance is 'averaged out' by the lower-level variation and response to variation in combination with disturbances. This relationship of disturbance 'buffering' among the various levels of biological organisation allows for the recovery time required for ecosystems to cope

with the frequency and magnitude of the disturbance if it is within a reasonable set of parameters (Herbert, 1977).

Nielsen et al. (2013) eloquently provides the most suitable explanation for this; consider a large landscape of approximately 10,000 km². If this landscape were to consist of only one type of ecosystem such as a wheat field, then it would be generally accepted by most ecologists and biologists that this ecosystem would be vulnerable to random disturbances such as floods, pests, drought, etc. as the ecosystem is resilient to a single set of disturbance factors due to its makeup. Now consider the same area but instead of only one ecosystem, there were multiple variations of ecosystems such as; wetlands, riverine areas, grasslands, forests, lakes, ponds and several different types of agricultural plantations. It would be generally accepted by the scientific community that the various ecosystems would be less vulnerable to random disturbances as each one would provide some degree of resistance to the disturbance. Therefore, the increased number of variations within the level of organisation provides a 'buffer' to the level above. For this particular example the region, biosphere and ecosphere levels, above that of the landscape level, would respond to a lesser degree as a result of the resistance provided from the levels below by a factor specific to the number of variations existing in the levels below (Jorgensen and Nielsen, 2013). The properties mentioned above highlight the importance of the correct selection of indicators with regard to the stressor that requires testing (Herbert, 1977).

Jorgensen and Nielsen (2013) further states that biodiversity would be an effective ecological indicator because high biodiversity provides a greater degree of variation to resistance against disturbance events. It is important to mention that different species have varying sensitivities to different impacts (Jorgensen and Nielsen, 2013). Some plants for example are resistant to potentially harmful heavy metals such as copper, while others may be more sensitive. An ecosystem containing many different plant species would provide better resistance to potentially harmful pollutants or other disturbance factors.

The increased resistance to disturbance provides a buffer effect to the levels of organisation above, meaning that ecosystems containing the highest number of different species provide the greatest degree of protection against disturbance events and therefore protection against disturbance to ecosystem processes, functionality and services rendered. Zavaleta et al. (2010) conducted a study on grassland ecosystems in the United States and found that higher biodiversity within grassland systems resulted in increased ecosystem functionality. Similarly, Allan et al. (2011) conducted a seven-year study on the relationship between plant communities and ecosystem functionality. They found direct correlations between diverse plant communities and improved ecosystem functionality over time. Finally, Tilman and Downing (1994) conducted in a long-term study on grassland habitat in the United States and found direct correlations

between loss of species and reduced ecosystem functionality and stability with response to drought. Furthermore, they found that the rate of recovery after the drought increased with higher species diversity and decreased with losses to biodiversity.

In conclusion, the use of biodiversity as an ecological indicator of ecosystem health has proven an effective tool. High biodiversity improves ecosystem resilience to disturbance events, provides improved ecosystem functionality, wider ranges ecosystem services and provides insight into the ability to predict responses to disturbance events (Tilman and Downing, 1994; Nielsen et al., 2000; Zavaleta et al., 2010; Allan et al., 2011; Jorgensen and Nielsen, 2013).

Riparian vegetation provides an extensive range of benefits and uses to both humans and the environment. The benefits include and are not limited to; soil stability, flood attenuation, habitat provision in the form of shelter, protection and breeding grounds for both terrestrial and aquatic biota, shaded areas that assist in temperature regulation and nutrient input, the absorption and trapping of potentially harmful pollutants, absorption of excess nutrients from anthropogenic sources, provision of resources for harvesting, food, medicine and fuel, water and food for livestock, etc. (Prosser, 1999; Terrill, 1999; Reinecke et al., 2015). Further benefits include the contribution to biodiversity which results in improved ecosystem resilience to disturbance events, improved functionality and increased services rendered (Tilman and Downing, 1994; Prosser, 1999; Terrill, 1999; Nielsen et al., 2000; Zavaleta et al., 2010; Allan et al., 2011; Jorgensen and Nielsen, 2013; Reinecke et al., 2013). Riparian vegetation and the associated inland freshwater ecosystems should be managed in a manner that protects ecosystem efficiency and functionality if we as humans hope to utilize the associated benefits (Naiman et al., 2008; Vörösmarty et al., 2010; Reinecke et al., 2013, 2015).

Terrestrial vegetation and riparian obligate vegetation are distinct in their evolutionary adaptations to the environments in which they are found. Riparian obligate vegetation possesses specialised adaptations that allow them to withstand the harsh environmental conditions associated with river systems such as floods, droughts and recurring seasonal flooding events known as “seasonal pulses” (Naiman et al., 2008). Some of the evolutionary adaptations they possess include the ability to survive extended periods of time completely inundated and the ability to withstand large amounts of water and debris moving down a river channel without being uprooted (Reinecke et al., 2013, 2015).

It is generally accepted that the quantity of available water decreases laterally as the distance increases from the surface water (Kleynhans et al., 2007; Reinecke et al., 2013, 2015). Riparian obligate vegetation responds by shifting through reorganisation according to any alterations that take place with reference to water availability. Reorganisation responses include deaths, recruitments and/or local extinctions (Hupp and Osterkamp, 1996; Kleynhans et al., 2007;

Naiman et al., 2008; Reinecke et al., 2015). The stability of riparian vegetation in riverine ecosystems are under threat due to alterations in natural flow regimes through the modification of river channels by water impoundment infrastructure and land-use activities (Dudgeon et al., 2006; Naiman et al., 2005, 2008; DWAF, 2013).

The links between riparian vegetation have been identified through their responses to alterations in natural flow regimes (King and Brown, 2006; Kleynhans et al., 2007; Naiman et al., 2005, 2008; James and King, 2010; Reinecke et al., 2013, 2015). Existing research relating to the links between riparian vegetation and responses to flow use a method whereby rivers are compartmentalized into various lateral zones. The names of the zones and the number of zones vary according to the different studies. The aspect that these studies have in common is that riparian vegetation are assigned and associated with each of the zones to allow for predictions of responses. The zone of association for riparian plants is dependent on the predicted hydraulic and ecological requirements of the plants. Their research aimed to utilize the zones along with the associated riparian vegetation as a means to predict the flow requirements of ecosystems to improve and/or maintain biodiversity for increased ecosystem functionality and resource availability (Naiman et al., 2005, 2008; King and Brown, 2006; Kleynhans et al., 2007; James and King, 2010; Reinecke et al., 2013, 2015).

The Kruger National Park Rivers Research Programme (KNPRRP) was to “translate catchment-level controls on river form” regarding the hydrology and sediment supply to a local scale with reference to hydraulic and geomorphic characteristics of rivers (Breen et al. 2000; Rogers and O’Keeffe, 2003). They noted that understanding biotic responses to abiotic drivers such as hydraulic and sediment features allow for the prediction capabilities. The programme used multiple conceptual models that provided links between a rivers function and structure (Breen et al. 2000; Rogers and O’Keeffe, 2003).

The *Breonadia* model was used to quantitatively determine the required ecological state and through this, the ecological reserve of rivers in a catchment. This method was used to represent riparian vegetation throughout the KNPRRP, specifically applied to the Sabie River catchment (MacKenzie et al., 1999). The model is population-based and specializes on a single riparian species (*Breonadia salicina*), to represent the ecological needs of riparian. The scale of the model is essentially a “river-section-scale” tool that can be applied on a catchment scale to inform water managers in their decisions and actions (MacKenzie et al., 1999).

The VEGRAI tool was developed with the lateral zonation methodology mentioned above. The tool was designed to be user friendly in that any person with limited botanical skills could conduct the survey with relative accuracy (Kleynhans et al., 2007). The aim of the tool was to assign a PES score and classification to a site, indicating the degree of deviation from expected

natural conditions referred to as the ‘reference condition’ (Table 2.1) (Kleynhans et al., 2007). The determination of reference conditions requires a degree of research into available data pertaining to the history of the area such as historical satellite imagery and local knowledge.

Table 2.1: Present Ecological Status (PES) categories for the Riparian Vegetation Response Assessment Index (VEGRAI) tool adapted from Kleynhans et al. (2007).

Ecological category	Description	Score (% of total)
A	Unmodified, considered natural conditions.	90-100
B	Mostly natural with few modifications. Small changes in natural habitats availability and biodiversity of biota may have occurred but ecosystem functionality is mostly unchanged.	80-89
C	Moderately modified ecosystems with losses and alterations to natural habitat availability. Basic ecosystem functioning still exists and are mostly unchanged.	60-79
D	Largely modified ecosystems with large losses in natural habitat availability, ecosystem functionality and biodiversity.	40-59
E	Seriously modified ecosystems where extensive losses in habitat, functionality and biodiversity have occurred.	20-39
F	Critically modified ecosystem that have been completely modified and where almost complete loss in biodiversity, functionality and habitat have occurred. Ecosystems in this state are generally destroyed beyond the ability for rehabilitation.	0-19

King et al. (2003) designed a tool commonly known as DRIFT (Downstream Response to Imposed Flow Transformations). The tool was designed to advise environmental managers on the correct procedures to assigning e-flows to rivers and catchment basins. Methodology utilized with regard to the riparian vegetation aspect of the tool included the identification and allocation of lateral zones in a river reach as well as FDC’s as an additional aspect. Surveyed cross-sections provided accurate cross-section channel profiles whereby zones were marked along the surveyed cross-section. FDC’s were then applied to the cross-sections according to elevation readings in order to inform of the percentage of time that each zone experienced inundation (King et al. 2003; Brown et al., 2005). Deviations from natural flow regimes with regard to the timing, frequency and duration intervals would elicit a response from the vegetation with reference to the zones in which they were allocated. Expected responses include the shrinkage of zones, shifts in communities within zones or disappearance of a zone from a river.

Challenges were identified during these studies with regard to the methodologies utilized, specifically pertaining to the zonation allocation (Brown et al., 2005; King and Brown, 2006; Kleynhans et al., 2007; James and King, 2010). Many of the studies above found that the identification and delineation of the various zones were subject to the sampling methodology utilized and the observer experience. In addition to this, they found that many rivers did not possess all of the zones.

It is clear that there is a need to establish methodology that utilizes riparian vegetation and/or biodiversity as indicators of ecological flow requirements (Naiman et al., 2005, 2008; Dudgeon et al., 2006; King and Brown, 2006; Kleynhans et al., 2007; Reinecke et al., 2013, 2015). The methodology should be sound, replicable and unbiased. It should also be aimed at optimizing biodiversity in order to improve and/or maintain ecosystem functionality, resilience to disturbance events and ensure a wider range of ecosystem services (Tilman and Downing, 1994; Nielsen et al., 2000; Zavaleta et al., 2010; Allan et al., 2011; Jorgensen and Nielsen, 2013; Schachtschneider et al., 2017).

The classification of rivers longitudinally and laterally are important aspects to consider when considering the use of riparian vegetation tools for e-flow determination (Rowntree and Wadeson, 1999). The understanding of different river types allows scientists to better understand river behaviour and morphology and to compare rivers from different regions that behave in similarly. Rowntree and Wadeson (1999) define ten distinct river zones categories, divided into two channel types: (1) normal channel which exhibits the typical 'concave' shape and (2) rejuvenated river which experiences 'steepening' in the downstream areas (Table 2.2). Identifying the river zone classification of a site location is essential if considering the geomorphological attributes of an area.

Table 2.2: Geomorphological zones of river channels, zones associated with a 'normal' profile. Table sourced from Rowntree and Kelly (2013), adapted from Rowntree and Wadeson (1999).

Longitudinal zone	Macro-reach characteristics			Characteristic channel features
	Valley form	Gradient class	Zone class	
A. Zonation associated with a ‘normal’ profile				
Source zone	V1	Not specified	S	Upland plateau with low gradients that is able to store water on spongy and peaty hydromorphic soils.
Mountain headwater stream	V6, V7	>0.1	A	Gradients are very steep and are dominated by waterfalls and pools. Rivers normally belong to first and second orders with bedrock fall and cascade reach types.
Mountain stream	V6, V7	0.04-0.099	B	Gradients are steep and are normally dominated by bedrock and boulders with local compositions of cobble and/coarse gravels in pools. Bedrock fall, cascades and step pool reach types are located in this zone. The zone is described as equal horizontal and vertical flows.
Transitional	V4, V6	0.02-0.039	C	Zone can be described as moderately steep streams that are dominated by bedrock and boulders. Plain-bed, pool riffle and pool-rapid reach types are present and the zone is mostly located within the valley floor where flood plain development is limited.
Upper foothills	V4	0.005-0.019	D	The zone is described as moderately steep with a cobble-bed or mixed bedrock-cobble. Reach types include plain-bed, pool-riffle or pool-rapids. The riffles and/or rapid and pool are often similar in length. Floodplains are often narrow with compositions of gravel, sand or cobbles.

Table 2.2: Continued

Lower foothills	V4, V2	0.001- 0.005	E	Alluvial channels dominated by gravel and sands with a lower gradient. Zone may be bedrock-controlled. The zone is typically including pool-riffles and pool-rapids with sand bars in pools. There is typically more extensive pool exist than rapids. Flood plains are often present within the zone.
Lowland river	V1, V2, V3	0.0001- 0.001	F	Zone dominated by alluvial channels with fine substrates. Reaches are typically regime and the zone described as confined fully developed meandering rivers. Distinct flood plains are present in unconfined areas where an increase in silt content is present in the bed or on the banks.
B. Additional zones associated with a rejuvenated profile				
Rejuvenated bedrock fall / cascades	V5	>0.02	Ar/Br/Cr	The gradient tends to be moderate to steep, often confined to gorges developed as a result of uplift. There is often limited lateral development of alluvial feature due to confined areas. Reach types expected to find here include bedrock fall, cascades and pool rapids.
Rejuvenated foothills	V4, V5	0.001- 0.02	Dr/Er	This zone is often located within or downstream of a gorge that is steepened as a result of uplift. The characteristics are similar to that of foothills with gravel/ cobble bed rivers with pool-rapid or pool-riffle morphology. This zone is however of a higher order than that of foothills. Compound channels are often present with an active channel within a macro channel that is generally only activated during infrequent flooding events and not seasonally. Flood plains may be present but are often limited.

Table 2.2: Continued

Upland flood plain	V1, V2, V3	<0.005	Fr	Characterised by a low gradient channel that is associated with high altitude plateaus. The zone is often described as meandering with floodplain wetlands. Erosion or cutting is generally limited due to the persistence of dolerite dikes.
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2.6 Water resources of the Olifants River Limpopo Catchment

The Olifants River originates within the Gauteng Province, east of Johannesburg. It then flows through Mpumalanga, Limpopo, into the KNP and exits South Africa's eastern border into Mozambique, discharging into the Indian Ocean approximately 200 km north of Maputo (McCartney et al., 2004; De Lange et al., 2005). The Olifants River is ~770 km long and drains approximately 73,534 km² when all tributaries are considered (De Lange et al., 2005).

The Olifants River falls within the responsibilities agreed upon in The Limpopo Watercourse Commission agreement (LIMCOM) established in 2003 (IEADB, 2003). The agreement highlights the importance of managing the catchment basin in a sustainable manner in order that the riparian countries directly affected by the rivers can also benefit from the ecological services and resources. The Olifants River passes into Mozambique from South Africa, it is therefore the responsibility of Department of Water and Sanitation (DWS) that the water is of an ethical quality and quantity in order for the riparian country to share in the benefits provided by the system (IEADB, 2003).

The Limpopo Catchment Basin, along with the Olifants River is currently considered one of the most water-stressed river basins on the African continent. The reason for these pressures is mostly due to the intensive and extensive agricultural, industrial, municipal and mining practices that rely upon the catchment (FAO, 1997; McCartney et al., 2004; Trambauer et al., 2014; Marr et al., 2017b). Mining practices relying upon the catchment include coal, copper, iron, vanadium, platinum and chrome (McCartney et al., 2004; Oberholster et al., 2010). The activities that rely upon the catchment produce approximately 6% of South Africa's annual GDP, therefore it is an important contributor towards the economic stability of the country (McCartney et al., 2004).

In addition to the intensive and extensive activities taking place in the catchment and along the Olifants River, the region is also frequently affected by severe drought events (Love et al., 2010; Trambauer et al., 2014). Despite the above, the Olifants River is one of the main rivers that runs through South Africa's iconic KNP, which is responsible for attracting over 1 million tourists every year (McCartney et al., 2004).

As a result of the drought events in combination with the importance of the resources to the South African economy, multiple water impoundment structures have been established in order to improve resource security within the catchment (DWAF, 2013; Trambauer et al., 2014; Seibert et al., 2017). Despite the implementation of the above-mentioned infrastructure in order to improve water security, South African statistics analysis and resource forecasting suggests that the country will still experience severe water resource shortages by the year 2030 (DWS, 2019b).

Donnenfeld et al. (2018) suggested that the main reasons for the predicted deficiencies will be due to; inappropriate infrastructure usage and choices, inefficient water usage, low water prices, inadequate cost recoveries, leakages and an increased demand in water from industry, agriculture and household/municipal. The DWS (2019b) further suggested that in order to mitigate the predicted challenges mentioned above, the country must work on reducing its current reliance on surface water resources which is currently situated at around 68% and increase its reliance on groundwater (13%), return flows (13%) and desalination (6%). As it stands, approximately 8% of South Africa's total land surface area contributes to approximately 50% of all utilized water resources (GreenCape, 2017).

South African water management is formally divided into nine Water Management Areas (WMAs). The Olifants River along with all of the associated tributaries are categorized into a water management region located across the eastern parts of Gauteng, Mpumalanga and Limpopo within South Africa (Figure 2.3) (GreenCape, 2017).

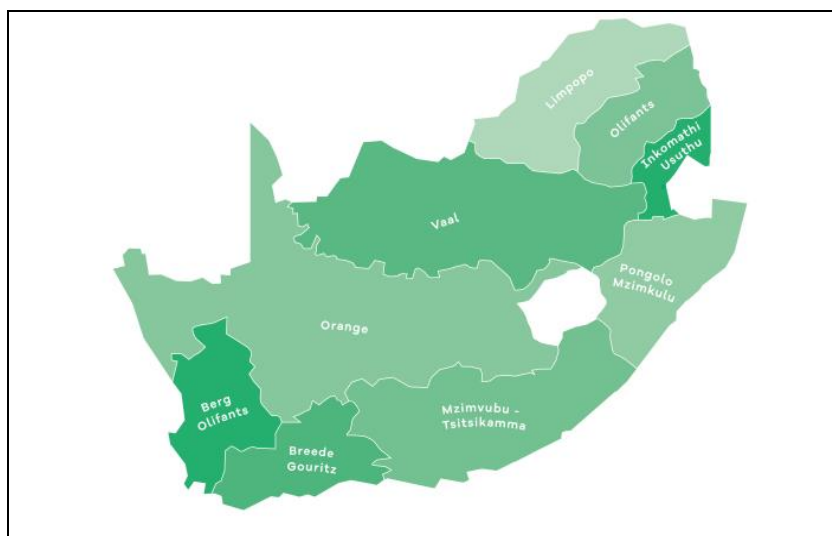


Figure 2.3: Water Management Areas (WMAs) of South Africa (GreenCape, 2017).

Despite the above-mention existing pressures on the Olifants River and associated region, predictions indicate that the region and associated rivers will be required to provide further

increased resources for anthropogenic utilization, resulting in further pressure to the environment and the associated ecological consequences (Figure 2.4)(Donnenfeld et al., 2018).

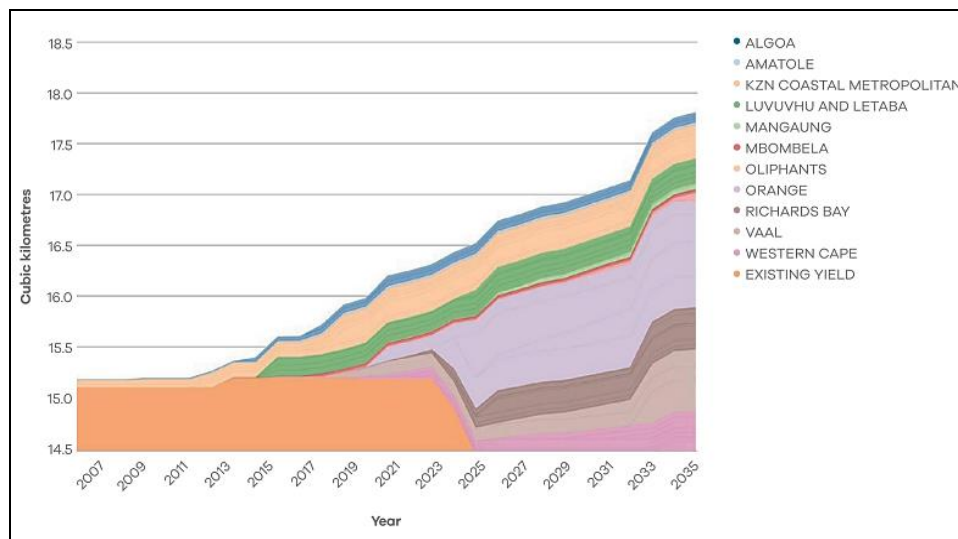


Figure 2.4: Expected predicted yield from various provinces and catchment basins within South Africa (Donnenfeld et al., 2018).

According to DWS (2019b), the amount of water allocated to south African nature conservation and livestock watering was a mere 2% in 2019. The e-flow requirements of a catchment basin should be determined through a formal process known as Resource Directed Measures (RDM), during which specific steps are taken so that all aspects and parties are considered when determining the water resource requirements of the various sectors (Horne et al., 2017).

2.6.1 The lower Olifants River catchment

This study took place at two sites (Mamba and Balule) along the lower Olifants River, situated within the iconic KNP in South Africa. The Olifants River is one of six major rivers that runs west-to-east within the KNP. The river is a tributary of the Limpopo River located within the Limpopo Catchment Basin which extends over four different countries; South Africa, Botswana, Zimbabwe and Mozambique (McCartney et al., 2004; Seibert et al., 2017). The entirety of the catchment encompasses an area of ~54,570 km² with elevations that vary from ~250-2000 mm (Heritage et al., 2014).

2.6.2 Quaternary catchment information

The lower Olifants River is classified as the section downstream with the confluence with the Selati River, up until the border to Mozambique (McCartney et al., 2004). The official quaternary classification for this section is B7 Secondary Catchment Identifier and no.3 Tertiary Catchment identifier and falls within the “Oliphants” water management region of South Africa (McCartney

et al., 2004; GreenCape, 2017). The major tributaries of the Olifants River include the Moses River, Klein Olifants, Elands, Steelpoort, Blyde, Wilge and Ga-Selati rivers (McCartney et al., 2004; Heritage et al., 2014).

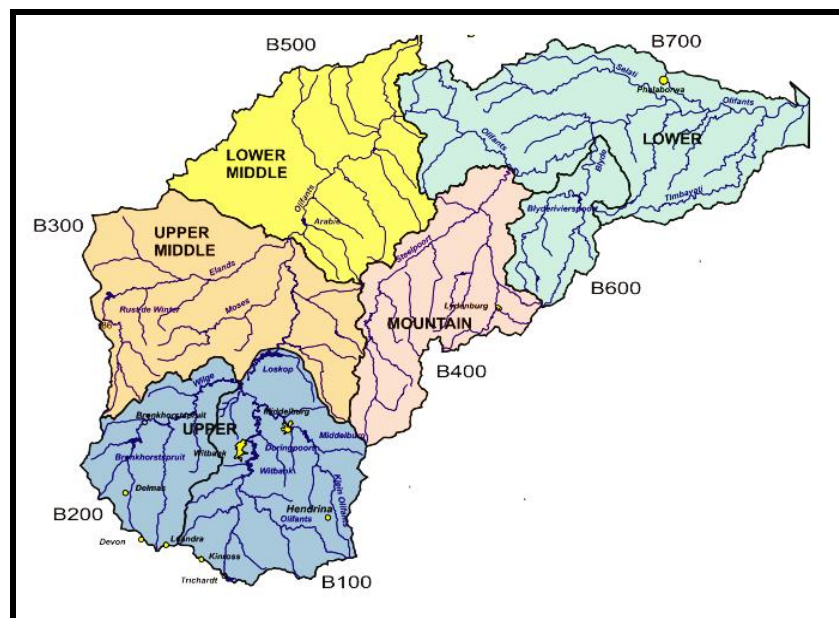


Figure 2.5: The main hydrological regions of the Olifants Catchment (De Lange et al., 2005).

2.6.3 Climate

(McCartney et al., 2004; Heritage et al., 2014). The areas receiving the highest annual rainfall of ~1000 mm is located along the escarpment as a result of pressure cells being forced to rise over it. The open water evaporation potential for the region far exceeds the annual precipitation at ~2000 mm per annum. The region in which this study took place receives rainfall during the summer (December to March) but rains can arrive as early as September (McCartney et al., 2004; Heritage et al., 2014).

The altitude of the catchment basin varies between ~250 and 2000 m as a result of the catchment extending over both the highveld and the lowveld. Temperatures range from as low as -4°C to as high as 45°C (De Lange et al., 2005; McCartney et al., 2004). The region is prone to frequent and intensive drought events (Love et al., 2010; Heritage et al., 2014; Trambauer et al., 2014).

The Olifants River sub-basin extends 900 km before reaching the confluence with the Limpopo River (Figure 2.6). The lower Olifants River is the section located between 700 to 950 km from the headwaters (SADC, 2021).

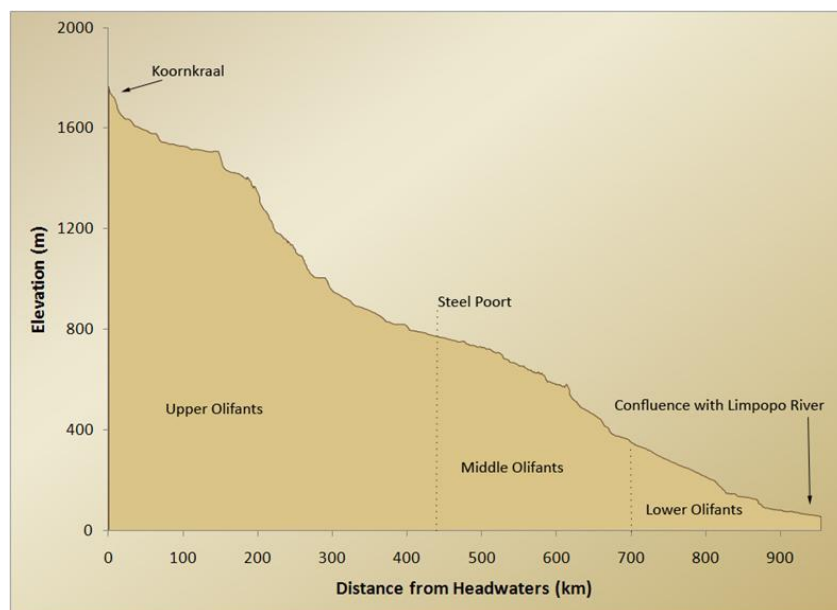


Figure 2.6: Distances and elevations from headwaters of various regions along the Olifants River to the confluence with the Limpopo River (SADC, 2021).

2.6.4 Geomorphology

The geology of the Olifant River Catchment is spatially diverse and is divided into six major geological systems. The oldest exposed rocks date back to the early Precambrian Era at ~4600 million years ago and the more recent rocks date back to only 1.65 million years ago. The KNP is divided vertically along its north-south orientation geologically. The western half is grouped into the Archaen Granite and Gneiss Basal Complex and the eastern half grouped into the

Karoo-related volcanic and intrusive rocks, classified as sedimentary rocks (Pollard and Laporte, 2014). The two sites in this study were located on different underlying geologies; Mamba was located on the western Archaen Granite and Gneiss Basal Complex, dominated by granitic geologies and the Balule was located on the eastern Karoo-related volcanic and intrusive rocks dominated by basaltic geologies.

The Archaen Granite and Gneiss Basal Complex falls under the oldest exposed rock formations within the catchment. The rocks date back to around 4600 to 2500 million years ago. The region is dominated by old Granite and Gneiss rock formations and old schistose rocks which include metamorphosed sediments. Some of these sediments include; phyllites, quartzite, limestone, conglomerate and banded ironstone. Some of the rocks are of igneous origin, including amphibolites, chlorite-schists and greenstone lavas (Pollard and Laporte, 2014). The Karoo Sequence region formed approximately 400 million to 120 million years ago. The majority of the area consists of sedimentary rocks arranged horizontally in a large basin. This plateau is in the process of being weathered by erosional processes. This region also possesses a band of coal that is located within the 'central sedimentary layers' (Pollard and Laporte, 2014). The Karoo sequence regions closer to the Mozambiquan border consists of a part of the Olifants River Catchment are volcanic and intrusive rocks. These areas are dominated by "rhyolitic ash-flow tuffs and ignimbrites and basaltic to andesitic lava flows". The alluvial deposits that exist in the area were formed approximately 65 million years ago and consist of sands created by erosion of older rocks (Pollard and Laporte, 2014).

The region experienced considerable stripping of sediments during the recent 2000 and 2012 floods (Heritage et al., 2014). The first flood left the rivers in the region vulnerable and exposed, the second event further exacerbating the condition. The result of the two consecutive events left the region transformed (Heritage et al., 2014). Finally, the region experienced a severe drought in 2016 which further affected vegetation composition and survivability (van Aardt et al., 2020). The result of the events has left the river primarily dominated by bedrock macro-channels frequently overlain with alluvial sediments (Van Niekerk et al., 1995). The geomorphological features of the river are dominated by braided channels, bedrock-dominated anastomosed channels, variations of pool types and rapid habitats.

Mamba site was described as a locally steepened bedrock-dominated channel located on a dolerite dyke that crossed the river at a 45° angle. According to Van der Waal (2021), "an anastomosing channel pattern developed through the bedrock, with bedrock core bars forming islands". Several low flow channels characterised by 'bedrock, boulder, cobble, gravel and sand' habitats were also present at the site. Non-woody and woody plants grew on core bars which provided substrate stability (Mackenzie, 2020; Van der Waal, 2021, 2020). The rapid habitats were dominated by bedrock and boulders whereas the riffles and runs were dominated by

cobbles and gravels. The local glide habitats were associated with gravels and coarse sands (Van der Waal, 2021). The section of the river at which the site was located could be described as a “wandering single channel or braided patterns where sand bars form in the channel” (Van der Waal, 2021).

Balule site could be described as anastomosing along the steeper sections and a “wandering channel or braided low flow channel” along the areas with more gentle gradients. Many high flow channels had the potential to become stagnant pools during low flow conditions (Van der Waal, 2021). The rapids, runs, glides, riffles and pools were associated with bedrock-dominated substrates while some glides and pools were associated with alluvial substrates. Bedrock core bars present at the site were well vegetated while “inset benches” were narrow and were poorly defined, mostly composed of fine to medium sands (Van der Waal, 2021). A flood bench was identified along the right bank and due to the incision of the river into the surrounding plain, there was no active floodplain.

2.6.5 Population

The human population within the Olifants Catchment Basin was approximately 3.4 million in 2011, representing approximately 7% of the nation’s population (Pollard and Laporte, 2014). Approximately 66% of the total populations were rural, residing mostly within the Elands (703 932) and Middle Olifants (691 986) regions (Figure 2.7). The Upper Olifants region contained the highest percentage of urban populations (561 942), namely Witbank (Emalahleni) and Middleburg (Pollard and Laporte, 2014). Population densities varied considerably within the catchment basin, ranging from as few as 40 people per km² to as much as 12,300 people per km².

The population distribution by age and gender showed that approximately 50% of the total human population residing within the catchment fell below the age of 24 years of age (DEA, 2009). The overall population distribution within the catchment was relatively typical of developing countries where there was a high proportion of young people versus older generations and short life expectancies. The sex ration was relatively even up to the age of 30 years of age, then the ratio increased to higher percentages of females. This is also typical of other countries as men generally have lower life expectancies than women (Pollard and Laporte, 2014).

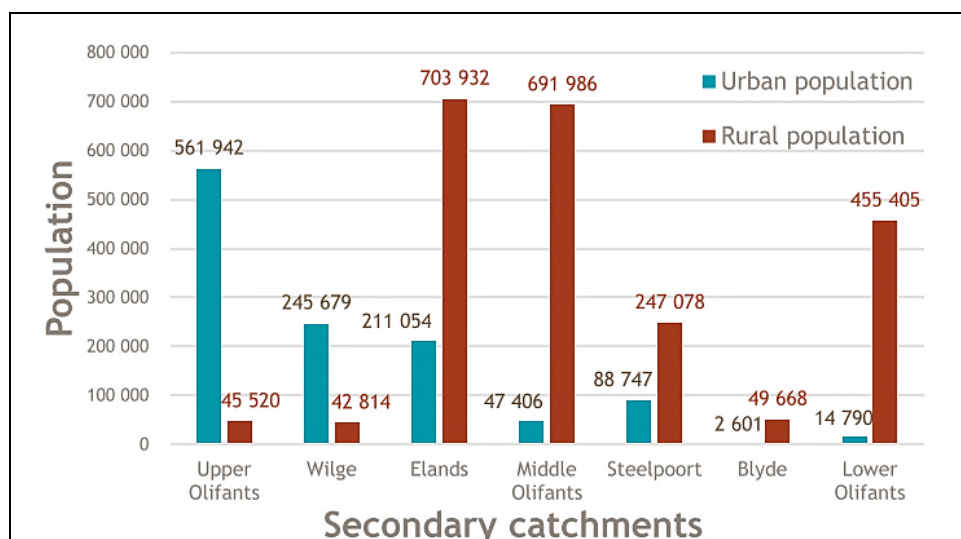


Figure 2.7: Urban and rural human population distributions of secondary catchments within the Olifants catchment (Pollard and Laporte, 2014).

2.6.6 Land use

The Limpopo catchment, including the Olifants River is considered one of the most water stressed rivers on the African continent (FAO, 1997; McCartney et al., 2004; Trambauer et al., 2014; Marr et al., 2017b). The catchment experiences intensive and extensive pressure from various activities that take place within and along the catchment, including; mining, industrial, agricultural and municipal sectors. The Limpopo Catchment and the Olifants River are important economic contributors to the nation, providing approximately 6% of the annual GDP (McCartney et al., 2004).

In addition to the intensive and extensive activities taking place within the catchment basin, the region is also affected by frequent and intensive drought and flooding events (Love et al., 2010; Trambauer et al., 2014). Numerous water impoundment infrastructures have been established within the catchment in order to improve water security. The country currently relies on approximately 68% of all its water resources on surface water sources, 13% on groundwater, 13% on return flows (recycled water) and only 6% on desalinisation (GreenCape, 2017). In addition to the above, Donnenfeld et al. (2018) states that forecasted deficiencies will also be a result of inefficient water usage, low water prices, inappropriate infrastructure usage and maintenance, inadequate cost recoveries, leakages and an increased demand from municipal, agricultural and industry.

The country is divided into nine water management areas, the Olifants Catchment as one of the nine. It is located across eastern Gauteng, Mpumalanga and Limpopo (GreenCape, 2017). Yields on the nine regions are expected to increase substantially by 2035, including that of the Olifants Catchment region.

2.6.7 Vegetation

According to Van Deventer et al. (2018) South Africa is divided into 37 vegetation bioregions which are further divided into 135 wetland ecosystem types. The study sites Mamba and Balule fell within the Olifants Catchment, primary catchment B which contained 49 of the 135 wetland ecosystems (Figure 2.8). Mamba site fell within the Mopane Bioregion, specifically within the Lowveld Rugged Mopaneveld and Balule fell within the Lowveld Bioregion, specifically within the Tshokwane-Hlane Basalt Lowveld. The Mopane Bioregion covers an area of approximately 2.6 million hectares within South Africa while the Lowveld Bioregion covers a larger area of approximately 6.8 million hectares (Van Deventer et al., 2018).

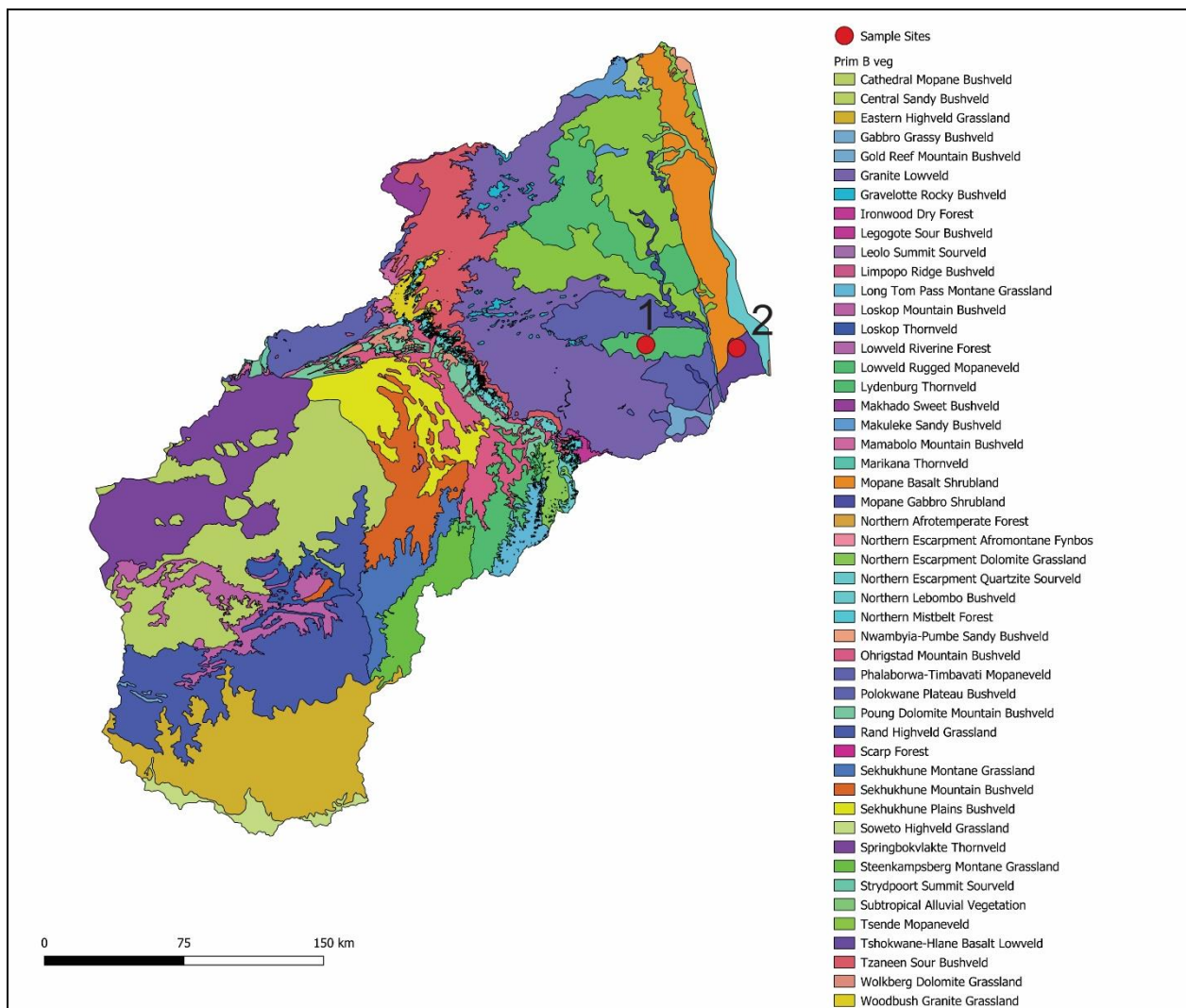


Figure 2.8: Map illustrating the study site locations (1 = Mamba and 2 = Balule) relative to the vegetation biomes within primary catchment B of the Olifants River Catchment, South Africa (Van Deventer et al., 2018).

The main vegetation types of the KNP can be broadly described as deciduous savannas which contain high species diversity and great variations in vegetation structure (Venter and

Gertenbach, 1986). Identified driving factors for terrestrial vegetation types are soil composition and fire. Vegetation assessments indicate that there are approximately 1968 recorded plant species within the KNP (Venter and Gertenbach, 1986). Riparian vegetation diversity assessments have not yet been undertaken in the park, however the high diversity of geological features and associated hydrogeomorphic processes in combination with post-flood conditions provided riparian habitat for high diversities of riparian vegetation (Van Coller et al., 1997; McCartney et al., 2004; Heritage et al., 2014).

The KNP can be divided into 14 broad vegetation classification categories (Figure 2.9) (Venter and Gertenbach, 1986). The compositions of these vegetation types have strong correlations to rainfall, soil composition and underlying geology. Due to the varying underlying geology at the two sites selected for this study, the vegetation compositions belong to different groups. The Mamba site is located approximately within the central-western sections of KNP, close to the town of Phalaborwa. This region can be broadly classified as 'Alternate *Combretum apiculatum* (Red Bushwillow) woodland or *Colophospermum mopane* (Mopane) tree savanna (Figure 2.9(D)). The *C. mopane* dominates areas with clayey soils that were formed from 'greenstones and dolerite dykes' as well as transitional areas from footslopes (Venter and Gertenbach, 1986). The *C. apiculatum* vegetation types are located in areas with sandy and gravelly of valley crests.

The Balule site is situated in the central-eastern sections of the KNP, south-west of Olifants Rest Camp. This region can be broadly classified as *C. mopane* shrubveld (Figure 2.9(J)) (Venter and Gertenbach, 1986). This region is underlain with basaltic geologies. The dominant vegetation types south of the Olifants River consist of *Senegalia nigrescens* (Knob-thorn acacia), *Sclerocarya birrea* subsp. *caffra* (Marula) known as Kokwaro savanna. The dominant vegetation north of the river consists of *C. mopane* (Mopane) shrubveld with *Combretum imberbe* (Leadwood tree) interspersed along the landscape (Venter and Gertenbach, 1986). This area also consists of a conspicuous grassland component consisting of *Themeda triandra* (Red grass), *Panicum coloratum* (Small buffalo grass) and *Bothriochloa radicans* (Stinking Grass) (Venter and Gertenbach, 1986).

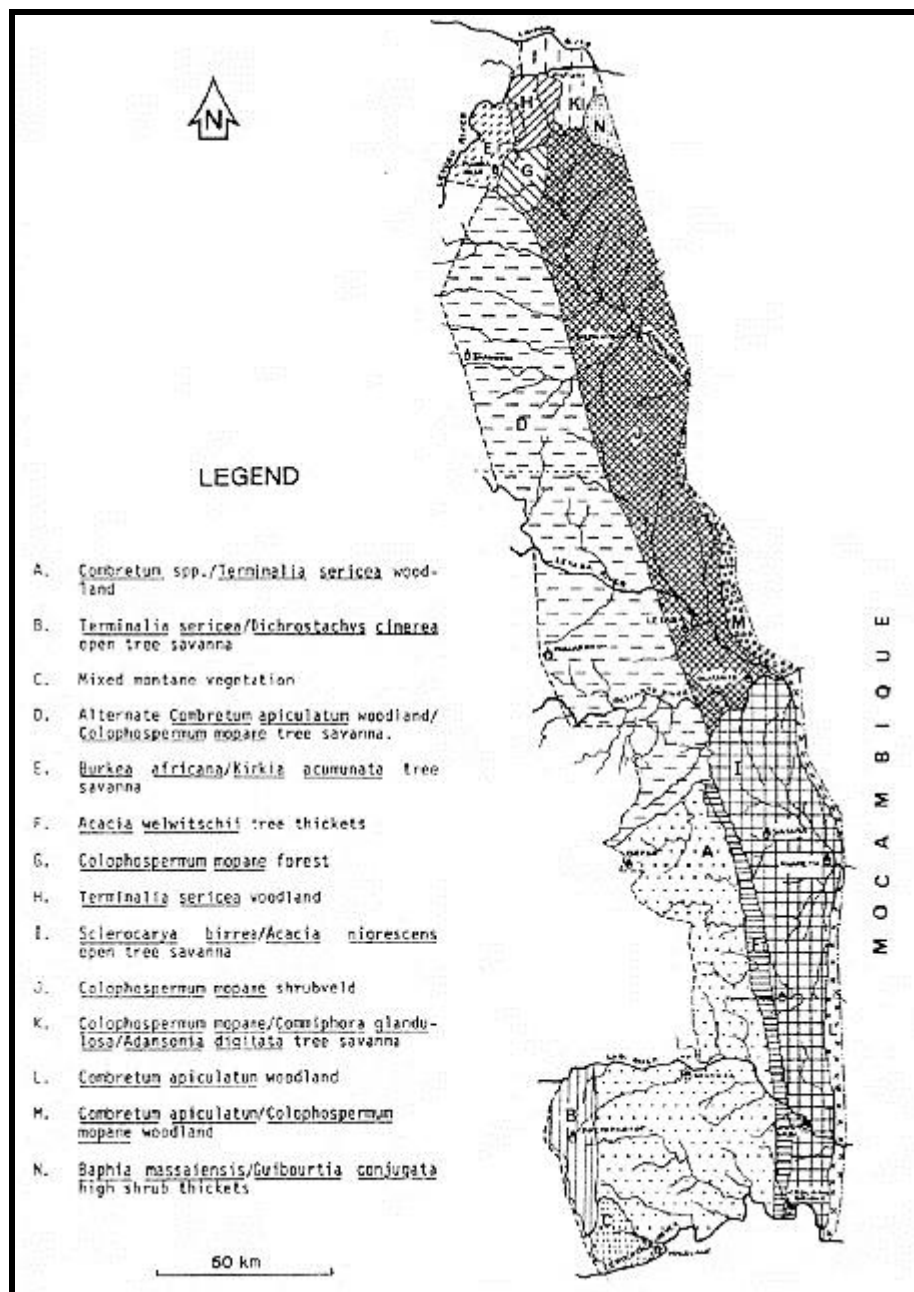


Figure 2.9: Generalised vegetation map of the Kruger National Park (Venter and Gertenbach, 1986).

Venter and Gertenbach (1986) stated that 'riparian thickets occur along all of the major drainage lines' within the KNP. They also stated that there was a correlation with denser thickets and the underlying granitic geologies than along rivers on basaltic geologies.

2.7 Use of riparian plants as ecological indicators in Olifants River

The Olifants River falls within an arid to semi-arid climate that experiences erratic climatic variations that include extended dry periods followed by intense rainfall events (Heritage et al., 2014). The Olifants River within the KNP is located within the lower Olifants regions; Secondary Catchment Identified B7, Tertiary Catchment Identifier 2 and 3 and Quaternary Catchment

Identifier A to K (10) and A to H (8) water management regions (McCartney et al., 2004). The official description for this section is; “Olifants to confluence with Selati River” and “Olifants from confluence with Selati River to the Mozambique border”. Climatic conditions that these rivers typically experience within this water management region include long dry periods with very low surface flows or even no flows with infrequent flooding events. The natural sediment supply for these rivers is erratic which result in diverse riparian vegetation community structures (McCartney et al., 2004; Heritage et al., 2014).

The Olifants River is intensively and extensively affected by mining, industry and agriculture through water extraction, nutrient input, heavy metal concentrations, pollution input and land-use activities (FAO, 1997; McCartney et al., 2004; Oberholster et al., 2010; Trambauer et al., 2014; Schachtschneider et al., 2017). Schachtschneider et al. (2017) conducted a study on the ability of riparian vegetation to phytoextract and phytostabilize metals in the upper regions of the Olifants River. Their study focused on the most common metals that were prevalent in the river as a result of acid mine drainage (AMD), including aluminium (Al), iron (Fe) and manganese (Mn) (Oberholster et al., 2010). They found that some species had a high ability to tolerate and mitigate the effects of heavy metals through either phytoextraction or phytostabilization (Schachtschneider et al., 2017). In conclusion they stated that maintaining high vegetation biomass and biodiversity of plant communities improved ecosystem resilience to high metal concentrations (Schachtschneider et al., 2017).

2.8 Resource Directed Measures

Resource Directed Measures (RDM) are rules set out to ensure a sustainable future of water resources within the various water management areas (WMA) or ‘subsidiary catchments’ (Ginsburg et al., 2010). Resource Directed Measures are based upon a framework that ensures the equal and fair distribution of water to all sectors and stakeholders, including the environment. The framework is based upon the National water Act (NWA) 36 in 1998 which, for the first time in South African history, ensures the rights to water for the environment (Republic of South Africa, 1998). The National Water Resource Strategy (NWRS) is a policy that developed from the NWA (DWAf, 2004). The aim of the NWRS is to “to strike a balance between the use of resources for livelihoods and conservation of the resource to sustain its functions for future generations, and promotes social equity, environmental sustainability and economic efficiency”. In order to achieve the above-stated aim, there will invariably be trade-offs and compromises from all those affected by the resources, normally in the form of water quality and quantity (DWAf, 2004; Ginsburg et al., 2010). The NWRS developed two essential strategies to achieve their desired aim, (1) “Resource Directed Measures (RDM) that undertake to protect water resources by setting goals and objectives for the desired condition of water resources in aquatic ecosystems” and (2) “Source Directed Controls (SDC) that specify criteria

for controlling water resource use activities and their impacts on aquatic ecosystems”. A major purpose of the RDM was to determine Management Class (MC) objectives for water quality and “overall health of the water resource” that must be maintained for a given area (Ginsburg et al. 2010). According to DWAF (2003) the term ‘resource quality’ is defined as the quantity, quality and the “character and condition of in- stream and riparian habitats, and the characteristics, condition and distribution of the aquatic biota”. The Water Resource Classification System (WRCS) 2 was used to determine the Management Classes. The Classes are described as; “Class I (minimally used), Class II (Moderately used), Class III (Heavily used)” (Dollar et al., 2007).

Management Classes are determined using the Water Resource Classification System (WRCS)2. The overall objective of the WRCS is to classify water resources in terms of Class I (Minimally used), Class II (Moderately used), Class III (Heavily used) (Figure 2.10)(Dollar et al., 2007). Based on the MC for each significant water resource, the Reserve3 and the resource quality objectives (RQOs) for that water resource are prescribed.

Class I Minimally used	Class II Moderately used	Class III Heavily used		Management Classes
Excellent	Good	Fair	Poor	Water Resource Classification
A	B	C	D	E/F
Minimal	Minimal	Moderate	Heavy	Unacceptable
Unmodified	Slightly modified	Moderately modified	Considerably modified	Critically modified
				Ecological Categories User Impact
				Ecological condition

Figure 2.10: A Diagram illustrating the proposed Management Class (MC) system and the relationship with other ecological classifications and categories (adapted from Palmer et al., 2004; Parsons and Wentzel, 2007; Dollar et al., 2007).

2.9 Environmental flows

According to the Arthington et al. (2018) as stated in the Brisbane Declaration and Global Action Agenda on Environmental Flows, e-flows are defined as “the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being”. The alteration of natural flow regimes and the associated disruption in sediment transport potential through the modification of river channels threatens ecosystem integrity and stability. The biological components of river ecosystems have adapted to natural seasonal and infrequent flooding

through the timing of essential life history events such as spawning, germinating, flowering, fruiting, etc. The disruption of these events alters the success rates for potential recruitment, potentially resulting in losses to biodiversity (Poff et al., 1997; Brown et al., 2005; The Brisbane Declaration, 2007; Naiman et al., 2008; Reinecke et al., 2013, 2015). This in turn can result in reduced ecosystem resilience to disturbances, reduced functionality and reductions in the range of services rendered (Tilman and Downing, 1994; Prosser, 1999; Terrill, 1999; Nielsen et al., 2000; Zavaleta et al., 2010; Allan et al., 2011; Jorgensen and Nielsen, 2013; Reinecke et al., 2013).

In order to replicate natural flow regimes, one must consider the most important driving factors, namely; the timing, frequency, magnitude and duration of flow releases from water impoundment infrastructure (Poff et al., 1997; Naiman et al., 2008; Reinecke et al., 2015; Horne et al., 2017). Important aspects to also consider when setting natural flow regimes are the rate of change, the predictability of the discharge events and the natural geomorphic processes associated with flow releases (Naiman et al., 2008; Navarro-Llácer et al., 2010; Reinecke et al., 2015).

There is a global movement towards the improvement of water management practices with the aims of achieving sustainable utilization of the resources associated with freshwater ecosystems and optimizing ecosystem functionality and integrity (Horne et al., 2017). The movement was driven by the degradation of rivers and the loss of associated essential services (King et al., 2003). This is further enhanced in developing countries with semi-arid to arid climatic conditions. The rivers in these countries experience particularly high competition for water resources as a result of fast-growing human populations and growing economies (King et al., 2003).

Catchment basins are unique in the pressures they experience from water resource users and the needs of the environment and should therefore be assessed individually (Naiman et al., 2008; Kleynhans et al., 2007; Reinecke et al., 2013, 2015). The environment was initially perceived as competition for water resources, but later this view changed to a base foundation of the resource, where the environments' water needs were seen as an essential aspect for maintaining functional services (King et al., 2003). South Africa implemented the National Water Act 36 in 1998, and with it, the environment's position was enhanced by providing it with 'rights to water' (Republic of South Africa, 1998). It was around this time that aquatic scientists were first tasked to speak on behalf of the environment through rigorous research and the development and implementation of complicated models that allow us to predict environmental responses to altered flows (King and Brown, 2006).

In 2007, the Brisbane Declaration and Global Action Agenda was established in Brisbane Australia. The document was the first consensus that successfully set a common vision and global objective for e-flows at an international scale. The Declaration highlighted that the sustainable management of e-flows defined as the “quantity, timing and quality” of flow regimes are essential for the wellbeing of freshwater ecosystems and the humans that depend upon them for their livelihood.

The product of the conference proceeding was a nine-point international agenda. Briefly described, the points identified were as follows: (1) The need to estimate e-flows globally as the vast majority of freshwater and estuarine flow requirements are unknown, (2) Environmental flows should be integrated into every aspect of management and development that directly or indirectly impacts the wellbeing of rivers, (3) Environmental flow should be applied to multiple institutions and should be maintained across political boundaries, (4) Improve wastewater treatment procedures in order to reduce the need for increased flows for dilution purposes, (5) Engage and consider all stakeholders directly or indirectly influenced by the resources, (6) Enforce e-flow regulations, (7) Identify and conserve free-flowing rivers on a global scale in order to maintain ecosystem functionality and integrity, (8) Improve capacity of experts in the field of e-flows and educate the general public and (9) Employ adaptive management strategies that are flexible and realistic.

In 2017 the declaration and action agenda were revised at the 20th International River symposium and Environmental Flows Conference which was also in Brisbane, Australia (Arthington et al., 2018). The purpose of the conference was to revise the action agenda and to identify and publicize the achievements over the past decade. The revised 2018 Brisbane Declaration highlight the urgent need to restore and protect e-flows for “their biodiversity, intrinsic values and ecosystem services” as the core element of water resource management for sustainable utilization (Arthington et al., 2018). A new addition to updating the agenda was the addition of sections relating to the inclusion of complete and equal participation of stakeholders from all cultures, respecting their cultural and religious rights and updated responsibilities when establishing e-flows for catchment basins.

There are numerous approaches to determining the e-flow requirements of a catchment basin (King and Louw, 1998; King et al., 1999; Tharme, 2003; Acreman and Dunbar, 2004; Pahl-Wostl et al., 2013; Poff and Matthews, 2013; Horne et al., 2017; O’Brien et al., 2018). In 2003 there were approximately 100 different approaches to establishing e-flows and over 30 different countries had begun to utilize the methods developed in order to improve management policies (King and Louw, 1998; King et al., 1999, 2003). The methods were divided into four main categories: (1) hydrological approaches, (2) hydraulic rating methods, (3) habitat rating methods and (4) holistic approaches (King et al., 1999). Recent studies (Pahl-Wostl et al., 2013; Poff and

Matthews, 2013) have progressively migrated towards more holistic e-flow assessments that consider multiple stressors to socio-ecological variables on regional scales that incorporate both risk evaluation and uncertainty (Poff et al., 2010; Acreman et al., 2014; O'Brien et al., 2018).

PROBFLO is an e-flow assessment tool that holistically assesses socio-ecological variables (O'Brien et al., 2018). The tool incorporates the Bayesian belief networks and Relative Risk Model (BN-RRM) in order to assess uncertainty and risk when determining the e-flow requirements of catchment basins. In addition to the incorporation of the BN-RRM, PROBFLO also takes into account historical, current and future water resource use in order to determine the consequences for both social and ecological endpoints (O'Brien et al., 2018). The tool is useful as it allows for adaptive management practices that take into account the multiple stressors impacting the e-flow determination procedure.

The process used to determine e-flows generally follow the same generic guideline (Horne et al., 2017). According to Horne et al. (2017) there are typically four main steps that must be taken in order to initiate the process, establish and maintain e-flows. The first step involves the initiation of the procedure as a response to observed ecosystem degradation or reduced resource availability. This step is usually initiated by a concerned citizen, private organisation or government department. The second step is responsible for the establishment of visions and objectives for the river or catchment basin based on the social and ecological requirements unique to the area in question. The third step is the actual determination of the e-flow requirements through scientific data collection. This step involves the holistic incorporation of all necessary variables including the multiple stressors that are appropriate and relevant to the area at a social and ecological scale. This includes the identification of all stakeholders directly or indirectly affected by the resource. The ecological e-flow determination not only includes the determination of the quantity of water that the ecosystem requires but also the determination of the natural flow regimes (timing, frequency and duration of flows) that coincide with the life histories of the biota directly and indirectly affected by the resources (Poff et al., 1997; Richter et al., 1997; Naiman et al., 2008). The fourth step is the integration of all information pertaining to social and ecological flow requirements into complex models that interpret and predict outcomes (such as PROBFLO). This step should also include a risk assessment analysis as well as compensate for any potential uncertainties (Horne et al., 2017; O'Brien et al., 2018). The fourth step is usually followed by monitoring, implementation and enforcement.

2.10 Current literature using riparian plants in environmental flow assessments

The links between riparian vegetation and flows have been established in previous literature (Naiman et al., 2005, 2008; King and Brown, 2006; Kleynhans et al., 2007; James and King, 2010; Reinecke et al., 2013, 2015). Some studies utilized cross-section surveying and the

relative elevation along cross-sections in combination with FDC's to determine the percentage of time that particular zones experienced inundation on a temporal scale (Brown et al., 2005; King and Brown, 2006). Flow duration curves were constructed with the use of historical natural and present-day hydrology. The use of these data allows ecologists and water managers to cross-reference the position of the zones along profiles to establish links between lateral zones and the percentage of time activation was achieved (Brown et al., 2005; King and Brown, 2006). FDC's are used in existing e-flow assessments in order to indicate flow variability and the frequency in which discharge requirements are met (King et al., 2003).

The VEGRAI tool is used to determine the PES category of riparian vegetation (Kleynhans and Mackenzie, 2007). Prior to the initiation of the assessment the ecologist is required to determine the reference condition – the expected condition of the site without anthropogenic influence. This is usually determined through background research of site locations. The final outcome of the survey is the assignment of a PES category ranging from category A to F, where A is described as unmodified or natural and F is described as critically modified. The process taken in order to achieve the final rating includes an assessment of the riparian vegetation community structures including alien invasive and native species compositions and degrees and sources of anthropogenic disturbances. The tool is flexible in that it can be applied at various levels of complexity depending on the observers' level of experience, accounting for the observer confidence. The tool is robust, user friendly and only requires limited botanical experience (Kleynhans et al., 2007).

3 Riparian vegetation of the lower Olifants River, Kruger National Park

3.1 Introduction

South Africa is considered a semi-arid country, receiving an annual rainfall of ~450 mm that is unevenly distributed on both a temporal and spatial scale (King and Pienaar, 2011). The combination of unpredictable climatic conditions and past drought events have resulted in the establishment of an increasing number of water impoundment infrastructure such as dams and weirs (DWAF, 2013; DWS, 2019a). These structures disrupt natural flow regime and other ecological processes such as sediment distributions and transportation potential which have negative effects on riparian vegetation through the disruption of life history events (Naiman et al., 2005, 2008; Reinecke and Brown, 2013; Reinecke et al., 2015).

The Olifants River is considered one of the most water-stressed basins on the African continent due to the over-allocation of water to the various sectors that rely upon the resources (McCartney et al., 2004). The basin supports intensive and extensive agricultural, industrial and mining activities along with the provision of resources and services for municipal, household, cultural, tourism and environmental sectors (FAO, 1997; McCartney et al., 2004; Oberholster et al., 2010; Trambauer et al., 2014; Marr et al., 2017; Schachtschneider et al., 2017). The activities that take place within the catchment are socially and economically importance to South Africa, contributing to an estimated 6% of the country's annual Gross domestic product (GDP), however the unsustainable utilization of riverine ecosystems could result in the reduced capacity to maintain associated ecosystem services due to compromised resilience and functionality (Tilman and Downing, 1994; Nielsen et al., 2000; Zavaleta et al., 2010; Allan et al., 2011; Jorgensen and Nielsen, 2013).

The lower Olifants River is classified as the section downstream of the confluence with the Selati River to the border with South Africa and Mozambique (McCartney et al., 2004). It is one of the six major rivers that run west to east within the Kruger National Park (KNP) and therefore is a socio-ecologically important river. The upstream activities that take place along the Olifants River put pressure on riverine ecosystems within the park, including the riparian vegetation that are responsible for the absorption of pollution and excessive nutrients from various upstream anthropogenic activities (Naiman et al., 2005, 2008; Dudgeon et al., 2006). In addition to the above-mentioned stressors, riparian plant communities are also under pressure from threats to biodiversity such as alien invasive plant species as well as natural events such as increased browsing and grazing pressure from wildlife during the dry seasons and natural drought and flood events (Morokong et al., 2016).

Riparian vegetation provides a wide range of services to both ecosystems and humans, including; shelter, protection and food for in-stream and terrestrial biota, nutrient input into rivers, the absorption of excessive nutrients from anthropogenic sources and the trapping and/or conversion of potentially harmful pollutants. They also provide stability to soils, flood attenuation services and temperature regulation of in-stream habitat. Services provided specifically for humans include water purification services from upstream sources including effluent discharges, harvestable sources of fuel, food for livestock and wildlife and medicinal plants (Prosser, 1999; Naiman et al., 2008; Reinecke and Brown, 2013; Reinecke et al., 2015; Schachtschneider et al., 2017; Rowiński et al., 2018).

Riparian vegetation arrange themselves perpendicular and longitudinally to flow within riverine environments. The arrangement of the communities depends upon a variety of characteristics, including sediment distributions, seasonal and infrequent intensive flooding events, the local topography and access to water through flow regimes (Hupp and Osterkamp, 1996; Kleynhans et al., 2007; Naiman et al., 2008; Reinecke and Brown, 2013; Reinecke et al., 2015). Alterations to these variables such as reduced flows result in alterations to sediment deposition and distributions can result in the reorganisation of community structures which can result in reduced biodiversity (Van Coller et al., 1997).

The Riparian Vegetation Response Assessment Index (VEGRAI) method was used as an additional tool to identify the current state of the study sites (Kleynhans et al., 2007). The VEGRAI method refers to this as a Present Ecological Status (PES) category. The PES category can be translated into the degree of deviation from expected natural conditions devoid of anthropogenic influence, referred to as the reference condition. The PES category is determined through the assessment of impacts and vegetation responses to impacts for the various lateral zones at a study site, allowing for an increased understanding of the disturbances that drive plant community structure (Kleynhans et al., 2007).

This chapter aims to establish an understanding of the drivers responsible for riparian vegetation community composition and distributions along the lower Olifants River within the KNP.

The main aims of this chapter are to:

- 1** Determine the riparian vegetation community composition and distributions in relation to environmental drivers at two sites along the lower Olifants River in the KNP.

Specific objectives in order to achieve this aim include the identification of community assemblages in relation to:

- a. Substrates
- b. Water quality
- c. Hydraulic preferences

- 2 Determine the PES of riparian vegetation with the use of the VEGRAI tool at two sites along the lower Olifants River within the KNP.

3.2 Materials and methods

3.2.1 Study area

The two locations that were used for this study included Balule and Mamba sites situated in the lower Olifants region along the lower Olifants River (Figure 3.1). The Mamba site (-24.086900, 31.250272) is downstream of the Klaserie River confluence, approximately 2.4 km downstream of Mamba Weir within the KNP. The site is located within the central-western regions of the park approximately 15 km from the town of Phalaborwa and ~65 km from the border with Mozambique and South Africa.

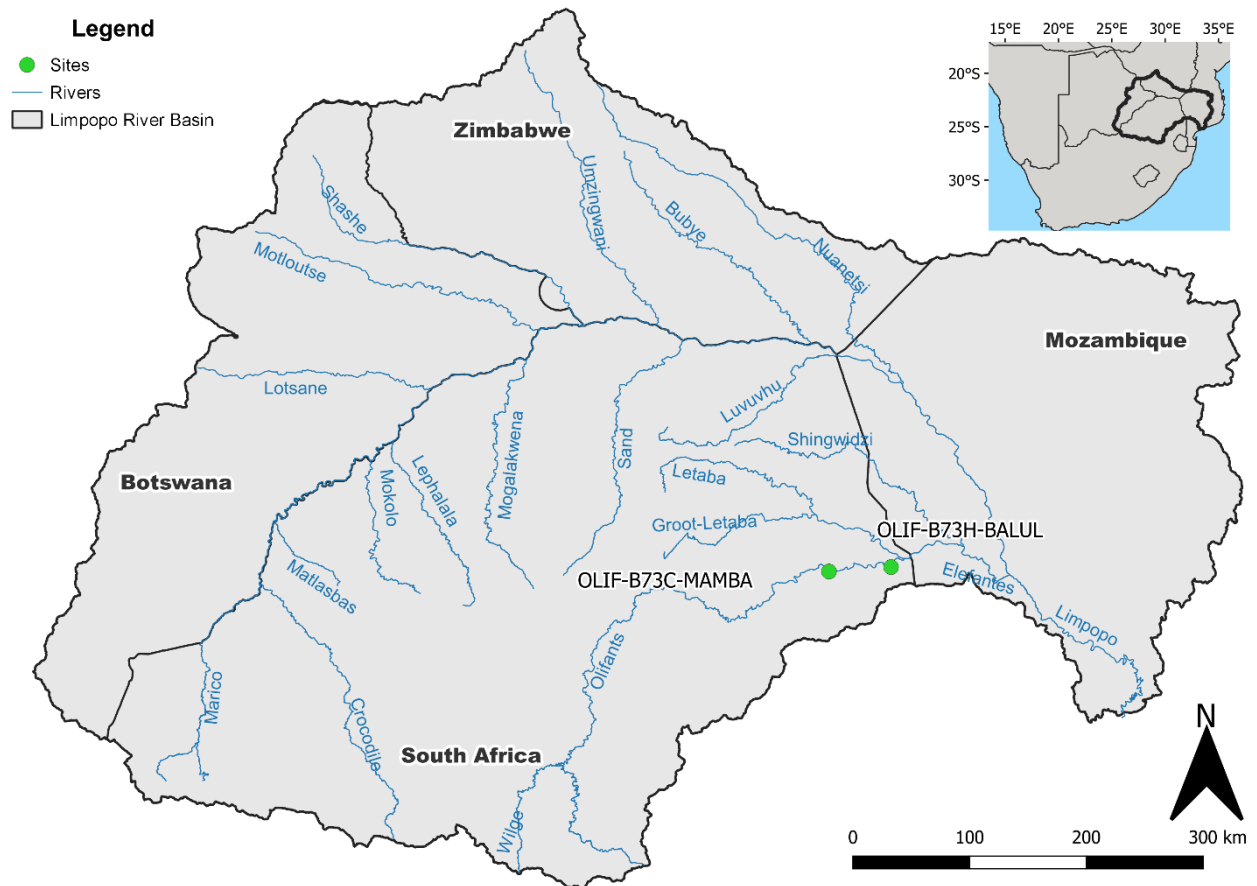


Figure 3.1: Study site locations of Mamba (1) and Balule (2) along the lower reaches of the Olifants River within the Kruger National Park.

Balule site (-24.053544, 31.728686) is 0.9 km downstream of Balule Weir along the Olifants River within the KNP. Geographically, the site was located approximately 5.5 km from Olifants Rest Camp and ~16.5 km from the border with Mozambique and South Africa. Two cross-section profiles were surveyed at each of the sites, positioned perpendicular to flow (Figure 3.2 and Figure 3.3).

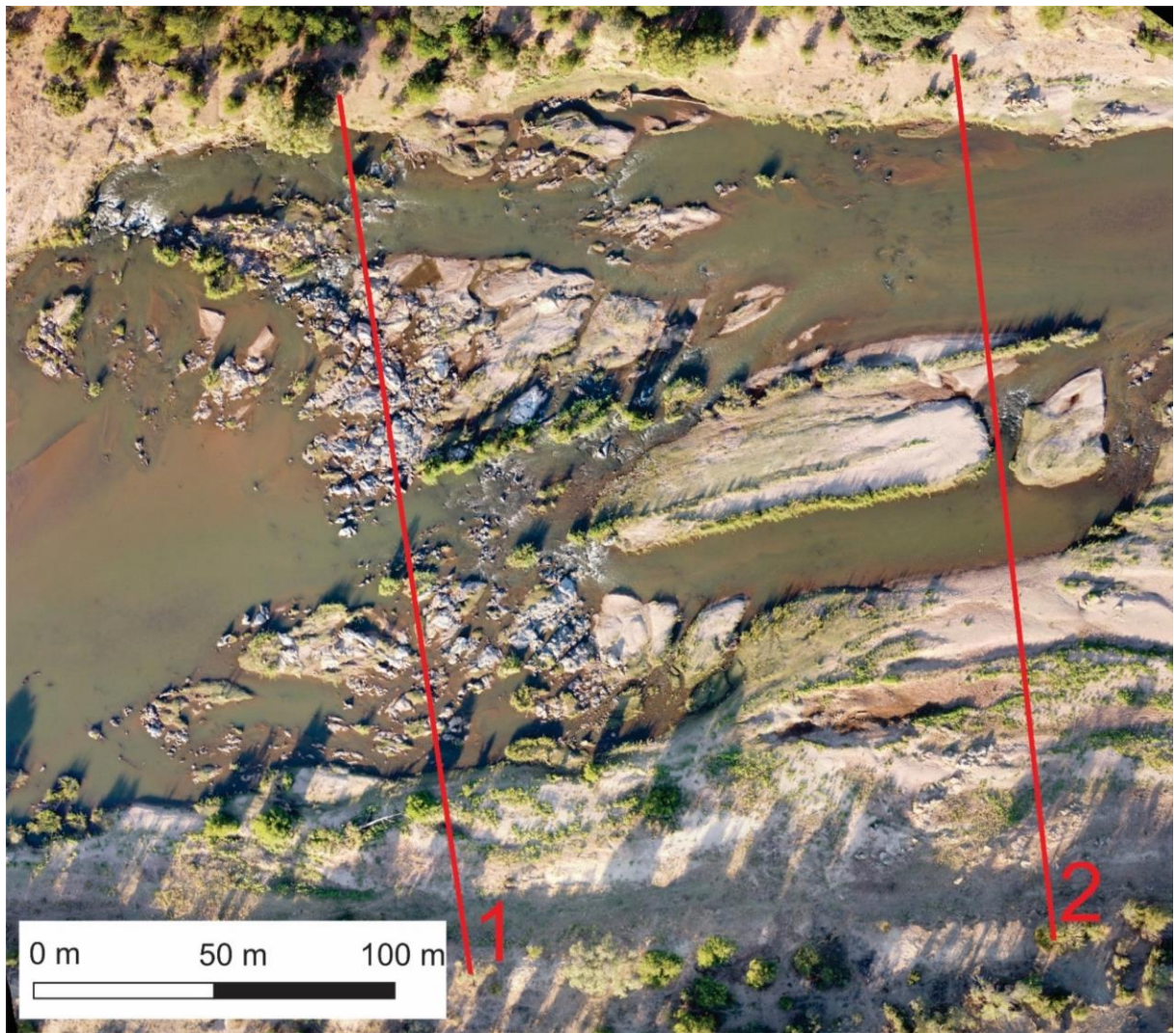


Figure 3.2: Image showing cross-section locations at Mamba site along the Olifants River, downstream of Mamba Weir within the Kruger National Park.

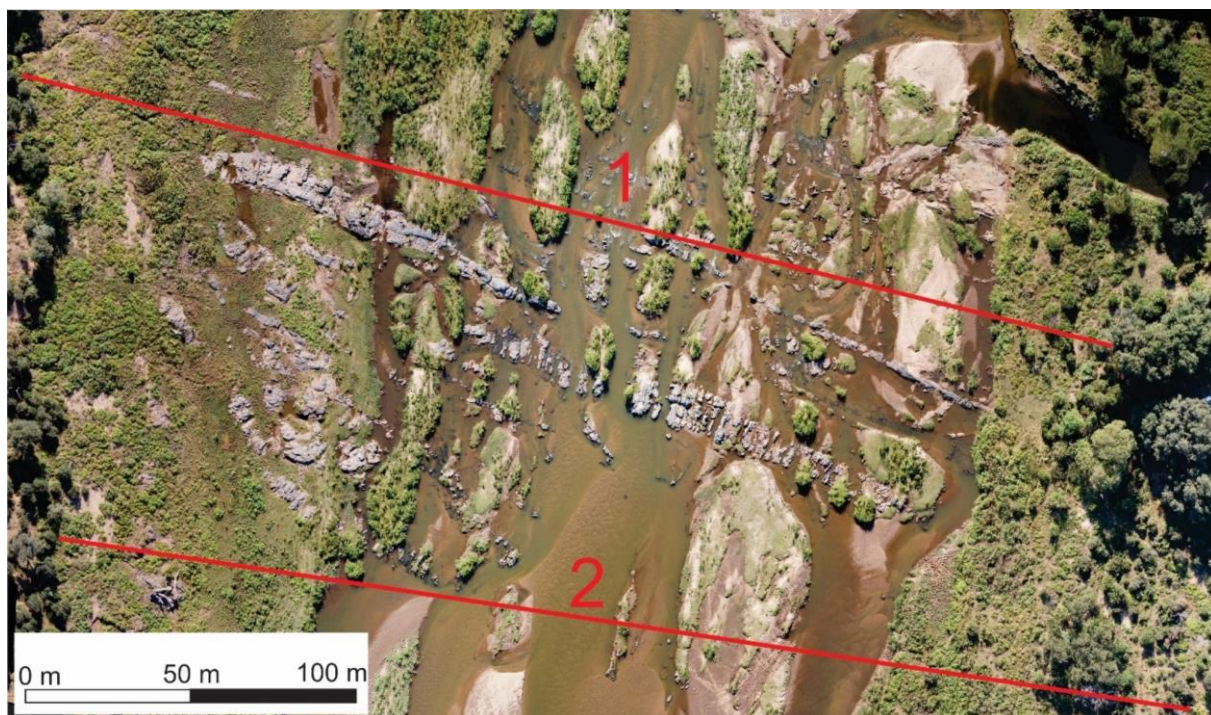


Figure 3.3: Image showing cross-section locations at Balule site along the Olifants River, downstream of Mamba Weir within the Kruger National Park.

3.2.2 Data Collection

Sampling regime

Sampling took place within the dry season flows between the months of September and October 2020 and follow-up sampling took place in May 2021. Dry season flows were selected due to accessibility, equipment usage and for increased visibility of potentially dangerous game such as hippopotamus (*Hippopotamus amphibius*) and crocodiles (*Crocodilus niloticus*) (Figure 3.4). Official KNP game guards were present with the research teams at all times in order to provide vigilance and protection - a mandatory requirement for surveys conducted within the KNP (Figure 3.5).



Figure 3.4: Potentially dangerous animals observed at Balule and Mamba sites along the Olifants River within the Kruger National Park. Frequent and numerous observations of *Crocodylus niloticus* (Nile crocodile) and *Hippopotamus amphibius* (Hippopotamus) at both of the study sites.



Figure 3.5: Kruger National Park game guard watching over the research team at Balule site along the Olifants River.

A follow-up survey was conducted in May 2021 in order to collect additional discharge and hydraulic data that were necessary to improve the accuracy of cross-section post-processing models. A minimum of two site visits are necessary in order to produce rating curves for cross-sections that are of reasonable accuracy (Van der Waal, 2020). In addition to hydraulic data, observations were made with regard to any potential changes that were noted from the previous

survey as tropical cyclone Eloise took place between the two sampling surveys in January 2021.

Cross-sections and hydraulics

Data collected along cross-section profiles were conducted with the use of surveillance equipment. Two cross-sections were conducted at each of the sites with the use of the following equipment; Leica TCR403 Power total station along with associated prism, staff and tripod (Figure 3.6). Discharge data were collected by recording gauge plate readings from upstream Mamba and Balule weirs on the day that surveys took place. Gauge plate values were cross-referenced with online rating tables provided to the general public by the South African Department of Water and Sanitation, Hydrological services (Republic of South Africa, 2021).



Figure 3.6: Data collection at Mamba and Balule sites along the Olifants River within the Kruger National Park; (A) photographing recordings of all vegetation, (B) cross sections with total station and (C) Gauge plate at Mamba Weir along the Olifants River within the Kruger National Park.

The locations of the cross-sections at each of the sites were advised by specialist riparian vegetation and specialist geomorphologist consultants that were present on the days at which surveys took place. Data that were surveyed and related to cross-section profiles included; two cross-sections at each of the sites, points indicating evidence of historical flood levels, water levels along cross-sections and upstream and downstream water level slope points.

It is important to note that under natural conditions a river may have multiple channels of which each channel may contain distinctly different water levels as water may be forced through wide or narrow channels, raising or lowering water levels. Therefore, a single cross-section with multiple channels may contain water levels that vary in elevation (Figure 3.7) (Van der Waal, 2020). Elevation values are always adjusted according to the lowest point along cross-sections, commonly referred to as relative elevation/height. Left and right bank are always determined when facing downstream. This stands for the rest of this dissertation.

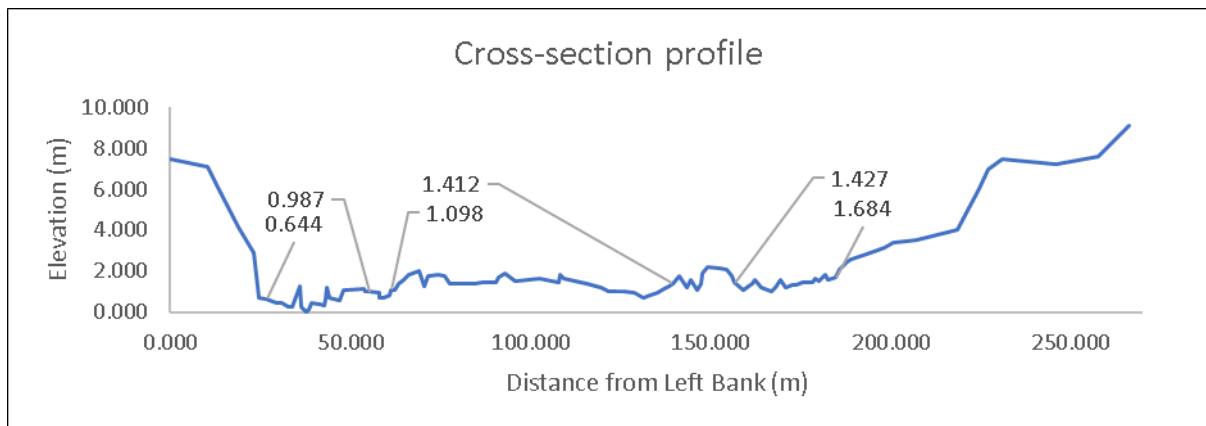


Figure 3.7: An example of a cross-section profile illustrating the multiple channels that vary in water levels (m). The illustration is arranged from left to right bank when facing downstream of a river.

It was also necessary to install a minimum of three permanent benchmarks at each of the sites. Benchmarks are permanent markers that are required when setting up a total station. They provide local orientation to the total station and allow for the replication of cross-section for future surveys (Van der Waal, 2020). Permanent benchmarks were installed in various forms, depending on the landscape and availability. These included; metal pegs inserted into the ground, metal pegs inserted into the bases of trees and drilled markers on large boulders or bedrock that were spraypainted to assist in future detection. The coordinates of each of the benchmarks, total station position and start and end of cross-sections were all recorded, also to allow for possible future replication.

Cross-section profile data were then surveyed along cross-sections, perpendicular to flow. The surveillance process included a surveyor based at the total station and a surveyor that recorded the profile with the use of a staff and prism. The surveyor based at the total station guided the other using coordinates provided by the total station to remain 'on-line' (perpendicular to flow). Points were captured through the activation of a sensor within the total station that recorded the relative position of the prism (X, Y and Z position). Additional information that was captured during the surveillance process included individual riparian vegetation plants, associated substrate compositions, on-line water levels and upstream and downstream water levels.

Cross-sections and hydraulics

Only cross-sections 2 were used to produce hydraulic rating curves as they were situated in locations that were considered acceptable for the formation of rating curves. Cross-section data collected with the use of surveillance equipment were imported into Microsoft Excel for the initial processing phase. During this phase the additional biotic and abiotic data that were collected along the cross-section profiles were superimposed onto cross-sections. The processing of cross-section data included the calculation of the 'chainage' and 'Z 0' values (Van der Waal, 2020). The chainage value is the application of the Pythagoras theorem whereby the formula (Equation 1) is applied to coordinates recorded by the total station:

Equation 1: Chainage

$$((X^1 - Y^1)^2 + (X^2 - Y^2)^2)^{0.5}$$

Superscript '1' represents the X and Y coordinates of the data row in question and superscript '2' represents the X and Y coordinates of the furthestmost point recorded from the location of the total station. The 'Z 0' value is the application of a formula that adjusts all elevation values relative to the lowest point recorded along the cross-section profile (Equation 2):

Equation 2: Z 0

$$Z^1 - (Z^2)$$

Z¹ represents the data row requiring adjustment and Z² represents the lowest recorded point along the cross-section. Additional calculations required at this level were the determination of the slope of the river landscape based on points recorded upstream and downstream of the cross-sections. These points were recorded approximately 300 m upstream and downstream of the cross-sections.

Slope is also referred to the energy gradient of a river landscape. It can be defined as a ratio of change in water level per unit of distance from the upstream water level and the downstream water levels (Figure 3.8) (Van der Waal, 2020). Slope is calculated through three separate steps; firstly, the chainage is calculated for the downstream slope point based on the upstream point (Equation 1). This value is labelled 'vertical distance'. Then the subtraction of the upstream 'Z 0' value from the downstream 'Z 0' value produces the 'horizontal distance' (Equation 2) and the final includes the calculation of the slope which is the division of the vertical distance value by the horizontal distance value. Slope water levels are typically taken as far as is practical (>300 m is normally acceptable) both upstream and downstream of the location of the cross-sections (Van der Waal, 2020).

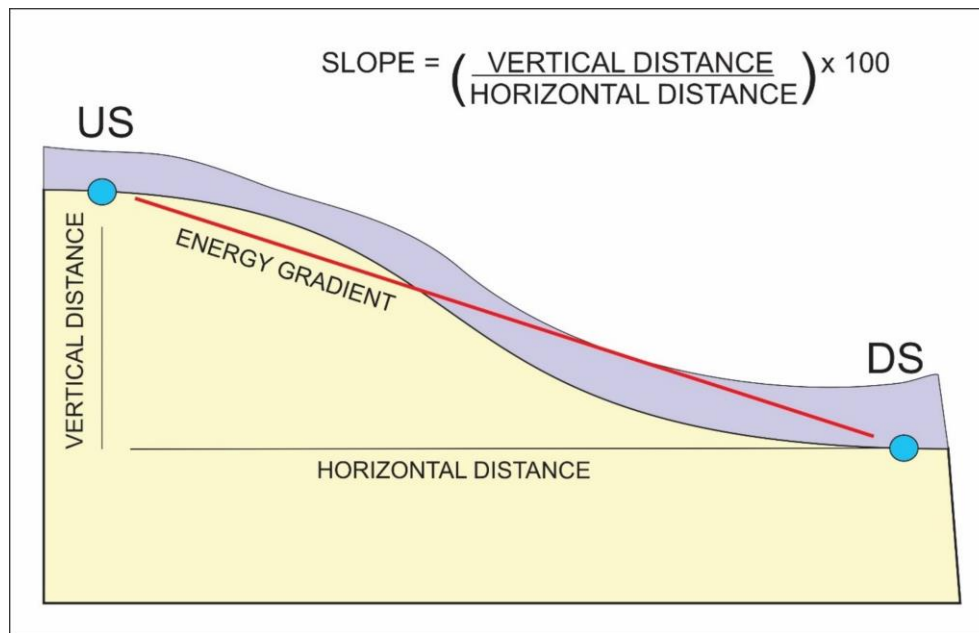


Figure 3.8: Illustration depicting the calculation of slope where the ratio is calculated based on the difference in vertical height and horizontal height of the upstream (US) and downstream (DS) water level points surveyed with a total station (surveillance equipment).

The final phase for the processing of the cross-section data included the importing of the data to the HEC-RAS software package for the generation of rating curves through 1-dimensional modelling (Gordon et al., 1992; Brown et al., 2005; HEC-RAS, 2020; Mackenzie, 2020; Van der Waal, 2020). This process was formally undertaken by specialist geomorphologist Dr. Van der Waal, B of Rhodes University, South Africa. The process that was followed included the importing of the chainage, Z 0 and slope values into the software program. Additional information that was required in order to generate the final outputs included; manning's n values (resistance), discharge readings on the day that the surveys took place, water levels and flood levels (Gordon et al., 1992; HEC-RAS, 2020; Van der Waal, 2020).

Manning's n is a value that represents the degree of resistance that water experiences when moving from one point to the next (Gordon et al., 1992). This resistance can be in any physical form, including vegetation, substrates or debris. The Manning's n value is determined by inserting a value into the 1D geometries section of HEC-RAS software and then testing the accuracy of the computed rating curve based on water level values recorded along cross-sections. If the observation does not fit to the produced rating curve, the manning's n is adjusted until the observation fits perfectly onto the model. It is for this reason that multiple water levels are required to produce accurate rating curves as Manning's n values differ at differing discharge values. For example, vegetation may be denser further up the bank or perhaps the landscape includes substrates that may provide resistance to water (i.e., large boulders) (Gordon et al., 1992; HEC-RAS, 2020; Van der Waal, 2020). The water level readings that were

recorded during this study included the initial survey in September and October in 2020 and a follow-up survey in May 2021 following heavy floods that took place.

Rating curves provide the ability to plot expected discharges at specific locations along profiles relative to channel shape, elevation and resistances (Brown et al., 2005; HEC-RAS, 2020; Van der Waal, 2020). They are designed specifically for each individual cross-section and therefore data pertaining to specific profile cannot be applied to different cross-sections, even at the same site. The outputs for rating curves are activation discharge (AD) values. Activation discharge can be defined as the discharge required for the species (datum) to become activated at the roots (HEC-RAS, 2020; Mackenzie, 2020; Van der Waal, 2020).

Surveyed cross-section profiles have been used in previous studies (Brown et al., 2005; King and Brown, 2006) to identify relationships between abiotic variables relative to vegetation. These studies conducted surveyed cross-sections along river profiles in order to produce elevation profiles that ultimately produced modelled rating curves specific to individual cross-section profiles with the use of hydraulic modelling software. Rating curves provided discharge reference tables specific to elevation points along cross-sections (Brown et al., 2005; King and Brown, 2006; HEC-RAS, 2020; Van der Waal, 2020).

Vegetation-related data

Vegetation-related data were collected along cross-section profiles and points recorded with surveillance equipment in order to allow for the superimposing and correlation of the data sets (Brown et al., 2005; King and Brown, 2006). Vegetation data collected included; species diversity, the height of woody species and the aerial cover percentage of non-woody species. Data were collected within a 1 m² area around the base of the staff as a standard. This included both canopy and ground-cover. Wherever possible, biological traits were observed of the various plant species that were surveyed, including; woody versus non-woody, root type, reproductive strategy and perennial versus annual/bi-annual features. Where this information was not possible through *in situ* observations, alternative reference materials were used.

Riparian vegetation species were primarily selected during the surveillance process due to time constraints and because all other species were considered during the application of the VEGRAI tool (described below). Some plants have been shown to prefer growing inside of the riparian ecosystems but are also found within terrestrial environment and therefore not considered as riparian obligate species (Mackenzie, 2020). These plant species were also recorded in the cross-sections but they were usually present at low densities.

Substrates

Relative substrate composition were recorded at every surveyed point along cross-section profiles. Grain size classes were visually identified based on Rowntree and Kelly (2013), adapted from the Wentworth scale (Table 3.1). The Wentworth scale was adapted from work done by Brakensiek et al. (1979). Substrate data were recorded as the aerial cover percentage of dominant substrates within a 1 m² around the base of the surveillance staff via visual estimations. The objective of the substrate data collection was to determine whether associations existed between substrate types and riparian plant communities and their biological traits. Studies have indicated that substrate types and underlying geological features were some of the most important drivers of plant community composition (Venter and Gertenbach, 1986; Allan et al., 2011; Theron et al., 2020).

Table 3.1: Substrate classes categorized by grain size, adapted from the Wentworth scale (Rowntree and Kelly, 2013).

Size class	Grain diameter (mm)	Feel or analogy
Boulder	>256	Too large to pick up
Cobble	64-256	Rugby ball
Coarse gravel	16-64	Cricket ball
Medium gravel	8-16	Golf ball
Fine gravel	2-8	Pea
Coarse sand	0.5-2	Brown sugar
Medium sand	0.125-0.500	White sugar
Fine sand	0.063-0.125	Caster sugar
Silt	0.002-0.063	Silky
Clay	<0.002	Sticky

Water quality

Sub-surface water samples were collected at each of the sites in triplicate of 250 ml with acid-washed polypropylene bottles (Musselman, 2012). Samples were stored on ice and were kept out of direct sunlight until they could be frozen and transported to the laboratory for further analyses. In addition to collected water samples, water quality data were also measured *in situ* with the use of an Extech EC500 pH/Conductivity and Extech D0600 Dissolved Oxygen meters. *In situ* measurements recorded included; water temperature, electrical conductivity (EC) measured in $\mu\text{S}/\text{cm}$, pH, dissolved oxygen (DO%), dissolved oxygen (DO mg/l) and total dissolved solids (TDS) measured in mg/l. Frozen water samples were allowed to thaw and tested for the following; turbidity, sulphates (SO_4^{2-}), ammonium (NH_4^+), nitrates (NO_3), nitrites

(NO₂⁻), phosphorus (PO₄³⁻), chloride, chemical oxygen demand (COD), magnesium (Mg) and calcium (Ca), using a Merck Pharo 100 Spectroquant with relevant test kits at the North-West University (North west province, South Africa).

Vegetation Response Assessment Index (VEGRAI)

The VEGRAI tool was applied to each of the sites to determine the PES category, ranging from categories A to F (Kleynhans et al., 2007). The purpose of the VEGRAI tool is to determine the degree of deviation from the expected reference condition at each of the sites. The reference condition can be defined as the expected state of a location devoid of anthropogenic influence (Kleynhans et al., 2007; Mackenzie, 2020). The survey can be completed at various levels based on user experience. The assessment can be completed up to level 4 where the user is required to provide detailed information pertaining to recruitment and population structure. This level was recommended to users who are familiar with the life history, morphological and biological traits and population dynamics of the species identified during surveys (Mackenzie, 2020). Assessments up to level 3 include the assessment of the impacts and responses of plants present at the site, divided into the various zones. The various zones including; the marginal zone, lower zone, upper zone and macro-channel bank. The responses of woody and non-woody plants are assessed separately (Kleynhans et al., 2007; Mackenzie, 2020). VEGRAI assessments conducted during this study were completed up to level 3.

The VEGRAI assessment included the following components; brief site description with the use of reference materials and descriptions of the various zones that were observed at the location. Dominant species and/or vegetation types were noted in this section on a broad perspective. Comprehensive species lists of all observed plant species were noted as well as the zones in which each of the species was observed. Individual zones were assessed according to impacts and responses relative to the intensity, extent and confidence. All of the above were scored 0 – 5 in increments of 0.5. Impacts were assessed according to the following criteria; the degree of native vegetation removal from any source originating from anthropogenic influences, the degree of alien invasion, the degree of alteration to water quality and quantity by anthropogenic sources and erosion from anthropogenic sources (direct or indirect) (Kleynhans et al., 2007; Mackenzie, 2020). All of the above categories were scored according to the intensity of the impact and the extent.

The response rating was scored separately for three categories; woody, non-woody (reeds) and other non-woody (excluding reeds). Reeds were excluded from the second non-woody class as they tend to respond differently than plants belonging to different non-woody classes. All responses were scored according to the degree of change from a reference state when considering all direct and indirect anthropogenic sources. The categories assessed for the

woody component included; change in aerial cover percentage, change in abundances, change in population structure and vertical structure, change in recruitment rates and change in species composition. Non-woody (reeds) response categories included; change in aerial cover percentage and abundance and non-woody (excluding reeds) response categories included the assessment in changes to aerial cover percentage, abundances and species compositions. The final section for individual zonation assessment was the ranking of the zone. Each category (woody, non-woody reeds and non-woody excluding reeds) were ranked according to the importance (dominant vegetation type) within each of the zones. They were ranked 1 – 3. In addition to the ranking, each category was allocated a percentage weighting where the category awarded 1 was always weighted 100% and the categories 2 and 3 were weighted with reference to category 1. All of the sections described above were allocated a confidence rating to reflect the degree of confidence that the surveyor felt towards the answer provided (Kleynhans et al., 2007; Mackenzie, 2020).

3.2.3 Statistical analysis

Multivariate statistical techniques in the form of redundancy analysis (RDA) and principal component analysis (PCA) approaches were used to assess the biological community structures and associated abiotic variables. The significance threshold selected for this study was $P = 0.05$ where $P < 0.05$ indicates significance and $P > 0.05$ indicates the results were not significant, as is commonly selected for biological evaluations (Ridley et al., 2007; Rosenthal and Rubin, 1979). Statistical analysis was conducted with the use of Canoco version 5.02 for Windows (ter Braak and Smilauer, 2012). RDA approaches have been utilized in similar biological community assessment studies (Brown et al., 2005; King and Brown, 2006; O'Brien et al., 2009). RDA ordinations were interpreted as two-dimensional tri-plots that illustrated the degree of similarities and dissimilarities between biological and environmental samples that were analysed (Shaw, 2003). The arrows represented a single variable, pointing in the direction that represented the steepest increase of value relative to the corresponding variable depicted in the tri-plot. The orientation of arrows with reference to one another indicated correlations between variables where correlations are considered positive when the angles between arrows measure less than 90° and negative when angles measure greater than 90° (O'Brien et al., 2009). The RDA approach was analysed in a constrained manner whereby samples were searched for driving variables (O'Brien et al., 2009). The substrate data were utilised as environmental variables in the RDA to identify the abiotic factors that drive the vegetation community structures.

The original data were first imported into Microsoft Excel spreadsheets (Microsoft Corporation, 2016) where it was organised into the appropriate formats. Thereafter the data were imported into Canoco 5.02 for further analysis. Vegetation-related data for woody height variables were

converted into percentages relative to the largest plants surveyed so that the values conformed to other biological formats which were also portrayed in percentage values. All other variables were imported into Canoco 5.02 based on original values and formats that were collected *in situ*.

Vegetation-related data analysis

Vegetation-related data that were collected along cross-section profiles were imported onto Microsoft Excel spreadsheets (Microsoft Corporation, 2016) where datapoints were superimposed onto cross-section profiles. Individual vegetation datapoint coordinates were converted into chainage (Equation 1) and Z 0 (Equation 2) values using the same formulas and methods described in 'cross-section analysis' section above (Van der Waal, 2020). The above values were plotted along cross-section profiles which provided relative elevation positions for each individual vegetation point.

Biological traits of the individual vegetation points were prepared for multivariate statistical analysis using Redundancy Analysis (RDA) with Canoco version 5.02 software package (ter Braak and Smilauer, 2012). Biological data in the form of woody height and non-woody aerial cover percentage collected *in situ* were assigned to individual vegetation points that were standardized through conversion into percentages for woody plants where the biological data for individual plants were converted into a percentage based on its current height and the largest plant recorded for that particular species on the cross-section in question. Raw data for non-woody plants were already expressed in percentages as they were collected in original relative abundances of aerial cover.

The assessment of biological traits was identified and assigned to each species, divided into four categories; woody versus non-woody, root type, reproductive strategy and perennial versus annual//bi-annual. Annual and bi-annual traits were combined for practicality. Biological data were combined (represented as relative abundances) for all plants belonging to the trait in question (i.e., all relative abundance data were merged for all woody species for each individual datapoint presented in rows). These data were compared to substrate data in its original form (collected and presented in aerial percentage cover within a m² area from the base of the staff).

Once the plant species data had been prepared for analysis with the use of Microsoft Excel software, a multivariate RDA analysis was run with Canoco software. The environmental data selected were limited to Mamba and Balule sites with associated biological vegetation data. The purpose of the analysis was to determine whether plant species displayed association preferences towards a particular site as a component to consider for the overall study.

In addition to plant species, spreadsheets containing biological trait-related data were also prepared for analysis. The biological traits included the following categories; woody versus non-woody, root type, perennial versus annual or bi-annual and reproductive strategy. An exception existed for one species with regard to woody versus non-woody trait i.e., *Gomphocarpus fruticosus*. The species is classified as a woody species (van Wyk et al., 2013) as well as an herbaceous non-woody plant (Naidoo, 2005) as it displayed characteristics of both categories (MacKenzie, 2020). For the purpose of this study, *G. fruticosus* was regarded as a woody plant as its behaviour at both Mamba and Balule sites conforms more towards a woody than non-woody species.

Vegetation Response Assessment Index (VEGRAI)

The analysis of data collected during VEGRAI assessments were analysed via a template in the form of an Excel document that was provided by the designers. The template version used for this study was VEGRAI 4.6. The template contained various tabs which the user is required to complete in order to achieve the final PES category. The categories are scored from A to F where 'A' is unmodified/natural and 'F' is critically modified (Kleynhans et al., 2007; Mackenzie, 2020). A PES category is determined by assessing a variety of factors at a site, including the degree of disturbance relative to reference conditions. The reference condition can be defined as the expected state of a location devoid of anthropogenic influence.

The reference condition was determined through the insertion of information pertaining to the expected vegetation compositions at the site, including expected substrates. The assessment required the user to provide information for both woody and non-woody plants which were assessed at the various zones; marginal, lower, upper and macro-channel bank (MCB) (Table 3.2). The macro-channel bank contains almost exclusively terrestrial species with interspersed riparian plants. This zone can be quite similar to the upper zone (Mackenzie, 2020).

Table 3.2: Zone descriptions and delineations according to the Vegetation Response Assessment Index (VEGRAI) (Kleynhans et al., 2007).

	Marginal	Lower	Upper
Alternative descriptions	Active features or Wet bank	Seasonal features or Wet bank	Ephemeral features or dry bank
Extends from	Water level at low flow	Marginal zone	Lower Zone

Table 3.2: Continued

Extends to	Geomorphic features / substrates that are hydrologically activated (inundated or moistened) for the greater part of the year.	Usually a marked increase in lateral elevation.	Usually a marked decrease in lateral elevation.
Characterized by	See above; Moist substrates next to water's edge; water loving-species usually vigorous due to near-permanent access to soil moisture.	Geomorphic features that are hydrologically activated (inundated or moistened) on a seasonal basis. May have different species than marginal zone.	Geomorphic features that are hydrologically activated (inundated or moistened) on an ephemeral basis. Presence of riparian and terrestrial species. Terrestrial species with increased stature.

Once the reference condition had been determined for each of the study sites, assessments were conducted based on present-day conditions for the various zones. The assessment process included the determination of the degree of impact of; vegetation removal, alien and invasive plants, water quality, water quantity and erosion within each of the various zones (Kleynhans et al., 2007; Mackenzie, 2020). Following this, the degree of response was determined for three different vegetation categories; woody vegetation, special vegetation category and non-woody vegetation (excluding reeds). Special vegetation category referred to reeds only while the second non-woody category contained all non-woody species except reeds (Mackenzie, 2020). The degree of confidence that the observer experienced was also recorded. Responses were measured based on the degree of change from expected reference condition. The categories assessed included; (1) woody category: cover, abundance, population structure, vertical structure, recruitment and species composition (2) special category: cover and abundance (3) non-woody (excluding reeds): cover, abundance and species composition. The user has the option to deactivate any of the categories listed above if they feel they are not confident in their understanding of the component.

The last section included the determination of the ranking and weighting for each of the three categories based on the prevalence of the category within the zone in question. An example of this might be that within the marginal zone at a specific site there were large quantities of reeds and no observed woody plants with infrequent observations of other non-woody (excluding

reeds). Special category containing reeds ranked 1 as this group was the most prevalent at that particular site. By default, the weighting awarded to the category ranked 1 is 100%. The non-woody category that excluded reeds ranked 2 and the weight of importance (recorded in percentage) was based on the degree of prevalence at the particular site. The woody category ranked lowest as a 3 and assigned a weighting based on observations at that particular site. If the surveyor did not observe any woody plants within the entire zone, then they had the option to deactivate that particular category therefore it is not considered at all.

Upon completion of the above, formulas within the template provide the final outcome of the assessment – the PES category which represented the degree of change from reference condition. This value was provided in the form of a letter and the percentage of change as well as the average confidence rating that the user provided based on each of the zones assessed.

3.3 Results

3.3.1 Vegetation community structure in relation to environmental variables

Cross-section profiles

Two cross-section profiles were surveyed at both Mamba and Balule sites along the lower Olifants River within the KNP (Figure 3.9, A and B). Water levels were recorded on the left and right edges of channels, measured in height relative to the lowest recorded point on the transect. Cross-section 1 at Mamba was 265 m in length and possessed four active channels (Figure 3.9, A). The four active channels accumulated to 62.5 m of inundated area. Cross-section heights (measured from macro-channel banks) ranged from 7.5 m on the far-left edge to 9.1 m on the far-right edge of the profile. Cross-section 2 was 224 m in length and ranged from 7.5 m on the far-left edge of the profile to 7.1 m on the far-right edge and possessed four active channels (Figure 3.9, B).

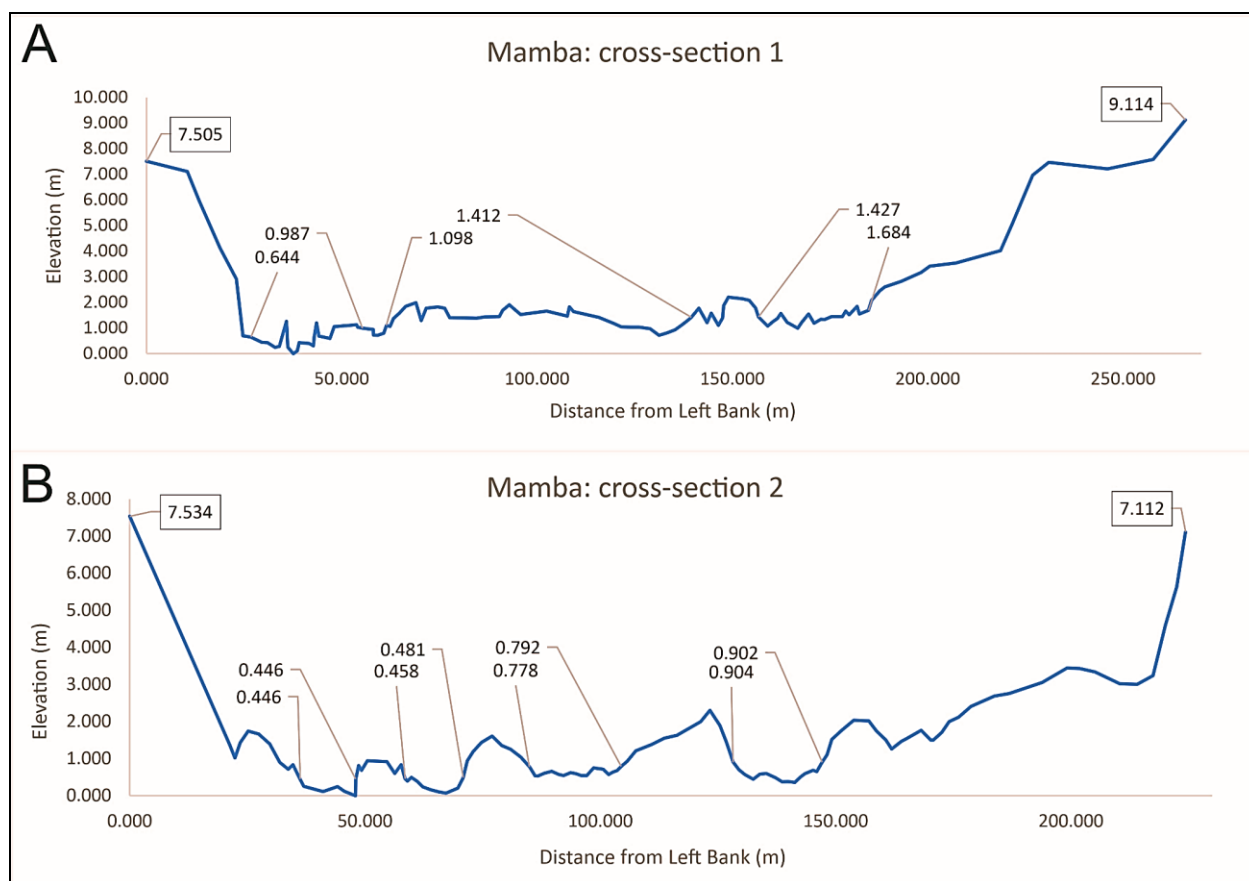


Figure 3.9: (A) Cross-section 1 and (B) cross-section 2 at Mamba site along the lower Olifants River within the Kruger National Park. Values on far left and right edges indicate relative heights of cross-section boundaries and values in between (arranged in pairs) represent relative elevation of water levels for the multiple channels across cross-section profiles.

Cross-section 1 at Balule was 308 m in length and ranged from 3.8 m in height from the far-left edge of the profile to 6.8 m on the far-right edge and possessed seven active channels (Figure 3.10A). Cross-section 2 was 388 m in length and ranged from 6.7 m in relative height at the far-left edge of the profile to 9.1 m on the far-right edge and possessed four active channels (Figure 3.10B). The four active channels at Balule accumulated to a total of 103.4 m of the cross-section profile.

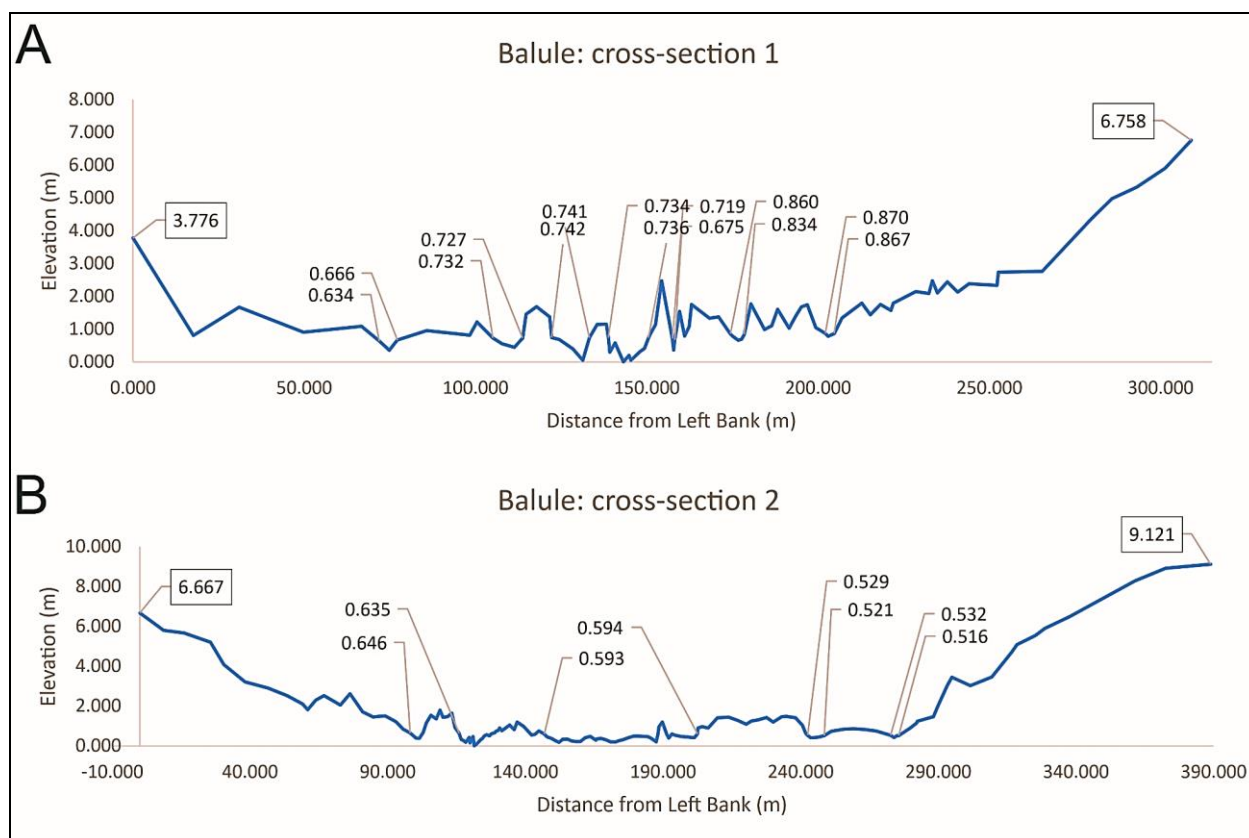


Figure 3.10: (A) Cross-section 1 and (B) cross-section 2 at Balule site along the lower Olifants River within the Kruger National Park. Values on far left and right edges indicate relative heights of cross-section boundaries and values in between (arranged in pairs) represent relative elevation of water levels for the multiple channels across cross-section profiles.

Hydraulic parameters were recorded for both Mamba and Balule sites (Table 3.3). The data were used for the production of 1-dimensional hydraulic modelling with the use of HEC-RAS software to produce hydraulic rating curves. Rating curves were only produced for cross-sections 2 at both Mamba and Balule, therefore hydraulic parameters were only provided for these. The discharge at Mamba was 50.6% lower than that of Balule while the relative water level heights (above the lowest point in the bed) at each of the sites differed by only 0.181 m. The cross-section lengths differed by 164 m (58%). Slope ratios differed by 0.05% and Manning's n values differed by a value of 0.01.

Table 3.3: Hydraulic parameters of cross-sections conducted at Mamba and Balule sites along the lower Olifants River within the Kruger National Park. Values include site locations, discharge readings on the day that cross-sections were conducted, observed relative water levels (m), slope readings to provide energy gradients for hydraulic modelling and vertical and horizontal distances that were used to produce the slope ratio.

Site Name	Date	Site location	Discharge (m ³ .s ⁻¹)	Water level (m)	Slope (% ratio)	Manning's n value	Notes
Mamba	30-09-2020	-24.086428, 31.250930	2.266	0.481	0.14	0.04	2nd Cross-Section
Balule	04-10-2020	-24.05214, 31.72879	4.476	0.662	0.19	0.05	2nd Cross-Section

Riparian vegetation

A total of 419 individual plants representing 18 taxa were recorded along all cross-sections with 184 individuals recorded at Mamba and 235 at Balule (Table 3.4). Fifteen taxa were recorded at Mamba site with 73 individual plants recorded along cross-section 1 and 111 along cross-section 2. Thirteen taxa were recorded at Balule site with 37 recorded along cross-section 1 and 198 individuals recorded along cross-section 2. Biological traits were recorded *in situ* with regard to degree of woodiness, reproductive strategy and relative longevity. Biological traits that were not observable *in situ* were sourced externally from literature.

Of the 18 taxa, nine were woody and nine were non-woody, 11 possessed tap root systems and 7 adventitious roots, 10 reproduced exclusively through sexual reproductive strategies, 2 exclusively asexual and 6 had the ability to reproduce via both sexual and asexual strategies. Finally, of the 18 taxa, 16 were perennial and 2 were annual or bi-annuals.

Table 3.4: Summary table of all plant species surveyed along cross-sections 1 and 2 at both Mamba and Balule sites along the lower Olifants River within the Kruger National Park. Abbreviated names are provided per species for convenience are used in graphs hereafter. Abundances of recordings per species are arranged into columns labelled 'M1 and M2' representing Mamba cross-section 1 and 2 and B1 and B2 representing abundances recorded along cross-sections 1 and 2 at Balule. Some traits are abbreviated for convenience where; 'W' refers to woody and 'N-W' refers to non-woody, 'Tap' refers to tap roots, 'Adv.' refers to adventitious roots, 'Repro.' refers to reproductive, 'ann.' refers to annual/bi-annual and 'Perr.' refers to perennial.

Scientific names	Common names	Abbr. names	M1	M2	B1	B2	W / N-W	Root type	Repro. strategy	Ann./ Perr.
<i>Breonadia salicina</i>	Matumi Tree	Bsal	5	26		4	W	Tap	Sexual	Perr.
<i>Ceratophyllum demersum</i>	Hornwort	Cdem	1				N-W	Adv.	Asexual	Perr.
<i>Cyperus sexangularis</i>	Bushveld Sedge	Csex		1		6	N-W	Adv.	Sexual	Perr.
<i>Flueggea virosa</i>	White berry-bush	Fvir				2	W	Tap	Sexual	Perr.
<i>Gomphocarpus fruticosus</i>	Milkweed	Gfru	6	2	5	14	W	Tap	Sexual	Perr.
<i>Gomphostigma virgatum</i>	River Star	Gvir		1		93	W	Tap	Sexual	Perr.
<i>Ischaemum fasciculatum</i>	Border Grass	Ifas				27	N-W	Adv.	Both	Perr.
<i>Lannea schweinfurthii</i>	False Marula	Lsch				1	W	Tap	Sexual	Perr.
<i>Ludwigia stolonifera</i>	Creeping Ludwigia	Lsto	3		1	3	N-W	Adv.	Both	Ann.
<i>Nuxia oppositifolia</i>	Water Elder	Nopp	2	1		2	W	Tap	Both	Perr.

Table 3.4: Continued

<i>Persicaria lapathifolia</i>	Pale Smartweed	Plap	1				N-W	Tap	Both	Ann.
<i>Philenoptera violacea</i>	Apple Tree	Pvio	4				W	Tap	Sexual	Perr.
<i>Phragmites mauritanus</i>	Lowveld Reed	Pmau	15	32	19	20	N-W	Adv.	Asexual	Perr.
<i>Pluchea dioscoridis</i>	Marsh fleabane	Pdio	8	29			W	Tap	Sexual	Perr.
<i>Potamogeton crispus</i>	Curled Pondweed	Pcri	4	6		1	N-W	Adv.	Both	Perr.
<i>Ranunculus baurii</i>	-	Rbau	13	6	4	10	N-W	Tap	Both	Perr.
<i>Schoenoplectu s brachyceras</i>	-	Sbra	10	7	8	15	N-W	Adv.	Sexual	Perr.
<i>Vachellia burkei</i>	Black Monkey- Thorn	Vbur	1				W	Tap	Sexual	Perr.
Sub-totals of each cross-section:			73	111	37	198				
Grand totals of sites shown separately:			184		235					

Mamba shared 67% species overlap with those species recorded at Balule. Species that were recorded at Mamba only included; *Ceratophyllum demersum*, *P. lapathifolia*, *P. dioscoridis* and *V. burkei* and those that were recorded at Balule only included; *F. virosa*, *I. fasciculatum* and *L. schweinfurthii*. The plant species that were recorded in the highest abundances at each of the sites included; *P. mauritanus* recorded 42 times, *P. dioscoridis* recorded 37 times and *B. salicina* recorded 31 times at Mamba and *G. virgatum* was recorded 93 times, *P. mauritanus* 39 times, *Ischaemum fasciculatum* 27 times, *S. brachyceras* 23 times and *G. fruticosus* was recorded 19 at Balule.

Substrates

Associations were identified between substrate types and species for all sample points at Mamba and Balule sites along the lower Olifants River within the KNP (Table 3.5 and Figure 3.11). Average of relative abundances for plant populations were determined individually for

Mamba and Balule sites (Figure 3.11) and combined for both sites to provide overall substrate associations for plant populations (Table 3.5). Plant populations that showed the greatest degree of association between substrate types based on combined relative abundances at both sites included; *L. stolonifera* and *C. demersum* that was recorded on silt substrates 71.4% and 60% of all combined records respectively, *L. schweinfurthii* and *F. virosa* were located on fine sands 100% and 65% of all records respectively, *V. burkei* was located on sands 70% of all records and *G. fruticosus* and *G. virgatum* were recorded on bedrock substrates 59.6% and 58.4% of all overall records respectively (Table 3.5).

Table 3.5: Overall contribution of different particle sizes to the substrate composition (expressed as %) with associated vegetation species recorded along cross-sections at Mamba and Balule sites along the lower Olifants River within the Kruger National Park. Abbreviations used include 'Spp.' which refers to species in the form of abbreviations.

Species	silt	fine sand	sand	coarse sand	gravel	coarse gravel	cobble	large cobble	boulder	large boulder	bedrock
Bsal	3.1	32.6	10.1	17.1	11.9	0	8.1	0	2	0	15
Cdem	60	40	0	0	0	0	0	0	0	0	0
Csex	12.9	50.7	20.7	15.7	0	0	0	0	0	0	0
Fvir	0	65	30	5.0	0	0	0	0	0	0	0
Gfru	10.4	9.8	3	4.4	2.6	0	8.7	0	1.9	0	59.6
Gvir	18.7	7.1	5	4.6	3.3	0	2.8	0.2	0	0	58.4
Ifas	19.6	29.1	23.5	23.9	0.9	0	1.1	0	0	0	1.9
Lsch	0	100	0	0	0	0	0	0	0	0	0
Lsto	71.4	11.4	2.9	7.1	1.4	0	2.9	0	0	0	2.9
Nopp	0	28	49	23	0	0	0	0	0	0	0
Pcri	8.2	14.1	18.6	28.2	27.3	0	3.6	0	0	0	0
Pdio	0.4	32.2	16.9	13.4	15	0	6.9	0	0	1.9	13.4
Plap	0	100	0	0	0	0	0	0	0	0	0
Pmau	10.4	37.7	18.5	20.7	3.4	0.1	1.2	0	0	0	7.8
Pvio	0	57.5	42.5	0	0	0	0	0	0	0	0

Table 3.5: Continued

Rbau	23.2	27.3	20.6	8.2	6.4	0	5.7	0	1.2	0	7.4
Sbra	6.8	38.8	25.5	19.4	0.9	0	1	0	0	0	7.8
Vbur	0	30	70	0	0	0	0	0	0	0	0

Associations between the averaged relative abundances of substrate types and plant populations were assessed for the combined cross-sections 1 and 2 at Mamba (Figure 3.11). Plant populations that showed the greatest degree of association between averaged relative abundances of substrate types included; *C. demersum* and *L. stolonifera* that both associated with silt an average of 60% of all records, *P. lapathifolia* and *P. violacea* that associated with fine sands 100% and 57.5% of all records and *N. oppositifolia* and *V. burkei* that associated with sand 55% and 70% of all records respectively.

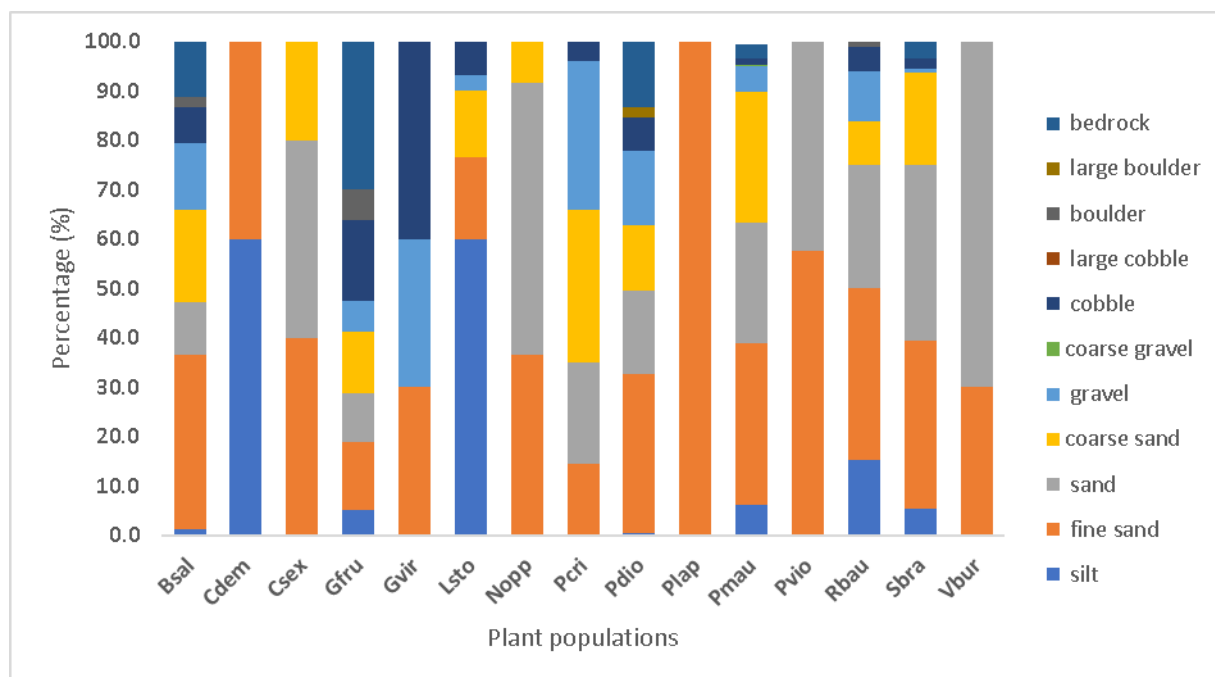


Figure 3.11: Average relative abundance substrate types and associated plant populations of cross-sections 1 and 2 at Mamba along the lower Olifants River within the Kruger National Park.

Associations between the averaged relative abundances of substrate types and plant populations were assessed for the combined cross-sections 1 and 2 at Balule (Figure 3.12). Plant populations that showed the greatest degree of association between averaged relative abundances of substrate types included *Ludwigia stolonifera* and *P. crispus*, which were located on 80% and 90% silt substrates of all Balule records, respectively. *Cyperus sexangularis*, *F. virosa* and *L. schweinfurthii* were located on fine sands an average of 52.5%, 65% and 100%

respectively. *Gomphocarpus fruticosus* and *G. virgatum* that were located on bedrock substrates an average of 72.1% and 59% of data points respectively.

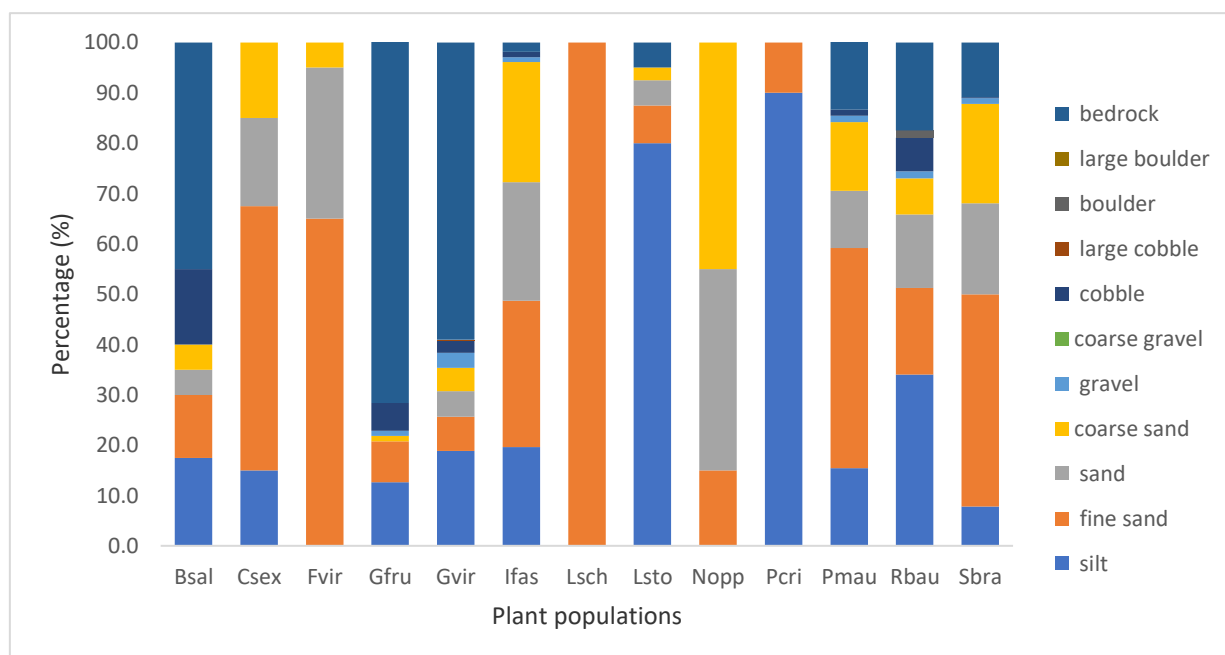


Figure 3.12: Average relative abundance substrate types and associated plant populations of cross-sections 1 and 2 at Balule along the lower Olifants River within the Kruger National Park.

An RDA multivariate analysis conducted for Mamba, combining substrate and plant community data collected along cross-sections 1 and 2 showed that significant associations existed ($F = 2.3$, $P = 0.001$) (Figure 3.13). Coarse sands and cobbles explained the highest variations, with P-values of 0.002 and 0.001, respectively.

Plant communities that showed the greatest associations towards substrate groups were; *Phragmites mauritianus* was significantly correlated with medium-sized substrate groups such as coarse gravel and coarse sands. *Pluchea dioscoridis* showed significant associations towards larger substrate groups such as gravel, bedrock and to a lesser degree large boulders. *Breonadia salicina*, *G. virgatum* and *G. fruticosus* showed associations towards cobbles and to a lesser degree boulders and lastly *S. brachyceras* and *L. stolonifera* showed significant associations towards fine sands.

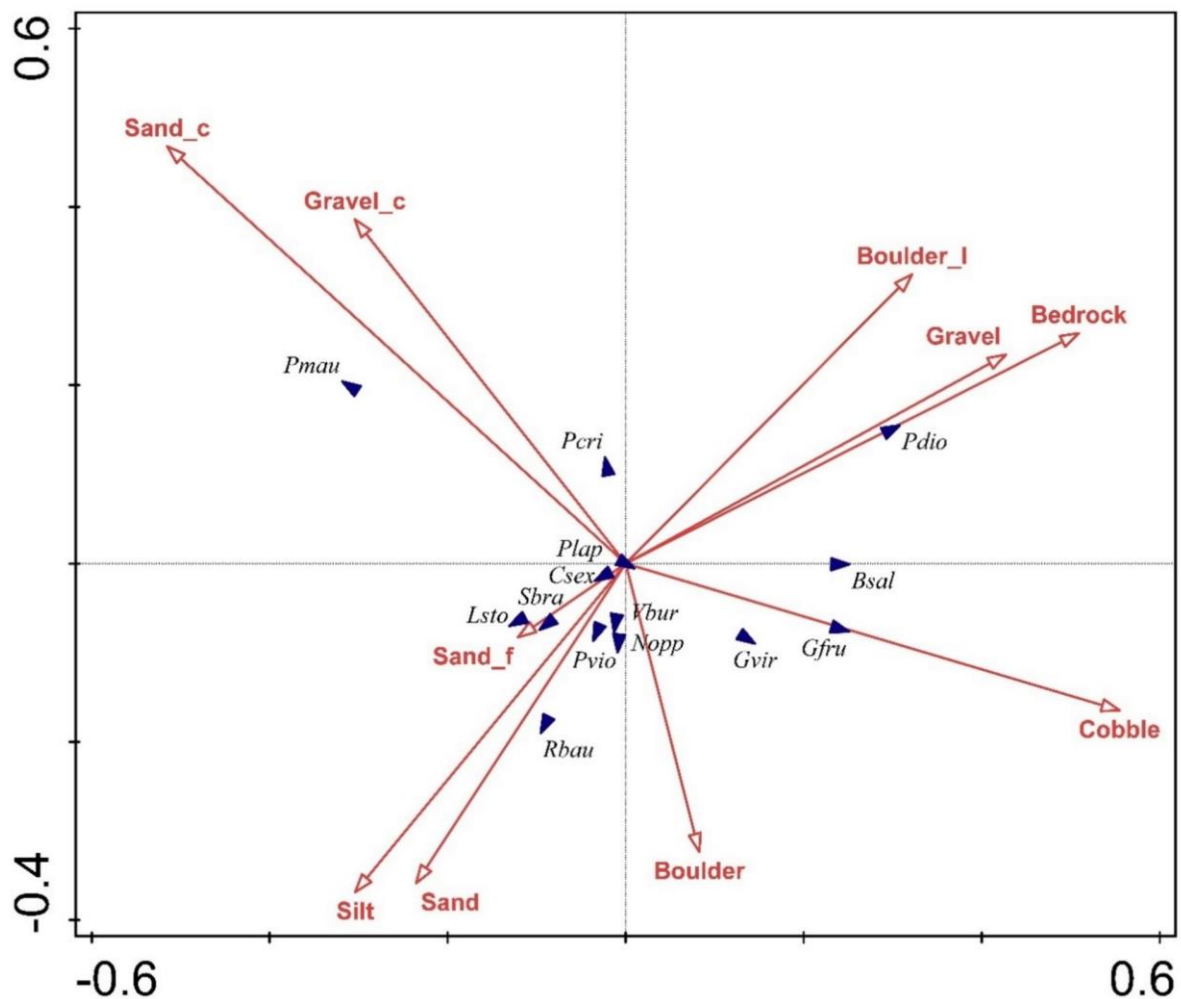


Figure 3.13: Redundancy analysis (RDA) tri-plot illustrating the associations between plant populations and substrate types at Mamba site along the lower Olifants River within the Kruger National Park. The tri-plot describes 6.8% of the total variation. Of the total fitted variation, 51.1% is explained on the first axis and 19.1% on the second axis, respectively. Abbreviations used in the plot included; 'boulder_l' = large boulders, 'sand_c' = coarse sand, 'sand_f' = fine sand and 'gravel_c' = coarse gravel.

An RDA multivariate analysis conducted for Balule, combining substrate and plant community data collected along cross-sections 1 and 2, showed that significant associations existed ($F = 5.2$, $P = 0.001$) (Figure 3.14). Bedrock substrates explained the highest percentage of variation at 12.8%, fine at 7.3%, sand explained 4.6% and coarse sands explained 3.2% of the variation portrayed on the plot.

The plant communities that showed the greatest degree of association towards substrate types were; *Ischaemum fasciculatum* that showed associations towards finer substrates such as sand and coarse sands. *Ranunculus baurii* and *L. stolonifera* showed correlations towards fine substrates such as silt, *G. virgatum* showed correlations towards larger substrates such as

bedrock and *B. salicina* and *G. fruticosus* showed significant correlations towards cobbles and to a lesser degree bedrock substrate types. Lastly, *P. mauritanus*, *S. brachyceras* and *C. sexangularis* showed associations towards fine sands.

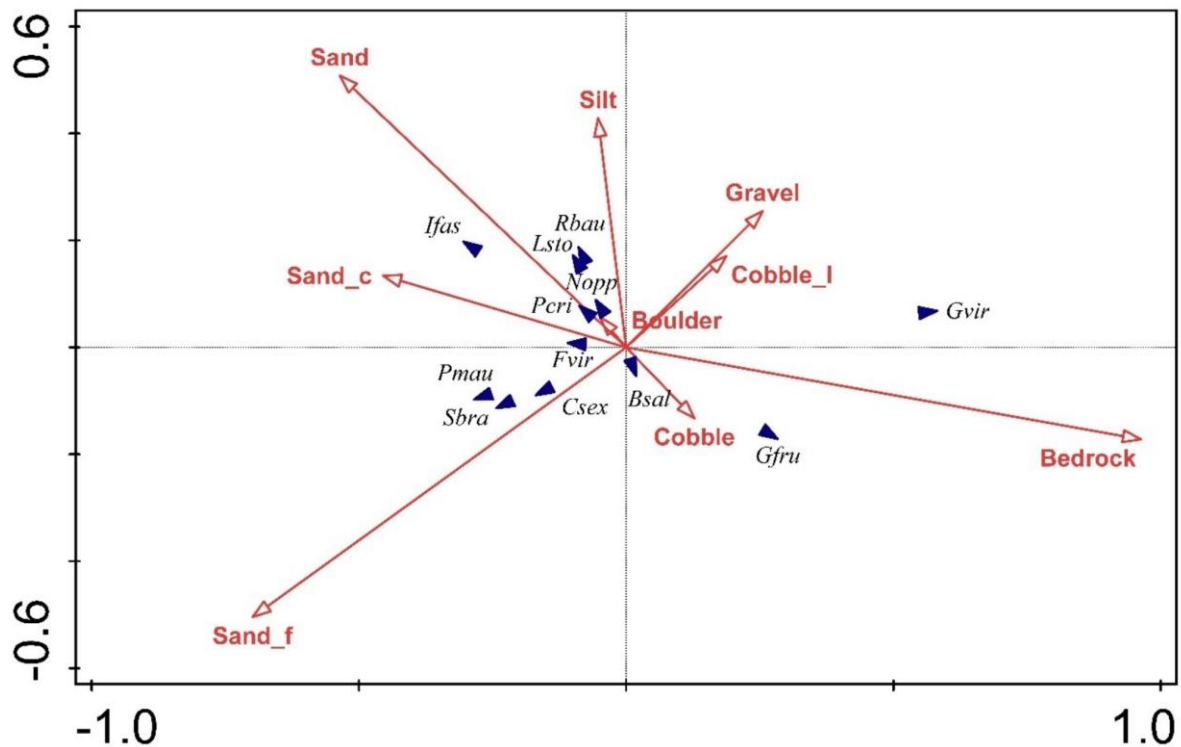


Figure 3.14: Redundancy analysis (RDA) tri-plot illustrating the associations between plant populations and substrate types at Balule site along the lower Olifants River within the Kruger National Park. The tri-plot describes 13.9% of the total variation. Of the total fitted variation, 79.6% is explained on the first axis and 10.7% on the second axis, respectively. Abbreviations used in the tri-plot include; ‘boulder_’ = large boulders, ‘sand_c’ = coarse sand, ‘sand_f’ = fine sand and ‘gravel_c’ = coarse gravel.

Associations between substrate types and biological traits

The relationships between substrates and biological traits were presented in the form of constrained multivariate RDA tri-plots that categorized all species into groups based on the biological traits at both Mamba and Balule sites (Figure 3.15, A-D and Figure 3.16, A-D). The biological traits that were tested for associations with substrate types included; woody versus non-woody, root types, reproductive strategies and annual/bi-annual versus perennial plant populations.

Mamba

The tri-plots showed significant associations between substrate types and woody versus non-woody biological traits ($F = 4.9$, $P = 0.001$), root types ($F = 4.2$, $P = 0.001$) and reproductive strategies ($F = 3.6$, $P = 0.001$) along cross-sections 1 and 2 at Mamba site. It was identified that significant relationships did not exist between substrate types and annual/bi-annual biological traits and substrate types.

The graphs indicated that woody plant populations, plants possessing tap roots and those that reproduced via sexual reproduction were associated with larger substrate types such as bedrock, cobbles, boulders and large boulders (Figure 3.15, A-C). In contrast, non-woody plant populations, those possessing adventitious root systems and those that had the ability to reproduce via both sexual and asexual reproductive strategies, were associated with finer substrates such as silt, fine sand, coarse sand and sand. Plant populations that reproduced exclusively through asexual reproduction showed the greatest associations towards coarse sand and coarse gravel (Figure 3.15, C).

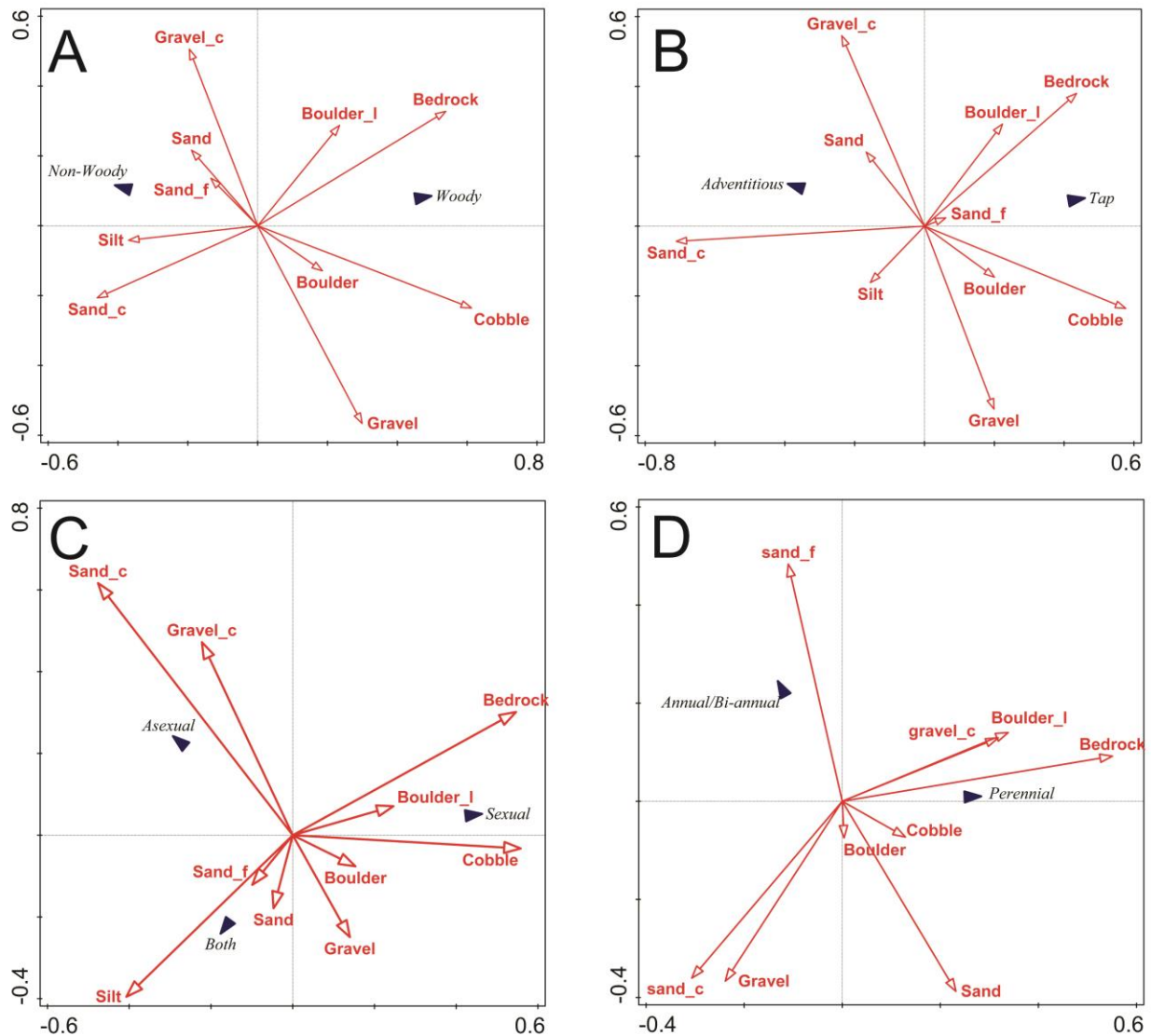


Figure 3.15: Constrained multivariate RDA tri-plots showing the relationships between substrate types and biological traits along cross-sections 1 and 2 combined at Mamba site along the lower Olifants River within the Kruger National Park. Graphs represent: (A) woody versus non-woody, (B) root systems: adventitious versus tap, (C) reproductive strategies: sexual, asexual and both strategies combined and (D) annual/bi-annual plants versus perennial. Tri-plot (A) describes 17.5% of the total variation. Of the total fitted variation, 95.4% is described on the first axis and 4.6% on the second axis respectively. Tri-plot (B) describes 15% of the total variation. Of the total fitted variation, 94.9% are described on the first axis and 5.1% on the second. Tri-plot (C) describes 12.6% of the total variation. Of the total fitted variation, 79.8 are described on the first axis and 17.6% on the second axes. Tri-plot (D) describes 2.7% of the total variation. Of the total fitted variation, 93.8% is described on the first axes and 6.2% on the second axes.

Associations between substrate types and biological traits were found to be significant for analyses comparing biological traits; woody versus non-woody ($F = 19.8$, $P = 0.001$), root types ($F = 17.1$, $P = 0.001$), reproductive strategies ($F = 7.9$, $P = 0.001$) and annual/bi-annual versus perennial ($F = 2$, $P = 0.031$) (Figure 3.16, A-D).

The graphs indicate that plant populations possessing woody traits, possessing tap root systems and those that reproduce via sexual reproduction were associated with larger substrates such as bedrock, cobbles, large cobbles and gravel. Plant populations possessing non-woody traits and those that reproduced exclusively through asexual reproduction and those that had the ability to reproduce both sexually and asexually showed the greatest associations with finer substrates such as fine sand, sand and coarse sands. The graphs displaying associations between biological traits annual/bi-annual versus perennial and substrate types indicated that those possessing annual/bi-annual traits were associated with silt and those possessing perennial traits were associated with sand, cobbles and large cobbles.

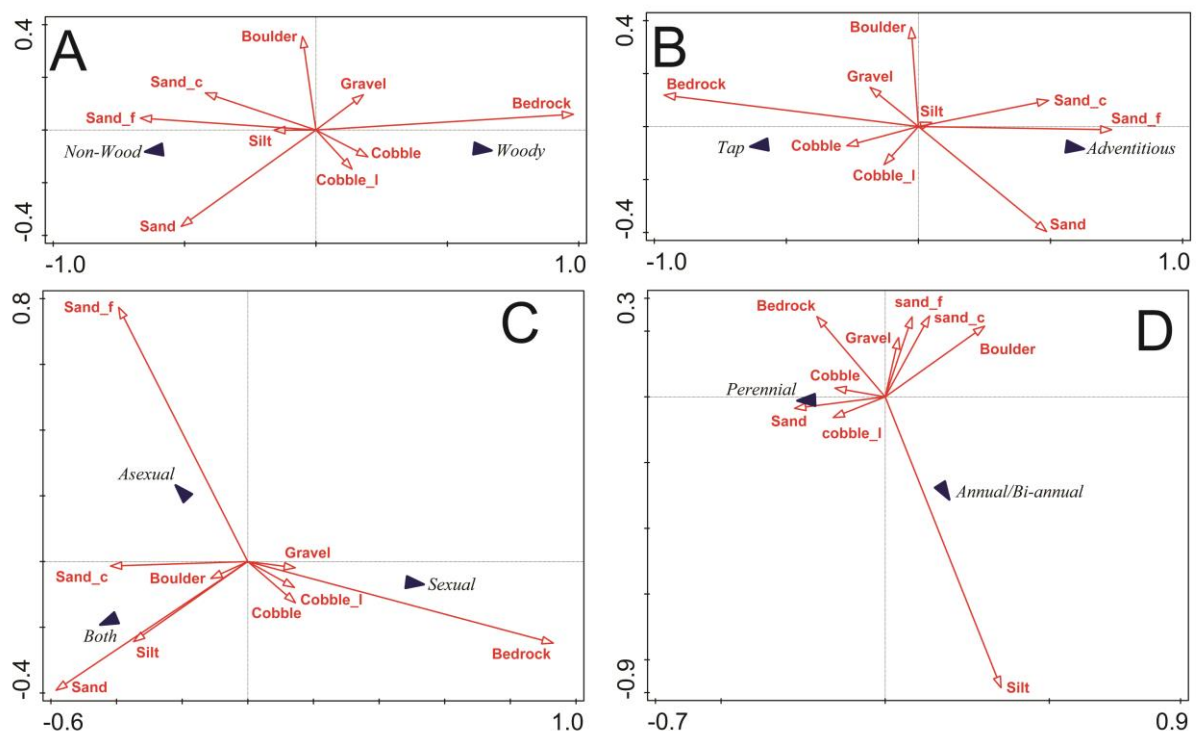


Figure 3.16: Constrained multivariate RDA tri-plots showing the relationships between substrate types and biological traits along cross-sections 1 and 2 combined at Balule site along the lower Olifants River within the Kruger National Park. Graphs represent: (A) woody versus non-woody, (B) root systems: adventitious versus tap, (C) reproductive strategies: sexual, asexual and both strategies combined and (D) annual/bi-annual plants versus perennial. Tri-plot (A) describes 41.9% of the total variation. Of the total fitted variation, 98.6% is described on the

first axis and 1.4% on the second axis respectively. Tri-plot (B) describes 38.2% of the total variation. Of the total fitted variation, 98.4% are described on the first axis and 1.6% on the second. Tri-plot (C) describes 21% of the total variation. Of the total fitted variation, 88.2% are described on the first axis and 10.5% on the second axes. Tri-plot (D) describes 3.8% of the total variation. Of the total fitted variation, 93.5% is described on the first axes and 6.5% on the second axes.

Water quality

In situ water quality analysis was conducted on the 29th September 2020 at Mamba site and 4th October 2020 at Balule site along the lower Olifants River within the KNP. Results indicate that electrical conductivity, temperature, pH, DO%, DO (mg/l) and TDS were higher at Mamba when compared to Balule.

Table 3.6: *In situ* physio-chemical water quality results for Mamba and Balule sites along the Olifants River, Kruger National Park.

SITE	EC $\mu\text{S/cm}$	$^{\circ}\text{C}$	pH	DO%	DO mg/l	TDS mg/l
MAMBA	1278.00	22.80	8.73	127.90	11.42	907.00
BALULE	547.00	20.30	8.60	109.50	10.20	642.00

Water quality received from laboratory tests show results for tested parameters (Table 3.7). Results show that turbidity, SO_4^{2-} , NO_2^- , Cl^- and COD were higher at Mamba while NH_4^+ , NO_3^- , PO_4^{3-} , Mg and Ca were higher at Balule.

Table 3.7: Laboratory results of water quality samples taken in triplicate from Mamba and Balule sites along the lower Olifants River within the Kruger National Park. Values are represented as averages of triplicate samples.

SITE	Turbidity	SO_4^{2-}	NH_4^+	NO_3^-	NO_2^-	PO_4^{3-}	Cl^-	COD	Mg	Ca
MAMBA	13.00	66.00	0.10	1.87	0.08	0.12	41.67	4.83	1.37	0.02
BALULE	12.00	62.70	0.12	1.97	0.01	6.20	32.70	4.30	26.60	21.40

Hydraulics: activation discharge

Activation discharge parameters were provided for cross-sections 2 at both Mamba and Balule in the form of average per species and lowest and highest recorded values per species at each of the sites (Table 3.8 and Table 3.9). *Potamogeton crispus* was located at the lowest average activation discharge at an average of $1.6 \text{ m}^3.\text{s}^{-1}$ at Mamba, while *N. oppositifolia* was located at the highest average AD of $491.6 \text{ m}^3.\text{s}^{-1}$ (Table 3.8).

Table 3.8: Activation discharge (AD) parameters of plant populations recorded along cross-section 2 at Mamba site along the lower Olifants River within the Kruger National Park illustrating average (ave.), median (med.), minimum (min.) and maximum (max.).

Scientific names	Abbreviated names	Ave.	Med.	Min.	Max.
<i>Breonadia salicina</i>	<i>Bsal</i>	61.4	54.4	20.5	89.7
<i>Cyperus sexangularis</i>	<i>Csex</i>	222.1	222.1	222.1	222.1
<i>Gomphocarpus fruticosus</i>	<i>Gfru</i>	101.7	101.7	67.2	136.2
<i>Gomphostigma virgatum</i>	<i>Gvir</i>	67.2	67.2	67.2	67.2
<i>Nuxia oppositifolia</i>	<i>Nopp</i>	491.6	491.6	491.6	491.6
<i>Phragmites mauritianus</i>	<i>Pmau</i>	92.3	68.4	5.2	294.1
<i>Pluchea dioscoridis</i>	<i>Pdio</i>	51.5	54.4	10.6	81.8
<i>Potamogeton crispus</i>	<i>Pcri</i>	1.6	1.3	0.0	5.2
<i>Ranunculus baurii</i>	<i>Rbau</i>	58.0	65	38.1	69.5
<i>Schoenoplectus brachyceras</i>	<i>Sbra</i>	78.3	69.6	15.1	139.7

Activation discharge readings at Balule site along cross-section 2 indicated that *P. crispus* was located at the lowest average value of $0.1 \text{ m}^3.\text{s}^{-1}$ and second to that was *L. stolonifera* at an average AD of $5.7 \text{ m}^3.\text{s}^{-1}$ (Table 3.9). *Lansea schweinfurthii* was located at the highest average AD of $8903.9 \text{ m}^3.\text{s}^{-1}$ and second to that was *F. virosa* at an average AD of $669.7 \text{ m}^3.\text{s}^{-1}$.

Table 3.9: Activation discharge parameters of plant populations recorded along cross-section 2 at Balule site along the lower Olifants River within the Kruger National Park illustrating average, median, minimum and maximum.

Scientific names	Abbreviated names	Ave.	Med.	Min	Max
<i>Breonadia salicina</i>	<i>Bsal</i>	41.8	28.8	21.6	88.2
<i>Cyperus sexangularis</i>	<i>Csex</i>	168.9	96.2	88.2	357.3
<i>Flueggea virosa</i>	<i>Fvir</i>	669.7	669.7	561.7	777.8
<i>Gomphocarpus fruticosus</i>	<i>Gfru</i>	67.9	26.5	17.8	266.1
<i>Gomphostigma virgatum</i>	<i>Gvir</i>	21.9	19	9.1	60.7
<i>Ischaemum fasciculatum</i>	<i>Ifas</i>	45.4	43	2.7	91.3
<i>Lannea schweinfurthii</i>	<i>Lsch</i>	8903.9	8903.9	8903.9	8903.9
<i>Ludwigia stolonifera</i>	<i>Lsto</i>	5.7	2.8	2.7	11.6
<i>Nuxia oppositifolia</i>	<i>Nopp</i>	355.7	355.7	149.8	561.7
<i>Phragmite mauritanus</i>	<i>Pmau</i>	93.4	63.6	9.1	561.7
<i>Potamogeton crispus</i>	<i>Pcri</i>	0.1	0.1	0.1	0.1
<i>Ranunculus baurii</i>	<i>Rbau</i>	22.8	14.6	0.3	60.7
<i>Schoenoplectus brachyceras</i>	<i>Sbra</i>	55.1	49.2	20.3	91.3

Activation discharge values along cross-section 2 at Mamba indicate that 80% of the plant populations ranged from 0 to 200 m³.s⁻¹ (Figure 3.17, A and B). Both *C. sexangularis* and *N. oppositifolia* were outside of that bracket and both were recorded only once along this cross-section. *Phragmites mauritanus* had the widest hydraulic range from 5.2 m³.s⁻¹ to 294.1 m³.s⁻¹. Plant populations that had AD of less than 100 m³.s⁻¹ included; *Breonadia salicina*, *G. virgatum*, *P. dioscoridis*, *P. crispus* and *R. baurii* while *P. crispus* had a maximum AD of less than 10 m³.s⁻¹.

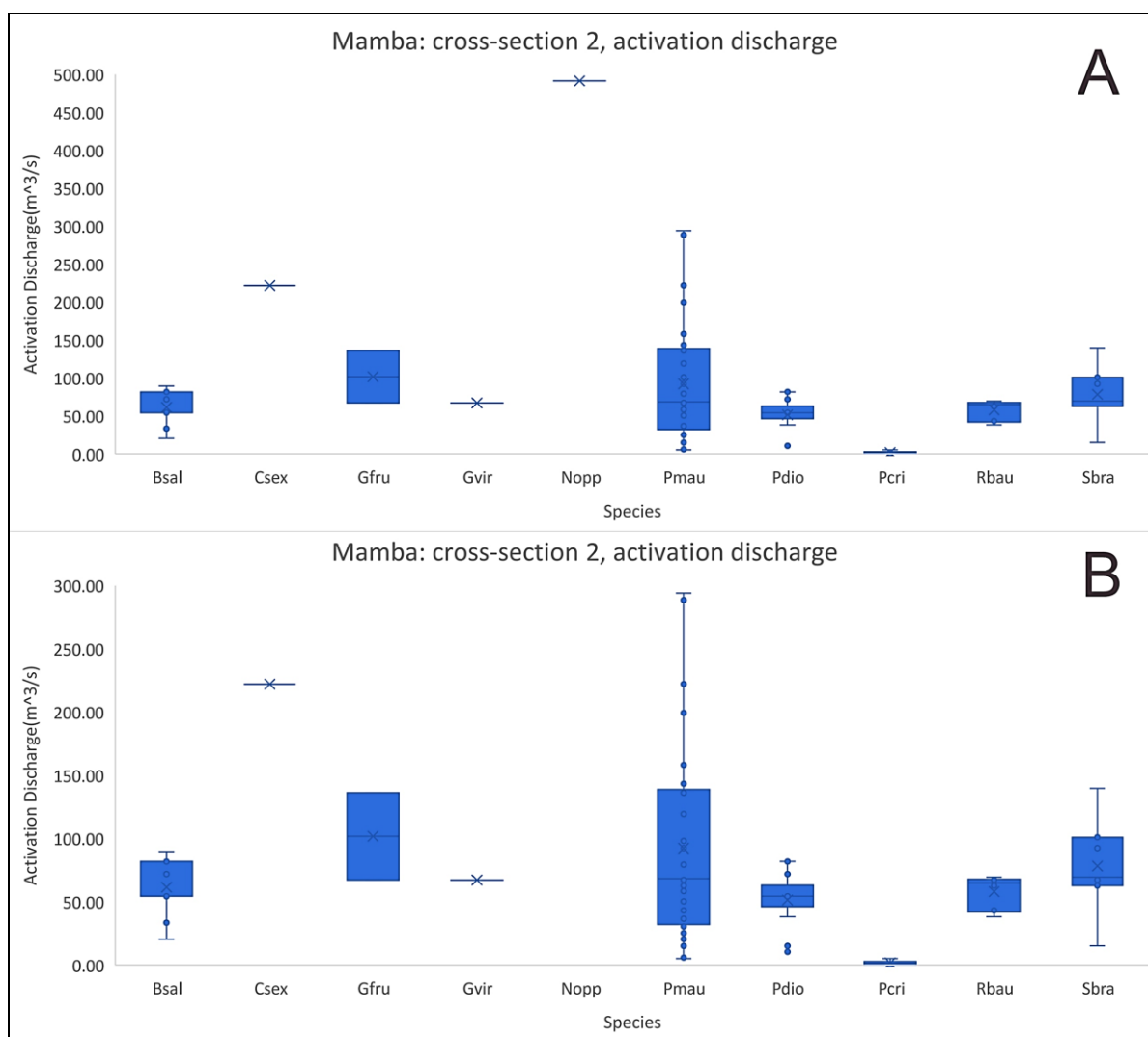


Figure 3.17: Box and whisker plot representing medians and 95th percentiles of hydraulic ranges of plant communities recorded along cross-section 2 at Mamba site along the lower Olifants River within the Kruger National Park. (A) represents the full spectrum of species recorded along the cross section and (B) removed *Nuxia oppositifolia* as an outlier for improved resolution of remaining species.

Activation discharge values along cross-section 2 at Balule indicate that 77% of plant populations did not exceed 300 m³.s⁻¹ (Figure 3.18, A and B). The upper limit of *Nuxia oppositifolia* exceeded this value by a small margin where *F. virosa* and *L. schweinfurthii* exceeded this by a large margin. *Flueggea virosa* ranged between 561.7 m³.s⁻¹ and 777.8 m³.s⁻¹ and *L. schweinfurthii* produced a maximum AD value of 8903.9 m³.s⁻¹. Both *N. oppositifolia* and *F. virosa* were recorded twice along this cross-section and *L. schweinfurthii* was recorded only once. Plant populations that fell below a maximum value of 100 m³.s⁻¹ included; *B. salicina*, *G. virgatum*, *I. fasciculatum*, *L. stolonifera*, *R. baurii* and *S. brachyceras* while *I. fasciculatum* fell below a maximum value of 15 m³.s⁻¹.

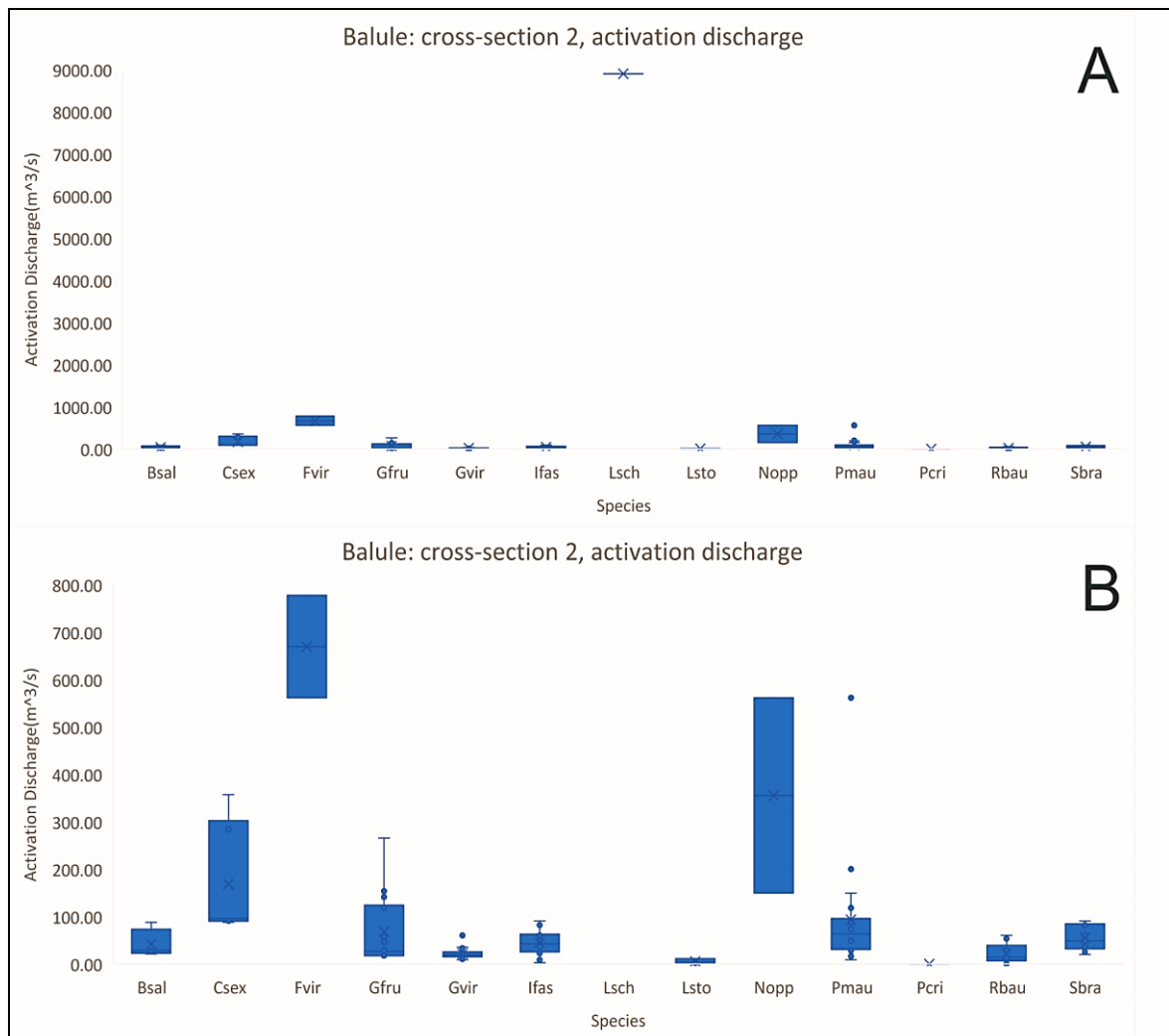


Figure 3.18: Box and whisker plots representing activation discharge range of plant communities recorded along cross-section 2 at Balule site along the lower Olifants River within the Kruger National Park. (A) Represents the complete composition of plant communities, while (B) represents all plant populations except that of *Lannea schweinfurthii* whose range far exceeded the remaining populations.

Variations between Mamba and Balule sites of plant populations that were recorded at both sites were narrow, differing by a maximum value of $8.8 \text{ m}^3\cdot\text{s}^{-1}$. *Breonadia salicina* recorded a maximum AD of $89.7 \text{ m}^3\cdot\text{s}^{-1}$ at Mamba and $88.2 \text{ m}^3\cdot\text{s}^{-1}$ at Balule while *G. virgatum* at $67.2 \text{ m}^3\cdot\text{s}^{-1}$ versus $60.7 \text{ m}^3\cdot\text{s}^{-1}$ and *R. baurii* at $69.5 \text{ m}^3\cdot\text{s}^{-1}$ versus $60.7 \text{ m}^3\cdot\text{s}^{-1}$, respectively (Table 3.8 and Table 3.9).

3.3.2 Determine the present ecological status (PES) of riparian vegetation with the use of the Riparian Vegetation Response Assessment Index (VEGRAI)

A. Mamba

Thirty plant taxa were observed at Mamba site which included aquatic/semi-aquatic, woody and non-woody species (Table 3.10). Five species were alien and/or invasive species and the remaining 25 were indigenous. The site was dominated by non-woody species with a well-developed tree-line. Prominent aquatic and semi-aquatic species observed included; *Ranunculus baurii*, *P. crispus*, *P. pectinatus* and *Azolla* sp. (Figure 3.19). Prominent woody species included *B. salicina*, *G. fruticosus* and *F. sycamorus*. Prominent non-woody species included; *Phragmites mauritianus* and *C. sexangularis*.

Table 3.10: Full list of plant species observed during a VEGRAI assessment at Mamba site along the lower Olifants River within the Kruger National Park.

SCIENTIFIC NAME	COMMON NAME	STATUS
<i>Azolla</i> sp.	Mosquito Fern	Alien
<i>Breonadia salicina</i>	Matumi Tree	Indigenous
<i>Ceratophyllum demersum</i>	Coontail	Indigenous
<i>Croton gratissimus</i>	Lavender Fever Berry	Indigenous
<i>Cyperus dives</i>	Giant sedge	Indigenous
<i>Cyperus sexangularis</i>	Bushveld sedge	Indigenous
<i>Datura stramonium</i>	Jimson Weed	Alien
<i>Diospyros mespiliformis</i>	Jackalberry	Indigenous
<i>Euclea crispa</i>	Blue guarri	Indigenous
<i>Euclea divinorum</i>	Magic guarri	Indigenous
<i>Ficus sycomorus</i>	Sycamore Fig Tree	Indigenous
<i>Flueggea virosa</i>	White berry-bush	Indigenous
<i>Gomphocarpus fruticosus</i>	Milkweed	Indigenous
<i>Gymnosporia senegalensis</i>	Confetti Spikethorn	Indigenous
<i>Ludwigia stolonifera</i>	Creeping Ludwigia	Indigenous
<i>Nuxia oppositifolia</i>	Water Elder	Indigenous
<i>Persicaria lapathifolia</i>	Pale Smartweed	Alien
<i>Phragmites mauritianus</i>	-	Indigenous
<i>Pluchea dioscoridis</i>	-	Indigenous
<i>Potamogeton crispus</i>	Curly-leaf pondweed	Indigenous

Table 3.10: Continued

<i>Potamogeton pectinatus</i>	Fennel pondweed	Indigenous
<i>Ranunculus baurii</i>	-	Indigenous
<i>Schoenoplectus brachyceras</i>	-	Indigenous
<i>Sclerocarya birrea</i>	Marula tree	Indigenous
<i>Sesbania punicea</i>	Red Sesbania	Alien
<i>Spirostachys africana</i>	Tamboti	Indigenous
<i>Sporobolus fimbriatus</i>	Perennial Dropseed	Indigenous
<i>Trichilia emetica</i>	Natal Mahogany	Indigenous
<i>Vachellia robusta</i>	Broadpod robust thorn	Indigenous
<i>Xanthium strumarium</i>	Large cocklebur	Alien



Figure 3.19: Some of the plant species recorded during the VEGRAI survey at Mamba where; (A) *Phragmites mauritianus*, (B) *Ranunculus baurii*, (C) *Potamogeton crispus* and *Azolla* sp., (D) *Cyperus sexangularis*, (E) *Gomphocarpus fruticosus*, (F) *Breonadia salicina* adult, (G) *Potamogeton pectinatus*, (H) *Ficus sycomorus* and (I) *Breonadia salicina* juvenile.

The VEGRAI assessment took place within the vicinity where the cross-section profiles were conducted at Mamba site, extending approximately 150-200 m upstream and downstream of position of the transects. The expected condition of Mamba site devoid of anthropogenic

influence (reference condition) most likely included lower abundances of woody plants within the marginal, lower and to a lesser degree the upper zone. The increased abundances of woody plants for the PES are likely due to flow restrictions allowing for terrestrial encroachment or the prevalence of woody riparian species within zones closer to the water's edge as reduced seasonal flooding provided for appropriate opportunity to expand their distribution perpendicular to flow. Furthermore, a site devoid of anthropogenic influence would exclude all alien plants.

1 Marginal Zone

The marginal zone was dominated by non-woody vegetation, primarily consisting of three species: *Ranunculus baurii*, *P. mauritanus* and *S. brachyceras* (Figure 3.20). The compositions within this zone were similar to what would have been expected under reference except for influences resulting from altered hydrological regimes which would have impacted the channel bed and sediment movement potential as a result of the Phalaborwa barrage upstream of the site location.



Figure 3.20: Mamba site along the lower Olifants River within the Kruger National Park showing a variety of landscapes within marginal zone where (A) represents an on-line view along cross-section 1, (B) a small area between cross-sections 1 and 2, (C) on-line along cross-section 2 and (D) a downstream view from cross-section 2.

Impacts

The impacts in the marginal zone were mainly due to reduced flows and potentially compromised water quality from upstream influences (Table 3.11). This resulted in increased aerial cover as a result of reduced consistent and regular uprooting from natural seasonal pulses. An additional response to reduced flows is the encroachment of woody plants that would normally have been removed through seasonal pulses. Observed vegetation removal was mainly due to herbivory from wildlife as a result of food scarcity which naturally coincides with the end of the dry season therefore the scores were not negatively impacted as the results were due to natural influences. Alien plants were present within the zone but in relatively low abundances, measuring <10% overall aerial cover for intensity and extent. Water quality probably had a degree of impact on the site as moderate amounts of algae were observed in nearby flowing channels and stagnant pools. The extent of this evidence was limited to smaller areas. There was no evidence of erosion by anthropogenic influence.

Table 3.11: Impacts recorded within the marginal zone during a VEGRAI assessment at Mamba site along the lower Olifants River within the Kruger National Park.

IMPACTS	INTENSITY	EXTENT	CONFIDENCE
REMOVAL	0.0	0.0	2.0
ALIEN INVASION	1.5	1.5	5.0
WATER QUANTITY	3.5	5.0	4.0
WATER QUALITY	2.0	2.0	1.0
EROSION	0.0	0.0	1.0
AVERAGE			3.0

Responses

The marginal zone was characterised by non-woody *P. mauritanus*, *S. brachyceras* and *L. stolonifera*. Factors that potentially affected woody species aerial cover percentage, abundance, recruitment and species composition included water quality and flow restrictions which have affected sediment movement potential. The ratings were allocated a low value with low levels of confidence (Table 3.12) as the woody components were limited at within the zone. Population structures of woody species were not assessed for this study.

The non-woody category including reeds were moderately reduced as a response to altered flow regimes when considering only anthropogenic influences. There was evidence of woody and non-woody plants that were uprooted from recent flooding events. The combination of the recent flood and drought events together with altered flow regimes and the resultant restriction

of natural sediment movement had resulted in scoured riverine landscapes dominated by bedrock superficially overlain with alluvial substrates. The reduction in alluvial habitat had resulted in reduced non-woody aerial cover percentages, abundances and species compositions. The browsing, grazing and floods were not considered when scoring this section as they fell under natural processes. The effect of alien and invasive plant species was rated low to moderate for this zone, therefore were considered a relatively minor impact on non-woody aerial cover percentage, abundances and species compositions. This particular site contained five alien and invasive species and were at relatively low abundances. These included; *Azolla* sp., *D. stramonium*, *S. punicea*, *P. lapathifolia* and *X. strumarium*. *Sesbania punicea* is considered a problematic alien species as it is perennial and can be invasive, competing with indigenous plants (Mackenzie, 2020).

Table 3.12: Response metric ratings of the marginal zone of a VEGRAI assessment at Mamba site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	RESPONSE METRIC	CONSIDER? (Y/N)	RATING	CONFIDENCE
WOODY	COVER	Y	0.5	2.0
	ABUNDANCE	Y	0.5	2.0
	POPULATION STRUCTURE	N	N/A	N/A
	VERTICAL STRUCTURE	Y	0.5	2.0
	RECRUITMENT	Y	0.0	2.0
	SPECIES COMPOSITION	Y	0.5	2.0
	AVERAGE		0.4	2.0
NON-WOODY CATEGORY (Including reeds)	COVER	Y	2.0	2.0
	ABUNDANCE	Y	2.0	2.0
	AVERAGE		2.0	2.0
NON-WOODY (Excluding reeds)	COVER	Y	2.0	2.0
	ABUNDANCE	Y	2.0	2.0
	SPECIES COMPOSITION	Y	1.0	2.0
	AVERAGE		1.7	2.0

Ranking

The non-woody category (including reeds) was considered the highest ranked category in the marginal zone at Mamba site because they dominate the zone, and are also expected to dominate the zone (Table 3.13). Non-woody (excluding reeds) ranked second and the woody component ranked third due to the low abundances of woody plants within the zone.

The marginal zone scored an overall score of 32.8% falling within the ecological category C with regard to the degree of change from reference condition as a result of anthropogenic influence. Category C is considered 'fair' and is described as moderately modified with reduced biodiversity and a high abundance of hardy species. Impaired functionality of the system could be evident at the lower end of this class (Kleynhans et al., 2007).

Table 3.13: Ranking and weighting of a VEGRAI assessment in the marginal zone at Mamba site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	CONSIDER? (Y/N)	RANK	WEIGHT	RATING	WEIGHTED RATING	MEAN CONFIDENCE
WOODY	Y	3.0	30.0	0.4	0.12	2.0
NON-WOODY CATEGORY (Including reeds)	Y	1.0	100.0	2.0	2.00	2.0
NON-WOODY (Excluding reeds)	Y	2.0	40.0	1.7	0.67	2.0
AVERAGE					2.79	2.0
CHANGE (%) IN VEGETATION COMPONENTS:					32.8	C
OVERALL CHANGE IN LATERAL ZONE CONDITION						

2 Lower Zone

The lower zone was dominated by *P. mauritianus* with moderate abundances of *S. brachyceras* and to a lesser degree *G. fruticosus* and a non-woody alien invasive *X. strumarium* (Figure 3.21). The expected reference state would likely have contained fewer woody plants and no alien invasive species. The woody plants are likely the result of flow restrictions and the resultant encroachment by woody individuals.



Figure 3.21: Photographs A to D illustrating the lower zone at Mamba site along the lower Olifants River within the Kruger National Park where (A) showed a view upstream of cross-section 2, (B) showed an on-line view on the left bank of cross-section 2, (C) showed a diagonal view of downstream of cross-sections 1 and 2 and (D) showed a downstream view from cross-section 1.

Impacts

The impacts in the lower zone were mainly due to alterations to natural flow regimes (Table 3.14). There was no evidence of vegetation removal via anthropogenic sources. Removal by natural herbivory was evident and the effects from the recent floods and drought was also evident however, these natural processes were not scored negatively during this assessment. Alien and invasive species had a moderate impact within the zone both intensively and extensively, falling within the aerial cover percentage bracket of 10-20% within the lower zone. Water quantity was another contributing factor to the vegetation located within this zone as a result of alterations to natural flow regimes and flow restrictions. Water quality was potentially a contributing factor to the wellbeing of the plants within this zone as high quantities of algae was observed in the nearby surface water. There was no evidence of erosion by anthropogenic influence.

Table 3.14: Impacts recorded within the lower zone during a VEGRAI assessment at Mamba site along the lower Olifants River within the Kruger National Park.

IMPACTS	INTENSITY	EXTENT	CONFIDENCE
REMOVAL	0.0	0.0	5.0
ALIEN INVASION	2.0	3.0	5.0
WATER QUANTITY	2.0	2.5	4.0
WATER QUALITY	1.0	1.5	2.0
EROSION	0.0	0.0	2.0
AVERAGE			3.0

Responses

The lower zone was dominated by *G. fruticosus*, *S. brachyceras*, *P. mauritanus* and the alien and invasive species *X. strumarium*. The less dominant woody species recorded within the zone included; *Nuxia oppositifolia* and the alien and invasive species *S. punicea*. Cover and abundance for both woody and non-woody categories were potentially reduced as a result of flow alterations and alien and invasive plant species that were present at moderate concentrations within the zone (Table 3.15).

Table 3.15: Response metric ratings of the lower zone of a VEGRAI assessment at Mamba site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	RESPONSE METRIC	CONSIDER? (Y/N)	RATING	CONFIDENCE
WOODY	COVER	Y	1.0	2.0
	ABUNDANCE	Y	2.0	2.0
	POPULATION STRUCTURE	N	N/A	N/A
	VERTICAL STRUCTURE	Y	1.0	2.0
	RECRUITMENT	Y	2.0	2.0
	SPECIES COMPOSITION	Y	2.0	2.0
	AVERAGE		1.6	2.0

Table 3.15: Continued

NON-WOODY CATEGORY (Including reeds)	COVER	Y	2.0	2.0
	ABUNDANCE	Y	1.5	2.0
	AVERAGE		1.8	2.0
NON-WOODY (Excluding reeds)	COVER	Y	1.0	2.0
	ABUNDANCE	Y	1.0	2.0
	SPECIES COMPOSITION	Y	2.0	2.0
	AVERAGE		1.3	2.0

Ranking

The non-woody category (including reeds) was weighted highest due to the large reed component within the zone (Table 3.16). Other non-woody components were weighted second and the woody component weighted last due to the low concentrations of woody plants within the zone. The lower zone was scored an overall rating of 32,2% which fell within the ecological category C which is described as “fair: moderately modified”.

Table 3.16: Ranking and weighting of a VEGRAI assessment of the lower zone at Mamba site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	CONSIDER? (Y/N)	RANK	WEIGHT	RATING	WEIGHTED RATING	MEAN CONFIDENCE
WOODY	Y	3.0	40.0	1.6	0.64	2.0
NON-WOODY CATEGORY (Including reeds)	Y	1.0	100.0	1.8	1.75	2.0
NON-WOODY (Excluding reeds)	Y	2.0	50.0	1.3	0.67	2.0
AVERAGE					3.06	2.0
CHANGE (%) IN VEGETATION COMPONENTS: OVERALL CHANGE IN LATERAL ZONE CONDITION			32.2	C		

3 Upper Zone

The upper zone contained a larger woody component consisting of *T. emetica*, *D. mespiliformis*, *S. africana*, *C. gratissimus* and *F. sycomorus* (Figure 3.22). This zone was similar to what would have been expected under reference conditions.

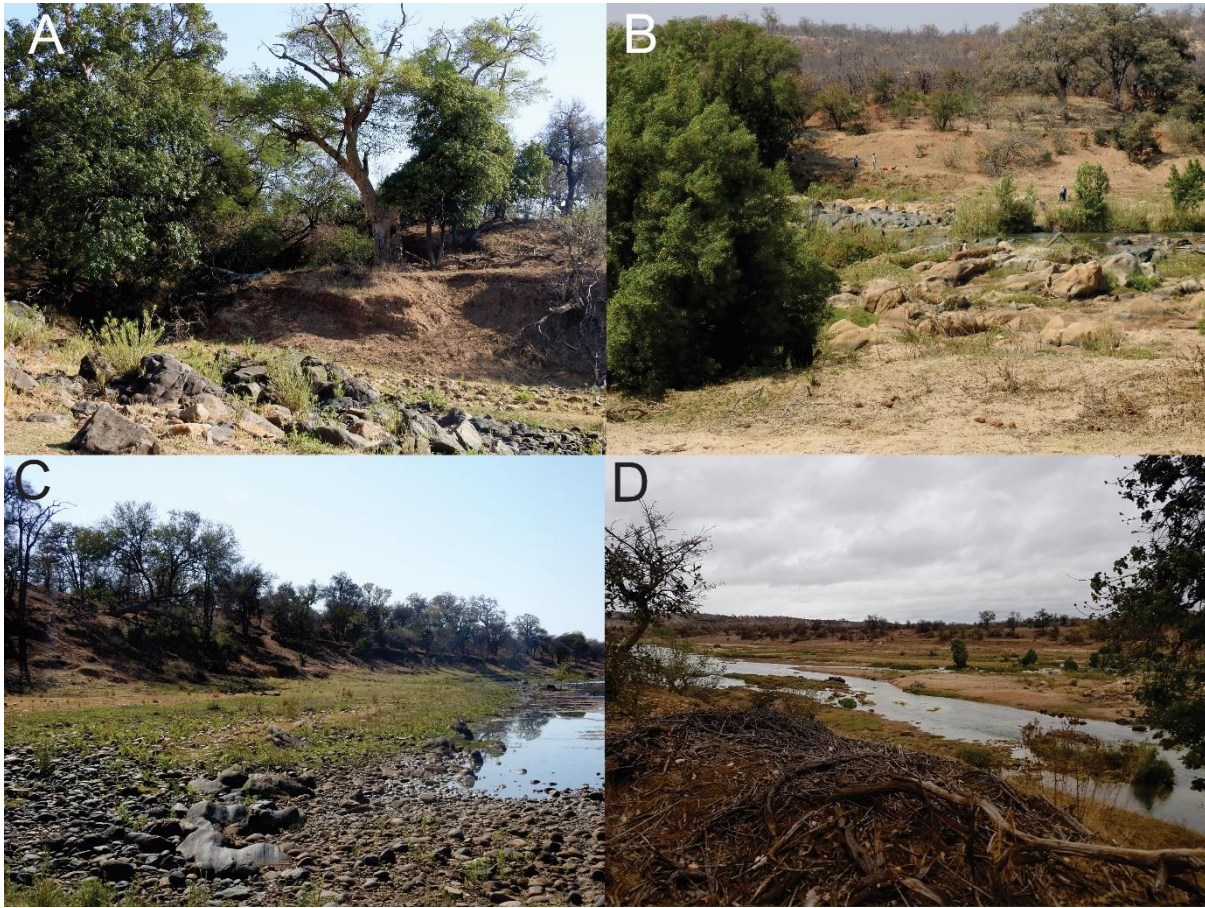


Figure 3.22: Photographs depicting various landscapes within the upper and macro-channel bank zones at Mamba site along the lower Olifants River within the Kruger National Park where; (A) shows an on-line view of the upper and macro-channel bank zones from cross-section 1, (B) shows an on-line view (from the left bank) of cross-section 1, (C) shows a downstream view from cross-section 2 and (D) shows a downstream view from cross-section 1.

Impacts

There was no observed evidence of vegetation removal by anthropogenic influence within the upper zone (Table 3.17). There were mild to moderate abundances of alien and invasive plants comprising of less than 10% of the total aerial cover. Impacts by water quantity were limited to larger floods with regard to flow restrictions. There were no observed signs of erosion by anthropogenic influences.

Table 3.17: Impacts recorded within the upper zone during a VEGRAI assessment at Mamba site along the lower Olifants River within the Kruger National Park.

IMPACTS	INTENSITY	EXTENT	CONFIDENCE
REMOVAL	0.0	0.0	4.0
ALIEN INVASION	2.0	2.0	5.0
WATER QUANTITY	1.0	1.0	4.0
WATER QUALITY	0.0	0.0	2.0
EROSION	0.0	0.0	2.0
AVERAGE			2.8

Responses

Overall responses by native vegetation scored low with regard to change from expected reference condition (Table 3.18). The cover percentage, abundance, vertical structure, recruitment and species composition all scored low for woody species. These scores were due to the mild to moderate abundances of alien and invasive plant species present within the zone. The non-woody category (including reeds) scored zero for both cover and abundance due to the low abundances of this category within the zone. Cover, abundance and species composition for non-woody category (excluding reeds) also scored low with regard to change from reference condition. This was also due to the alien and invasive plants present within the zone.

Table 3.18: Response metric ratings of the upper zone of a VEGRAI assessment at Mamba site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	RESPONSE METRIC	CONSIDER? (Y/N)	RATING	CONFIDENCE
WOODY	COVER	Y	1.0	2.0
	ABUNDANCE	Y	1.0	2.0
	POPULATION STRUCTURE	N		
	VERTICAL STRUCTURE	Y	1.0	2.0
	RECRUITMENT	Y	1.0	2.0
	SPECIES COMPOSITION	Y	1.0	2.0
	AVERAGE		1.0	2.0

Table 3.18: Continued

NON-WOODY CATEGORY (Including reeds)	COVER	Y	0.0	2.0
	ABUNDANCE	Y	0.0	2.0
	AVERAGE		0.0	2.0
NON-WOODY (Excluding reeds)	COVER	Y	1.0	2.0
	ABUNDANCE	Y	1.0	2.0
	SPECIES COMPOSITION	Y	1.0	2.0
	AVERAGE		1.0	2.0

Ranking

Woody plants were the most prominent category in this zone; therefore, they were ranked as the most important (Table 3.19). The non-woody plants category (excluding reeds) was ranked the second most important and woody plants category (including reeds) was ranked lowest. The overall score assigned to the upper zone was 18,6% deviation from reference condition with an ecological category of a B/C which translated to “good to fair: largely natural with few modifications to moderately modified” (Kleynhans et al., 2007).

Table 3.19: Ranking and weighting of a VEGRAI assessment of the lower zone at Mamba site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	CONSIDER? (Y/N)	RANK	WEIGHT	RATING	WEIGHTED RATING	MEAN CONFIDENCE
WOODY	Y	1.0	100.0	1.0	1.00	2.0
NON-WOODY CATEGORY (Including reeds)	Y	3.0	10.0	0.0	0.00	2.0
NON-WOODY (Excluding reeds)	Y	2.0	30.0	1.0	0.30	2.0
AVERAGE					1.30	2.0
CHANGE (%) IN VEGETATION COMPONENTS: OVERALL CHANGE IN LATERAL ZONE CONDITION			18.6	B/C		

4 Macro-channel bank

The macro-channel bank was very similar to that of the upper zone, the only distinguishing difference was a slightly reduced amount of alien and invasive plants and a higher woody component. Similar to the upper zone, dominant plant species included; *Trichilia emetica*, *D. mespiliformis*, *S. africana*, *C. gratissimus* and *F. sycomorus* (Figure 3.22). This zone was similar to what would have been expected under reference conditions.

Impacts

There were no observed impacts regarding the removal of vegetation, no affects by water quality or quantity and no observed impacts by erosions relating to anthropogenic influences (Table 3.20). There were however mild abundances of alien and invasive vegetation observed within the zone.

Table 3.20: Impacts recorded within the macro-channel bank zone during a VEGRAI assessment at Mamba site along the lower Olifants River within the Kruger National Park.

IMPACTS	INTENSITY	EXTENT	CONFIDENCE
REMOVAL	0.0	0.0	2.0
ALIEN INVASION	1.0	1.0	5.0
WATER QUANTITY	0.0	0.0	4.0
WATER QUALITY	0.0	0.0	2.0
EROSION	0.0	0.0	2.0
AVERAGE			3.0

Responses

Responses to the impacts by the mild influence of the alien and invasive plants observed were minimal and determined with low levels of confidence due to the potentially minimal impact at such low concentrations (Table 3.21). All categories for the woody component were scored 0,5/5 for deviation from reference condition. Non-woody category (including reeds) was not rated for this zone as there were no observed plants recorded within this zone. Non-woody category (excluding reeds and related) scored 0,2/5 also due to the low abundances observed within the zone.

Table 3.21: Response metric ratings of the macro-channel bank zone of a VEGRAI assessment at Mamba site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	RESPONSE METRIC	CONSIDER? (Y/N)	RATING	CONFIDENCE
WOODY	COVER	Y	0.5	2.0
	ABUNDANCE	Y	0.5	2.0
	POPULATION STRUCTURE	N		
	VERTICAL STRUCTURE	Y	0.5	2.0
	RECRUITMENT	Y	0.5	2.0
	SPECIES COMPOSITION	Y	0.5	2.0
	AVERAGE		0.5	2.0
NON-WOODY CATEGORY (Including reeds)	COVER	N	N/A	N/A
	ABUNDANCE	N	N/A	N/A
	AVERAGE		N/A	N/A
NON-WOODY (Excluding reeds)	COVER	Y	0.5	2.0
	ABUNDANCE	Y	0.5	2.0
	SPECIES COMPOSITION	Y	0.5	2.0
	AVERAGE		0.5	2.0

Ranking

The woody component ranked highest for this zone with non-woody category (excluding reeds) as second (Table 3.22). The macro-channel bank zone at Mamba scored an overall PES score of 10%, falling within the ecological category A/B, describing the zone as “excellent to good: unmodified to largely natural” (Kleynhans et al., 2007).

Table 3.22: Ranking and weighting of a VEGRAI assessment of the macro-channel bank zone at Mamba site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	CONSIDER? (Y/N)	RANK	WEIGHT	RATING	WEIGHTED RATING	MEAN CONFIDENCE
WOODY	Y	1.0	100.0	0.5	0.50	2.0
NON-WOODY CATEGORY (Including reeds)	N	N/A	N/A	N/A	N/A	N/A

Table 3.22: Continued

NON-WOODY (Excluding reeds)	Y	2.0	20.0	0.5	0.10	2.0
AVERAGE					0.60	2.0
CHANGE (%) IN VEGETATION COMPONENTS: OVERALL CHANGE IN LATERAL ZONE CONDITION			10.0	A/B		

Overall ranking

Mamba scored **79% for the PES with an average confidence of 2**, meaning that the site deviated from expected reference state by 21%. The score fell within the **PES category B/C** indicating that the area was between a site that was in a largely natural state with few modifications to a site in fair condition that was moderately modified with a lower-than-expected species diversity (Kleynhans et al., 2007). The overall score was calculated based on individual scores taken from all four zones that were assessed (marginal, lower, upper and macro-channel bank) (Table 3.23). The marginal and lower zones scored lowest at 67.2% and 67.8% as a result of altered flow regimes. The position of the zones relative to the potential for impacts by hydraulic influences increased the degree of alteration to these zones. The upper and MBC zones scores were a result of mild to moderate degrees of alien and invasive plant abundances and diversity.

Table 3.23: Summary table illustrating the individual scores from the various zones during a VEGRAI assessment at Mamba site along the lower Olifants River within the Kruger National Park.

	Marginal zone	Lower zone	Upper zone	Macro-channel bank (MBC)
VEGRAI PES % per zone	67.2	67.8	81.4	90.0
Category per zone	C	C	B/C	A/B
Confidence per zone	2.0	2.0	2.0	2.0

B. Balule

Balule site contained 24 taxa which included a large non-woody *P. mauritanus* component and high concentrations the woody of *G. virgatum* and some well-established *B. salicina* individuals (Table 3.24). The marginal, lower and upper zones were dominated by non-woody plants while the macro-channel bank had a well-developed tree-line. The site also displayed evidence of previous flood and drought events. Five species were alien and/or invasive and the remaining

19 were indigenous. Prominent woody species included; *Breonadia salicina*, *G. fruticosus* and *G. virgatum*. Prominent non-woody species included *S. brachyceras*, *P. mauritanus*, *D. stramonium* and *X. strumarium* (Figure 3.23).

Table 3.24: Full list of plant species observed during a VEGRAI assessment at Balule site along the lower Olifants River within the Kruger National Park.

SCIENTIFIC NAME	COMMON NAME	STATUS
<i>Argemone ochroleuca</i>	White Flowered Mexican Poppy	Alien
<i>Breonadia salicina</i>	Matumi Tree	Indigenous
<i>Cynodon dactylon</i>	-	Alien
<i>Cyperus dives</i>	Giant sedge	Indigenous
<i>Cyperus longus</i>	Sweet Cyperus	Indigenous
<i>Cyperus sexangularis</i>	Bushveld sedge	Indigenous
<i>Datura stramonium</i>	Jimson Weed	Alien
<i>Flueggea virosa</i>	Whiteberry Bush	Indigenous
<i>Gomphocarpus fruticosus</i>	Milkweed	Indigenous
<i>Gomphostigma virgatum</i>	River Stars	Indigenous
<i>Ischaemum fasciculatum</i>	Border grass	Indigenous
<i>Isolepis sp.</i>	-	Indigenous
<i>Juncus effusus</i>	Common Rush	Indigenous
<i>Ludwigia stolonifera</i>	Creeping Ludwigia	Indigenous
<i>Melia azedarach</i>	Syringa Berrytree	Alien
<i>Nuxia oppositifolia</i>	Water Elder	Indigenous
<i>Philenoptera violacea</i>	Apple leaf	Indigenous
<i>Phragmite mauritanus</i>	-	Indigenous
<i>Pluchea dioscoridis</i>	-	Indigenous
<i>Potamogeton crispus</i>	Curly-leaf pondweed	Indigenous
<i>Ranunculus baurii</i>	-	Indigenous
<i>Schoenoplectus brachyceras</i>	-	Indigenous
<i>Sclerocarya birrea</i>	Marula Tree	Indigenous
<i>Xanthium strumarium</i>	Large cocklebur	Alien

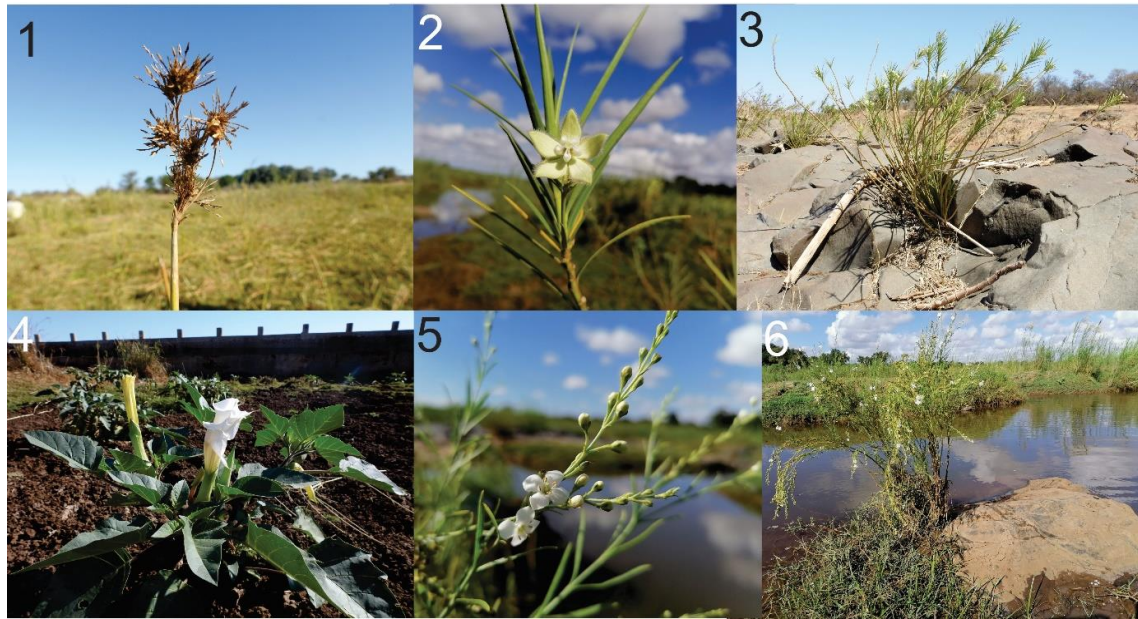


Figure 3.23: Photographic illustrations of taxa observed at Balule site along the lower Olifants River within the Kruger National Park where; (1) *Schoenoplectus brachyceras* (2) *Gomphocarpus fruticosus*, (3) *Gomphocarpus fruticosus* responding to bedrock substrates, (4) alien and invasive species *Datura stramonium*, (5) *Gomphostigma virgatum* (6) *Gomphostigma virgatum* responding to bedrock substrates.

The VEGRAI assessment took place within the vicinity where the cross-section profiles were conducted at Balule site, extending approximately 200 m upstream and downstream of position of the transects. Similar to Mamba site, it was expected that the condition of the Balule site should be devoid of anthropogenic influence (reference condition) and most likely include lower abundances of woody plants within the marginal and lower zones as a result of flow restrictions and seasonal flood alleviation. In addition, the upper zone was expected to contain higher densities of woody plants which were reduced as a result of the intensive and extensive alien and invasive plants that were present.

1 Marginal Zone

The marginal zone was dominated by non-woody *S. brachyceras*, *Cynodon dactylon*, *I. fasciculatum* and *P. mauritanus* with low to moderate abundances of *R. baurii* and *Cyperus longus* and semi-aquatic species *L. stolonifera* and *P. crispus* (Figure 3.24). Prominent woody species observed within this zone were *B. salicina* and *G. virgatum*. This zone was similar to what would have been expected under reference conditions.

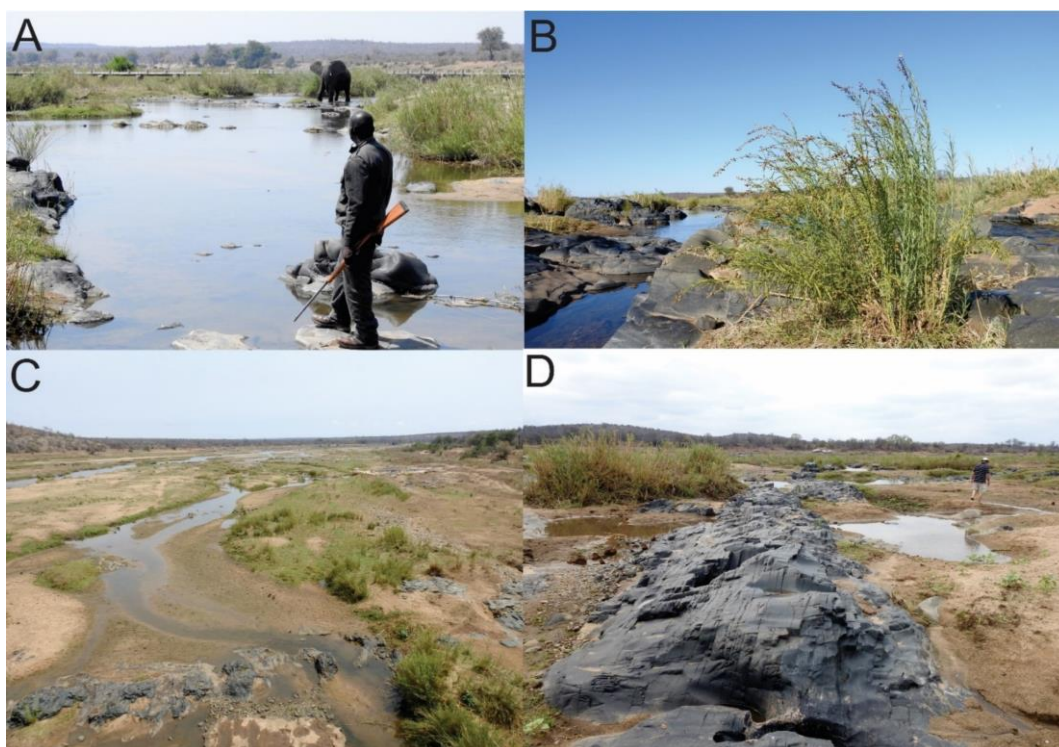


Figure 3.24: Various landscapes of the marginal and lower zones at Balule site along the lower Olifants River within the Kruger National Park where (A) shows a downstream view from cross-section 1, (B) shows an upstream view from cross-section 1, (C) shows an aerial view looking upstream from cross-section 1 and (D) shows the prominent dyke from the right bank, looking towards cross-section 1.

Impacts

Impacts observed within the marginal zone at Balule site included low abundances of alien and invasive plants and moderate to high effects by flow reductions and altered flow regimes (Table 3.25). Low impacts by water quality were recorded and there were minimal erosional responses.

Table 3.25: Impacts recorded within the marginal zone during a VEGRAI assessment at Balule site along the lower Olifants River within the Kruger National Park.

IMPACTS	INTENSITY	EXTENT	CONFIDENCE
REMOVAL	0.0	0.0	4.0
ALIEN INVASION	1.5	2.0	5.0
WATER QUANTITY	3.5	5.0	4.0
WATER QUALITY	1.0	5.0	2.0
EROSION	1.0	1.0	2.0
AVERAGE			3.4

Responses

Native vegetation responses observed within the marginal zone included mild affects to non-woody category (including reeds) through potential reduction in cover and abundances (Table 3.26). This was likely due to flow reductions and mild affects to non-woody category (excluding reeds) through a potential to reduced cover percentage, abundances and species compositions as a result of flow modifications and alien and invasive plants observed within the zone.

Table 3.26: Response metric ratings of the marginal zone of a VEGRAI assessment at Balule site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	RESPONSE METRIC	CONSIDER? (Y/N)	RATING	CONFIDENCE
WOODY	COVER	Y	0.5	2.0
	ABUNDANCE	Y	0.5	2.0
	POPULATION STRUCTURE	N	N/A	N/A
	VERTICAL STRUCTURE	N	N/A	N/A
	RECRUITMENT	N	N/A	N/A
	SPECIES COMPOSITION	Y	0.5	2.0
	AVERAGE		0.5	2.0
NON-WOODY CATEGORY (Including reeds)	COVER	Y	1.0	2.0
	ABUNDANCE	Y	0.0	2.0
	AVERAGE		1.0	2.0
NON-WOODY (Excluding reeds)	COVER	Y	1.0	2.0
	ABUNDANCE	Y	1.0	2.0
	SPECIES COMPOSITION	Y	1.0	2.0
	AVERAGE		1.0	2.0

Ranking

The non-woody category (including reeds) ranked highest within this zone due to high abundances and aerial cover of *P. mauritanus* (Table 3.27). Non-woody category (excluding reeds) ranked second most important with a weighting of 80% and woody category ranked third, however still maintained a relatively high rating for this zone due to the high abundances of woody *B. salicina* and *G. virgatum* that were responding to the bedrock substrates. The marginal zone scored an overall ecological category of B/C “Good to fair: largely natural to moderately modified” with 18.6% deviation from reference condition (Kleynhans et al., 2007).

Table 3.27: Ranking and weighting of a VEGRAI assessment of the marginal zone at Balule site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	CONSIDER? (Y/N)	RANK	WEIGHT	RATING	WEIGHTED RATING	MEAN CONFIDENCE
WOODY	Y	3.0	30.0	0.5	0.15	2.0
NON-WOODY CATEGORY (Including reeds)	Y	1.0	100.0	1.0	1.0	2.0
NON-WOODY (Excluding reeds)	Y	2.0	80.0	1.0	0.80	2.0
AVERAGE					1.95	2.0
CHANGE (%) IN VEGETATION COMPONENTS: OVERALL CHANGE IN LATERAL ZONE CONDITION			18.6	B/C		

2 Lower Zone

The lower zone was also dominated by non-woody components including; *Cynodon dactylon*, *P. mauritanus* and *S. brachyceras* (Figure 3.24). Additional species that were present in lower concentrations included; *Cyperus dives*, *C. longus*, *C. sexangularis*, *Isolepis sp.*, *J. effusus* and *R. baurii*. Woody species that were observed within the zone included; *G. virgatum* and *P. dioscoridis* as well as the alien and invasive species *D. stramonium*, *X. strumarium* and *M. azedarach*. This zone contained some woody plants that would not have been expected under reference conditions, a likely result of flow modifications. Alien and invasive plants would also not have been present under reference conditions.

Impacts

Impacts observed within the lower zone at Balule site included moderate to high concentrations of alien and invasive plants, reduced flows and flow regime modifications (

Table 3.28). Limited evidence of impacts by water quality were observed within the zone.

Table 3.28: Impacts recorded within the lower zone during a VEGRAI assessment at Balule site along the lower Olifants River within the Kruger National Park.

IMPACTS	INTENSITY	EXTENT	CONFIDENCE
REMOVAL	0.0	0.0	4.0
ALIEN INVASION	2.5	3.0	5.0
WATER QUANTITY	3.5	3.0	4.0
WATER QUALITY	1.0	2.0	2.0
EROSION	1.0	1.0	2.0
AVERAGE			3.4

Responses

Observed responses by native plants included mild responses by woody plants and moderate responses by both non-woody plant categories (Table 3.29). Low responses were recorded by woody plants as the most abundant woody plant was *G. virgatum* which responded to bedrock substrates. The response to these substrates reduced the competition for space between alien and invasive plants as these species tended to respond to finer sandy substrates. Responses by both non-woody plant categories scored moderate ratings as a result of increased competition between alien and invasive plants and potential effects of water quantity and quality as a result of flow modifications from the upstream weir and resultant sediment distribution alterations.

Table 3.29: Response metric ratings of the lower zone of a VEGRAI assessment at Balule site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	RESPONSE METRIC	CONSIDER? (Y/N)	RATING	CONFIDENCE
WOODY	COVER	Y	0.5	2.0
	ABUNDANCE	Y	0.5	2.0
	POPULATION STRUCTURE	N	N/A	N/A
	VERTICAL STRUCTURE	Y	0.5	2.0

	RECRUITMENT	N	N/A	N/A
	SPECIES COMPOSITION	Y	1.0	2.0
	AVERAGE		0.6	2.0

Table 3.29: continued

NON-WOODY CATEGORY (Including reeds)	COVER	Y	2.0	2.0
	ABUNDANCE	Y	2.0	2.0
	AVERAGE		2.0	2.0
NON-WOODY (Excluding reeds)	COVER	Y	2.0	2.0
	ABUNDANCE	Y	2.0	2.0
	SPECIES COMPOSITION	Y	2.0	2.0
	AVERAGE		2.0	2.0

Ranking

The non-woody category that included reeds ranked highest for this zone due to the large reed component (Table 3.30). The non-woody category excluding reeds ranked second most important at a rating of 70% and the woody component ranked least important between the three due to the relatively low abundances of woody plants compared to that of the non-woody. Overall, the lower zone at Balule site was awarded an ecological category of C “Fair: Moderately modified” at a score of 33,8% alteration from expected reference condition. These scores were awarded as a result of the moderate to high abundances of alien and invasive plants as well as the observed affects by flow alterations.

Table 3.30: Ranking and weighting of a VEGRAI assessment of the lower zone at Balule site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	CONSIDER? (Y/N)	RANK	WEIGHT	RATING	WEIGHTED RATING	MEAN CONFIDENCE
WOODY	Y	3.0	50.0	0.6	0.31	2.0
NON-WOODY CATEGORY (Including reeds)	Y	1.0	100.0	2.0	2.0	2.0
NON-WOODY (Excluding	Y	2.0	70.0	2.0	1.40	2.0

reeds)			
	AVERAGE	3.71	2.0
CHANGE (%) IN VEGETATION COMPONENTS: OVERALL CHANGE IN LATERAL ZONE CONDITION	33.8	C	

3 Upper Zone

The upper zone was dominated by a non-woody alien and invasive species *X. strumarium* to the almost complete exclusion of all other plants (Figure 3.25). This species is a known invader in the KNP but higher densities are present along river ecosystem due to the hydrochloric behaviour of the species whereby seeds are dispersed via water (Mackenzie, 2020). River sections that experience hydraulic disturbances from anthropogenic structures such as bridges and weirs provide refuge for *X. strumarium* therefore populations tend to be intensive and extensive by nature (Mackenzie, 2020). Some other species were observed in isolated populations and also in low concentrations. These included; *Cynodon dactylon*, *C. sexangularis* and another alien and invasive species *A. ochroleuca*. The zone also included a larger woody component than that of the marginal and lower zones, including species; *Flueggea virosa*, *G. fruticosus* and *N. oppositifolia*. High densities and abundances of alien and invasive plants would not have been present under reference conditions, which would have likely resulted in higher abundances of woody plants that were competing for space.



Figure 3.25: Intensive and extensive alien and invasive *Xanthium strumarium* present within the upper zone at Balule site along the lower Olifants River within the Kruger National Park.

Impacts

The observed impacts in the upper zone comprised a high degree alien and invasive plants of the species *X. strumarium* and to a lesser degree *A. ochroleuca* (Table 3.31). The invasion was

both intensive and extensive within the upper zone. No other impacts were observed within the zone except that of the alien and invasive plants.

Table 3.31: Impacts recorded within the upper zone during a VEGRAI assessment at Balule site along the lower Olifants River within the Kruger National Park.

IMPACTS	INTENSITY	EXTENT	CONFIDENCE
REMOVAL	0.0	0.0	4.0
ALIEN INVASION	4.0	4.0	5.0
WATER QUANTITY	0.0	0.0	4.0
WATER QUALITY	0.0	0.0	2.0
EROSION	0.0	0.0	2.0
AVERAGE			3.4

Responses

The observed response by native species included competition for space within the zone for both woody and non-woody species (Table 3.32). Some woody species such as *G. fruticosus* avoided competition through their preference towards bedrock substrate types whereas the alien and invasive species showed a preference for sandy substrates. The high degree of competition between native non-woody plants and alien species affected the cover, abundance and species composition. Non-woody category (including reeds) was excluded from this assessment for the upper zone due to the negligible densities or being absent.

Table 3.32: Response metric ratings of the upper zone of a VEGRAI assessment at Balule site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	RESPONSE METRIC	CONSIDER? (Y/N)	RATING	CONFIDENCE
WOODY	COVER	Y	1.0	2.0
	ABUNDANCE	Y	1.0	2.0
	POPULATION STRUCTURE	N		
	VERTICAL STRUCTURE	N		
	RECRUITMENT	Y	1.0	3.0

NON-WOODY CATEGORY (Including reeds)	SPECIES COMPOSITION	Y	1.0	3.0
	AVERAGE		1.0	2.5
	COVER	N	N/A	N/A
	ABUNDANCE	N	N/A	N/A
	AVERAGE		N/A	N/A

Table 3.32: Continued

NON-WOODY (Excluding reeds)	COVER	Y	3.0	2.0
	ABUNDANCE	Y	3.0	2.0
	SPECIES COMPOSITION	Y	3.0	2.0
	AVERAGE		3.0	2.0

Ranking

The non-woody category ranked as the most important category for the upper zone at Balule site with the woody category ranking second (Table 3.33). The non-woody category (including reeds) was not considered due to the low concentrations of plants observed within the zone. The upper zone scored an overall ecological category D, defined as “Poor: largely modified” at a percentage of 48.6% from expected reference condition as a result of the highly intensive and extensive alien invasion present within the zone.

Table 3.33: Ranking and weighting of a VEGRAI assessment of the upper zone at Balule site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	CONSIDER? (Y/N)	RANK	WEIGHT	RATING	WEIGHTED RATING	MEAN CONFIDENCE
WOODY	Y	2.0	40.0	1.0	0.40	2.5
NON-WOODY CATEGORY (Including reeds)	N	N/A	N/A	N/A	N/A	N/A
NON-WOODY (Excluding reeds)	Y	1.0	100.0	3.0	3.00	2.0
AVERAGE					3.40	2.3
CHANGE (%) IN VEGETATION COMPONENTS: OVERALL CHANGE IN LATERAL ZONE CONDITION			48.6	D		

4 Macro-channel bank

The macro-channel bank was dominated by a woody component with a well-defined treeline. Species observed within the zone included; *Sclerocarya birrea*, *F. virosa*, *G. fruticosus*, *N. oppositifolia* and *P. violacea*. Non-woody species observed included; alien and invasive *X. strumarium* and *A. ochroleuca* as well as native *C. dactylon* and *C. sexangularis*. This zone was similar to what would have been expected under reference conditions with the exclusion of mild invasive of alien plants.

Impacts

Impacts to native species recorded within the macro-channel bank were low to mild abundances of alien and invasive plants from *X. strumarium* and *A. ochroleuca* to a lesser degree (Table 3.34). The impact was neither intensive nor extensive when compared to the upper zone. Low impacts by removal of vegetation were evident as a result of dirt roads that were present at the site.

Table 3.34: Impacts recorded within the macro-channel bank zone during a VEGRAI assessment at Balule site along the lower Olifants River within the Kruger National Park.

IMPACTS	INTENSITY	EXTENT	CONFIDENCE
REMOVAL	0,5	0,0	4,0
ALIEN INVASION	2,0	2,0	5,0
WATER QUANTITY	0,0	0,0	4,0
WATER QUALITY	0,0	0,0	2,0
EROSION	0,0	0,0	2,0
AVERAGE			3.4

Responses

Responses by native species were also minimal as the impact was so low within this zone (

Table 3.35). The responses by cover, abundance, recruitment rates and species composition for both woody and non-woody (excluding reeds) scored low. Non-woody plants belonging to the category that included reeds were not considered for this zone due to the low abundances.

Table 3.35: Response metric ratings of the macro-channel bank zone of a VEGRAI assessment at Balule site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	RESPONSE METRIC	CONSIDER? (Y/N)	RATING	CONFIDENCE
WOODY	COVER	Y	1.0	2.0
	ABUNDANCE	Y	1.0	2.0
	POPULATION STRUCTURE	N		
	VERTICAL STRUCTURE	N		
	RECRUITMENT	Y	1.0	2.0
	SPECIES COMPOSITION	Y	1.0	2.0
	AVERAGE		1.0	2.0
NON-WOODY CATEGORY (Including reeds)	COVER	N	N/A	N/A
	ABUNDANCE	N	N/A	N/A
	AVERAGE		N/A	N/A
NON-WOODY (Excluding reeds)	COVER	Y	1.0	2.0
	ABUNDANCE	Y	1.0	2.0
	SPECIES COMPOSITION	Y	1.5	2.0
	AVERAGE		1.2	2.0

Ranking

The woody component ranked highest for the macro-channel bank zone while the non-woody component (excluding reeds) ranked second (Table 3.36). The non-woody category (including reeds) was not considered for this zone due to the low concentrations observed within this zone. The macro-channel bank zone scored an overall ecological category B/C at 21,1% modified from reference condition, which translated to “Good to fair: largely unmodified to moderately unmodified”. This score was largely due to the mild to moderate alien and invasive plants within the zone.

Table 3.36: Ranking and weighting of a VEGRAI assessment of the macro-channel bank zone at Balule site along the lower Olifants River within the Kruger National Park.

VEGETATION COMPONENTS	CONSIDER? (Y/N)	RANK	WEIGHT	RATING	WEIGHTED RATING	MEAN CONFIDENCE
WOODY	Y	1.0	100.0	1.0	1.00	2.0
NON-WOODY CATEGORY (Including reeds)	N					
NON-WOODY (Excluding reeds)	Y	2.0	50.0	1.0	0.58	2.0
AVERAGE					1.58	2.0
CHANGE (%) IN VEGETATION COMPONENTS: OVERALL CHANGE IN LATERAL ZONE CONDITION			21.1	B/C		

Overall ranking

Balule was awarded a score of **69% for the PES with an average confidence of 2.1**, translating to the site deviating from expected reference conditions by 31%. The PES score fell within **category C** which is defined as fair and moderately modified. Locations falling within this category have lower species richness and contain intolerant species (Kleynhans et al., 2007)

Moderately modified. A lower-than-expected species richness and presence of most intolerant species. Most of the characteristics of the biotic assemblages have been moderately modified from its naturally expected condition. Some impairment of health may be evident at the lower

end of this class. The overall score was calculated based on individual scores taken from all four zones that were assessed (marginal, lower, upper and macro-channel bank) (Table 3.37).

The marginal and lower zones scored lowest at 67.2% and 67.8%. The upper and MBC zones scores were a result of mild to moderate degrees of alien and invasive plant abundances and diversity. The lower and upper zones scored the lowest as a result of the intensive and extensive alien and invasive plants that were present. The scores within the marginal zone were a result of modified flow regimes and the score allocated to the MBC was a result of alien and invasive plants.

Table 3.37: Summary table illustrating the individual scores from the various zones during a VEGRAI assessment at Balule site along the lower Olifants River within the Kruger National Park.

	Marginal zone	Lower zone	Upper zone	Macro-channel bank (MBC)
VEGRAI PES % per zone	81.4	66.3	51.4	78.9
Category per zone	B/C	C	D	B/C
Confidence per zone	2.0	2.0	2.3	2.0

3.4 Discussion

3.4.1 Riparian vegetation community structure in relation to environmental variable

Site comparisons and substrates

Mamba and Balule sites shared similarities and differences; both sites were located along exposed bedrock-dominated dykes with different underlying geologies (Pollard and Laporte, 2014; Van der Waal, 2021, 2020). Mamba was located on underlying granitic geology while Balule on basaltic geology. Cross-sections at Mamba and Balule were conducted within similar time-frames however, when the cross-section was conducted at Balule, discharges were higher than when cross-sections were conducted at Mamba. Despite the differences in discharge readings, observed water levels differed by only 0.181 m in relative height and both profiles contained four active channels. The increased area of inundation when combining the total area of the four active channels at Balule (103.4 m) when compared to the combined active channels at Mamba (62.5 m) is likely to account for the similarities in relative water levels despite differences in discharge.

The differences in underlying geologies at Mamba and Balule is the most likely explanation for the differences in substrate compositions. Results obtained from multivariate RDA analysis of

substrate types at Mamba and Balule sites indicate that finer substrates account for the greatest degree of statistical significance at Mamba and larger substrates such as bedrock at Balule. Finer substrates at Mamba indicates higher degrees of sub-surface flows which provides additional explanation as to why discharge values were lower at Mamba but relative water level heights were similar (Van der Waal, 2020, 2021).

The lower Olifants region has been affected by recent floods that occurred in 2000 and 2012. These events resulted in sediment stripping on two consecutive intensive and extensive events that left the region scoured (McCartney et al., 2004; Heritage et al., 2014). Water impoundment infrastructure such as dams and weirs are known to restrict sediment transportation potential and sediment recovery after such events (Poff et al., 1997; Naiman et al., 2005, 2008). Riparian vegetation has the ability to survive harsh environmental conditions associated with riverine ecosystems. Some of these adaptations include the ability to survive extended periods of inundation by intensive and extensive flooding events, the ability to survive a wide range of temperature fluctuations and the ability to survive extended drought events such as that experienced in 2016 (Naiman et al., 2008; Reinecke et al., 2013, 2015). Intensive and extensive flooding events are essential for the removal of terrestrial plants encroaching into the riparian zone and prevent dominances by single species or guilds (Mackenzie, 2020).

Water resource managers need to consider how natural events affect ecosystem and ecosystems' to naturally recover from natural disturbances. It is likely that the sediment compositions at both Mamba and Balule sites are a result of the combination of anthropogenic influence and in a state of recovery from natural disturbances events.

Substrate as drivers of riparian vegetation community composition

An assessment of associations between substrate types and biological traits identified definite relationships between substrate compositions and plant community structure. Clear trends identified included; associations between larger substrate types and woody plants, those possessing tap root systems and those that have the ability to reproduce sexually. In retrospect, similar associations were identified between finer substrate types and non-woody plants, those that possessed adventitious root systems and those that had the ability to reproduce asexually and via both strategies.

Recent studies and the analysis of historical evidence indicates that substrate compositions are one of the primary drivers of plant community compositions and ecosystem evolution (Venter and Gertenbach, 1986; Ewing, 2002). The alteration of substrate composition and transportation potential through altered flow regimes results in losses to biodiversity and the resultant losses to ecosystem resilience and range of services rendered (Tilman and Downing, 1994; Nielsen et al., 2000; Zavaleta et al., 2010; Allan et al., 2011; Jorgensen and Nielsen, 2013).

Improved understanding of potential drivers of community structure allows managers to improve adaptive management policies with the aim to improve biodiversity as was highlighted by the KNPRRP (Breen et al., 2000). Improved biodiversity will result in improved ecosystem functionality, ecosystem resilience and a wider range of services rendered for the benefit of both humans and the environment (Tilman and Downing, 1994; Nielsen et al., 2000; Zavaleta et al., 2010; Allan et al., 2011; Jorgensen and Nielsen, 2013; Schachtschneider et al., 2017).

Water quality

Results for water quality analysis indicated that the EC, DO%, DO (mg/L), SO_4^{2-} and Cl were higher at Mamba when compared to Balule. The elevated concentrations are likely a result of upstream anthropogenic activities from the nearby town of Phalaborwa. These findings are the likely explanation for the increased concentrations of algae at Mamba (Figure 3.26 and Figure 3.27). Shikwambana et al. (2021) conducted a study on the responses of diatoms to water quality within the KNP. Findings from this study indicated that elevated EC and in-stream nutrients resulted in the prevalence of nutrient-tolerant diatom species (*Rhoicosphenia abbreviate* and *Epithemia sorex*), known to specifically associate with such conditions. Their findings further indicated that these species only became dominant within the Olifants River in 2015, indicating relatively recent alterations to water quality compositions.



Figure 3.26: High algae concentrations at Mamba site along the lower Olifants River within the Kruger National Park on the day of analysis and water sample collection.



Figure 3.27: Balule site along the lower Olifants River within the Kruger National Park on the day of *in situ* water analysis and water sample collection. The photograph shows clear water with low algae abundance when compared to that at Mamba site.

Water quality results from Balule indicate that NH_4^+ , NO_3 , PO_4^{3-} , Ca and Mg were all higher at Balule when compared to Mamba with emphasis on PO_4^{3-} concentration which were elevated (6.2mg/l). Gerber et al. (2015) also found that nutrients were the main driving variables influencing the water quality at this site. These findings are likely due to contributions by hippopotamus populations upstream of the Balule site (Figure 3.28) (Dutton et al., 2018, 2021). Studies have shown that nutrient input by sedentary hippopotamus populations have the ability to cause hypoxia and resultant fish kills after hydraulic events and the flushing of pools. The studies found significant reductions in dissolved oxygen and increases in in-stream nutrients (Dutton et al., 2018, 2021). Large, sedentary pods of hippopotami with numbers exceeding 20 individuals were observed upstream of Balule site in pools both above and below Balule Weir. The fact that Balule had higher nutrient levels than Mamba (which was upstream of Balule) indicate that the source of the elevated readings originated from within the KNP and were therefore unlikely to have been sourced from anthropogenic influences.



Figure 3.28: Photographic evidence of large pod of hippopotami that frequent Balule Weir located upstream of Balule site along the lower Olifants River within the Kruger National Park.

Hydraulic parameters: activation discharge

Activation discharge values are datasets specific to a site as they consider site-specific morphology and unique channel shape. Both Mamba and Balule sites were located within river classification zone E, therefore shared geomorphological characteristics, however they also differed in their underlying geologies which impacts the lateral arrangement of plant populations along a river profile, which is based on accessibility to water through substrates (Hupp and Osterkamp, 1996; Kleynhans et al., 2007; Naiman et al., 2008; Reinecke et al., 2013, 2015).

Nine plant species were recorded along cross-sections 2 at both Mamba and Balule sites. Activation discharge (AD) readings were compared between the two sites and of the nine plant species, only four exhibited overlap that exceeded 50% relative abundance when compared. Results indicate that AD values are not useful when comparing sites as values relate to unique site characteristics, however they are useful for local determination of species-specific hydraulic requirements. If applied locally, AD can be a useful tool for understanding plant population behaviour at a local scale. The information could be applied to management practices for rehabilitation programs, focused at specific species or encompassing the local plant community. Furthermore, species-specific AD values could be used as a biological component in environmental flow (e-flow) determination (O'Brien et al., 2018). The values retrieved for species-specific hydraulic niche requirements could be inserted into PROBFLO and Bayesian belief networks and relative risk models as nodes representing the local hydraulic requirements of riparian vegetation plant communities (O'Brien et al., 2018).

3.4.2 Riparian Vegetation Response Assessment Index (VEGRAI) to determine the present ecological status (PES) of riparian vegetation

Mamba site scored an overall PES of a B/C with a percentage of 79% at an average confidence of 2. The marginal and lower zones scored the lowest at 67.2% and 67.8%, both falling into PES category C, described as “Fair: Moderately modified” (Kleynhans et al., 2007). These two zones scored lowest as they had been moderately impacted by reduced flows, modified flow regimes and compromised water quality. A possible explanation for the impacts is a result of the upstream water impoundment infrastructure and upstream activities within the town of Phalaborwa (Figure 3.29). Riddell et al. (2019) noted that following the discovery of phosphate and copper reserves within the vicinity of the Ga-Selati River (tributary of the Olifants River) mines were established in the area. The combination of salt enrichment from effluent releases originating from Phalaborwa municipal releases and leached metals from mining activities notably compromised the water quality along the Olifants River. The KNP successfully lobbied against mining releases (zero discharge) from the mining complex in 2002 which improved the situation however, heavy metal concentrations within the Olifants River are well known (Riddell et al., 2019).



Figure 3.29: Mamba weir located upstream of Mamba study site along the lower Olifants River within the Kruger National Park.

The impacts of two relatively recent flood and drought events in combination with flow restrictions have left the area scoured with superficial alluvial substrates on bedrock (Van Niekerk et al., 1995; Heritage et al., 2014; Van der Waal, 2021). Upstream water impoundment infrastructure affects sediment transportation potential which hinders the natural restoration of sediment compositions after recent flood events. All the zones had been affected by alien invasive plants that were present at the site but at low abundances at the time at which the surveys took place. The overall impression at Mamba site was mild to moderately disturbed; the major impacts a result of flow restrictions, modified flow regimes (and resultant disruptions to sediment transportation potential) and mild invasions of alien plants.

Balule site scored an overall PES of a C with a percentage of 69% with an average confidence of 2.1. The zone that scored the lowest at this site was the upper zone which scored 51.4%, falling within PES category D and second to that was the lower zone at 66.3% falling within PES category C. These zones scored low as a result of the highly intensive and extensive alien invasive plants that were present with the dominant contributor being the species *X. strumarium*. Altered flow regimes were also evident at Balule site as a result of the upstream Balule Weir. Hydraulic disruptions and influences were also evident as a result of the downstream bridge. The combination of altered flow regimes, reduced flows and hydraulic disruptions are likely contributors to the success of alien invasive plants present at the site as *X. strumarium* is hydrophilic and therefore found in greater abundances near water sources.

All of the zones were affected by alien invasive plants to some degree while lower zones were impacted most by modified flow regimes and flow restrictions. High degrees of alien invasive plants in the upper and macro-channel bank seemed to be a result of soil disturbances by recent natural flooding events as uprooted plant were observed in the area that seemed to have taken place within the past 12 months. It is likely that native species will recolonize to some degree through natural succession processes, however existing hydraulic and hydrological influences from anthropogenic infrastructure will likely affect success rates of recolonization.

Findings from the VEGRAI assessments conducted at both Mamba and Balule sites indicate that the marginal and lower zones (those closer to the water's edge) were more sensitive to hydraulic disturbance when compared to zones further up the banks. In addition to hydraulic disturbances, plant communities situated closer to the water's edge had increased exposure to alien plant seeds transported by water. The overall scores tended to increase laterally from the water's edge, indicating that riparian zones can act as buffers to disturbance to terrestrial vegetation.

The PES categories assigned to both Mamba and Balule indicate that the sites have deviated from expected natural conditions and been negatively affected by anthropogenic influences.

The disturbances that were most notable included the impact by alien invasive plants species and modifications to natural flow regimes through channel modifications and the resultant disturbances to substrate compositions. Responses were observed from plant biota through alterations in plant composition and plant community structure. Based on the PES scores B/C for Mamba and C for Balule, the sites were in fairly natural to moderately modified states. The resultant mild to moderate alterations in ecosystem integrity are likely affecting the stability and functionality of natural process relating to riparian vegetation and are probably affecting the ability of the ecosystem to provide resources and services at optimal capacity.

3.5 Conclusion

An analysis of riparian plant communities with the use of hydraulic cross-sections at Mamba and Balule sites along the lower Olifants River within the KNP indicate that substrates are a major driver for plant community compositions. Plant populations possessing specific biological traits showed preferences towards specific substrate types, indicating that substrate diversity directly affects plant community composition and local biodiversity, corresponding with findings derived from the Kruger National Park Rivers Research Programme (KNPRRP) (Breen et al. 2000). Geomorphology, channel morphology and sediment transportation potential are directly affected by flow regimes and natural hydraulic events. Alterations to these natural processes with the implementation of in-stream infrastructure and flow restrictions lead to reduced sediment movement potential, altered flow regimes and adverse impacts on physico-chemical properties of water quality parameters (Naiman and Decamps, 1997; Poff et al., 1997; Rowntree and Wadeson, 1999; Dudgeon et al., 2006; Rowntree and Kelly, 2013). These findings can be applied to management for use in the prediction of potential changes to plant community compositions from foreseen upstream land-used alterations or channel modifications.

Water quality parameters indicated that Mamba site contained elevated salt concentration while Balule elevated nutrients. The most likely explanation for the elevated salt content at Mamba could be due to the upstream town of Phalaborwa which were sourced from effluent releases as addressed by Riddell et al. (2019). Elevated nutrient levels at Balule are likely a result of large, sedentary pods of hippopotami located upstream of the site as revealed by previous studies (Dutton et al., 2018, 2021). Altered flow regimes and reduced flushing events likely exacerbate these conditions through increased quantities of stagnant pools and disconnected channels.

With the use of the VEGRAI tool, the PES was determined for both Mamba and Balule sites. Findings from the analysis indicate that Mamba site deviated only mildly from the expected reference condition, falling within category B/C. Balule site deviated from reference condition moderately, classified in category C (Kleynhans et al., 2007). Riparian plant communities were affected by modifications to natural flow regimes and to a lesser degree, alien invasive plants.

Improved management practices are necessary to optimize on the resources and services rendered by riparian vegetation and associated freshwater ecosystems. The links between riparian vegetation and their use for e-flow determination have been identified through previous literature (Brown et al., 2005; Naiman et al., 2005; Kleynhans et al., 2007; James and King, 2010; Reinecke et al., 2015). This component of the study aimed at assessing the hydraulic niche requirements of riparian plant communities at Mamba and Balule sites through an assessment of AD values. Findings indicated that comparisons of plant populations between the two sites did not prove effective. This was likely due to differences in site characteristics including; geology, geomorphology and channel morphology. The finds were however useful on a local scale. They informed of hydraulic niche requirements of plant populations locally. This information that could be applied to reserve managers for site rehabilitation, rehabilitation of specific plant population or for the overall improvement of water management practices with the objective of improving local biodiversity and ecosystem services provision. The findings from this section could also be used in the applications of e-flow determination for site-specific requirements of local plant communities. This could be applied with the use of the holistic PROBFLO method that incorporates the Bayesian belief networks and relative-risk models (O'Brien et al., 2018).

The use of riparian plant communities as indicators of e-flow requirements through the determination of their hydraulic niche requirements is effective on a local scale. There is a need to develop an unbiased, reliable and replicable method for the determination of environmental flow requirements for riparian plant communities that can be transferred across sites.

4 Riparian vegetation as indicators of flows in the lower Olifants River, Kruger National Park

4.1 Introduction

Increasing water demands are degrading freshwater ecosystems on a global scale (King et al., 2003). Dams and weirs are essential for growing economies, human populations and increased water resource security in water scarce countries; however, they threaten the integrity, functionality and resilience of inland freshwater ecosystems (Gleick, 2003; Poff et al., 2007; Naiman et al., 2008; Navarro-Llácer et al., 2010; Jager et al., 2012; DWAF, 2013; Reinecke et al., 2015). The alteration of natural flow regimes such as the timing, duration and frequency of seasonal and infrequent flood events result in loss of biodiversity to biotic organisms that have evolved their life history events to coincide natural flow regimes (Naiman et al., 2008; Reinecke et al., 2013).

There is a global movement towards the identification of the environmental flow (e-flow) requirements of catchment basins in order to achieve sustainable utilization goals (Horne et al., 2017; Arthington et al., 2018). Environmental flows are defined as “the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being” as stated in the Brisbane Declaration and Global Action Agenda on e-flows (Arthington et al., 2018). The management of e-flows should aim to replicate the natural flow regimes specific to a catchment basin (Naiman et al., 2008). The Brisbane Declaration and Global Action Agenda that took place in 2007 and 2017 highlighted the urgency of this matter and identified several recommended agendas to be implemented on both national and international scales. A key agenda that was identified was the need to establishment e-flows for every catchment basin and the maintenance of catchment management across political boundaries (Arthington et al., 2018).

The effective management of freshwater ecosystems to optimize on functionality and the range of services provided is achieved through the establishment of e-flows. A key element in the process involves the utilization of biological indicators (Niemi and McDonald, 2004). Biological indicators are used to determine the ecological health of a system and if paired with precise, unbiased and accurate methodology can be used to predict responses to change. An important variable to consider when selecting the appropriate indicator group and level of organisation is the establishment of the linkages between responses and stressors. The identification of these linkages provides scientists with the ability to understand present-day assemblages and to predict environmental responses throughout the management process (NRC, 2000; Niemi and McDonald, 2004).

The links between riparian vegetation and flow have been established (Naiman et al., 2005, 2008; King and Brown, 2006; Kleynhans et al., 2007; James and King, 2010; Reinecke et al., 2013, 2015). Previous literature utilized the approach whereby river sections were categorized into various zones relative to physical characteristics and hydraulic experiences. The labels assigned to the various zones varied according to the methodologies and approaches. Riparian vegetation were assigned to the various zones based on their expected or observed lateral location.

The Riparian Vegetation Response Assessment Index (VEGRAI) tool, discussed in the previous chapter, is used in e-flow studies. The determination of reference conditions and present ecological states (PES) using VEGRAI are complimented through the application of flow duration curves (FDC's) (Brown et al., 2005; King and Brown, 2006; James and King, 2010; Horne et al., 2017). These FDC's utilize hydrological data to produce tables and graphs that present the hydrology for a given area at natural, present-day and base flow scenarios to determine the percentage of time that the various zones experienced inundation on various temporal scales.

The Olifants River and associated rivers are classified as one of the nine water management areas within South Africa (GreenCape, 2017). The region is currently under stress due to intensive and extensive land-use activities. These stressors are predicted to increase by 2035 with increasing human population and the associated increase in demand (Donnenfeld et al., 2018). In order to ensure the future wellbeing of the management region, sustainable management practice must be applied if we wish to make use of the resources and services provided by the ecosystems. In 2019 only 2% of water resources utilized from the region were allocated for livestock watering and nature conservation (DWS, 2019b). At present no e-flows have been established for the Limpopo Catchment Basin, which includes the lower Olifants River in the Kruger National Park (KNP) (DWS, 2019b). The Ecological Water Requirement (EWR) was however formally gazetted in 2018 for the catchment where Natural Mean Annual Runoff (NMAR) was calculated for specific sites along the catchment basin (Republic of South Africa, 2018).

The main aim for this chapter is to:

- 1** To quantify e-flow requirements for the wellbeing of riparian vegetation in the lower Olifants River within the KNP.

Specific objectives in order to achieve this aim include:

- 1** Review of hydraulic and hydrological preferences of riparian plant communities along the lower Olifants River within the KNP.

- 2 Identify the hydraulic requirements of riparian vegetation at two sites on the lower Olifants River within the KNP.

4.2 Materials and methods

4.2.1 Study area

This study took place at two sites along the lower Olifants River, situated within the KNP, South Africa. The KNP is an important economic contributor to the South African economy, attracting over one million guests annually (McCartney et al., 2004). Two sites were selected at Mamba and Balule as described in detail in Section 3.2.1 (Figure 4.1).

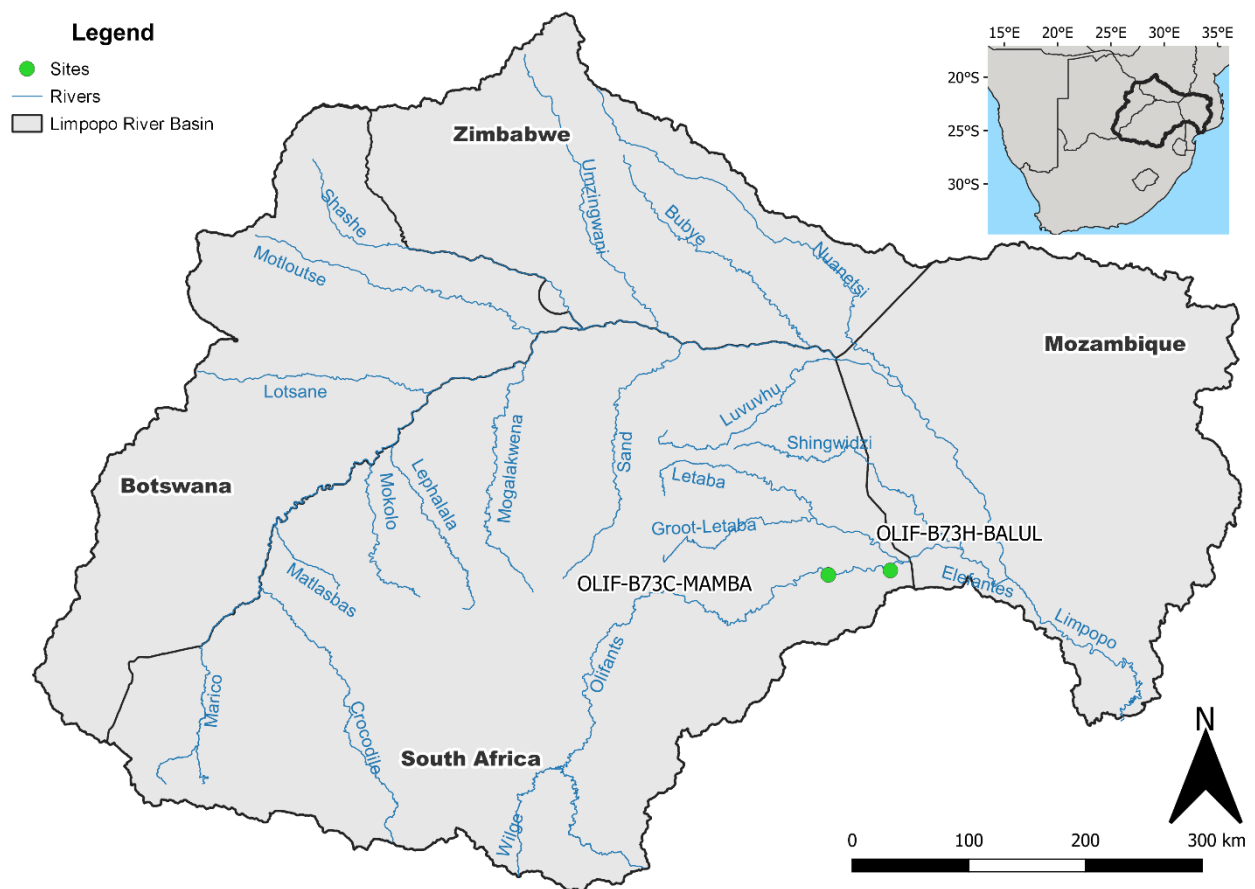


Figure 4.1: Study site locations of Mamba (1) and Balule (2) along the lower reaches of the Olifants River within the Kruger National Park.

4.2.2 Data collection

Sampling regime

Surveys took place within the dry season flows between the months of September and October 2020 and follow-up sampling to acquire additional hydraulic measurements took place in May 2021. Surveying of cross-sections took place during the dry season as it allowed for

accessibility into rivers with equipment and allowed for increased safety while sampling as potentially dangerous animals were present at both Mamba and Balule. Follow-up wet season surveys were conducted in May 2021 to collect additional hydraulics parameters that improved the accuracy of hydraulic models. (Van der Waal, 2020).

Cross-sections and hydraulics

Detailed information relating to the cross-sections are provided in Section 3.2.2. In summary cross-section profiles were surveyed at both Mamba and Balule sites. Two cross-sections were conducted, however only one cross-section (labelled cross-section 2) was suitable for hydraulic modelling purposes at each of the sites. Surveillance equipment used included a Leica TCR403 Power total station with associated tripod, staff and prism. Benchmarks were installed to allow for future replication and GPS coordinates were collected for each, including the position of the total station, the far left-edge of the cross-section and the far right-edge. Discharge data were collected from upstream Mamba and Balule weirs by retrieving gauge plate readings on the days that surveys took place and cross-referencing values with online rating tables associated with each of the weirs (Figure 4.2) (Republic of South Africa, 2021).



Figure 4.2: Gauge plate at Mamba Weir showing relative discharge that was later applied to rating tables provided by the South African Department of Water and Sanitation, Hydrological Services.

Cross-sections were selected in order that local hydraulics could be accurately represented and to adequately and sufficiently represent local riparian vegetation biodiversity. Hydraulic parameters that were recorded included; on-line water levels indicating left and right edges of active channels (the edges were always named when looking downstream) and upstream and

downstream water levels to indicate the slope of the landscape. Water level slope data were recorded approximately 300 to 500 m upstream and downstream of cross-sections.

Vegetation-related data

Vegetation data relating to the presence or absence of plant species were recorded as supplementary data during the surveillance procedure. This allowed for the corresponding surveyed data point to provide elevation and coordinate readings to points on which plants were recorded as was conducted in previous studies of a similar nature (Brown et al., 2005; King and Brown, 2006). Indigenous riparian vegetation species were specifically selected during the surveillance process with the aim of increasing datum to effectively represent selected species during the allocated time-frames.

4.2.3 Data analysis

The multivariate statistical techniques used and the hydraulic data analyses are described in detail in Section 3.2.3.

Hydrology and hydrological exceedance tables

Flow exceedance tables were obtained from the Limpopo River Basin eFlow reports (Palmer, 2000; Stassen, 2016). Exceedance tables inform of the percentage of time that a specific location plotted along a cross-section profile experienced activation. The values were expressed in the percentage of time activation was experienced temporally. Hydrological exceedance tables for Mamba were sourced from an original study conducted in 2000 for the ecological reserve determination of the Upper Olifants River (Palmer, 2000). The tables generated for Balule were produced from a 2016 reserve determination, review and implementation project that focused on the Olifants and Letaba catchment systems (Stassen, 2016). Hydrological data for both Mamba and Balule were extrapolated from records retrieved from 1920 to 2004.

Exceedance tables were produced for three different scenarios; expected natural flow conditions, present-day flows and a theoretical scenario of base-flows extracted from present-day conditions. The base-flow scenario, often referred to as 'flattening-the-curve' is where present-day flow data were averaged to produce a theoretic scenario whereby large floods increase low flow conditions and visa-versa (Mackenzie, 2020). Base-flow scenarios are purely theoretical, similar to natural flow scenarios, the plant populations were not currently experiencing those flow conditions. Example: a river reach could be experiencing dry season base flows of $1 \text{ m}^3 \cdot \text{s}^{-1}$ and wet season base flows of $10 \text{ m}^3 \cdot \text{s}^{-1}$ with four large seasonal pulses, all which exceeded $100 \text{ m}^3 \cdot \text{s}^{-1}$. Base-flow scenarios would average this information to make it seem as though the plants are constantly experiencing a theoretic discharge of $15 \text{ m}^3 \cdot \text{s}^{-1}$ on a daily

basis because of the large but brief seasonal pulses. Therefore, the application of this scenario is to test whether the plants were currently experiencing this scenario or if they respond more towards current, present-day situations, which is the more likely outcome. Natural hydrological scenarios represent expected natural hydrology from historical sources dated back as far as 1920. Present-day scenarios represent the present hydrological conditions taking place at the site location and conditions currently exerted upon the plants.

Multivariate statistical analyses were conducted with the use of Canoco 5.02 in the form of constrained Redundancy Analysis (RDA) tests where species and environmental variables were tested where a Log^2 conversion was applied. The objective of the tests was to identify whether associations existed between the relative abundances of hydrological exceedance values and plant populations for three hydrological scenarios at Mamba and Balule sites along the lower Olifants River within the KNP.

Vegetation-related data analysis

Vegetation data in the form of presence versus absence was superimposed onto cross-section profiles in Microsoft Excel (Microsoft Corporation, 2016). This process allowed for the determination of relative elevation values for individual vegetation points and then later the determination of activation discharge (AD) values for each individual plant, population and the overall plant community represented along cross-sections 2 at Mamba and Balule sites. The purpose of this study was to determine whether hydrological exceedance tables could be applied to vegetation datapoints in order to remove site-specific variables. The application of flow exceedance table via three separate scenarios were applied to AD values associated with each datapoint containing vegetation observations. These data provided information that informed of the percentage of them that individual plants experienced activation.

4.3 Results

4.3.1 Hydraulic and hydrological preferences of riparian plant communities

Cross-sections and hydraulic parameters

Cross-section profiles were surveyed at Mamba and Balule sites along the lower Olifants River within the KNP (Figure 4.3). Rating curves were designed for each cross-section individually using hydraulic parameters such as surveyed water levels along profiles and upstream and downstream slope water levels. There were four active channels at both Mamba and Balule. The cross-section profile at Mamba had an average water level reading of 0.680 m relative elevation (relative to the lowest point along the transect) and Balule had an average water level of 0.570 m relative elevation. The discharge readings were $2.266 \text{ m}^3\cdot\text{s}^{-1}$ at Mamba and 4.476

$\text{m}^3\cdot\text{s}^{-1}$ at Balule site on the day that cross-sections were surveyed. Resistance values in the form of Manning's n were 0.04 at Mamba and 0.05 at Balule. The cross-section profile was 224 m in length at Mamba and 388 m at Balule site with an accumulated length of 62.5 m for all four active channels at Mamba and 103.4 m at Balule.

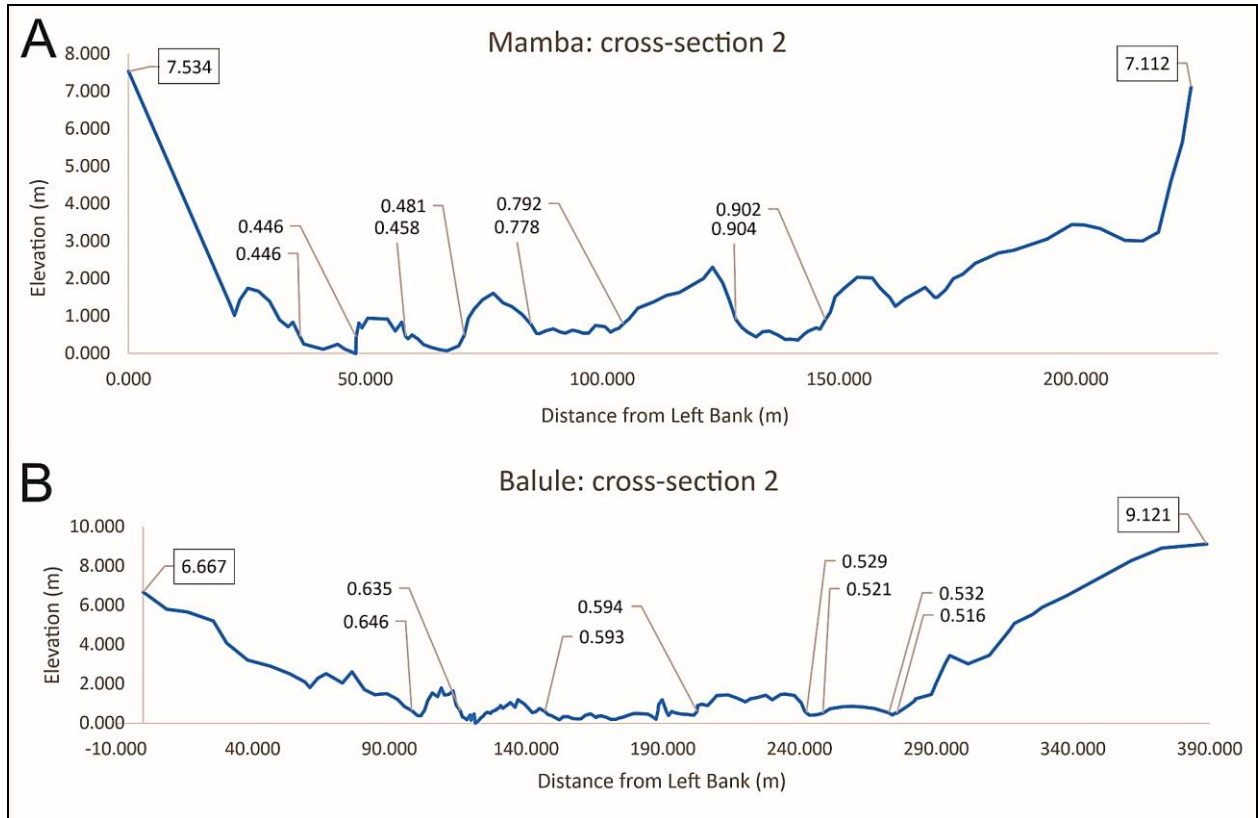


Figure 4.3: Cross-section profiles recorded at Mamba (A) and Balule (B) sites along the lower Olifants River within the Kruger National Park. The profile indicates the left bank, right bank and water levels of active channels (arranged in pairs of left and right edge).

A total of 14 taxa were recorded along cross-sections 2 at Mamba and Balule sites. (Table 4.1) Ten taxa were recorded at Mamba site with a total of 68 vegetation datapoints and an average of four datapoints per species. Thirteen taxa were recorded at Balule with a total of 138 vegetation datapoints and an average of eight datapoints per species. The combination of samples per species increased the overall average sample size per species to 15.

Table 4.1: Summary list of plant species that were sampled in this chapter. Information provided includes scientific names, common names, abbreviations used throughout (abbr.) and the number of datapoints per species that were recorded along cross-section profiles at each of the study sites.

Scientific names	Common names	Species abbr.	Datum per site		Individuals per species
			Mamba	Balule	
<i>Breonadia salicina</i>	Matumi Tree	Bsal	6	4	10
<i>Cyperus sexangularis</i>	Bushveld Sedge	Csex	1	5	6
<i>Flueggea virosa</i>	White berry-bush	Fvir	0	2	2
<i>Gomphocarpus fruticosus</i>	Milkweed	Gfru	2	11	13
<i>Gomphostigma virgatum</i>	River Star	Gvir	1	37	38
<i>Ischaemum fasciculatum</i>	Border Grass	Ifas	0	27	27
<i>Lannea schweinfurthii</i>	False marula	Lsch	0	1	1
<i>Ludwigia stolonifera</i>	Creeping Ludwigia	Lsto	0	3	3
<i>Nuxia oppositifolia</i>	Water Elder	Nopp	1	2	3
<i>Phragmites mauritianus</i>	Lowveld Reed	Pmau	32	20	52
<i>Pluchea dioscoridis</i>	Marsh fleabane	Pdio	6	0	6
<i>Potamogeton crispus</i>	Curled Pondweed	Pcri	6	1	7
<i>Ranunculus baurii</i>	-	Rbau	6	9	15
<i>Schoenoplectus brachyceras</i>	-	Sbra	7	16	23
Average datum per species:			4	8	15
Total datapoints:			68	138	206

Activation discharge values of plant populations that were located at both Mamba and Balule sites differed across sites (Table 4.2). Species that were recorded along cross-sections at both sites included; *Breonadia salicina*, *C. sexangularis*, *G. fruticosus*, *G. virgatum*, *N. oppositifolia*,

P. mauritanus, *P. crispus*, *R. baurii* and *S. brachyceras*. Average AD results for *P. mauritanus* populations were similar at Mamba and Balule sites, differing by a value of 1.1, while *P. crispus* populations differed by an average of 1.5 between sites. The plant population that differed most between Mamba and Balule sites was *N. oppositifolia* that differed by an average of 135.8. The remaining species differed by an average that ranged from 20 to 53.

Table 4.2: Activation discharge values ($\text{m}^3\cdot\text{s}^{-1}$) for plant populations recorded along cross-sections 2 at Mamba and Baule sites along the lower Olifants River within the Kruger National Park. The table provides the minimum (min.), maximum (max.) and average (ave.) of activation discharge.

Species	MAMBA			BALULE		
	Min.	Max.	Ave.	Min.	Max.	Ave.
Bsal	20.5	89.7	61.4	21.6	88.2	41.8
Csex	222.1	222.1	222.1	88.2	357.3	168.9
Fvir	N/A	N/A	N/A	561.7	777.8	669.7
Gfru	67.2	136.2	101.7	17.8	266.1	67.9
Gvir	67.2	67.2	67.2	9.1	60.7	21.9
Ifas	N/A	N/A	N/A	2.7	91.3	45.4
Lsch	N/A	N/A	N/A	8903.9	8903.9	8903.9
Lsto	N/A	N/A	N/A	2.7	11.6	5.7
Nopp	491.6	491.6	491.6	149.8	561.7	355.7
Pmau	5.2	294.1	92.3	9.1	561.7	93.4
Pcri	0.0	5.2	1.6	0.1	0.1	0.1
Pdio	10.6	81.8	51.5	N/A	N/A	N/A
Rbau	38.1	69.5	58.0	0.3	60.7	22.8
Sbra	15.1	139.7	78.3	20.3	91.3	55.1

4.3.2 Hydraulic niche requirements of riparian vegetation

Application of activation discharge to present-day hydrological exceedance tables

Activation discharge values were overlain onto present-day hydrological exceedance tables for both Mamba and Balule sites (Table 4.3, Table 4.4 and Table 4.5). The AD represents the amount of discharge ($\text{m}^3\cdot\text{s}^{-1}$) required to activate the plant (reaching root level), accounting for all values for each individual datum for each species. The minimum recorded value and the maximum recorded value are represented on the exceedance table as the percentage time within each month that range is met. These values ultimately represent the hydraulic niche of a species at each of the sites based on the elevation (relative heights) and lateral location at which they were recorded along surveyed cross-section profiles.

When comparing hydraulic niches of plant populations at Mamba and Balule sites, it is apparent that the range of hydraulic requirements differ intra-specifically. There are however clear similarities in the monthly trends with regard to the percentage time that the plant population's requirements were met throughout the months of the year (Table 4.3). Hydraulic niches could not be determined for species that were recorded only once along cross-sections.

Table 4.3: Activation discharge values ($\text{m}^3\cdot\text{s}^{-1}$) overlain onto hydrological exceedance tables. Numerical values represent different species (1 - 5), while (a) represents Mamba and (b) Balule sites. Only species that were recorded at both Mamba and Balule are shown here as well as species that were recorded more than once along cross-sections.

1a. <i>Breonadia salicina</i>													1b. <i>Breonadia salicina</i>												
Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7	0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7
1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7	1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7
5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9	5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9
10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9	10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9
15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7	15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7
20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0	20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0
30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1	30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1
40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5	40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5
50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2	50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2
60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0	60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0
70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8	70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8
80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5	80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5
85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4	85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4
90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3	90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3
95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2	95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2
99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1	99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1
99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0	99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0

2a. <i>Gomphocarpus fruticosus</i>													2b. <i>Gomphocarpus fruticosus</i>												
Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7	0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7
1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7	1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7
5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9	5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9
10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9	10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9
15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7	15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7
20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0	20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0
30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1	30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1
40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5	40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5
50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2	50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2
60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0	60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0
70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8	70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8
80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5	80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5
85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4	85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4
90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3	90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3
95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2	95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2
99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1	99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1
99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0	99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0

Table 4.3: Continued

3a. <i>Phragmites mauritianus</i>													3b. <i>Phragmites mauritianus</i>												
Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7	0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7
1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7	1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7
5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9	5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9
10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9	10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9
15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7	15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7
20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0	20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0
30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1	30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1
40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5	40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5
50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2	50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2
60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0	60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0
70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8	70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8
80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5	80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5
85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4	85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4
90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3	90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3
95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2	95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2
99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1	99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1
99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0	99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0

4a. <i>Ranunculus baurii</i>													4b. <i>Ranunculus baurii</i>												
Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7	0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7
1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7	1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7
5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9	5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9
10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9	10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9
15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7	15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7
20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0	20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0
30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1	30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1
40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5	40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5
50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2	50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2
60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0	60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0
70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8	70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8
80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5	80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5
85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4	85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4
90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3	90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3
95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2	95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2
99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1	99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1
99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0	99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0

5a. <i>Schoenoplectus brachyceras</i>													5b. <i>Schoenoplectus brachyceras</i>												
Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7	0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7
1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7	1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7
5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9	5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9
10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9	10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9
15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7	15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7
20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0	20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0
30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1	30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1
40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5	40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5
50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2	50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2
60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0	60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0
70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8	70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8
80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5	80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5
85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4	85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4
90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3	90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3
95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2	95	0.0	0.										

Table 4.5: Activation discharge values ($\text{m}^3\cdot\text{s}^{-1}$) overlain on hydrological exceedance tables at Balule site along the lower Olifants River within the Kruger National Park. Tables below include species that were recorded at Balule only or those that were recorded more than once along cross-sections at Balule only.

1. *Cyperus sexangularis*

Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7
1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7
5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9
10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9
15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7
20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0
30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1
40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5
50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2
60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0
70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8
80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5
85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4
90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3
95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2
99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1
99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0

2. *Flueggea virosa*

Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7
1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7
5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9
10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9
15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7
20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0
30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1
40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5
50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2
60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0
70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8
80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5
85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4
90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3
95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2
99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1
99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0

3. *Gomphostigma virgatum*

Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7
1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7
5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9
10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9
15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7
20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0
30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1
40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5
50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2
60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0
70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8
80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5
85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4
90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3
95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2
99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1
99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0

4. *Ischaemum fasciculatum*

Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7
1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7
5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9
10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9
15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7
20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0
30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1
40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5
50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2
60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0
70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8
80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5
85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4
90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3
95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2
99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1
99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0

5. *Ludwigia stolonifera*

Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7
1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7
5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9
10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9
15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7
20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0
30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1
40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5
50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2
60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0
70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9	0.8
80	0.1	0.5	5.8	12.6	12.0	13.4	11.2	8.0	5.1	2.6	1.3	0.5
85	0.0	0.1	4.3	7.8	10.7	10.1	9.3	7.0	4.3	2.3	1.1	0.4
90	0.0	0.0	3.3	5.5	8.8	6.6	8.8	5.8	3.8	2.0	0.9	0.3
95	0.0	0.0	0.9	3.7	6.9	5.6	6.3	4.8	3.2	1.6	0.7	0.2
99	0.0	0.0	0.0	1.1	2.9	3.8	2.5	1.6	1.1	0.7	0.3	0.1
99.9	0.0	0.0	0.0	0.1	0.5	1.7	0.9	0.5	0.3	0.2	0.1	0.0

6. *Nuxia oppositifolia*

Percentiles	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
0.1	12.6	154.6	344.1	511.3	993.7	588.9	376.3	87.1	34.6	16.6	12.2	7.7
1	9.3	128.8	181.4	437.9	932.5	563.8	199.1	86.4	32.4	15.8	11.0	6.7
5	5.7	70.0	139.7	294.2	481.2	275.6	119.5	49.7	24.1	13.2	8.8	4.9
10	4.3	53.9	103.8	231.1	310.7	211.6	101.9	38.8	19.4	10.2	6.7	3.9
15	3.7	38.7	81.7	156.9	278.1	156.1	85.6	32.5	17.3	9.4	6.1	3.7
20	2.9	23.0	64.6	115.1	208.8	121.8	67.9	28.9	15.5	8.6	5.7	3.0
30	1.5	13.2	47.7	63.7	85.5	93.9	48.1	25.1	13.3	7.3	4.3	2.1
40	0.7	7.3	33.4	48.7	49.6	46.2	37.7	17.9	11.3	6.0	3.4	1.5
50	0.5	5.8	23.2	32.5	29.8	27.6	23.8	15.8	9.7	5.2	2.6	1.2
60	0.4	3.6	14.3	22.6	25.8	21.6	18.6	13.4	7.6	4.6	2.3	1.0
70	0.2	2.6	10.4	16.6	21.4	17.7	14.5	9.2	6.3	3.4	1.9</	

temporally compared to the remaining species. This was due to the species' high hydraulic activation requirement of $491 \text{ m}^3.\text{s}^{-1}$ (minimum) and therefore high relative elevation. This species was recorded only once at Mamba and twice at Balule, indicating insufficient datum to fully represent the species' hydraulic requirements. The minimum recorded activation discharge requirement at Balule was $149 \text{ m}^3.\text{s}^{-1}$, considerably lower than the single individual recorded at Mamba.

Results at Balule indicate that *P. crispus* and *L. stolonifera* (both semi-aquatic species) experienced hydraulic activation most frequently, both intra- and inter-monthly. Similar to findings at Mamba under present-day flow conditions, this is expected due to the low relative elevation of the species, therefore requiring low discharges to activate. Plant populations that experienced hydraulic activation least were *L. schweinfurthii* and *F. virosa*. Based on recorded datum at Balule, *L. schweinfurthii* has a minimum hydraulic activation requirement of $8903 \text{ m}^3.\text{s}^{-1}$ and *F. virosa* a minimum of $561 \text{ m}^3.\text{s}^{-1}$. *Lannea schweinfurthii* was recorded only once at Balule and *F. virosa* only twice. There are two possible explanations; either these two species are not riparian plant species, but rather woody encroachers and therefore the low abundances within the riparian zone are expected, or secondly, they are in fact riparian plant species but respond to infrequent intensive flooding events.

The theoretical base-flow scenarios indicate that plant populations at both Mamba and Balule sites (Figure 4.4(B) and Figure 4.5(B)) would have experienced hydraulic activation on a less frequent basis for the majority of the species. *Potamogeton crispus* would have been activated more frequently at both sites as it is considered a semi-aquatic plant species with a minimum activation discharge of $0 \text{ m}^3.\text{s}^{-1}$ (if located on the river bed, at the lowest point along the cross-section) and a maximum activation discharge of $5.2 \text{ m}^3.\text{s}^{-1}$, therefore the species requires low discharge values to activate. The base-flow scenarios were designed from present-day data by 'flattening-the-curve' whereby high flow events were suppressed and as a result, low flows were resultantly increased. This is why species that require low discharge values would be activated more frequently and those with higher requirements would experience activation less frequently as seasonal pulse events are 'flattened' or averaged. This is valuable information as this theoretical scenario informs us that the majority of the species recorded at both Mamba and Balule sites rely upon the seasonal pulses that are removed if flows are restricted or provided in steady, low discharges. These discharges seemingly increase overall monthly discharge but remove crucial seasonal events that riparian plants rely upon for life history events.

An assessment of the modelled natural scenario and theoretic base-flow scenarios indicate that the plant populations at both Mamba and Balule sites (Figure 4.4(C) and Figure 4.5(C)) would experience hydraulic activation for a greater proportion of time both inter- and intra-monthly. There have been limited studies conducted on the inundation tolerances of riparian plant

communities and it is likely that the current arrangement (relative lateral elevation) of the plant populations at Mamba and Balule differ considerably than what would have been expected under natural flow conditions, therefore it may be that the percentage of time that plants are activated (expressed in the natural scenario) exceed their tolerances and that the communities would rearrange themselves laterally along a river profile if they were exposed to higher flow conditions.

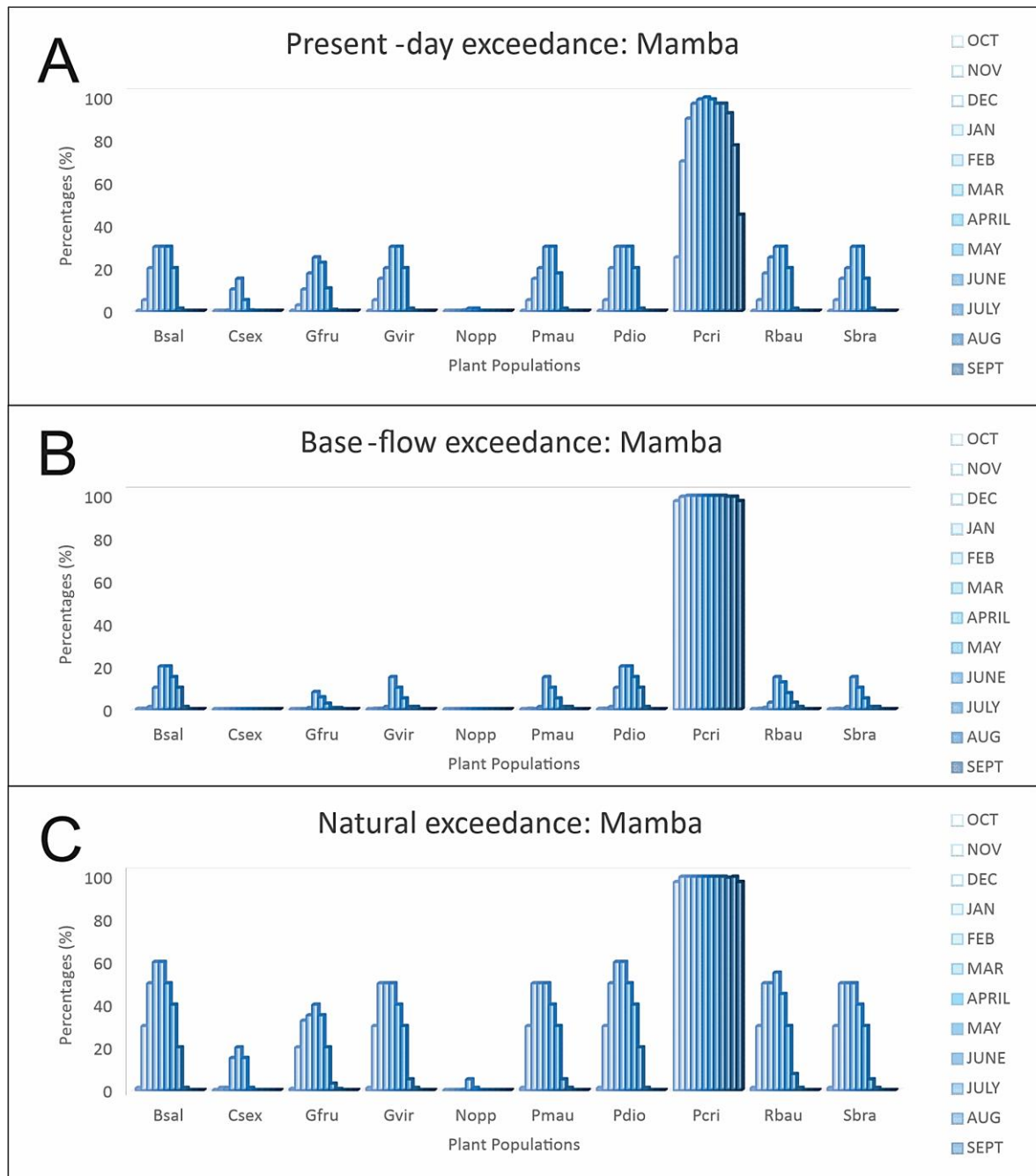


Figure 4.4: Relative abundances of median exceedance values and plant populations representing three scenarios for Mamba site along the lower Olifants River within the Kruger National Park. Scenarios represent (A) present-day, (B) base-flow and (C) natural exceedance values expressed in the 12-months of a year.

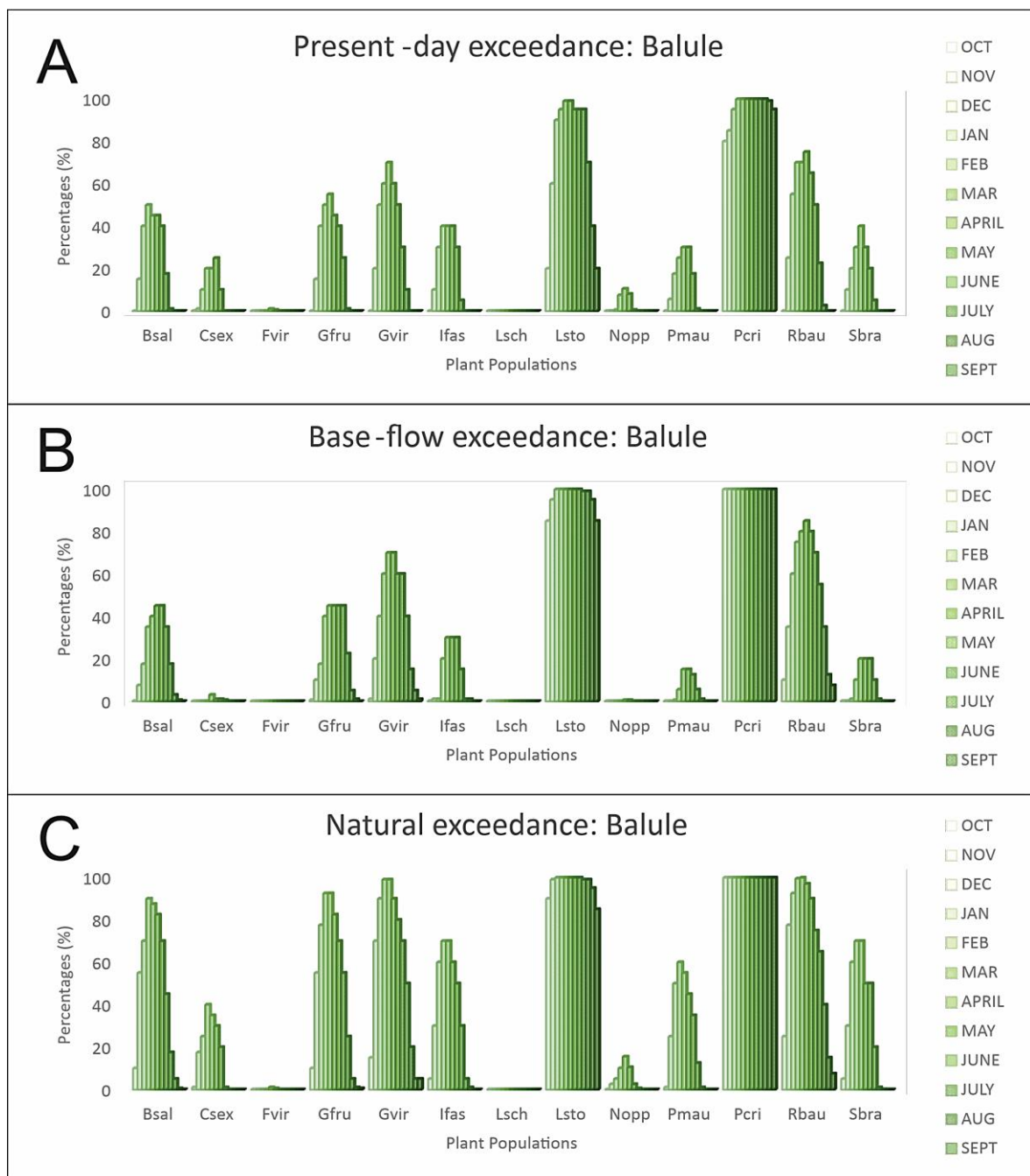


Figure 4.5: Relative abundances of median exceedance values and plant populations representing three scenarios for Balule site along the lower Olifants River within the Kruger National Park. Scenarios represent (A) present-day, (B) base-flow and (C) natural exceedance values expressed in the 12-months of a year.

4.4 Discussion

The findings from this study indicate that activation discharge values are useful for the establishment of rules pertaining to the full range of hydraulic preferences of riparian plant populations at a local scale. This information could be effectively applied as a biological node representing riparian vegetation in e-flow determination (O'Brien et al., 2018). Activation

discharge has been found ineffective when comparing values between sites as unique site characteristics such as morphology, geomorphology and underlying geology influence values associated with the hydraulic range of preference (Venter and Gertenbach, 1986; Pollard and Laporte, 2014; Van Deventer et al., 2018; Van der Waal, 2021, 2020). Despite these differences, there were clear similarities in temporal responses intra-specifically where species overlap existed between the two sites. Most of the species exhibited the same trends, responding to hydraulic activation at a similar relative distribution.

While activation discharge values did not provide the ability to directly compare values across sites, the conversion of hydraulic activation discharge value into percentiles with the use of hydrological flow exceedance tables successfully allowed for this. The conversion effectively removed site-specific variables through the interpretation of data relative to the percentage of time that hydraulic activation was achieved and not the value directly related to the lateral position along cross-section profiles. This information is expressed in the percentage of time hydraulic activation is experienced for each species, expressed in months. Similar to activation discharge, the information informs of hydraulic preferences of plant populations based on their lateral position along a river, providing insight into the most important time to conduct releases and the quantities requires. The additional component that the application of activation discharge values to exceedance tables provides is the ability to apply these 'rules' at a larger scale by removing site-specific variables.

Another important finding for this study was revealed when comparing present-day flow scenarios to base-flow scenarios. Findings indicated that by 'flattening-the-curve' and removing high flow events, many of the plant populations that associated most to wet season flows and had higher hydraulic activation requirements experienced hydraulic activation less frequently, however those that had very low activation discharge requirements were activated more frequently. This information informs that if a system is managed with a constant rate of flow (even if the dry season base flow is higher than is typical), many of the plant populations will experience hydraulic activation on a less frequent basis. This is because 'flattening-the-curve' provides a steady, but higher base flow whereby you remove essential hydraulic events in the form of seasonal pulses (Poff et al., 1997; Dudgeon et al., 2006; Naiman et al., 2008). These hydraulic events are essential for the life histories of plant populations with which they have evolved.

Findings also indicated that some plant species were not fully represented due to insufficient datum during the course of this study. There are two possible explanations as to why so few points were recorded for some of the plant species: (1) the species could have been terrestrial species encroaching into the riparian zone, therefore low abundances are expected or (2) the species are typically located at high relative elevations as they are species that typically

respond to intensive, infrequent flood events, therefore models that only encompass a 12-month period would not sufficiently represent these plant species.

4.5 Conclusion

Increasing pressure on freshwater ecosystems has fuelled the growing need to establish holistic and inclusive e-flows for all catchment basins (Naiman et al., 2005; Dudgeon et al., 2006; Horne et al., 2017; O'Brien et al., 2018). The accurate and holistic determination of e-flows can be achieved if all biological components are adequately represented in the models (O'Brien, 2021). The precise requirements with regard to timing, duration and frequency for individual biological groups can only be achieved through studies that focus on particular groups. This study was able to adequately determine the quantity and timing requirements of riparian vegetation at Mamba and Balule sites through two separate scenarios; hydraulic activation discharge was useful on a local scale and could be successfully used to set local hydraulic rules for plant species, populations and communities. This method would be useful for local reserve managers as it allows for specific, focused projects such as rehabilitation of a site or species. The method is also useful in the determination of e-flows for site-specific locations if inserted into models such as PROBFLO and Bayesian belief networks as separate nodes to represent riparian vegetation as a biological component (O'Brien et al., 2018). The second component of this chapter looked at the application of hydraulic activation values to hydrological flow exceedance tables in order to allow for site comparisons. This method utilized plant population AD data and was applied to tables set out over a 12-month period. The outputs of the conversion represented AD as a percentage of time that plant populations experienced hydraulic activation.

Mamba and Balule sites differ geomorphologically, morphologically and in their underlying geologies (Venter and Gertenbach, 1986; Van der Waal, 2021, 2020). According to Rowntree and Wadeson (1999), they fall within the same river classification zone E, defined as "lower foothills", therefore they are still comparable at a geomorphological level. Outputs for this component supports this through clear similarities and trends that were identified when comparing the response distributions of plant populations whose presence overlapped between the two sites. This study proves that hydraulic rules can be applied to plant populations across multiple sites once larger databases have been established for each individual species. This information would be invaluable for the representation of riparian vegetation in e-flow determination assessments. The method would also allow for the identification of a broader set of rules that could be utilized by water resource managers across sites as guidance on the correct timing and quantity of water in order to maintain or improve biodiversity and ecosystem functioning for the benefit of associated biota and the ultimate benefit of humans that either directly or indirectly rely upon the resources and services derived from the system.

5 Conclusions and recommendations

Freshwater ecosystems are some of the most threatened ecosystems on the planet (Dudgeon et al., 2006; Vörösmarty et al., 2010; Dudgeon, 2014). Increasing water demands has resulted in increasing pressure on ecosystem processes and the associated biota (Dudgeon, 2014). The development of effective and efficient methodology for the determination of environmental flow (e-flow) requirements with holistic and inclusive approaches is essential for the future of freshwater ecosystems (Dudgeon, 2014; Horne et al., 2017; O'Brien et al., 2018).

The key to optimizing the management of any biological ecosystem is in the understanding of what drives the system and how to effectively manage the drivers (Dudgeon et al., 2006; Horne et al., 2017; O'Brien et al., 2018). Chapter 3 focused on the assessment of the drivers of riparian plant communities at Mamba and Balule sites along the lower Olifants River within the Kruger National Park (KNP). The drivers considered were substrate preferences, water quality and the identification of hydraulic niche requirements of plant populations. Chapter 4 focused on the review of hydraulic niche requirements and the application of activation discharge to hydrological flow exceedance tables.

The findings in Chapter 3 indicated that substrates are an important driver to plant community compositions. There were clear associations between plant species possessing specific biological traits and associations with certain substrate groups. Results from this section indicated that woody traits were most frequently combined with tap root systems and sexual reproduction traits while non-woody traits were most frequently combined with adventitious root systems and reproductive strategies that possessed both the ability to reproduce sexual and asexual. The woody groups associated most towards larger substrate groups while non-woody groups showed associations towards finer substrates. Clear trends were evident for individual plant species and populations, providing insight into how substrate compositions drive plant community structure. The placement of in-stream water impoundment infrastructure such as dams and weirs as well as modifications to land-use activities affect sediment loads and substrate transportation potential, which directly affects downstream substrate compositions (Naiman et al., 2005, 2008; DWAF, 2013). This information can be applied to water resource managers through the ability to predict potential responses by riparian vegetation with changes in land-use activities and with the implementation of upstream dams or weirs.

The water quality analysis component of this study indicated that while humans were the likely source of disturbance at Mamba site, hippopotamus (*Hippopotamus amphibius*) were one possible source of disturbance at Balule site in the form of excess nutrients. Previous studies have shown that sedentary pods of hippopotami have been the sources of fish kills through anoxia post-flushing events at multiple locations (Dutton et al., 2018, 2021). An analysis of the water quality variables at Mamba indicated high salt concentrations and slightly elevated

organic matter. These findings coincide with a previous study that investigated the impacts to water quality within KNP river systems (Riddell et al., 2019). This study found that elevated salt concentrations and nutrients were a result of effluent input from Phalaborwa and heavy metal input from mining activities taking place within the Ga-Selati River. Long-term studies focused on identifying the responses between water quality parameters and their effect on riparian communities as ecosystem drivers would yield more conclusive results.

The hydraulic activation discharge (AD) was determined for individual plant populations at both Mamba and Balule sites. Hydraulic AD values provided information pertaining to the preferred lateral position of plant populations within the riparian zone, informing of the minimum and maximum range of preference. The application of this information to e-flow determination networks as nodes representing riparian vegetation flow requirements would provide an essential contribution to represent the biological group if surveys were conducted over a range of different sites. This information would also prove useful to water resource managers as it informs of the amount of discharge required to activate a plant at root level, which would provide insight into species-specific requirements for intensive management programmes such as rehabilitation and the improvement of local biodiversity and restoration of ecosystem service provision potential.

A riparian vegetation response assessment index (VEGRAI) was applied to both Mamba and Balule sites in order to determine the present ecological state (PES). An assessment of Mamba site provided a score of 79% with an average confidence of 2 which associated with category B/C. The score informs that the site was considered to be in a good “mostly natural with few modifications” and/or fair state “moderately modified with lower-than-expected species richness” (Kleynhans et al., 2007; Mackenzie, 2020). Balule site provided a score of 69% with an average confidence of 2.1 which associated with category C. Category C is described as fair as described above. The riparian vegetation at both Mamba and Balule sites were negatively affected by impacts associated with modifications to natural flow regimes and flow restrictions. Responses were observed within the marginal and lower zones that were adjacent or in close proximity to the water’s edge. Both sites were also negatively affected by alien invasive plant species, however invasions at Balule were of a greater extent and intensity than those recorded at Mamba.

Insight into the determination of the PES with the use of the VEGRAI tool for Mamba and Balule sites informs that the modification of flow regimes and flow restrictions in the form of seasonal pulses negatively impact riparian ecosystems through the restriction of sediment transportation potential and the provision of essential hydrological events (Poff et al., 1997; Naiman et al., 2005; Dudgeon, 2014). It is apparent from this assessment that sediment compositions at both Mamba and Balule were in a modified state and that plant community compositions were likely altered as a result. Compounding on the pressures by flow restrictions and modifications is the

intensity and extent of alien invasive plants that were observed in intensities that excluded all other plant life in certain sections at Balule. It is possible that the restoration of natural flow regimes and hydraulic seasonal pulses may result in the replacement of alien invasive plants. Future studies focused on the restoration of natural flow regimes as a tool for the removal/replacement of alien and invasive plants could yield interesting results.

The final component of this study assessed the effectiveness of the application of hydraulic AD values to hydrological flow exceedance tables, also known as Look-up Tables (LUT). Activation discharge values were converted from local discharge requirements to relative temporal values described over a 12-month period. Despite differences in site morphology, geomorphology and underlying geology, the vast majority of plant populations showed clear temporal similarities and trends. Both Mamba and Balule sites are located in river classification zone E, therefore although differences exist on a local scale, according to Rowntree and Wadeson (1999), they fall within the same geomorphological region, therefore they are comparable.

The information provided by hydrological exceedance tables would allow for the use of riparian vegetation as one of the biological indicators of e-flow requirements. The application of hydrological flow exceedance data could be applied on a species, population or community level by incorporating the full hydraulic range to monthly and annual requirements. The rules would coincide with life history events of plants (if located within the same regions) and therefore optimize on the biodiversity potential and the resultant resources and services provided by an optimally functioning system.

*Based on the above results therefore **support Hypothesis 1** that the application of activation discharge and hydrological exceedance values to riparian plant communities can be utilized as part of water resource management in the setting of environmental flow requirements.*

*The above results also **support Hypothesis 2** which states that the environmental flow requirements of riparian vegetation are useful for water resource management.*

The Olifants sub-catchment basin is a part of the Limpopo Catchment basin that encompasses three riparian countries (McCartney et al., 2004). The Limpopo Catchment has been classified one of the most water-stressed catchment basins on the African continent and predictions indicate that further pressure will be exerted upon the catchment with increasing water resource demands (McCartney et al., 2004; Trambauer et al., 2014; Marr et al., 2017a; Donnenfeld et al., 2018). Based on the predicted increase in demands on an already water-stressed system, it is unlikely that systems under intensive and extensive utilization such as the Limpopo Catchment will be restored to optimally functioning capacity with maximum e-flow recommendations. A compromise is however necessary if humans wish to make use of the ecological services and resources provided by freshwater ecosystems. In cases such the Limpopo Catchment, hydrological flow exceedance values applied to riparian plant communities can be particularly

useful as they inform of the minimum required discharge to maintain biological communities and the resultant ecosystem processes derived from the systems, therefore a threshold of hydraulic tolerance.

The application of activation discharge values to hydrological exceedance tables proved successful for this study, however for some species there may have been insufficient datasets to fully represent the taxon. Future recommendation relating to this study include two case test scenarios: (1) to statistically test the effectiveness of riparian vegetation as indicators in e-flow determination at a limited number of sites but with increased samples sizes in the form of numerous surveyed cross-section profiles and (2) to statistically test the effectiveness of riparian vegetation as indicators of e-flow determination at numerous sites within a catchment through rapid sampling techniques whereby only one cross-section is conducted per site. This method may yield smaller sample sizes but will encompass a larger area for improved representation of the variety of ecosystems within a catchment basin.

e-flow assessments usually take place over a large quantity of site locations and budget and time allocations are limited (Horne et al., 2017; O'Brien, 2021). This study was a part of a larger project associated with the Limpopo Watercourse Commission (LIMCOM) for the establishment of e-flows for the Limpopo Catchment basin with the use of the holistic PROBFLO methods that incorporates the Bayesian belief network as well as the relative-risk models. The activation discharge values for riparian plant communities generated during the course of this study were incorporated into the model as nodes representing riparian vegetation hydraulic niche requirements for Mamba and Balule sites.

Additional recommendations for future studies relating to this dissertation include the laboratory testing of inundation tolerances of selected riparian vegetation indicator species with regard to inundation duration tolerances and velocity tolerances over time. The addition of these aspects would provide essential information pertaining to the threshold of tolerance with regard to inundation duration and the flow-velocity tolerances associated with high discharge scenarios. Finally, the application and testing of the effectiveness of hydrological flow exceedance data to sites belonging to different river classification zones. Rowntree and Wadeson (1999) suggest that biological responses differ when comparing different river zones as a result of the varying environmental pressures and differences in geomorphological components, therefore testing this theory would confirm or disprove whether this rule applies to hydrological exceedance percentiles for riparian vegetation.

6 References

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