FLOOD ALLEVIATION AND RESTORATION ON THE LOURENS RIVER, SOMERSET WEST, SOUTH AFRICA

by

Dirk Jacobus Martins Campher

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Supervisor and co-supervisors:
Prof. Dominic Mazvimavi
Prof. Cate Brown
Dr Karl Reinecke

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‘Soft’ engineering

‘Urban stream syndrome’

Abstract

Flood alleviation and restoration on the Lourens River, Somerset West. South Africa

Dirk J.M. Campher

MSc. Dissertation, Department of Earth Sciences, Faculty of Natural Sciences, University of the Western Cape.

Somerset West and Strand in the Western Cape, South Africa, were developed on the Lourens River floodplain. This hardened the catchment and reduced the capacity of the river to transport and store floodwaters. The result was recurrent flooding of residential and industrial areas and a fear that this could lead to loss of human life. In response to these concerns, the City of Cape Town implemented flood alleviation measures with a ‘soft’ engineering approach that incorporated geomorphological and ecological principles into their design. This was one of the first engineer/ecologist collaborations in South Africa, which attempted to make better decisions for the river ecosystem within the constraints imposed on it by urban development; and in so doing to create a self-sustaining river that requires little ongoing manipulation. The aim of this dissertation was to assess the extent to which ecological considerations were incorporated into the flood alleviation works on the Lourens River and whether this improved physical habitat and the diversity of riverine biota. Physical habitat was mapped from 1:50 000 topographic maps and aerial imagery in a GIS, and cross-sectional profiles, diversity of hydraulic biotopes and subtsrate composition were surveyed in the field. River ecosystem data comprised plants species and aquatic macroinvertebrate family distribution and abundance. The study demonstrates that incorporation of geomorphological and ecological principles into flood alleviation measures increased the river’s capacity to carry flood waters, improved physical habitat and biodiversity and resulted in a generally healthier river ecosystem. This is evident from the macro-invertebrate and riparian vegetation assemblages now established in river reaches where river works were completed. There are also signs that the river ecosystem is on a trajectory towards once again becoming a self-sustaining ecosystem, although there are issues that need to be addressed if this trajectory is to be maintained. These include the continuous urban sprawl, bank stabilizing structures that require maintenance, proliferation of alien vegetation, water quality, and vagrants living in the river corridor and disconnect between catchment managers and stakeholders of the river.

Declaration

“I declare that, *Flood alleviation and restoration on the Lourens River, Somerset West*, *South Africa,* is my own work, that it has not been submitted for any degree or examination in any other university and that all the sources I have used or quoted have been indicated and acknowledged by complete references.”

Full name: Dirk Jacobus Martins Campher **Date:** June 2021

Signed...

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Acronyms

ANOSIM - Analysis of Similarities
ASPT – Average Score per Taxon
Appx – Appendix
BON – Balance of Nature
CCA – Crowther Campbell and Associates
CoCT – City of Cape Town
DISS/SD - Dissimilarity Coefficient/Standard Deviation
DWAF – Department of Water Affairs and Forestry
DWS – Department of Water and Sanitation
FFG’s - Functional Feeding Groups
FON – Flux of Nature
GPS – Global Positioning System
GSM – Gavel-Sand-Mud
IHAS - Invertebrate Habitat Assessment System
ISC - Impervious Surface Cover
LRAC – Lourens River Advisory Committee
LRCS – Lourens River Conservation Society
MAC - Management Advisory Committee
m.a.m.s.l - meters above mean sea level
MAR – Mean annual runoff
MCM - Million Cubic Meters
MDS – Multi-Dimensional Scaling
NEMA – National Environmental Management Act
NGI – National Geo-Spatial Information
PNE – Protected Natural Environment
Q - Discharge
RHP - River Health Programme
SACS – South African Scoring System
SANBI - South African National Biodiversity Institute
SASS – South African Scoring System
SER – Society of Ecological Restoration
SIC - Stones-In-Current
SIM/SD – Similarity Coefficient/Standard Deviation
SIMPER – Similarity Percentages
SOOC – Stones-Out-of-Current
SSI – Stewart Scott International
UNISDR – United Nations Office for Disaster Risk Reduction
WRC – Water Research Commission

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1 Introduction

1.1 Introduction

For centuries, rivers were the foundation upon which civilizations developed (Everard and Powel 2002; Mays 2008; Mihov and Hristov 2011). Considered as essential features of the landscape, rivers provide important benefits to people such as freshwater for drinking; food, in the form of fish, frogs, crustaceans, molluscs and edible plants; building materials, of sand, gravel and wood; transport; irrigation; and power generation (Everard and Powel 2002; Gilvear *et al.* 2013; Ekka *et al.* 2020). The provisioning of these benefits is supported by key regulatory services, such as, water purification, nutrient cycling and flood regulation (Giller 2005; Millennium Ecosystem Assessment 2005; Thorp *et al.* 2010; Gilvear *et al.* 2013; Ekka *et al.* 2020). Human development, however, has degraded rivers, undermining their productivity and resilience with the consequent loss of biodiversity and valued ecosystem services (Poff *et al.* 1997; Naiman *et al.* 2005; Giller 2005; Vermaat *et al.* 2016; Mondal and Patel 2018; Ekka *et al.* 2020). This loss is most acute in urban and peri-urban areas where wholesale changes to the landscape and confinement of river systems to canals and stormwater sewers, alters hydrological and sediment regimes (Poff *et al.* 1997; Paul and Meyer 2001; Yuan *et al.* 2006; Wen *et al.* 2015), and polluted effluents and runoff impair water quality regimes (Poff *et al.* 1997; Gilvear *et al.* 2002; Ren *et al.* 2014; Mwangi 2014; Petersen 2019; Ekka *et al.* 2020; Duan and Tukara 2020). This continuous disruption can cause the collapse of natural river ecosystem functioning, rendering urban rivers dangerous to humans (Schmutz and Sendzimir 2018).

One of the most pervasive effects of urbanization on river ecosystems is that of catchment hardening resulting in changes in the natural flow regime of rivers. Concrete, tarmac and roofs mean less infiltration into the soils and more runoff draining the surrounding landscape (Poff *et al.* 1997; Chin 2006; O'Driscoll et al 2010; Wen *et al.* 2014; Zahara *et al.* 2016). This leads to floods of shorter duration, with steeper rising curves and higher peak discharges and diminished groundwater recharge, which negatively affects baseflows in the dry season (Poff *et al.* 1997; Yuan *et al.* 2006; Wen *et al.* 2014; Zahara *et al.* 2016). These changes in the flow regime, combined with the act of confining rivers and subsequent loss of capacity to transport flood waters, results in recurrent flooding within urban areas, highlighting the consequences of managing river systems poorly.

The field of river restoration ecology emerged in the 1970s in response to the realization that river ecosystem degradation caused by past practices not only damages rivers, but also diminishes the health and welfare of people (Dodds and Whiles 2010; Seidl and Stauffacher 2013; Coux *et al.* 2015; Moore and Rutherfurd 2017; Gregory 2019). River restoration is at the forefront of applied hydrological science (Wohl *et al.* 2005), recognizing that rivers and associated riparian vegetation are important natural resources, even in urban areas and aims to address the challenges of urban development in a manner that supports rather than impairs river (and estuary) ecosystem functioning (Poff *et al.* 1997; White and Greer 2006; Palmer *et al.* 2014; Addy *et al.* 2016; Perini and Sabbion 2017; Staentzel *et al.* 2019). It aims to create characteristic, dynamic and self-sustaining physical habitat that promotes biological recovery and restores the accrued benefits that people rely on, i.e., regulation of flood waters (Addy *et al.* 2016). This is done by adhering to principles of geomorphology, natural physical processes (e.g., variation in the movement of water and sediment), macro- and micro-channel features and physical habitats (e.g., maintenance of floodplain and riparian wetlands, river channel shape, substrate) and maintenance of biodiversity within the riparian zone. This is particularly challenging in urban and peri-urban planning and management initiatives because of the constraints imposed by urban sprawl, i.e., residential, industrial and commercial developments. As such, the practice of river restoration often requires a blend of engineering, ecological, social and economic and management practices.

1.2 Background

In common with many cities around the world, Somerset West and Strand, in the Western Cape of South Africa, were developed along the banks of a river, in this case the Lourens River and its tributaries. Early settlers were drawn to the fresh water and fertile farmland along the river banks (Cliff 1982; Brown and Magoba 2009). Over time, agriculture gave way to housing, industrial developments and roads, which encroached onto the floodplains and hardened the surrounding catchment, preventing rainwater infiltration (Poff *et al.* 1997; Chin 2006; Yuan *et al.* 2006); leading to a concomitant increase in the intensity of flood events and a reduction in the capacity of the river channel and floodplain to transport and store floodwaters. The result was recurrent flooding of residential and industrial areas and by the late 1980s it became clear that this could lead to a loss of human life (Compion and Rooseboom 1996; SSI 1998; du Plessis *et al.* 2014).

Three significant flood events occurred in short succession in 1976, 1981 and 1983 (Hill Kaplan Scott Inc. 1986; SSI 1998; du Plessis *et al.* 2014). The flood peak on 25 January 1981 was the highest recorded by the DWS gauging station at 273 m^3/s and resulted in the flooding of Somerset Oaks Old Age Home and the Pick and Pay supermarket near the old historic bridge. According to du Plessis *et al. (*2014), there was an even larger flood than the 1981 flood which occurred in 1954 and was estimated to have a peak discharge of 300 m^3/s.

In 1996, Compion and Rooseboom (1996) working on behalf of the City of Cape Town, identified an old distributary of the Lourens River that had carried floodwaters before humans settled in the valley, but which had subsequently been reduced to an irrigation furrow, as a possible solution to alleviating the pressure of the main channel of the Lourens River during flood events. This option, however, was not implemented and by the late 1990s, urban development, including a Vergelegen Mediclinic hospital and a retirement home, had been built across the path of the distributary all but eliminating its formal use as a flood channel. The flood event in 2013, however, resulted in considerable damage to the hospital, leading to new calls to incorporate the distributary into flood alleviation measures in the Lourens River valley (du Plessis *et al.* 2014).

In 2000, the City of Cape Town re-initiated a programme of flood alleviation measures, which focused on increasing the in-channel carrying capacity of the Lourens River and on identifying off-channel flood attenuation areas (CCA 2000). Early suggestions and designs were for a traditional hard engineering approach, which called for deepening and widening the river channel with canalization in places; however, these ideas were tempered through consideration of geomorphological and ecological principles. This resulted in the adoption and subsequent phased implementation, of a series of softer options that represented a hybrid between engineering and ecological concerns, such as multistage channels and protection barriers. Thus, while its origins were purely engineering, the Lourens River Flood Alleviation study morphed into a river restoration study; albeit one driven mainly by engineering considerations.

1.3 Motivation and hypothesis

The outcome of river restoration projects are often not fully evaluated in terms of their success (Coux *et al.* 2015). Many papers have highlighted the lack of information on the success of restoration projects leading to this paucity in data and knowledge gaps (Bernhardt *et al.* 2005; Roni *et al.* 2008; Beechie *et al.* 2010; Coux *et al.* 2015; Addy *et al.* 2016; Mondal and Patel 2018; Cao and Tukara 2020). The prerogatives to protect human life and property whilst protecting ecosystem and biodiversity values often appear conflicting, particularly given the constraints imposed by historical developments, budgets and politics (Terrado *et al.* 2016). Thus, demonstrating success in implementation and the accrued benefits of river restoration projects where these conflicting objectives are balanced (even partially) is vital for guiding future urban and peri-urban planning and development, especially if restoration measures are to be carried out in an efficient and cost effective manner (Thorp *et al.* 2010; Gilvear *et al.* 2013; Coux *et al.* 2015; Terrado *et al.* 2016 Vermaat *et al.* 2016).

The aims of this dissertation were (1) to assess the extent to which ecological principles, in terms of channel shape, treatment of the banks and bed, in-channel habitat and landscaping were incorporated into the flood alleviation works along the Lourens River; and (2) whether their incorporation improved the suite of ecological benefits relative to those that would have accrued had the original engineering proposals been implemented. To address the first objective, the study considered the initial engineering plans to address flooding, adjustments to those plans after geomorphological and ecological inputs, the actual river works that were implemented and the resultant changes in channel planform and in-channel and riparian habitats. The second objective was addressed through comparisons of the condition (health) of the river ecosystem before and after implementation of the river works.

The outcomes include a review of the original motivation for the flood alleviation works, the scope and detailed design of original engineering proposals, adjustments to integrate ecological principles, ecological principles incorporated into completed works and the outcomes in terms of channel morphology (planform and in-channel habitats). They also include an assessment of changes in ecosystem condition as a result of the implementation of the flood alleviation works. These are discussed in the light of the prevailing constraints and concerns in the catchment, advances in river restoration, lessons-learnt through the implementation of the works and speculation on the likely ecological condition had the original engineering proposals been implemented.

Aims 1 and 2 are addressed in Chapters 4 and 5, respectively. The hypotheses associated with each are:

Hypothesis 1: River works and associated landscaping improved the diversity of habitats and riparian plant species present and recruiting along the river and thus contributed to a higher Ecological Integrity.

Hypothesis 2: River works and associated landscaping improved the diversity of aquatic invertebrates, thus contributing to a higher Ecological Integrity.

1.4 Thesis outline

Chapter 1 presents the context within which the study was undertaken. It also motivates for the need to further our knowledge and understanding of river restoration so that future projects do not repeat the mistakes of the past.

Chapter 2 reviews scientific literature. The concepts of river classification are reviewed first to provide an understanding of river form and pattern over a range of spatial, i.e., catchment to micro-habitat. This is followed by a brief description of the pioneering concepts that addressed river function and river functionality across time and space. The literature on structure and function of river systems is then reviewed, highlighting important processes and the relations between fluvial geomorphology and ecology. This is followed by a review of the impacts of anthropogenic activities on river form and function. The chapter concludes with review of river restoration concepts.

Chapter 3 is an overview of the Lourens River catchment, the study area and the study reaches. Information is presented on characteristics such as geology, climate, catchment, flora, land use and water chemistry.

Chapter 4 is an assessment of the physical habitat of the river in terms of: the rivers longitudinal profile, channel planform, landuse, extent of floodplain available, bankside woody vegetation continuity, macro-features of the river channel, bank stabilising structures, cross-sectional profiles, diversity of hydraulic biotopes and substrate composition.

Chapter 5 is the assessment of the ecological integrity of the river in terms of macro-invertebrate and riparian vegetation.

Chapter 6 is a brief discussion on the success of incorporating geomorphological and ecological principles into the Lourens River Flood Alleviation Project.

2 Literature Review

2.1 River morphology

A rivers' morphology, its form and function, is driven primarily by climate, geology and topography and an array of smaller-scale catchment and channel drivers (Figure 2.1; Dardis *et al.* 1998; Rowntree 1991; Rowntree and Dollar 1996a; Rowntree and Wadeson 1999; Naiman *et al.* 2005; Fryirs and Brierley 2013). The main drivers are, in turn, influenced by the corresponding smaller scale drivers that interact with one another through complex processes. Catchment drivers include the hydrological regime, soil depth and type, catchment vegetation and management, which govern the timing and volume of water and sediment supplied to a river channel, i.e., the channel drivers (Rowntree 1991). Channel drivers include the channel long profile, discharge, sediment load, bed and bank material and riparian vegetation. These controls regulate the transport of sediment and geomorphological processes; and thus, the stability of river bed and banks. Shifts in these drivers alter rates of erosion and deposition and ultimately lead to changes in river form and function (Dardis *et al.* 1998; Rowntree 1991; Rowntree and Dollar 1996a).

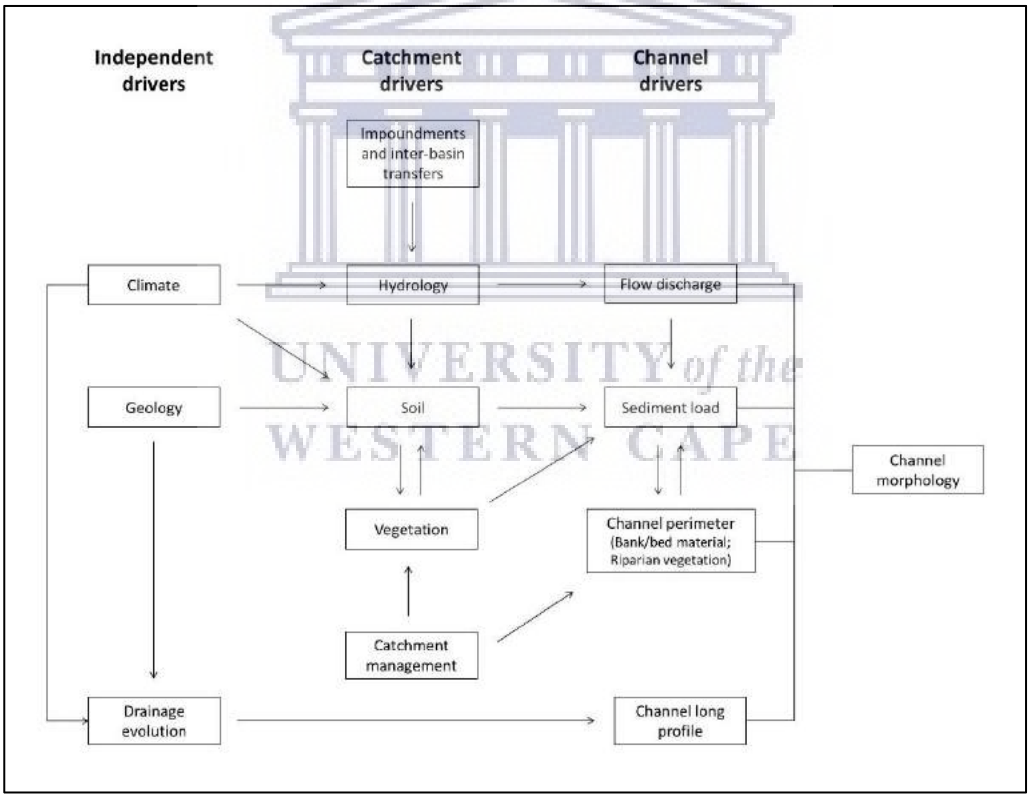

Figure 2.1 Drivers affecting river channel structure. Modified from Rowntree and Wadeson (1999).

Rivers usually rise in the mountains either as springs or seeps and begin their journey to the sea or a lake (Davies and Day 1998). The longitudinal profile of a river represents the change in elevation of the river channel from its headwaters to its end; thereby showing the rate of change of slope (gradient) as a function of distance downstream (Knighton 1984; Rowntree and Wadeson 1999; Fryirs and Brierley 2013). Most rivers adjust their channels to create a smooth, concave longitudinal profile (Figure 2.2), with a steady decrease in the slope and energy with distance downstream, termed a ‘graded river’ (Morisawa 1985; Rowntree and Wadeson 1999; Fryirs and Brierley 2013). Graded rivers have sufficient energy to transport the sediment load supplied from the surrounding catchment and generally exist in a state of equilibrium; any change will cause the system to shift in a direction that will absorb the effect of change, i.e., a state of erosion or deposition (Fryirs and Brierley 2013).

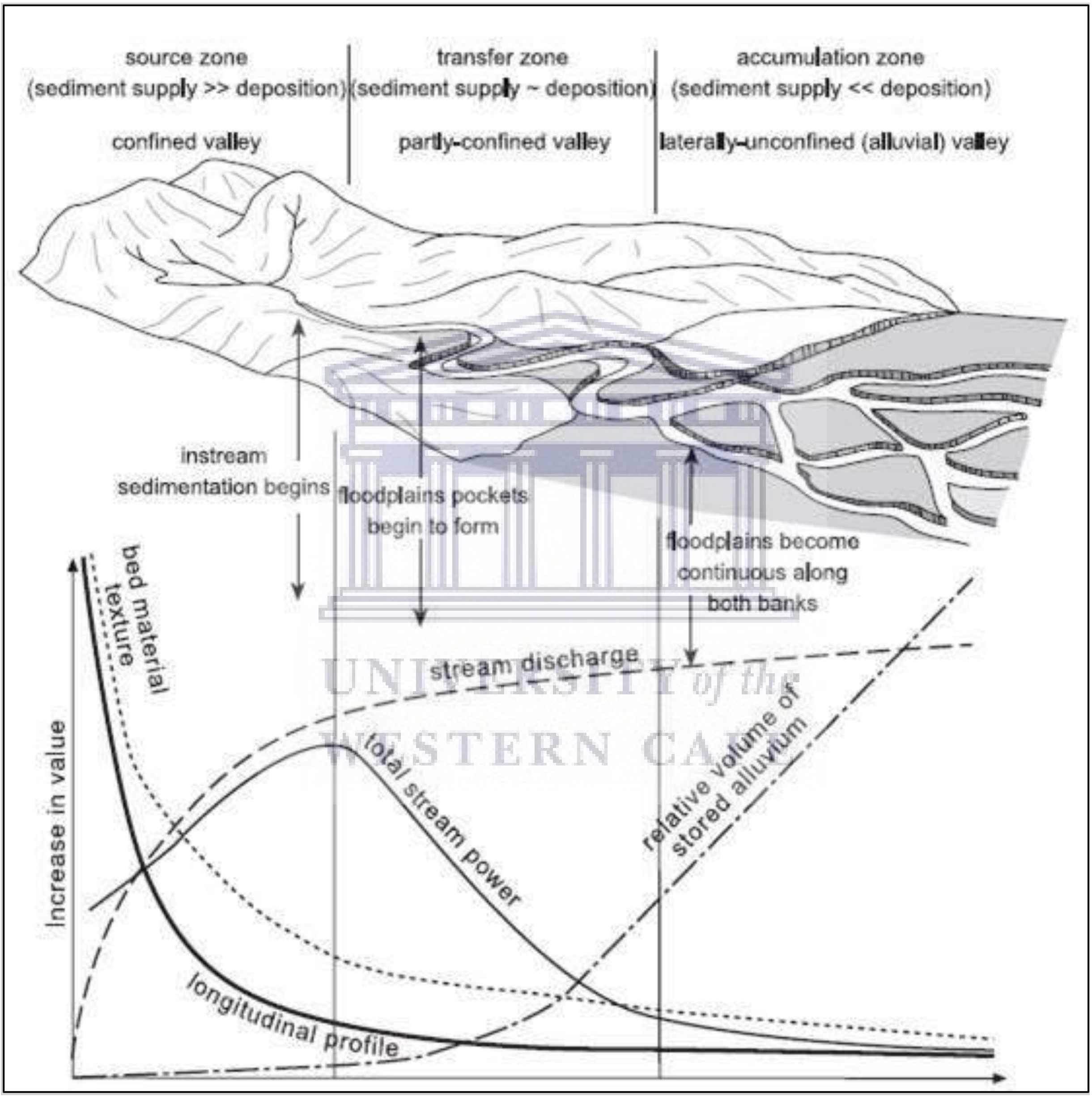

Figure 2.2 **Schematic representation of the relationship between downstream changes in slope, discharge, bed material texture, total stream power and stored alluvium along a typical concave-up longitudinal profile and associated transitions in sediment process zones and valley-setting pattern (Modified from Fryirs and Brierley 2013).**

The discharge of a river often increases with distance downstream in response to changes in the steepness of slope, widening of the channel, spilling of water onto adjacent banks and floodplains and the emptying of smaller tributaries into a larger, slower flowing river (Freeman and Rowntree 2005; Wohl *et al.* 2015; Fryirs and Brierley 2013). The gradual changes in discharge lead to changes in the transportation of sediment and thus the geomorphological processes occurring within a river channel. The result is a pattern of distinct geomorphological features along the course of a river system; with coarser sediment material in the steeper reaches and finer sediment grains in the flatter reaches (Rowntree and Wadeson 1999; Rowntree *et al.* 2000; Fryirs and Brierley 2013).

Rivers also exhibit considerable variability in their flow regime over time in response to changes in rainfall and infiltration capacity (Poff *et al.* 1997; Ward *et al.* 2001; Buffington and Montgomery 2013; Fryirs and Brierley 2013). Rivers can be classified into three main categories based on the temporal variation in their flow regime; perennial, intermittent (seasonal) and ephemeral (episodic) (Fryirs and Brierley 2013). Perennial rivers flow throughout the year, whereas an intermittent river dries up from time to time on an irregular basis. Ephemeral rivers are dry throughout most of the year and generally only flow after rainfall events, there are exceptions where some have seasonal flow.

Fryirs and Brierley (2013) describe the relationship between rainfall, infiltration and runoff (Figure 2.3). Generally, infiltration rates of soil are at their highest at the start of a rainfall event and steadily decrease as the soils become saturated, until an equilibrium state is reached (Fryirs and Brierley 2013). When soils become saturated, excess rain is converted into runoff that flows over the landscape and drains into river channels. Peak runoff generally lags behind rainfall because of the buffer created by the porous soil. Runoff can continue even after rainfall has stopped as excess rainwater continues to drain from the surrounding landscape. Understanding this temporal flow variability is critical for interpreting the behavioural changes in river systems (Fryirs and Brierley 2013).

The flow regime of a river is defined by the pattern of its discharge quantity, timing and variability (Poff *et al.* 1997). There are five components of the flow regime that are crucial for regulating ecological processes in river ecosystems; magnitude, frequency, duration, timing and the rate of change of hydrologic conditions (Poff and Ward 1989; Walker *et al.* 1995; Poff *et al.* 1997). These components can be used to characterize the variations in flow regime ranging from baseflows to flood events (Poff *et al.* 1997).

The temporal variation of runoff is commonly depicted on a hydrograph, which is a visual representation of the magnitude of runoff over time (Figure 2.4 and Table 2.1; Fryirs and Brierley 2013). Prolonged and heavy rainfall events commonly result in flood events that occur when river systems are unable to convey the quantity of runoff draining from the surrounding landscapes (Fryirs and Brierley 2013). A flood occurs when the river flow overflows the banks (Jones 1997; Poff *et al.* 1997; Wohl 2000a; Smith-Adao 2004; Fryirs and Brierley 2013). Whether or not flooding in a river occurs is dependent on two factors: firstly, the volume of direct surface or near-surface runoff and secondly, the travel times of runoff from different parts of the catchment (Jones 1997; Smith-Adao 2004).

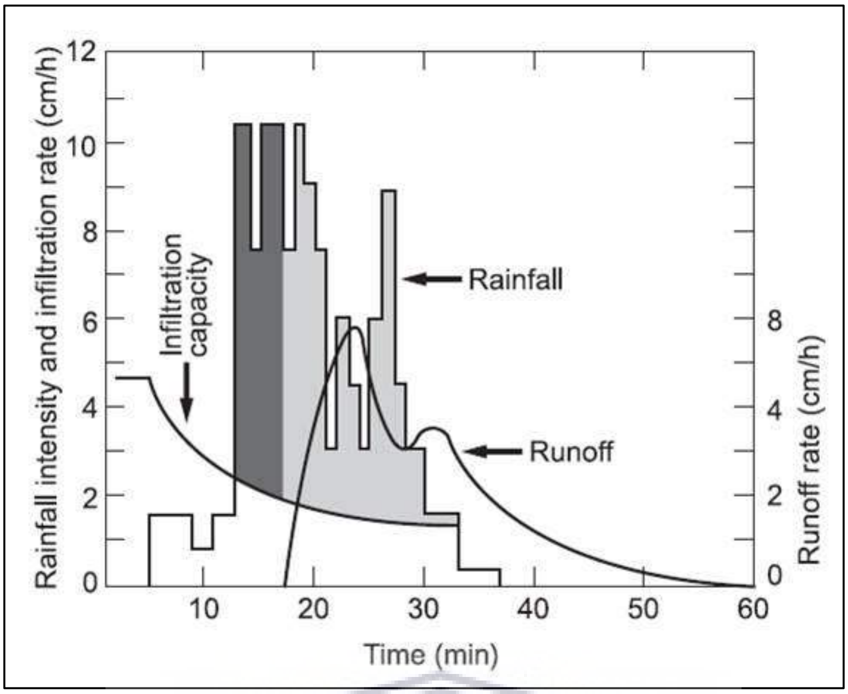

Figure 2.3 Schematic representation of the relationship between rainfall, infiltration and runoff (Fryirs and Brierley 2013). Dark Grey = rainfall infiltrating into soil; Light Grey = Excess runoff.

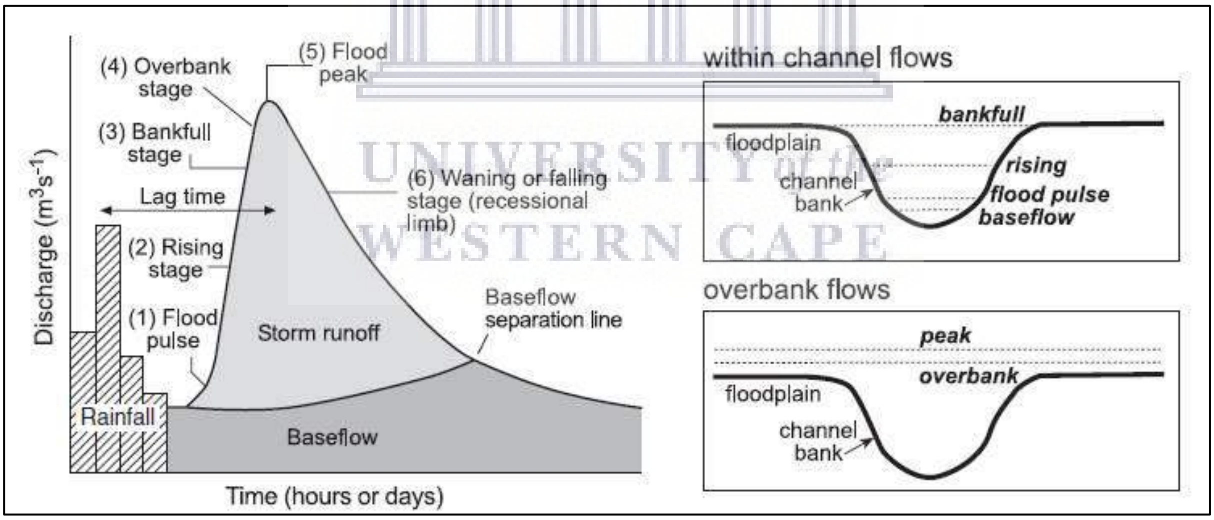

Figure 2.4 Flow stages on a hydrograph. Six stages of flood flow are differentiated on the hydrograph and as flows through channel cross-sections. Modified from Fryirs and Brierley (2013).

Table 2.1 Description of the flow stages on a hydrograph (Fryirs and Brierley 2013).

Stage	Description
Baseflow	The low flow or average flow in a channel.
Stage 1; Flood pulse	The first increase in flow above baseflow conditions.

Stage	Description
Stage 2; Rising stage	A steep increase in the volume of water being carried by a channel.
Stage 3; Bankfull stage	The channel is filled to the top of the banks (without spilling onto the floodplain).
Stage 4; Overbank stage	Flow spills onto the floodplain, where it spreads and dissipates energy
Stage 5; Flood peak	The stage at which the volume of water is at its maximum.
Stage 6; Falling stage	The gentle receding limb of the floodwaters back towards baseflow conditions.

There are several factors that control the shape of a hydrograph, these include; topography, soil type and depth and vegetation type and density (Figure 2.5; Horton 1932; Ramírez 2000; Gordon *et al.* 2004; Fryirs and Brierley 2013; Del Rio *et al.* 2020). These factors affect the rate at which precipitation in the catchment drains in a river; and hence, affect the shape of its hydrograph and the amount of sediment it carries. In a natural system, the flow regimes of rivers draining small, steep basins tend to be 'flashier' than those draining large basins, which reacts more slowly following rainfall (Horton 1932; Chow *et al.* 1988; Ramírez 2000; Gordon *et al.* 2004; Fryirs and Brierley 2013). Steep slopes lead to a rapid transfer of water and shorter lag times, whereas gentle slopes slow the transfer of water and long lag times. Areas with deep permeable soils infiltrate more water, which attenuates peak flows and results in runoff of slower magnitude and longer duration. Areas with impermeable surfaces result in less infiltration and more rapid overland flows. Water flows quickly in basins with little or no vegetation compared to basins with dense vegetation that intercepts rainfall, thereby altering and slowing its path to the river.

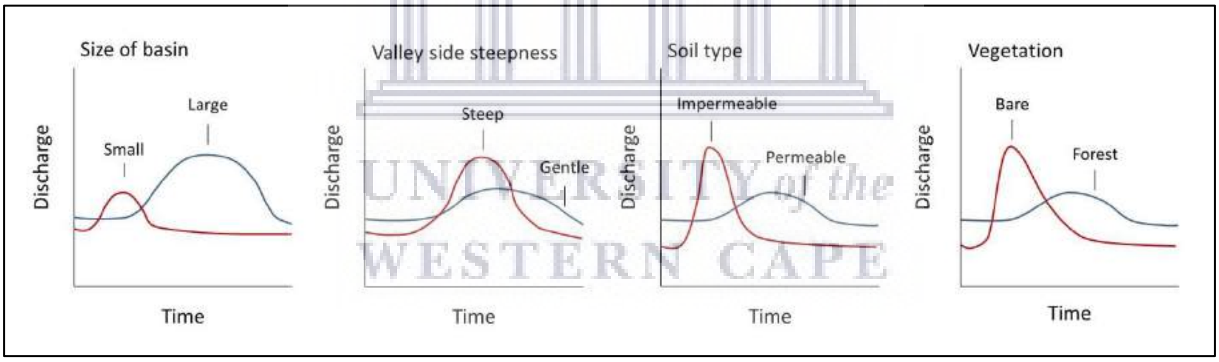

Figure 2.5 Stylized differences in the shape of flood hydrographs with basin area, gradient, soil type and vegetation cover. Modified from BBC (2019).

Three approaches commonly used to represent a river's flow regime include hydrographs and flow duration curves (Fryirs and Brierley 2013). Hydrographs provide graphical representations of flow over time, whether it is daily, monthly, or annual flows (Fryirs and Brierley 2013). Measures of flow variation help relate historical flood events to geomorphic and landscape changes. Hydrographs demonstrate seasonal variation in flows, when floods of various magnitudes occurred and the timing, magnitude of flood events. The variability of flow is determined using a coefficient of variation (Fryirs and Brierley 2013). A high coefficient of variation indicates that flows are more variable from year to year. Finally, flow duration curves show the percentage of time that a given flow magnitude is equalled or exceeded (Fryirs and

Brierley 2013). Daily, monthly, or annual flow data can be used to construct flow duration curves.

The fact that river flow varies over time indicates that river systems are continuously changing. These changes occur across all three spatial dimensions (longitudinally, laterally and vertically) and time scales from hours to thousands of years. While variations in rainfall–runoff relationships and resistance factors lead to changes in geomorphological processes (i.e., erosion and deposition) over a short term (e.g., days, weeks and months), over decades, this may influence the erosion-deposition equilibrium of a river. These shifts, however, are still minor in comparison to transformations in the landscape from climatic and geologic events (glacial/interglacial and earthquakes) that occur over tens of thousands of years. This means managers and stakeholders must consider the present state of river ecosystems and their historical past. When looking at rivers through a lens of short time scales, rivers appear to be controllable in ignorance of unforeseen events. It is therefore critical to consider processes occurring at much long time scales to understand that many of these processes and events are out of human control.

2.1.1 Geomorphological processes that influence river channels

River channels are defined by the geological template through which they flow and comprise three main types; bedrock channels, alluvial channels and mixed channels (Schumm 1985; Rowntree and Dollar 1996a; Rowntree and Wadeson 1999).

Bedrock channels are underlain by solid rock, which means that the river bed is resistant to erosion (Schumm 1985; Rowntree and Dollar 1996a; Rowntree and Wadeson 1999). The channels are commonly referred to as ‘bed rock controlled’ channels because their form is determined by bedrock controls, rather than by variations in the flow regime. Bedrock channels are fixed in position and remain stable over long periods of time. Alluvial channels comprise bed material, i.e., boulders, cobbles, gravel and sand (Table 2.2; Wentworth 1922) that is transportable by flow (Schumm 1985; Rowntree and Dollar 1996a; Rowntree and Wadeson 1999). Their form is determined by the flow regime, the available sediment, sediment size and the rate at which sediment is supplied to the channel. Alluvial channels are highly susceptible to change in their form, pattern and position as sediment is eroded, transported and deposited (Rowntree and Wadeson 1999), with those comprising smaller particles, e.g., sand and gravels, being more susceptible to change than those comprising larger particles, e.g., cobbles and boulders (Rowntree and Wadeson 1999; Smith-Adao 2004). Mixed channels consist of alternating bedrock and alluvial channel sections (Schumm 1985; Rowntree and Dollar 1996a; Rowntree and Wadeson 1999).

Gravel- or coarse-bed alluvial channels differ from sand bed channels not only in the size of their particles but also with respect to channel morphology and their topographic setting (Rowntree and Wadeson 1999; Smith-Adao 2004). These channels are dominated by gravel with small percentages of sand. The substrate is usually transported during high flow with slow rates of particle transport. Gravel beds have low sediment loads and relatively large proportions of debris. Meso-scale alluvial features associated with gravel beds are pools and riffles (Hey and Thorne 1986; Rowntree and Wadeson 1999).

Table 2.2 Sediment particle sizes (Wentworth 1922).

Class name	Substrate grain size (mm)
Clay particle	<0.0039
Silt particle	0.0039 - 0.0625
Very fine sand	0.0625 - 0.125
Fine sand	0.125 - 0.25
Medium sand	0.25 - 0.5
Coarse sand grain	0.5 - 1
Very coarse sand	1 - 2
Granular gravel	2 - 64
Pebble gravel	
Cobble gravel	64 - 256
Boulder	>256

Cobble and boulder channels are dominated by large particle sizes that require high thresholds of discharge for any movement to take place (Rowntree and Wadeson 1999; Smith-Adao 2004). These channels generally comprise relatively immobile channel structures through which fine materials (i.e., gravel, sands and silt) are transported. Cobble and boulder channels are therefore known to have a wide range of particle sizes that are poorly sorted.

A river's physical template is a fundamental concept in river ecology (Vannote *et al.* 1980; Southwood 1977), encompassing a range of geomorphological processes that influence channel morphology and other factors such as hydraulics, erosion rates and sediment supply (Smith-Adao 2004; Fryirs and Brierley 2013; Wohl *et al.* 2015). A river maintains a channel morphology that is most suited to the transportation of its sediment load (Schumm 1977; Smith-Adao 2004; Fryirs and Brierley 2013).

Sediment load is defined as the total mass of sediment that is being transported through a cross-section of a river over a given time period, measured in units (i.e., kilograms per second or tonnes per year; Rowntree and Wadeson 1999; Fryirs and Brierley 2013). The sediment load quantifies the amount of sediment moved through the river channel. The sediment load may be subdivided into four groups, namely; 1) bed load or traction load, 2) suspended load, 3) solute or dissolve load, and 4) wash load (Knighton 1984; Summerfield 1991; Sear 1996; Rowntree and Wadeson 1999; Rowntree *et al.* 2000; Wohl 2000c; Smith-Adao 2004; Fryirs and Brierley 2013).

1) The bed load comprises coarse materials that make up the river bed and include particles that range in size from boulders to sand (Rowntree and Wadeson 1999; Fryirs and Brierley 2013). These coarse materials are sourced from erosion of bedrock in the channel bed and/or the surrounding landscape in the steep upper catchment, i.e., headwater streams. Particles of this size are transported at or close to the river bed in a rolling, sling, or saltating manner and are often in limited supply (Sear 1996; Rowntree and Wadeson 1999; Smith-Adao 2004; Fryirs and Brierley 2013). The transport of

bedload material is episodic in that the material is transported through the channel system in a series of pulses, i.e., larger than normal flows (Rowntree and Wadeson 1999; Fryirs and Brierley 2013). Bed load material is stored in the river bed as alluvial bars, which form major components of channel form, or in channel banks. A river lacking in bedload material significantly restricts the range of geomorphic features found in riparian ecosystems, which means that there is less suitable habitat for plants and animals (Fryirs and Brierley 2013).

2) The suspended load is the material suspended in flowing water by turbulent eddies and includes finer materials such as medium to fine sand, silt and clay (Sear 1996; Rowntree 2000; Smith-Adao 2004; Fryirs and Brierley 2013). These materials are transported at much faster rates than bed load; however, they can become bed load when the flow velocity is less than the settling velocity of material making up this load.

3) Dissolved load is made up ionic solutes (dissolved material) derived from the weathering of bedrock (Summerfield 1991; Sear 1996; Rowntree 2000; Rowntree and Wadeson 1999; Smith-Adao 2004; Fryirs and Brierley 2013). Although dissolved material may not have direct morphological significance, it is a critical component of water quality (e.g., nutrient inputs; Rowntree and Wadeson 1999). This solute affects morphology indirectly through its influence on the erodibility of cohesive sediments (Sear 1996).

4) Wash load is made up of very fine materials transported in suspension and washed throughout the entire system; these include fine silts and clay (Morisawa 1985; Summerfield 1991; Knighton 1984; Rowntree and Wadeson 1999; Smith-Adao 2004; Fryirs and Brierley 2013). These materials are deposited in areas with no or very low flow, (e.g., backwaters).

Stream power and shear stress are influenced by flow velocity which is affected by the changes in elevation of the river bed. Stream power determines the volume and nature of the sediment transported by the stream (Hjulstrom 1935; Dardis *et al.* 1988; Gordon *et al.* 2004; Fryirs and Brierley 2013). For sediment to move, the shear stress needs to exceed the forces that hinder movement, e.g., gravity, friction and resistance by surrounding plants and animals. Fryirs and Brierley (2013) define stream power as an expression for the rate of potential energy expenditure against the bed and banks of a river channel per unit downstream length, which reflects the total energy available to do work along the river. Shear stress, also referred to as ‘tractive force’, is the force applied by the flowing water to its boundary of the channel (Hjulstrom 1935; Fryirs and Brierley 2013). Hjulstrom (1935) describes the velocity required to move sediment particles of specific sizes (Figure 2.6). Small sediment particles such as clay and silt are moved with by water flowing at a lower velocity, where larger sediment particles such as gravel, cobbles and boulders are move at higher velocities.

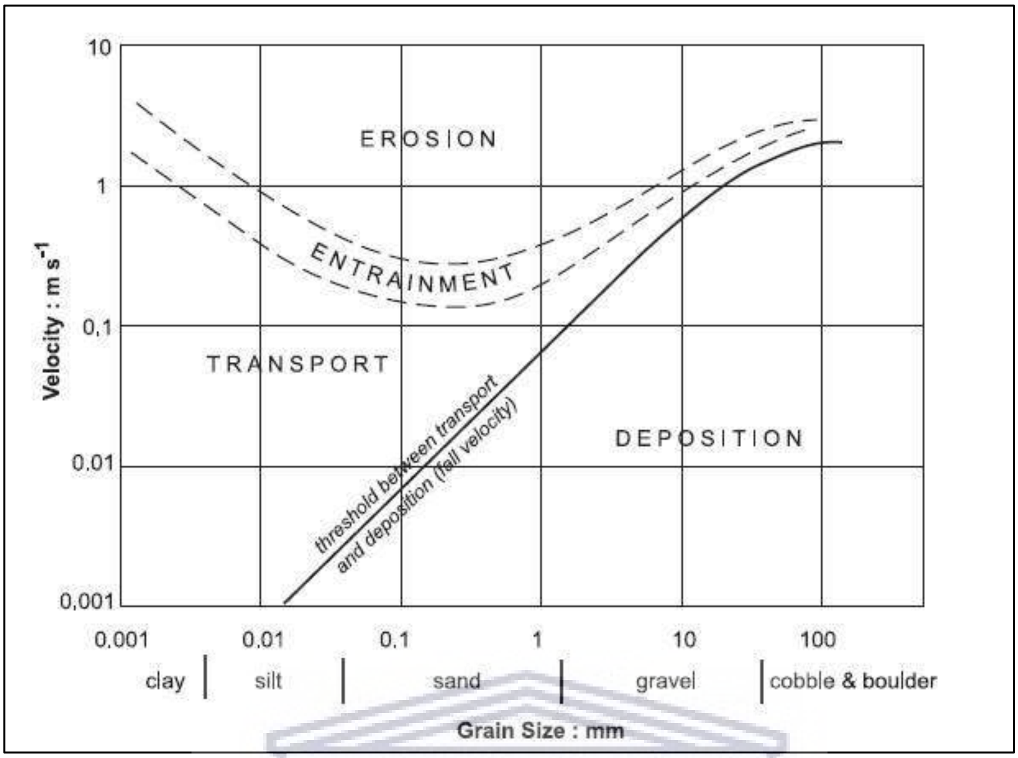

Figure 2.6 **The Hjulström diagram (Hjulstrom 1935) depicts phases of sediment entrainment (erosion), transport and deposition based on the grain size of the sediment and the velocity of flow (Fryirs and Brierley 2013).**

Changes in river morphology usually only occur when thresholds of stream power are exceeded (Carling and Beven 1989; Smith-Adao 2004; Fryirs and Brierley 2013). For instance, 'Flood A' (Figure 2.7; Fryirs and Brierley 2013), does not extend beyond the alluvial erosion threshold and is therefore geomorphically ineffective. 'Flood' B is more effective; however, has a short duration beyond the alluvial erosion threshold (Fryirs and Brierley 2013). 'Flood C' is the most geomorphically effective flood because the energy available to do work is high, the duration of the event long and the thresholds of both alluvial and bedrock erosion are exceeded.

The magnitude-frequency concept assumes that channel form in alluvial rivers can be related to a specific magnitude and frequency of discharge (Lacey 1930; Smith-Adao 2004; Fryirs and Brierley 2013). While magnitude refers to the size of an event and is normally expressed in m^3/s, frequency refers to the number of times a given event of a given size occurs and its duration (Leopold and Wolman 1957; Poff *et al.* 1997; Rowntree and Wadeson 1999; Fryirs and Brierley 2013). Magnitude-frequency analysis is used to interpret changes in channel form based on historic flood events and provides an understanding of the flows needed to maintain the form and structure of the river channel (Wolman and Miller 1960; Fryirs and Brierley 2013).

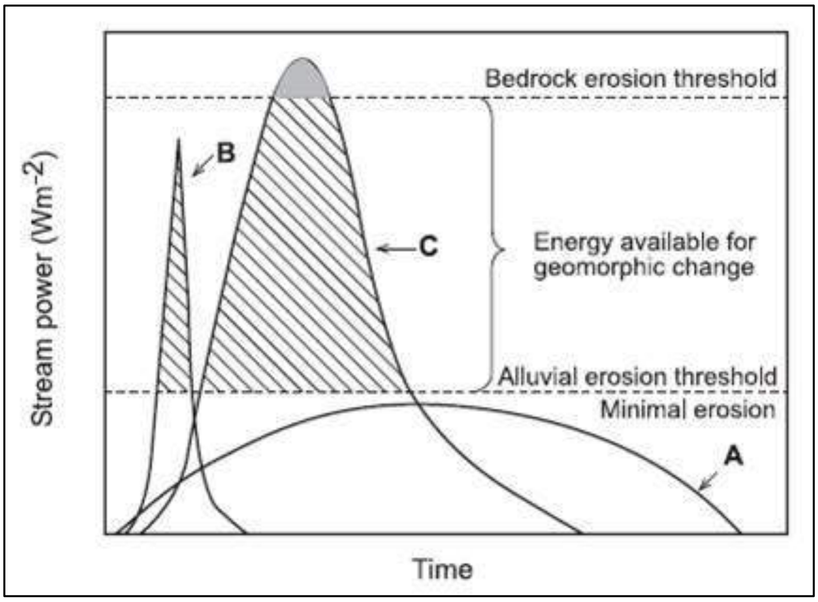

Figure 2.7 **A conceptual approach to analysis of the geomorphic effectiveness of floods (Fryirs and Brierley 2013).**

The use of terms such as dominant discharge, effective discharge and bankfull discharge, provide some further insight to the magnitude-frequency concept (Leopold and Wolman 1957; Wolman and Miller 1960; Pickup and Warner 1976; Fryirs and Brierley 2013).

The term “dominant discharge” was first introduced by Inglis (1941), who described it as the discharge to which a channel returns annually. A state of equilibrium is most closely approached at dominant discharge because flows are considered to be constant and the tendency of the channel morphology to change is low (Inglis 1941; Smith-Adao 2004). Since then, various attempts have been made to define and describe it (Wolman and Leopold 1957; Wolman and Miller 1960; Rowntree and Wadeson 1999; Rowntree *et al.* 2000). The most recent definition is the discharge that transports the most sediment through the river channel over time and is thus responsible for maintaining channel morphology (Rowntree *et al.* 2000).

The term ‘effective discharge’ is defined by Pickup and Warner (1976) as the range of discharge that transports the most sediment over a period of time. According to Pickup and Warner (1976), a river channel is shaped by flood events with low to moderate magnitude and high frequency, i.e., 2 to 5 times a year. The definition provided by Andrews (1980) is similar, however, defines it as the discharge that transports the most sediment annually over a period of years. According to Rowntree and Wadeson (1999), defining a river in terms of its effective discharge is challenging as the rate at which sediment moves through a river is difficult to determine.

The term ‘bankfull discharge’ has been used since the mid-1900s and has a wide range of definitions (Wolman and Leopord 1957; Wolman and Miller 1960; Pickup and Warner 1976; Rowntree and Wadeson 1999; Rowntree *et al.* 2000; Fryirs and Brierley 2013). In South Africa, Rowntree and Wadeson (1999) and Rowntree *et al.* (2000) describe it as the discharge that is sufficient to just fill the river channel without overflowing onto the flood plain. Smith-Adao (2004) mentions a few useful indicators of bankfull stage, which include; the height of depositional features (i.e., the top of a point bar), or a change in vegetation, slope or topographic breaks across the river bank, a change in the particle size of the bank material (e.g., the boundary between fine-grained sand and gravel), or undercut banks and stain marked lines along the bank. In alluvial rivers, the highest potential energy to do 'geomorphic work' is at bankfull discharge. The term 'geomorphic work' is defined as the channel's capacity to transport sediment during discharges of a certain magnitude and duration. This means discharges of varying magnitude, frequency and duration bring about different changes in river morphology rather than a single event (Fryirs and Brierley 2013). Floods generally erode the river bed and banks and transport bed material, leading to changes in channel morphology, while baseflows deposit fine sediment particles.

Riparian zones and their associated floodplains are an integral part of the catchment (Tockner *et al.* 2010) and are the interface between aquatic and terrestrial ecosystems and are sensitive to environmental changes (Malanson 1993; Naiman and Decamps 1997; Decamps 2001). Examples of these interfaces include river margins, riparian forests, marginal wetlands, littoral lake zones, floodplain lakes and forests, and areas with groundwater-surface water exchanges (Malanson 1993; Naiman and Decamps 1997; Richardson *et al.* 2007, Arizpe *et al.* 2008). Riparian zones typically comprise the thalweg, the active channel and the macro-channel, which encompass the floodplain and the associated terraces and lateral benches (Figure 2.8; Rowntree and Wadeson 1999; Freeman and Rowntree 2005).

The thalweg represents the lowest or deepest section of the river within the active channel. The active channel is part of the river channel that is inundated or flooded at regular intervals (e.g., at least once a year; Rowntree and Wadeson 1999). Frequent flooding maintains the channel form and keeps it free from established terrestrial vegetation. The active channel is usually marked by noticeable and well-defined banks on either side of the channel (Rowntree and Wadeson 1999; Freeman and Rowntree 2005).

The macro-channel comprises the outer-most river bank, distinguishing the borders of the river channel within which all channel processes occur including all flood events (Rowntree and Wadeson 1999; Freeman and Rowntree 2005). The boundary of a macro-channel is marked by the upper-most boundary of the floodplain, formed by the highest water mark from the largest flood events within a particular river system. Hence, macro-channels are flooded less frequently than the active channel (e.g., once every 20 or 50 years). The floodplains are the relatively level alluvial areas adjacent to the active channel (Rowntree and Wadeson 1999; Freeman and Rowntree 2005). These are formed when the bankfull discharge of the active channel is exceeded and flood waters spill onto the adjacent land, depositing sediment and providing nutrient rich soil for terrestrial vegetation. Terraces are geomorphic features of floodplains that appear as a set of relatively level steps or benches marking the various high-water levels of different flood return periods (e.g., 20-, 50-, 100-year return period). These bench-like features form as the result of active down cutting during flood events (Rowntree and Wadeson 1999).

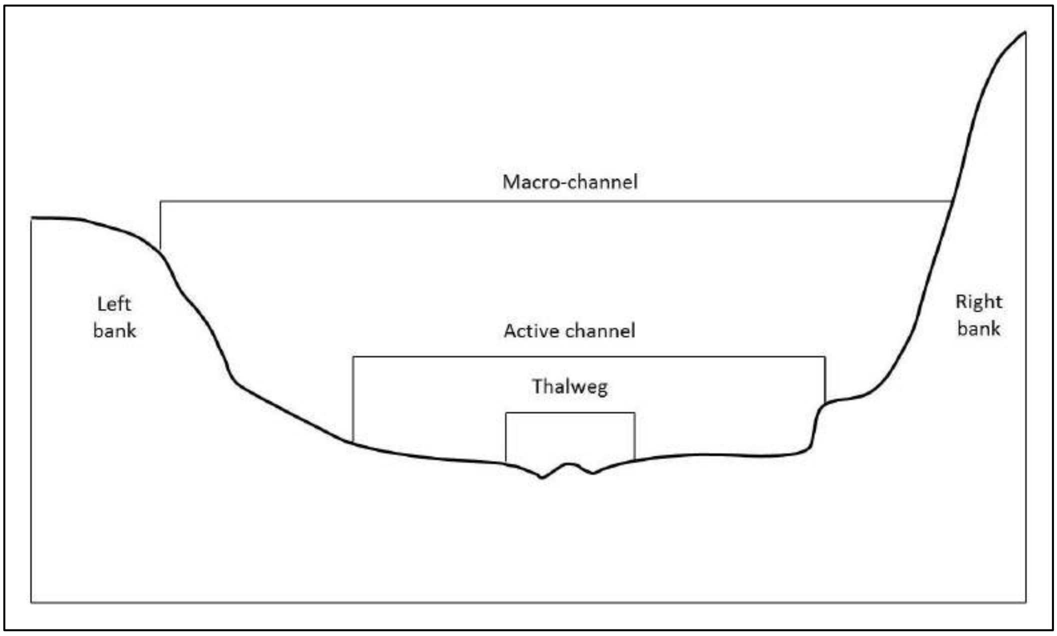

Figure 2.8 Example of riparian zone comprising: the thalweg, the active channel and the macro channel. Modified from Rowntree and Wadeson (1999).

Cross-sectional profiles should include the entire riparian zone and under natural circumstances can be highly variable even in a single reach (Knighton 1998). Profiles are classified according to the presence or absence or sediment deposits and their relationship to the existing channel. Parameters commonly used to describe cross-sectional profiles include channel width or bankfull width, water surface width, average channel depth, wetted perimeter, cross-sectional area of flow and hydraulic radius (Figure 2.9; Knighton 1998; Rowntree and Wadeson 1999). Although channel width (w) and depth (d) are the most commonly used parameters, they do not provide a measure of channel shape (Knighton 1998; Rowntree and Wadeson 1999). They are, however, combined in the Form Ratio index (F = W/d), which is a useful measure of channel shape. Width and depth are among the most adjustable components of channel geometry and adjust rapidly to changing conditions resulting from various environmental influences (Gordon *et al.* 1992).

Changes in channel morphology can occur over short time scales (days) within a local area, or over extended periods at the scale of the entire drainage network (Rowntree 1991; Rowntree and Wadeson 1999; Fryirs and Brierley 2013). For instance, bed and bank scouring and in-filling are localised processes that occur over hours or days, whereas degradation and aggradation processes occur over longer times, and affect long river reaches or whole river systems, which in turn, can also exacerbate localised processes (Wohl 2000c; Fryirs and Brierley 2013).

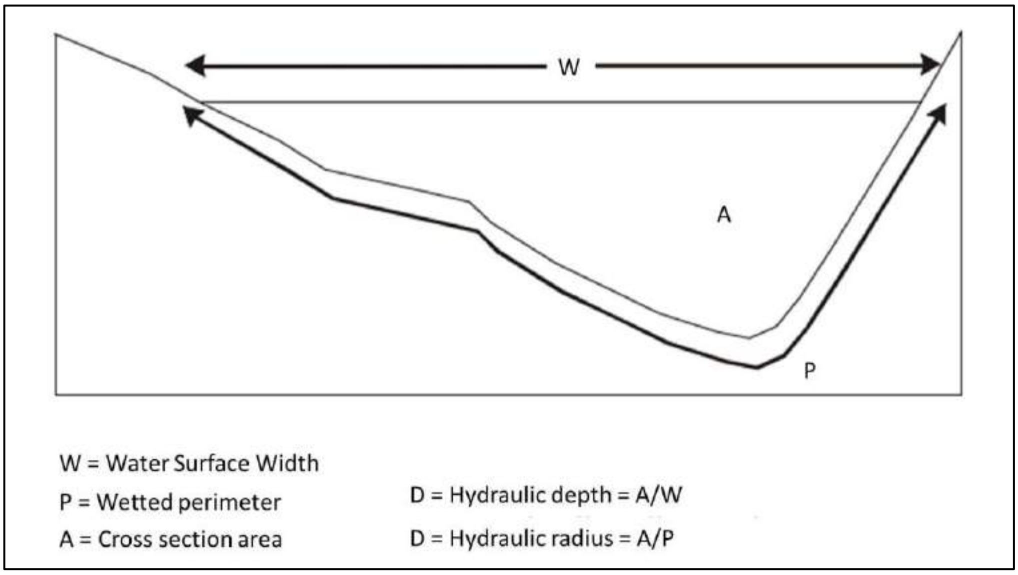

Figure 2.9 Cross section form variables. Modified from Smith-Adao (2004).

Degradation and aggradation represent decreases and increases in bed elevation over years, respectively (Smith-Adao 2004; Fryirs and Brierley 2013). Three main processes contribute to bed erosion: a reduced sediment supply due to upstream dams or weirs, an increase in bed slope due to excavation and, an increase in discharge in response to rainfall. Geomorphic indicators of bed degradation include extensive bank erosion on both sides of a river, steep mobile riffles, waterfalls, vertical head cuts and exposure of rock bars in the stream bed. On the contrary, deposition occurs when sediment supply overwhelms flow transport capacity (Wohl 2000c; Smith-Adao 2004; Fryirs and Brierley 2013). Indicators of bed aggradation include extensive bar deposits, mobile point bars, islands associated with encroaching vegetation and decrease bank heights in downstream zones.

Accelerated processes of erosion or deposition are often a sign of problems with the flow regime or an over or undersupply of sediment through the system (Fryirs and Brierley 2013; Wohl *et al.* 2015). In some rivers, thresholds in behaviour can be crossed where the regime switches. For example, if sediment supply reduces to a point where the river becomes 'starved' of sediment, an erosive regime may develop that can result in increased channel size, lateral migration, or both (Kondolf 1997; Rowntree and Wadeson 1999; Rowntree *et al.* 2000; Fryirs and Brierley 2013). Conversely, a change from an erosion or transport dominated regime to a deposition dominated regime can cause a major geomorphological response, with new in-channel sediment forms developing (Rowntree and Wadeson 1999; Rowntree *et al.* 2000; Fryirs and Brierley 2013). The geomorphological responses to a change in sediment regime can lead to a major change in the types of habitats supported by the river (Rowntree and Wadeson 1999; Rowntree *et al.* 2000; Fryirs and Brierley 2013).

The changes in river morphology are reflected in the channel geometry, a description of form and pattern such as the longitudinal profile, channel planform, cross-sectional profile and channel bed (Dardis *et al.* 1988; Sear 1996; Knighton 1998; Fryirs and Brierley 2013).

Channel planform refers to the various patterns and characteristics of the channels within a river system (Schumm 1985; Rosgen 1994; Rowntree and Wadeson 1999; Batelli *et al.* 2017). These patterns provide information on the physical character of rivers and a better understanding of how they might behave when subjected to disturbance (Schumm 1985; Chruch and Ferguson 2015). An understanding of channel planform also provides a basis for understanding historic geomorphic deposits in river systems and an experimental basis for determining past river morphology and paleo-hydrology (Schumm 1977, Galloway and Hobday 1983; Schumm 1985). Channel planform can be studied at different scales, depending on the size of the river and the part of the fluvial system that is under consideration (Schumm 1985), for example river drainage networks are viewed at a catchment scale and described in terms of their patterns (e.g., dendritic, parallel, trellis) and sinuosity (Howard 1967; Fryirs and Brierley 2013), normally using aerial imagery (Schumm 1985; Rowntree and Wadeson 1999).

At a reach scale, hydraulics, sediment transport and the potential for bank erosion, i.e., stream power, become important and are considered. At this scale, the focus is on smaller features (Schumm 1985), such as lateral and mid-channel bars. Rivers are categorized into single channel and multi-channel patterns (Figure 2.10 and Table 2.3; Schumm 1985; Kellerhals and Church 1989; Rosgen 1994; Rowntree and Wadeson 1999). Single channel patterns are further sub-divided into straight and meandering, and multi-channel patterns into braided and anastomosing or anabranching. Furthermore, very few natural river channels are truly straight; they generally display some degree of sinuosity, a measure of the length of the active channel divided by the valley length (Schumm 1985; Kellerhals and Church 1989; Knighton 1998; Rosgen 1994).

A meandering channel refers to the shape of the river channel (Schumm 1985; Buffington and Montgomery 2013; Polvi and Wohl 2013). This is a behaviour resulting from selective bank erosion or point bar development. The upper reaches of a catchment generally have channels with low sinuosity while lower reaches have high sinuosity. High sinuosity in the lower reaches is due to fining and weathering of bank and bed materials.

In a system with a braided channel pattern, the water flow is interrupted by multiple alluvial bars or islands (Figure 2.10; Schumm 1985; Knighton 1998; Rowntree and Wadeson 1999; Eaten *et al.* 2010; Buffington and Montgomery 2013). Braided channels are classified into two categories; laterally stable, straight or sinuous regime channels with braid morphology, or laterally unstable, shifting multi-stage channel patterns with a braided pattern (Schumm 1985; Knighton 1998; Rosgen 1994; Rowntree and Wadeson 1999; Polvi and Wohl 2013). These patterns generally occur in high energy fluvial environments with steep valley gradients, large and variable discharges, dominant bedload transport and non-cohesive banks that lack stabilisation by vegetation (Richards 1982; Rowntree and Wadeson 1999). Because of the high energy environment within which braided channels are formed, they are always shifting and are typified by erodible banks and high channel widths.

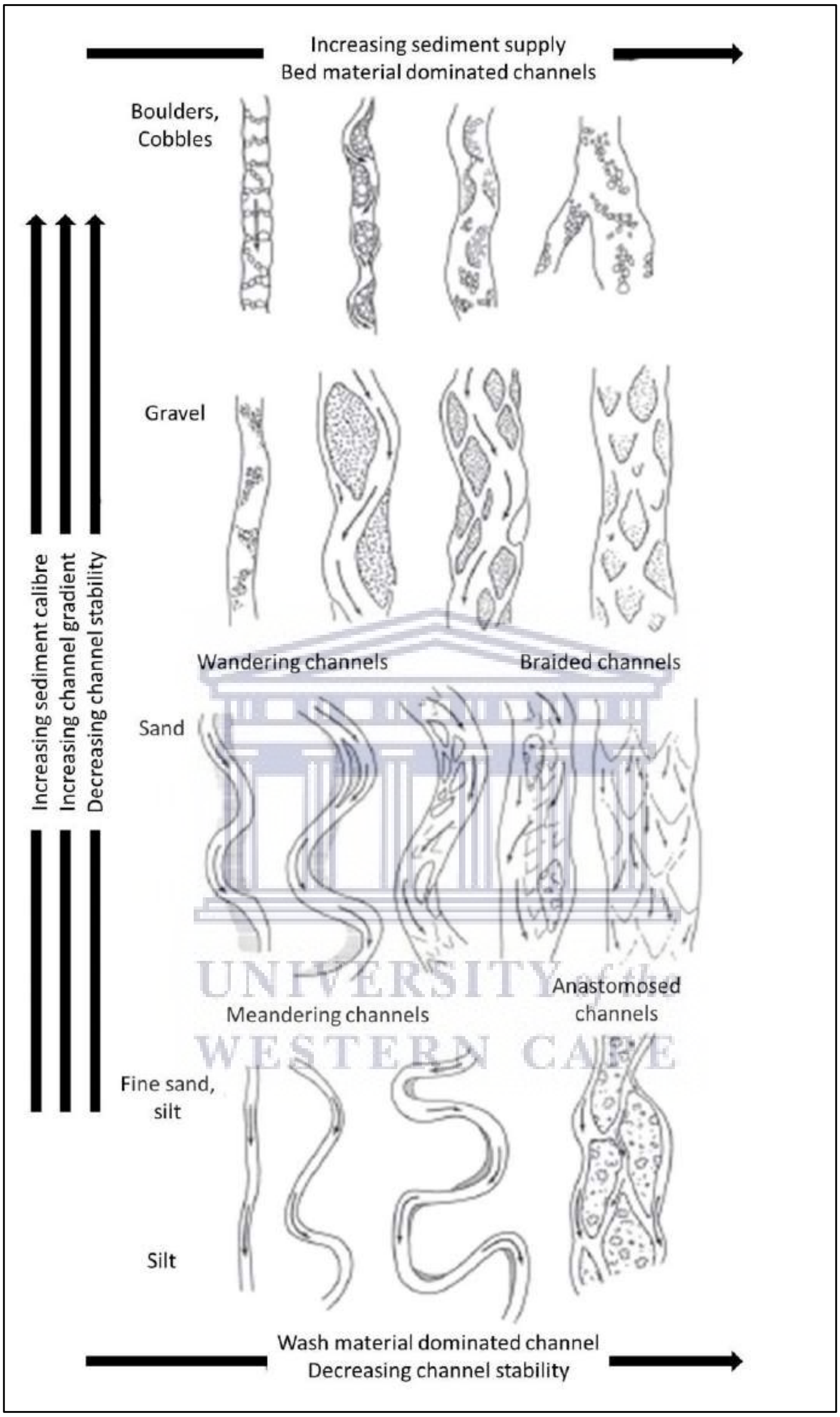

Figure 2.10 **Schumm's (1977, 1981, 1985) classification of channel planform and response potential. Modified from Buffington and Montgomery (2013).**

Anabranching or anastomosing channels are multiple channels (two or more anabranches) separated by vegetation or otherwise stable islands or bedrock (Schumm 1985; Knighton 1998; Rosgen 1994; Rowntree and Wadeson 1999; Eaten *et al.* 2010; Buffington and

Montgomery 2013; Polvi and Wohl 2013; Baletti *et al.* 2017). These channels are normally stable and retain their identities with changes in the flow regime over time. Different types of anabranching channels can be recognized based on flood-dominated flow regimes, bank resistance and conditions that induce channel avulsion.

Table 2.3 Classification of river patterns. Modified from Smith-Adao (2004).

Type	**Morphology**	**Sinuosity**	**Load-type**	**Width/depth ratio**	**Erosive behaviour**	**Depositional behaviour**
Straight	Single channel with pools and riffles, meandering thalweg	<1.05	Suspension or mixed bedload	<40	Minor channel widening and incision	Skew shoals
Sinuous	Single channel with pools and riffles, meandering thalweg	>1.05 <1.05	Mixed	<40	Increased widening and incision	Skew shoals
Meandering	Single channels (may be inner point bar channel)	>1.5	Suspension or mixed bedload	<40	Channel incision, meander widening	Point bar formation
Braided	Two or more channels with bars and small islands	>1.3	Bedload	>40	Channel widening	Channel aggradation, mid-channel bar formation
Anabranching	Two or more channels with bars and small islands	>2.0	Suspension load	<10	Slow meander widening	Slow bank accretion

2.1.2 Geomorphological classification of South African rivers

The classification of rivers in terms of the driving forces described above is essential for managing catchments, because this provides a) a framework for understanding similarities and differences between rivers and river reaches, b) clear definitions to support communication within and between disciplines, and c) a means to extrapolate experience and knowledge gained on one river to other similar rivers (Frissel *et al.* 1986; Mosley 1987; Rowntree and Wadeson 1999). Classification tools address spatial scales ranging from catchment to macro and micro-habitat features (i.e., reach, morphological units and hydraulic biotopes). Rowntree *et al.* (2000) developed a hierarchical zonal river classification system for South African rivers that delineated the longitudinal profile of a river into zones (Rowntree *et al.* 2000) using variations in physical characteristics. The longitudinal profiles of rivers are commonly divided into three zones; the upper (source) zone, the middle (transfer) zone and the lower (depositional) (Schumm 1977). This concept has been adapted for use by different researchers (Dallas and Day 1993; Rowntree and Dollar 1996b; Rowntree and Wadeson 1999; Fryirs and Brierley 2013) but essentially is based on changes in gradient and sediment transport. (1) The 'source zone' in the upper reaches of a catchment is characterised by sediment production. (2) The 'transfer zone' in the middle reaches is defined by sediment movement. (3) The 'deposition zone' in the lower reaches by sediment deposition (Figure 2.2).

The shape of a rivers longitudinal profile is representative of large scale, long-term environmental changes and landscape evolution within the catchment (Rowntree and Wadeson 1999; Rowntree *et al.* 2000; Fryirs and Brierley 2013). It is therefore one of the most important components of river morphological research (Knighton 1984; Rowntree and Wadeson 1999; Fryirs and Brierley 2013). These profiles serve as the basis for classifying river reaches into slope categories that reflect changes in profile morphology and can be inferred from topographical maps (Rosgen 1994).

The South African Classification System takes this into account and describes six nested levels; catchment, zone, stream segment, reach, morphological unit and hydraulic biotope (Figure 2.11 and Table 2.4; Rowntree *et al.* 2000). Each level provides input into the levels below, which allows catchments (large scale feature) to be linked to macro- and micro-habitats (small scale feature) within the channel.

Application of SACS requires combination of desktop and field information. Catchment and zone classification levels are derived from desktop exercises using secondary data sources (i.e., 1:50 000 topographical maps). Segment, reach, morphological unit and hydraulic biotope classification levels are derived from field surveys aided by topographical maps and aerial photographs (Rowntree *et al.* 2000). The main engine of the system is the delineation of zones based on longitudinal slope, which describes how channel features change in a downstream direction in response to changes in valley shape and sediment transport (Table 2.5).

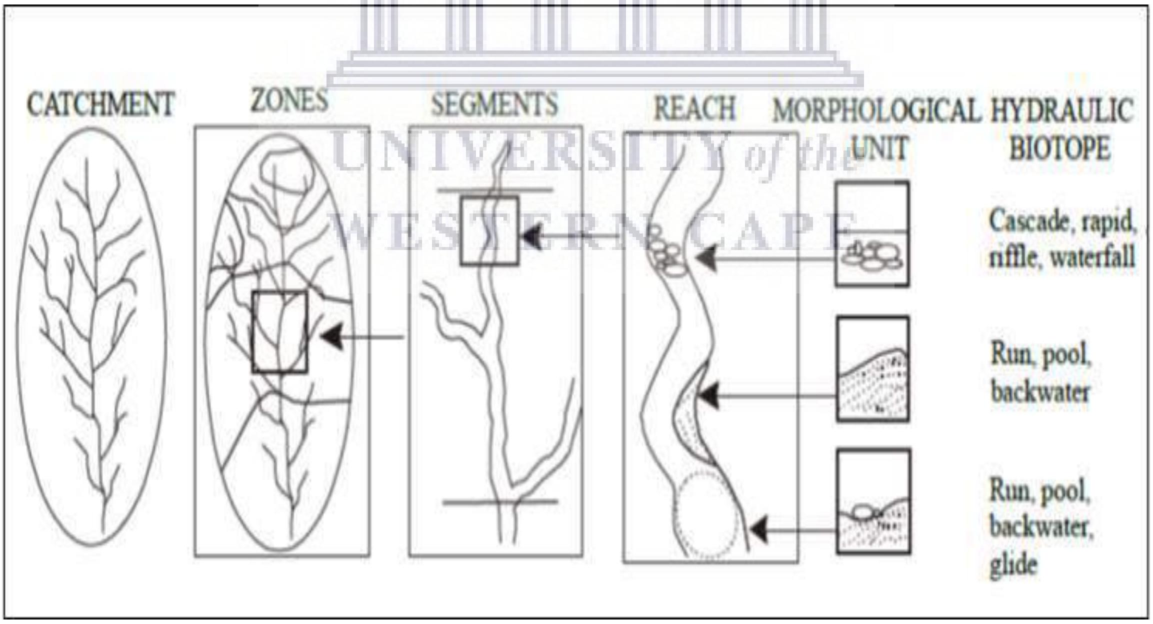

Figure 2.11 The geomorphological hierarchy used in the SACS (Rowntree and Wadeson 1999).

Table 2.4 Description of hierarchical levels of the South Africa classification system (Rowntree and Wadeson 1997).

Hierarchical classification levels	Description
Catchment	The land surface which contributes water and sediment to any given stream network.
Zone	Areas within a catchment which can be considered as homogenous with respect to flood runoff and sediment production.
Segment	The length of channel along which there is no significant change in the imposed flow discharge or sediment load. Classified in terms of an index of sediment/discharge ration and average channel gradient.
Reach	A length of channel within which the constraints on channel form are uniform so that a characteristic assemblage of channel forms occurs.
Morphological units	The basic structures recognised by fluvial geomorphologists as comprising the channel morphology, formed from the erosion of bedrock (e.g. rapids, waterfalls, etc.) or from the deposition of alluvium (e.g. sand or gravel bars, pools, etc.).
Hydraulic biotopes	The habitat assemblages which can be equated to morphological units, their recognition is determined by the temporarily variable hydraulic and substrate characteristics associated with each morphological unit.

Table 2.5 Geomorphological zonation of river channels (Rowntree *et al.* 2000).

Zone	Zone class	Gradient class	Characteristic channel features
A. Zonation associted with a 'normal' profile			
Source Zone	S	Not specified	Low gradient, upland plateau or upland baasin able to store water. Spongy or peaty hydromorphic soils.
Mountain head water stream	A	>0.1	A very steep gradient stream dominated by vertical flow over bedrock with waterfalls and plunge pools. Normally first or second order. Reach types include bedrock fall and cascades.
Mountain stream	B	0.04-0.099	Steep gradient stream dominated by bedrock and boulders, locally cobbel or coarse gravels in pools. Reach types include cascades, bedrock fall, step-pool. Approximate equal distribution of 'vertical' and 'horizontal' flow components.
Transitional	C	0.02-0.039	Moderately steep stream dominated by bedrock or boulder. Reach types include plane bed, pool-rapid or pool riffle. Confined or semi-confined valley floor with limited floodplain development.
Upper foothills	D	0.005-0.019	Moderately steep, cobble bed or mixed bedrock-cobbel bed channel, with plane bed, pool-riffle or pool-rapid reach types. Lengths of pools and riffle/rapids similar. Narrow floodplain of sand, gravel or cobble often present.
Lower foothills	E	0.001-0.005	Lower gradient mixed bed alluvial channel with sand and gravel dominating the bed, locally may bed bedrock controlled. Reach types typically include pool-riffle or pool-rapid, sand bars common in pools. Pools of significantly greater extent tha rapids or riffles. Floodplain often present.
Lowland river	F	0.0001-0.0009	Low gradient alluvial fine bed channel, typically regime reach type. May be confined, but fully developed meandering

Zone	Zone class	Gradient class	Characteristic channel features
			pattern within a distinct floodplain develops in unconfined reaches where there is an increased salt content in bed or banks.
B. Additional zones associated with a rejuvenated profile			
Rejuvenated bedrock fall/cascades	Ar, Br or Cr	>0.02	Moderate to steep gradient, confined channel (gorge) resulting from uplift in the middle to lower reaches of the long profile, limited lateral development of alluvial features, reach types include bedrock fall, cascades and pool-rapid.
Rejuvenated foothills	Dr or Er	0.001-0.019	Steepened section within middle reaches of the river caused by uplift, often within or downstream of gorge; characteristics similar to foothills (gravel/cobble bed rivers with pool-riffle/ pool-rapid morphology) but of a higher order. A compound channel is often present with an active channel contained with a macro channel activated only during infrequent flood events. A limited floodplain may be present between the active and macro-channel.
Upland floodplain	Fr	<0.005	An upland low gradient channel, often associated with uplifted plateau areas as occur beneath the eastern escarpment.

2.2 Riparian vegetation

Indigenous riparian plant communities provide a variety of benefits to aquatic ecosystems. The stability of river banks depends on the strength of the bank material, which in turn, is dependent on riparian vegetation (Hickin 1984; Rowntree 1991). Riparian vegetation promotes the deposition of fine sediment that contributes to the cohesiveness of bank material by binding the soil and, ultimately, improves bank stability (Thorne 1982; Friedman and Auble 2000; Rutherfurd *et al.* 2000; Bendix and Stella 2013).

Vegetation also influences patterns and rates of flow dynamics adjacent to the river banks. Their presence increases channel roughness and reduces the erosive forces (i.e., shear stress) acting upon the surface of the banks and thereby increases the resistance of banks to shear stress (Hickin 1984; Thorne 1990; Rowntree 1991; Allen and Leech 1997; Tabacchhi *et al.* 2000; Uys 2003; Bendix and Stella 2013). River banks that are vegetated therefore have the ability to attenuate flood flows by slowing the flow velocity and raising the elevation of inundation at any given discharge, forcing the water to spread higher onto the floodplain. The density and pattern of trees have a significant influence on the distribution of drag, which influences the potential for detachment and soil entrainment. For example, a river migrating through cultivated land may erode twice as fast as those in a forested (vegetated) floodplain, provided that discharge, slope, bend curvature, bank texture and bank heights are constant (Fryirs and Brierley 2013). Non-vegetated banks on the other hand are five times more likely to be eroded than vegetated floodplain. In order for vegetation to effectively protect river banks, it must extend to at least to the average water edge during low flow (Rowntree *et al.* 1991). Even though plant species along the bank are more tolerant to floods than terrestrial plants species, a combination of both is needed to maximize overall bank protection. Vegetation also provides a distinct environment by reducing the flow velocity and provides shelter for fauna that are poorly adapted to fast flowing water, e.g., most *Coleoptera* (Harper *et al.* 1997). The riparian vegetation is also known to provide support and protection against predators (Cyr and Downing 1988; Feldman 2001; Tessier *et al.* 2008).

Flood events are the primary source of disturbance in riparian ecosystems and the driving force behind the structure of both aquatic and riparian vegetation (Nilsson *et al.* 1994; Rowntree *et al.* 2000; Friedman and Auble 2000). The strong influence of plants on riparian ecosystems is due to the principal mechanisms of flood regimes: 1) they function as transport vectors, 2) they affect the moisture regime of the riparian zone, influencing plant survival; 3) they can cause waterlogged and anoxic soils that produce severe stress for terrestrial vegetation; and, 4) they result in physical disturbance that can damage and remove plants.

Floods benefit plants by dispersing seeds and floating vegetative propagules (e.g., rhizomes or branch fragments) of riparian plant species (Friedman and Auble 2000). Riparian plants are known to release their seeds at times of the year that coincide with the wet season, which is also when sediment, organic matter and nutrients are exchanged between the river channel and the floodplain (Friedman and Auble 2000; Rutherfurd *et al.* 2000; Richardson *et al.* 2007). The nutrient rich sediment transported during flooding facilitates the establishment of seeds released during these same events. Thus, riparian vegetation types can be classified according to their lateral zonation, where those closer to the water edge are more tolerant to flooding and those on the upper dry banks less tolerant to flooding (CCA 2000; Brown *et al.* 2000; Richardson *et al.* 2007; Reinecke 2013).

Floods can also affect riparian vegetation negatively by inundating the plants for extended periods of time, by reducing plant growth and can result in mortalities (Friedman and Auble 2000; Hupp 2000; Smith-Adao 2004). This is particularly true where flooding is infrequent because the vegetation may not be adapted to such disturbances. The survival of plant species depends on the type and size of the plant, depth of water in the inundated area, water temperature and clarity, and the timing of inundation relative to the growing season (Gill 1970; Thorne 1990; Friedman and Aube 2000; Smith-Adao 2004). Drowning is strongly related to the duration and timing of inundation. Adult plants are generally able to survive because they are less likely to be completely submerged (Gill 1970) and because, they usually have energy reserves, they can survive on for a prolonged period of time.

Flood can also physically damage riparian plants, which is related to the magnitude of the event (Osterkamp and Costa 1987; Hupp 1988; Thorne 1990). Floods influence plants indirectly by means of transported bed material and deposition of fine sediments, and directly by uprooting them from the river bed or banks. Floods that uproot vegetation may also result in what is referred to as ‘secondary succession’, which occurs when indigenous vegetation has been disturbed or destroyed and creates patches of bare soil, which are in turn, colonised by other plants (Gioria *et al.* 2014; Nsikani *et al.* 2020). The first plants that colonise these areas are usually pioneer species (e.g., annuals) that grow close to the ground, many of which produce large populations over a short period. Secondary succession begins at a location where indigenous vegetation has been disturbed or destroyed but the soil of bottom sediment remains. Primary succession, in contrast, involves the establishment of a species in a barren habitat with little or no topsoil (e.g., bare rock) (Miller 1996; Smith-Adao 2004).

Alien plant species often adapt to an environment they get introduced and grow in abundance and often becoming a nuisance or pest, particularly in riparian corridors (Bromilow 1995; Tickner *et al.* 2001). Their ability to establish is a result of high dispersal capacity over large distances, rapid seed growth and establishment, wide tolerance of environmental factors (i.e., flooding), self-compatibility and strong competitiveness (Hill 1997; Tickner *et al.* 2001). In addition to this, riparian corridors are more prone to invasion by alien species in comparison to terrestrial environments (Rowntree 1991). The vulnerability of riparian corridors is linked to their being continuously disturbed, periodically naturally and regularly anthropogenically, which creates new habitat for colonising species with readily available moisture and a continuous replenishment of nutrients (Rowntree 1991; Hupp and Osterkamp 1996; Tickner *et al.* 2001). Alien plants are known to alter channel bank resistance and stability, hydraulic roughness, sedimentation, channel width and channel pattern (Rowntree and Dollar 1996a, Rowntree and Dollar 1999, Wohl 2000b). The impact of alien vegetation on river morphology is a major concern of river managers (Rowntree 1991; Rowntree 2000; Fryirs and Brierley 2013; Liu *et al.* 2018) and is related to their growth form, surface biomass and above-ground density (i.e., percentage cover) and below-ground density (i.e., root matrix). For instance, on the Disa River in Cape Town, Versfeld (1995) reported that establishment of *Acacia mearnsii* (Black Wattle) caused severe bank erosion, which in turn, led to channel widening. *Acacia mearnsii* has a shallow root system which is unable to withstand floods and is consequently removed during flood events, which exposes the river bank, resulting in bank collapse (Rowntree 1991; Rowntree and Dollar 1996a, Rowntree and Dollar 1999; Smith-Adao 2004).

2.3 Aquatic macro-invertebrates

Riparian vegetation plays a vital role in supporting large macro-invertebrate populations (Gilinsky 1984; Harper *et al.* 1997; Tessier *et al.* 2008; Alberts *et al.* 2018). Gerber and Gabriel (2000) describe invertebrates as organisms without backbones that live part of their lives in freshwater and are large enough to be seen by the naked eye. The macro-invertebrates found in rivers mostly comprise insects that are in their larval and nymph stages (Gerber and Gabriel 2002), with the exception of some beetles, bugs and crustaceans i.e., *Gyrinidae, Nepidae, Amphipoda*.

Their habitat is determined by variations in the physical (i.e., discharge and local hydraulics, physical habitat), chemical (temperature, pH, dissolved oxygen) and biological (i.e., aquatic and riparian vegetation) template that vary in space and time (Bovee 1982; Orth 1987; Modde *et al.* 1991; Cummins 1993; Thirion *et al.* 2016). Aquatic macro-invertebrates inhabit the channel bed (e.g., cobbles, sand and mud) and the aquatic and marginal vegetation of a river ecosystem (Harper *et al.* 1997; Dickins and Graham 2002; Dallas 2007; Duan *et al.* 2011). In South Africa, three groups of habitats, referred to as ‘biotopes’, are recognised when macroinvertebrate assessments are undertaken; 1) stones, 2) vegetation and 3) gravel, sand and mud (SASS5 rapid bioassessment, Dickens and Graham 2002), each of which are further sub-divided into fast and slow flowing hydraulic biotopes. Gordon *et al.* (1992) reported that a combination of hydraulic biotopes with varying flow velocities at a local scale, i.e., slow-flowing and fast-flowing, provide a greater diversity of habitats to support a wider variety of macro-invertebrate taxa. For instance, some macro-invertebrates live on the upper surface of stones and gravel in fast-flowing water, while others live under stones in slow-moving backwater areas

(Gordon *et al.* 1992; Dallas *et al.* 1994; Davies and Day 1998). The diversity of macro-invertebrates is positively related with heterogeneity and stability of the river bed (Brown and Brussock 1991; Duan *et al.* 2011). Different macro-invertebrate assemblages prefer different substrate sizes, the complexity of which therefore dictates the distribution and occurrence of individual species (Harper *et al.* 1997; Buss *et al.* 2004; Duan *et al.* 2011). Some macro-invertebrates have a preference for fine sediment particles such as gravel, sand and mud (e.g., *Gomphidae*); however, excessive sediment loads are known to impair overall habitat availability and quality by smothering and abrading the invertebrates themselves, reducing their periphyton food supply or quality and reducing available interstitial habitat thus, altering community structure (Jowett 2003; Duan *et al.* 2011).

Indigenous plants provide organic matter, minerals and nutrients to the channel (Rutherfurd *et al.* 2000; Richardson *et al.* 2007). Allochthonous organic matter (i.e., leaves, twigs, flowers, bark and fruit) that falls from the riparian canopy or is blown in from the surrounding terrestrial vegetation is a principal food source for macro-invertebrates (Mason and McDonald 1982; Cummins 1974; Dallas and Day 1998; Alberts *et al.* 2018). Many studies have highlighted the importance of allochthonous organic matter on macro-invertebrate assemblages and have shown that the life history traits of many are closely linked to riparian vegetation (Petersen *et al.* Cummins 1974; Mason and McDonald 1982; Speaker *et al.* 1984; Richardson 1992; Harvey *et al.* 1997; Verblerk *et al.* 2008; Jayawardana and Westbrook 2010; Alberts *et al.* 2018). The distribution of macro-invertebrates longitudinally along a river is driven by the different types of habitats and food sources available (Vannote *et al.* 1980; Jayawardana and Westbrook 2010; Alberts *et al.* 2018). Macro-invertebrates feed on the various plant sources, breaking down organic matter, recycling minerals and nutrients and contributing to energy in the channel at various trophic levels, and thus play an important role in freshwater ecosystems (Cummins 1974; King *et al.* 2000; Nery and Schmera 2016; Gal *et al.* 2020). Not only do macro-invertebrates contribute energy through nutrient recycling and transportation in and out of the river, they themselves are a major food source for other fauna in the river ecosystem. For example, beetles are an important food source for frogs, fish and a variety of birds (Cushing and Allan 2001).

To gain a better understanding of the processes of energy flow, material cycling and river ecosystem function, Cummins (1973) categorized macro-invertebrates into five groups based on their food requirements. These trophic groups include; 1) grazers, which are adapted to graze or scrape material (periphyton or attached algae and its associated microbiota) from mineral and organic substrates; 2) shredders, which feed primarily on large pieces of decomposing vascular plant material or coarse particulate organic matter (CPOM) along with the associated microflora and fauna; 3) gatherers or collectors, which feed primarily on fine particulate organic matter (FPOM) deposited in rivers; 4) filterers, animals with specialised anatomical structures (e.g., setae, mouth brushes, fans) or silk suspensions that feed on suspended particulate matter; and 5) predators, which feed primarily on animal tissue by either engulfing their prey or piercing and sucking out body contents (Cummins 1973; Cushin an Allan 2001; Jayawardana and Westbrook 2010).

Vannote *et al.* (1980), on the other hand, identified four functional feeding groups (FFGs) based on how the organisms gather their food. Because macro-invertebrates are adapted to feeding on different kinds of food, they use different food gathering methods. The functional feeding groups include shredders, collectors (gatherers, scrapers or filterers), grazers and predators. FFGs are trophic guilds of macro-invertebrates that use resources in a morpho-behaviourally similar manner (Duan *et al.* 2011). Along the longitudinal profile of the river, shredders generally dominate the headwaters of a river where coarse organic material from overhanging trees is the main energy input; these include stoneflies (*Plecoptera*) and dragonflies (*Odonata*) (Vannote *et al.* 1980; Davies and Day 1998; King *et al.* 2000; Jayawardana and Westbrook 2010). The foothills in the middle reaches are dominated by grazers such as mayflies (*Ephemeroptera*), and collectors such as blackflies (*Simuliidae*). These two FFGs in the middle reaches use benthic primary producers and the finer organic material transported from the upper reaches. In the lower reaches, collectors such as oligochaete worms and bivalve molluscs dominate because of the availability of fine particulate material and phytoplankton.

Macro-invertebrates have adapted their feeding, growth, behaviour and reproductive habitats to be able to survive variations in the flow and sediment regimes (Southwood 1977; Stearns 1976; Gordon *et al.* 1992; Davies and Day 1998; Verblerk *et al.* 2008). Since benthic macro-invertebrates have specific habitats, seasonal variation within these may lead to seasonal changes in the distribution and abundance of benthic macro-invertebrates (Jacobson 2005, Fourie *et al.* 2014; Thirion *et al.* 2016). Seasonal variations in discharge lead to changes in wetted perimeter, hydraulic condition and biotope availability (O’Keeffe *et al.* 2002; Dallas 2004a; Thirion *et al.* 2016), for example runs become riffles under low flow and marginal vegetation changes from lotic to lentic (Chessman *et al.* 1997; Dallas 2004a). Discharge may further alter macro-invertebrate assemblages by affecting water temperature (Dallas 2004a; Thirion *et al.* 2016), which affects their rate of development, reproductive periods and emergence times (Kosnicki and Burian 2003, Dallas 2004a; Thirion *et al.* 2016). Changes in temperature outside of their optimal growth, reproduction and general fitness temperatures will exclude some taxa from persisting (Hawkins *et al.* 1997; Thirion *et al.* 2016).

2.4 Unifying concepts

Effective management of rivers necessitates an understanding not only of geomorphological context but also increasingly of biological functioning and interactions longitudinally, laterally onto surrounding floodplains, vertically into the hyporheic zone and temporally over days, months, seasons and years (Baturina 2018; Thompson and Lake 2010; Zelewski *et al.* 2004). A more holistic understanding of ecological processes, founded on a strong conceptual base, advances the discipline, but also enhances the effectiveness of conservation and restoration initiatives (Ward *et al.* 2002; Baturina 2018).

The first and possibly best known of the concepts on the biological nature of rivers are the River Continuum Concept (RCC; Vannote *et al.* 1980), the serial discontinuity concept (Ward and Stanford 1983), the flood pulse concept (Junk *et al.* 1989) and the hyporheic corridor concept (Stanford and Ward 1993). Other concepts build on these to address more complex process at finer spatial scales (Baturina 2018) and include the patch dynamic concept (Townsend 1989), fluvial hydro-systems (Petts and Amoros 1996), the process domain concept (Montgomery 1999), the network dynamics hypothesis (Benda *et al.* 2004), riverine ecosystem synthesis (Thorp *et al.* 2006), rheobiome (Bogatof 2013) and hierarchical classification tools (Frissel *et al.* 1986; Rowntree and Wadeson 1999).

The River Continuum Concept (RCC; Vannote *et al.* 1980) describes how physical characteristics affect the biological structure of communities (i.e., vegetation and macro-invertebrates) longitudinally along the river. It is based on understanding of what is happening upstream and what is entering the incremental catchment (Bredenhand 2005). The RCC describes three zones along a continuum (Table 2.6 and Figure 2.12): the headwater zone, the foothill zone and the lower zone governed by changes in topography and the physical character of the river such as width, depth, flow characteristics, size of bed substrate and temperature, which dictate the patterns of biological and community structure.

In the headwater zone, river reaches are steep with V-shaped valleys, often forming knickpoints such as waterfalls. In this zone, flowing water has high energy and can pick up and transport sand and gravels, leaving only boulders and bedrock behind (Vannote *et al.* 1980). The channels are narrow and shaded by overhanging canopy cover, which reduces the temperature of the water and inhibits algal growth. The high canopy cover supports aquatic invertebrates that shred and collectors leaf particles.

In the foothill zone the gradient is less steep and the channel wider with some meanders (Vannote *et al.* 1980). Flowing water has much less energy and progressively deposits smaller and smaller particles. The open canopy allows more sunlight penetration, which promotes higher temperatures and a greater abundance of algae for aquatic macro-invertebrates to graze.

The lower zone has a wide channel and shallow slope so only fine clay and silt particles are left in suspension (Vannote *et al.* 1980). The low canopy cover leaves the channel exposed to sunlight, with higher temperatures and algal abundances than upstream. The lower zone is dominated by collectors, with very few or no shredders and grazers present.

Despite challenges (e.g. Winterbourn *et al.* 1981; Lake *et al.* 1986; Young and Huryn 1997), the RCC remains an important contribution to the development of ecological theory due to its recognition of flow of material between adjacent habitats and its importance in describing the structure and patterns of local biological communities (Thompson and Lake 2010).

The Flood Pulse Concept (FPC; Junk *et al.* 1989) focuses on the lateral linkages between the river channel, its riparian areas and surrounding floodplain. This concept emphasises the importance of alternating dry and wet phases in enhancing biodiversity and productivity (Junk *et al.* 1989). The flood-pulse concept explains that properties of the floodplain and riparian area are not determined by their position on the river longitudinally, but rather by the magnitude, duration and frequency of the floods they experience (Magoba 2018). Floods lead to the exchange of water, sediment, organic matter and nutrients between river channels and their riparian zones and floodplains (Junk *et al.* 1989; Poff *et al.*1997; Fremier 2004; Wohl *et al.* 2015). Thus, FPC recognizes that the predictable advance and retraction of water on the floodplain is the principal agent controlling the adaptation of most riverine biota. The FPC implies that biota occupying the riparian zones have adapted to repetitive flooding to the extent that their vitality and survival is dependent thereon (Hupp 1988; Junk *et al.* 1989; Wohl 2000a; Smith-Adao 2004). Flooding, therefore, is not a disturbance, but a natural phenomenon on which a healthy riverine ecosystem depends (Fremier 2004).

The FPC can be described in five stages based on how an annual hydrological cycle influences the riparian area and floodplain (Figure 2.13; Junk *et al.* 1989; Fremier 2004). The life histories of many riverine plants and animals, such as the release seeds or spawning, are linked to changes in flow and sediment regimes (Junk *et al.* 1989; Fremier 2004). Fish and macro-invertebrates use seasonally flooded areas as refuges and for breeding and feeding. Increased floodplain inundation also creates new nursery habitat for fish and optimal environments for many invertebrates especially those allied with macrophytes. While water is rising, plant, fish and macro-invertebrate production is high due to the release of nutrients from newly inundated soil. Floodwaters also pick up a nutrient from the surrounding floodplain that have been mineralized on land and then redistributes them through the river system. This movement of water, sediment and nutrients from the river channel onto the surrounding floodplain also helps to purify the water before it returns to the river channel (Junk *et al.* 1989).

Table 2.6 Summary of River Continuum Concept's Characteristics. CPOM = Coarse Particulate Organic matter; FPOM = Fine Particulate Organic matter. Modified from Bredenhand (2005).

Characteristics	Headwater zone	Foothill zone	Lower zone
Light penetration	Low	High	Low
Water clarity	High	High	Low
Temperature	Low	Moderate	High
Current	Varied	Varied	High
Shading	High	Moderate	Low
Bed composition	Rock	Cobble/Gravel	Sand/silt
Habitat diversity	Low	High	Low
Habitat type	Fall/pool	Riffle/pool	Run
Width	Low	Moderate	High
Depth	Low	Varied	High
Dissolved gases	High	Moderate	Low
Major ions	Low	Moderate	High
Nutrients	Low	Moderate	High
Dominant food type	CPOM/FPOM	Periphyton	Phytoplankton
Dominant feeding group	Shredders/Collectors	Grazers/Collectors	Collectors
Plants	Attached mosses	Attached periphyton	Floating phytoplankton

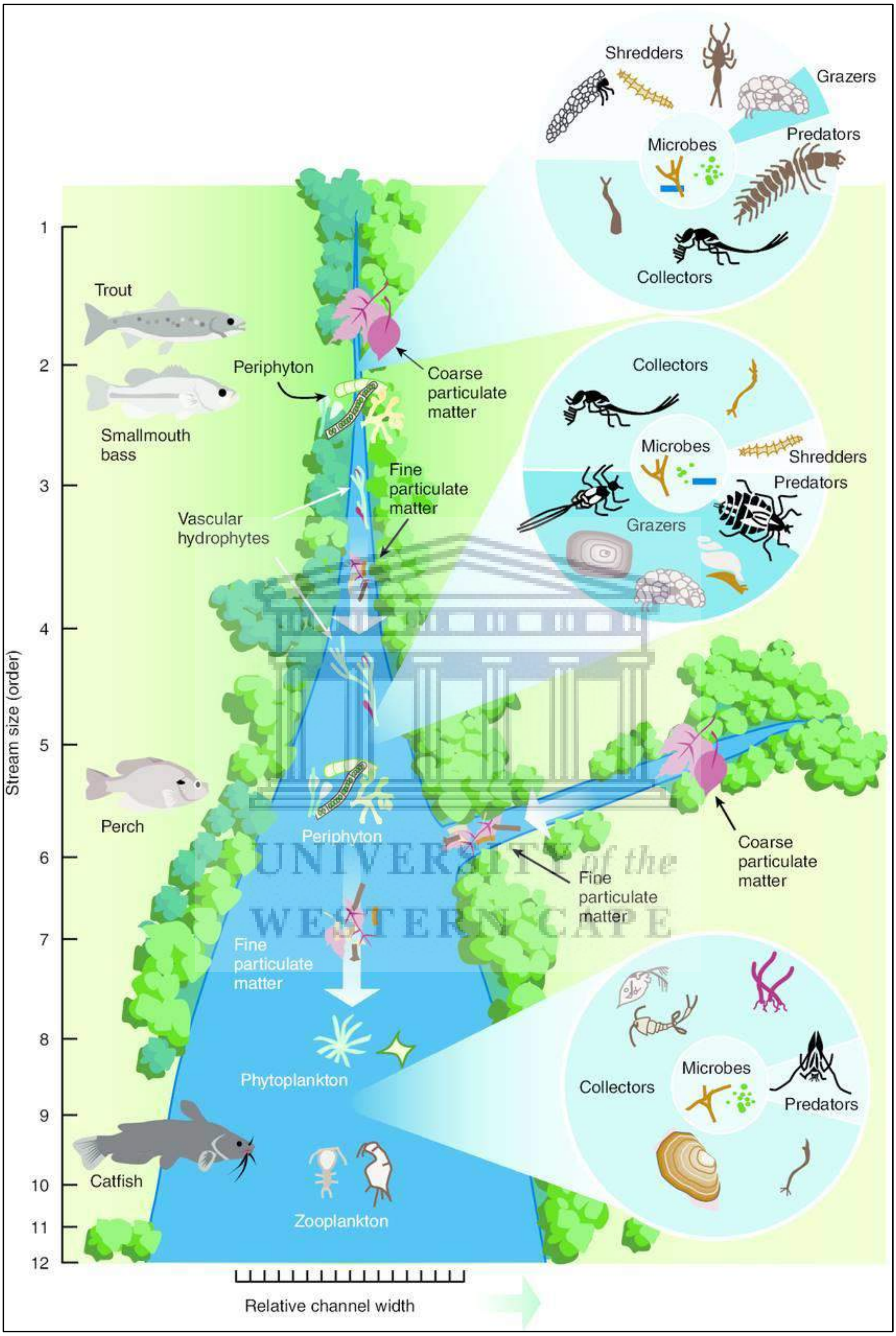

Figure 2.12 **The River Continuum Concept (RCC; Vannote *et al.* 1980). Reproduced from Bredenhand (2005).**

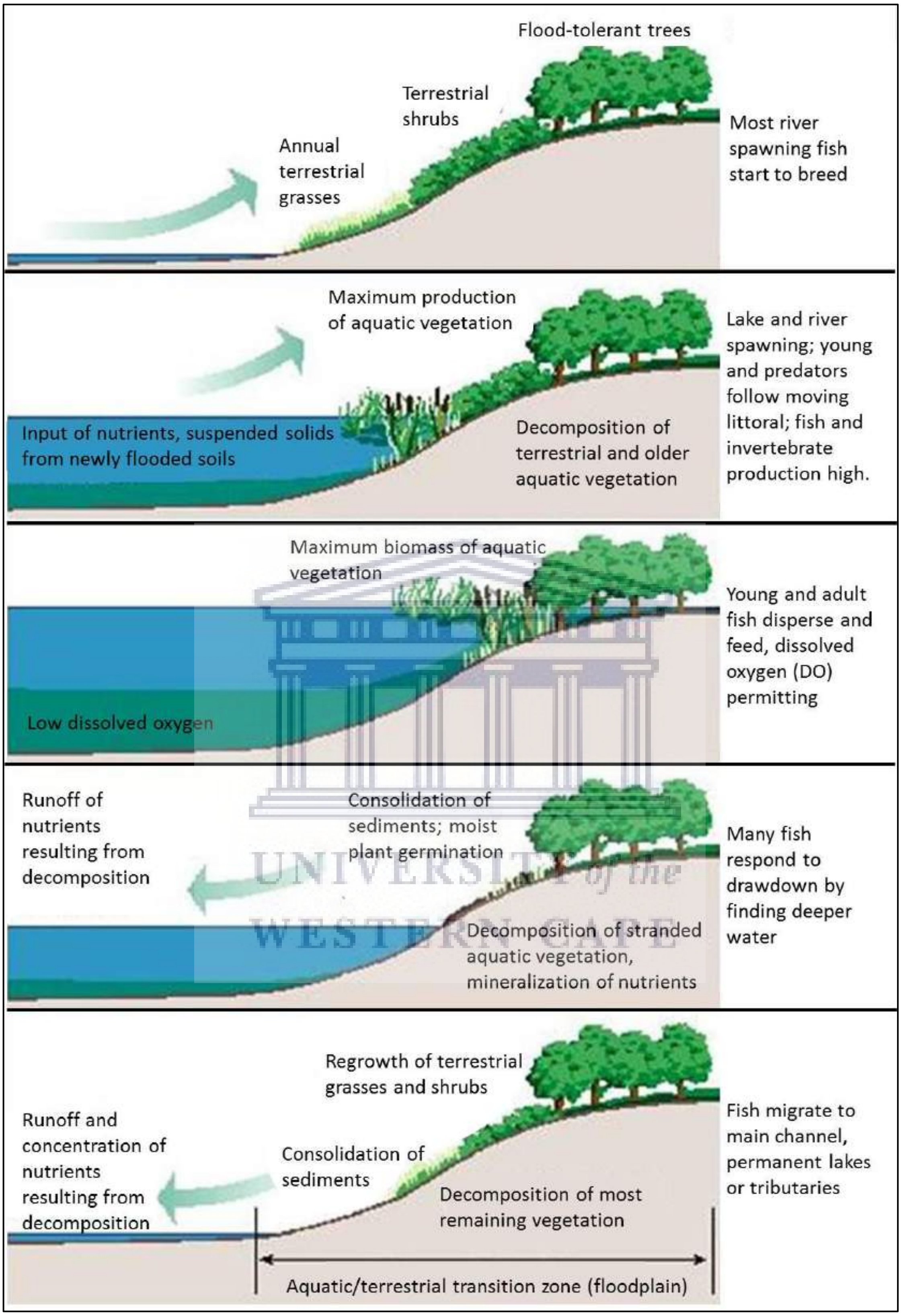

Figure 2.13 The flood pulse concept (Junk *et al.* 1989) in five stages of an annual hydrological cycle. The left column = nutrient movement and the right = life history traits. Modified from Fremier (2004).

The Hyporheic Corridor Concept (HCC; Stanford and Ward 1993) is an extension of the FPC (Junk *et al.* 1989) and describes how rivers function vertically by focusing on the linkages between the river channel and its hyporheic zone. Hyporheic zones are the sediment space beneath the channel bed where there is a mixing of surface and groundwater flow (Stanford and Ward 1993; Butarina 2018). Exchange of water, sediment, organic matter and nutrients occurs between the river channel and the hyporheic zone (Figure 2.14; Stanford and Ward 1993). These exchanges generally occur over short flow paths and the rate of exchange depends on variations in discharge, bed topography and porosity of the river bed and bank.

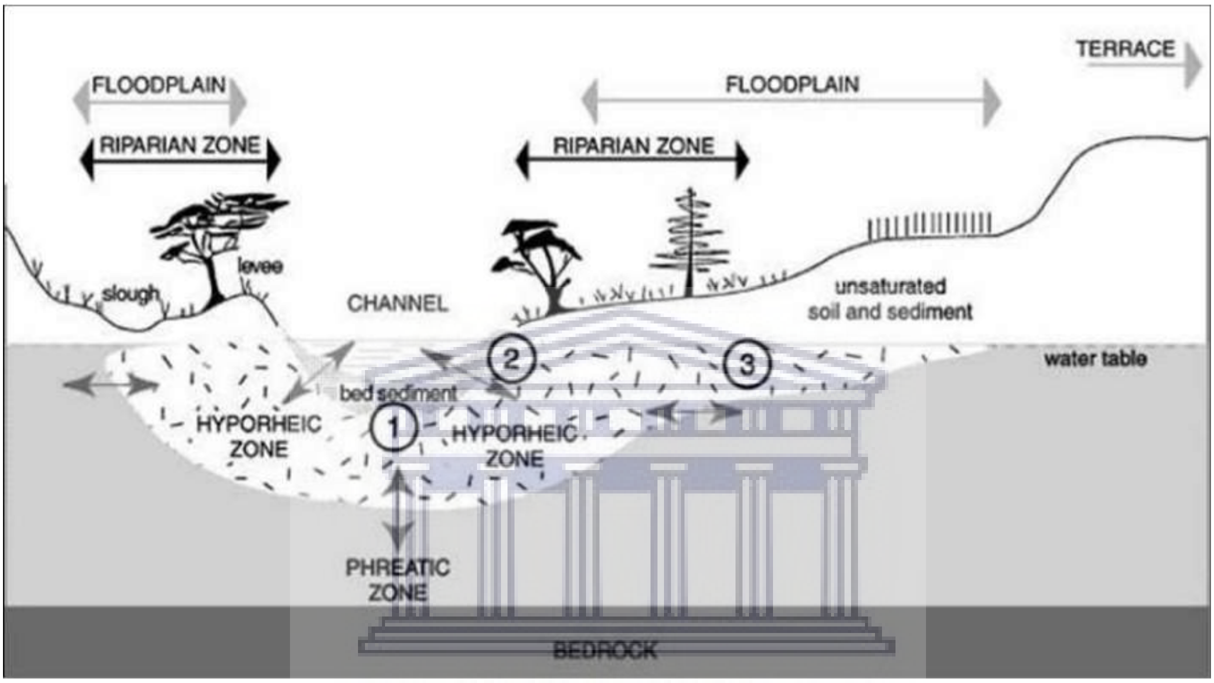

Figure 2.14 A conceptual diagram outlining the three zones of hyporheic exchange: (1) vertical hyporheic exchange, (2) horizontal hyporheic zone and (3) the floodplain hyporheic exchange. Reproduced from Janzen (2008).

Surface water – groundwater interactions that occur within the hyporheic zone is important for regulating temperatures of the water, especially during the summer months (Stanford and Ward 1993; Janzen 2008). Water passing into the hyporheic zone moves much slower than water in the stream and is cooled while being in this zone. The water in the hyporheic zone is eventually released back into the river channel and being colder than the water within the channel reduces the overall temperature

Changes in the groundwater levels in relationship to the hyporheic zone affect the exchange of water between the river channel and groundwater (Stanford and Ward 1993; Cey *et al.* 1998, Janzen 2008). When the water table is higher than the river bed, groundwater can contribute to river discharge. This discharge of groundwater can affect the physiochemical characteristics of river water. Where this occurs for extended periods, this affects the river ecosystem (Lautz *et al.* 2006, Janzen 2008).

The hyporheic zone is a habitat for numerous aquatic invertebrates and bacterial and algal communities (Stanford and Ward 1993; Baturina 2018). Water that enters this zone provides the inhabitant microbe, micro-invertebrates and algae with dissolved oxygen and organic matter; while water moving from this zone supplies organisms in the river channel with nutrients. The exchange of water between anaerobic groundwater systems and the aerobic surface water systems creates conditions of tightly spaced oxic and anoxic environments (Stanford and Ward 1993; Triska *et al.* 1993, Lautz and Siegel 2006, Janzen 2008). It is within these environments and these conditions that nutrient and sediment transformations and transport take place, such as the denitrifying of nitrate to ammonium in areas with low dissolved oxygen and organic carbon. These environments also host increased redox reactions which feed microbial activity. The above processes increase the concentrations of solutes and nutrients, which increases the productivity of plants and, as a result, strengthens the stability of river banks, further attenuates floods and reduces the stream sediment loads (Stanford and Ward 1993; Freeman and Rowntree 2005, Janzen 2008).

2.5 Anthropogenic influences on rivers and their biological communities

Humans have long used rivers for water supply, transportation, agriculture and power generation (Poff *et al.* 1997). Unfortunately, the management of rivers focused primarily on the consumptive need of society, without consideration of them as dynamic, functioning ecosystems (Orsborn and Anderson 1986; Carr *et al.* 1999; King *et al.* 2003). As a result, the majority of the world’s rivers are threatened by anthropogenic activities that drive changes of climate, hydrological cycles, surrounding landscapes, channel planform, water quality, habitat diversity and biodiversity. Many rivers are no longer able to support indigenous species or sustain healthy functioning ecosystems which can provide important goods and services (White and Pickett 1985; Naiman *et al.* 1995; Poff *et al.* 1997; Allan 2004; Giller 2005; Sabater and Stevenson 2010; Rolls *et al.* 2012; Kovalenko *et al.* 2014; Iñiguez-Armijos *et al.* 2018; Mondal and Patel 2018; Ekka *et al.* 2020; Beechie *et al.* 2021). Sabater and Stevenson (2010) stated that these changes originate from economic and social processes, which collectively are drivers of global change. Ekka *et al.* (2020) mentions that modifications of river landscapes results from divergent preferences and choices among stakeholders, which either directly impact ecosystem functions or accelerate natural processes that effect river-flow.

Prior to 1960, very little attention was given to the influence of human activities on river channel morphology or ecological functioning. However, since then considerable advances have been made in understanding river ecosystems and our impact on them (Gregory 2019). Increasingly river management is attempting to reconcile human activities with the conservation of biota (Gislason 1994). To do this, managers need to distinguish between changes brought about by humans and those that are part of the natural cycle (Orian *et al.* 1986; Gislason 1994)

The form and function of a river are altered by human modifications that change the surrounding landscape and affect, inter alia, flow and sediment regimes that govern geomorphological processes responsible for river morphology (Poff *et al.* 1997; Allan 2004; Sabater and Stevenson 2010; Ekka *et al.* 2020; Duan and Tukara 2020). Alteration to the geomorphic structure of rivers has enormous implications for the operation of biophysical fluxes that affect the movement of water, sediment, nutrients and organic matter (Fryirs and

Brierley 2013). Sabater and Stevenson (2010) list these as a combination of water flow interruptions, loss of hydrological connectivity, higher water residence times, simplified physical structure, elevated temperatures, increased nutrient and sediment loads, increased point source and non-point source pollution, greater exposure to invasive species, and biodiversity losses.

Some of these impacts are indirect, such as those that result in changes at the catchment scale, e.g., inter-basin water transfers, land-use change linked to agriculture and urbanization, and surface and subsurface flow modifications linked to groundwater abstraction (Paul and Meyer 2001; Chu *et al.* 2013; Iñiguez-Armijos *et al.* 2018; Duan and Tukara 2020; Ekka *et al.* 2020). Among the most extreme of these is catchment hardening, which refers to the sealing of the drainage areas by impervious surfaces such as roads, pavements, pathways and stormwater drains (Poff *et al.* 1997; Paul and Meyer 2001). Other impacts are direct, such as those that result from instream dams and weirs that disrupt flow, channelization or canalization and infilling of floodplains to develop them for agricultural and urban uses. Most catchments are affected by several if not all of these (Ekka *et al.* 2020).

One of the most pervasive practices is clearing natural vegetation for cultivation (Paul and Meyer 2001; Allan 2004; Liu *et al.* 2018; Duan and Tukara 2020). These cultivated landscapes generally have much less vegetation cover, which reduces the infiltration rate of water into the soil and increases surface water runoff (Figure 2.15; Paul and Meyer 2001; Allan 2004; Liu *et al.* 2018; Duan and Tukara 2020; Ekka *et al.* 2020). The resultant increase in runoff leads to larger and more frequent flood events (Poff *et al.* 1997; Paul and Meyer 2001; Allan 2004). The reduction of infiltration into the landscape means that groundwater is not being replenished as in natural circumstances, leading to reduced baseflows (Poff *et al.* 1997; Allan 2004; Ekka *et al.* 2020). According to Allan (2004), the effect of agriculture on a river's flow regime depends on the extent of agriculture on the landscape, infiltration capacity of the soil, crop production practices and the evapotranspiration rates of cultivated vegetation when compared with indigenous vegetation. Cultivation will change hydrological responses, i.e., flashier flood flows and reduced dry season flows, increased sediments and pollutants (fertilizers, insecticides and pesticides, among several others) into the river, which in turn, impairs physical habitats, water quality and the associated biological assemblages and ecosystems services provided by rivers (Osborn and Wiley 1988; Cooper 1993; Richards *et al.* 1996; Allan 2004; Smith-Adao 2004; Duan and Tukara 2020). Gerth *et al.* (2017) states that the physico-chemical changes of river flows associated with agriculture can reduce aquatic-macroinvertebrate taxonomic richness and increase the proportional abundances of invertebrates. The specific impacts vary with the types of crops (e.g., annual row crops vs. perennial or orchard crops) or animals being reared and the intensity of production (Gerth *et al.* 2017). Each macro-invertebrate species responds differently to water quality changes and exhibits specific tolerance levels and preferences to pollution (Dallas and Day 1993; King *et al.* 2000).

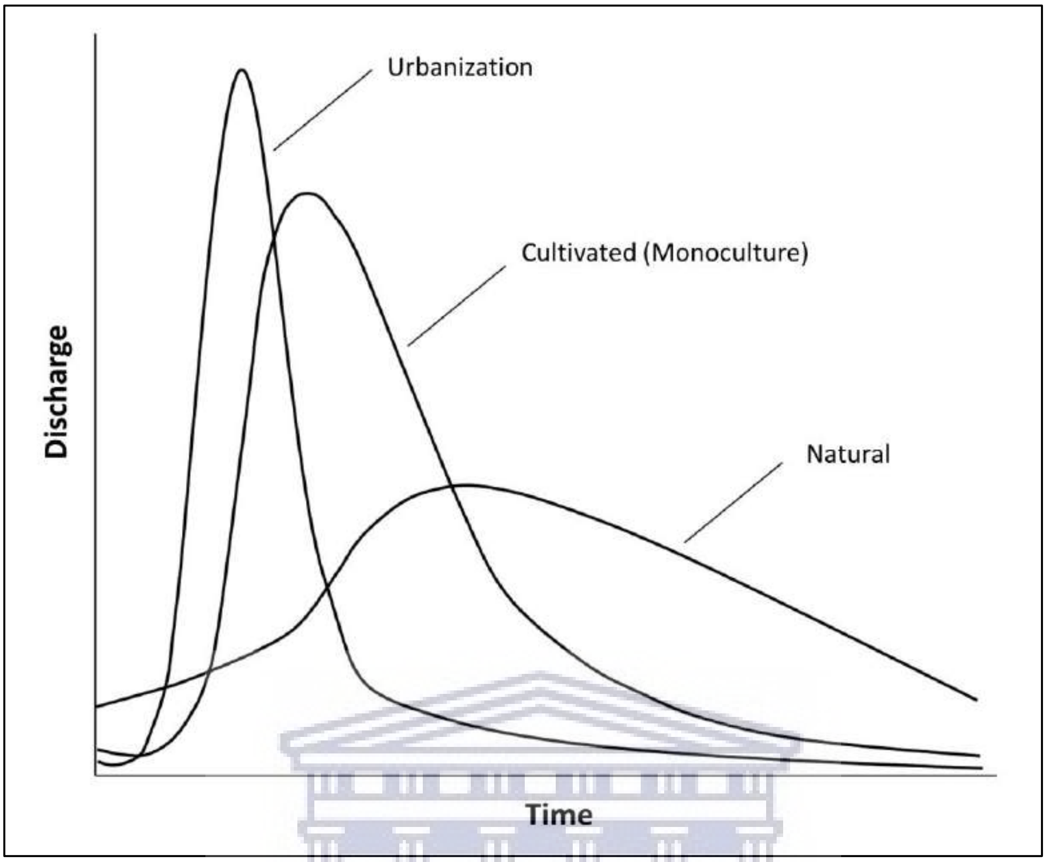

Figure 2.15 Hypothetical hydrographs showing storm runoff from natural, cultivated[1] and urbanised catchments.

Agricultural activities are strongly associated with the loss of riparian and terrestrial vegetation (Allan 2004; Fryirs and Brierley 2013), which is often cleared to the edge of the river channel bank, leading to bank instability and sedimentation (Wolman 1967; Walser and Bart 1999; Allan 2004; Morrochi *et al.* 2021). The influx of sediment impairs quality of habitat for aquatic organisms, fills interstitial spaces between cobbles used by invertebrates and fish, reduces stream depth heterogeneity and biodiversity, decreasing primary production and food quality that form the based on the food webs and coats gills and other respiratory surfaces (Walser and Bart 1999; Allan 2004; Ekka *et al.* 2020). The loss of riparian vegetation also reduces shading and increases exposure to sunlight (Allan 2004), which increases light penetration, increases temperature and promotes the growth of algae (Allan 2004; Gerth *et al.* 2017; Fierro *et al.* 2021; Morrochi *et al.* 2021). Changes in temperature affect the rate of development, reproductive periods and emergence time (Kosnicki and Burian 2003, Dallas 2004a; Thirion *et al.* 2016) of riverine animals. Macro-invertebrate assemblages are also impacted by the change in algal biomass and species composition arising from agricultural pollutants, such as fertilizers and pesticides (Allan 2004; Gerth *et al.* 2017; Ekka *et al.* 2020; Fierro *et al.* 2021; Morrochi *et al.* 2021). A common response to the loss of riparian cover is an increase in invertebrate abundance, particularly grazers, who feed on the algae (Delong and Brusven 1998; Quinn 2000; Allan 2004). According to Allan (2004), rivers draining agricultural

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[1] Monoculture represents agriculture and plantations; however, this is not to say that they are the same.

landscapes support fewer sensitive taxa of macro-invertebrates and fish relative to those that drain naturally vegetated catchments. This is supported by Fierro *et al.* (2021) who found agricultural activity in the landscape resulted in lower numbers of sensitive taxa and higher numbers of tolerant taxa, such as chironomids, oligochaetes and snails.

Macro-invertebrates are also impacted by flood events of high magnitude that erode the river bed and bank and lead to changes in their physical habitat (Allan 2004; Fryirs and Brierley 2013). Not all macro-invertebrates are able to tolerate more increases in frequency of floods of a higher magnitude (Allan 2004). Many macro-invertebrate taxa are also vulnerable to such disturbances during sensitive life stages. According to Richards *et al.* (1997), macro-invertebrates that are typically found in a catchment subject to agricultural activities tend to be those that are able to withstand dislodgment or have short life cycles and good colonizing abilities.

The impacts on rivers associated with urbanization are similar to those from agriculture but considerably more extreme (Figure 2.15; Poff *et al.* 1997; Paul and Meyer 2001; Allan 2004; Findlay and Taylor 2006; Wen *et al.* 2014; Cao and Natuhara 2020; Ekka *et al.* 2020), particularly with respect to catchment hardening. The suite of physical, biogeochemical and biological impairments on river systems in urbanized catchments are labelled as the “urban stream syndrome” (Walsh *et al.* 2005a; O’Driscoll *et al.* 2010; Hughes *et al.* 2014; Zahara *et al.* 2016). Urbanization results in altered baseflows and unstable flow regimes with more frequent, short-duration high peak floods; modifications of channel shape; and, elevated concentrations of nutrients and contaminants (Poff *et al.* 1997; Paul and Meyer 2001; Walsh *et al.* 2005b; White and Greer 2006; Yuan *et al.* 2006; O’Driscoll *et al.* 2010; Chu *et al.* 2013; Cao and Natuhara 2020; White and Walsh 2020).

Three stages of urbanization have been identified in association with river channels: 1) natural phase, 2) a period of construction and 3) a final stage of the urban landscape and associated impervious surfaces (Figure 2.16; Wolman 1967a; Chin 2006). In the natural phase, the river channel is at a stable equilibrium regarding the balance between erosional and depositional processes (Wolman 1967a; Chin 2006). During the urban construction phase, there is an increase in sediment production, resulting from the increased erosion rates of exposed bare land surface. This results in excess sediment deposition that in-fill the interstitial spaces between cobbles and boulders and leads to changes in the geomorphological features found in a natural river system. In turn, these changes reduce the availability of certain physical habitats required by algae, aquatic invertebrates and fish. After the completion of construction impervious areas often dominate, leading to increased magnitude and frequency of flashy floods in the wet season and reduces baseflows during the dry season. Little erosion and transport of sediment can occur over the landscape, which reduces the production of sediment in the system (Chin 2006). Flows moving through such environments become sediment hungry and tend to erode river banks and channels, which led to widening and deepening of the channel (Kondolf 1997; Grimaud *et al.* 2015; Fryirs and Brierley 2013).

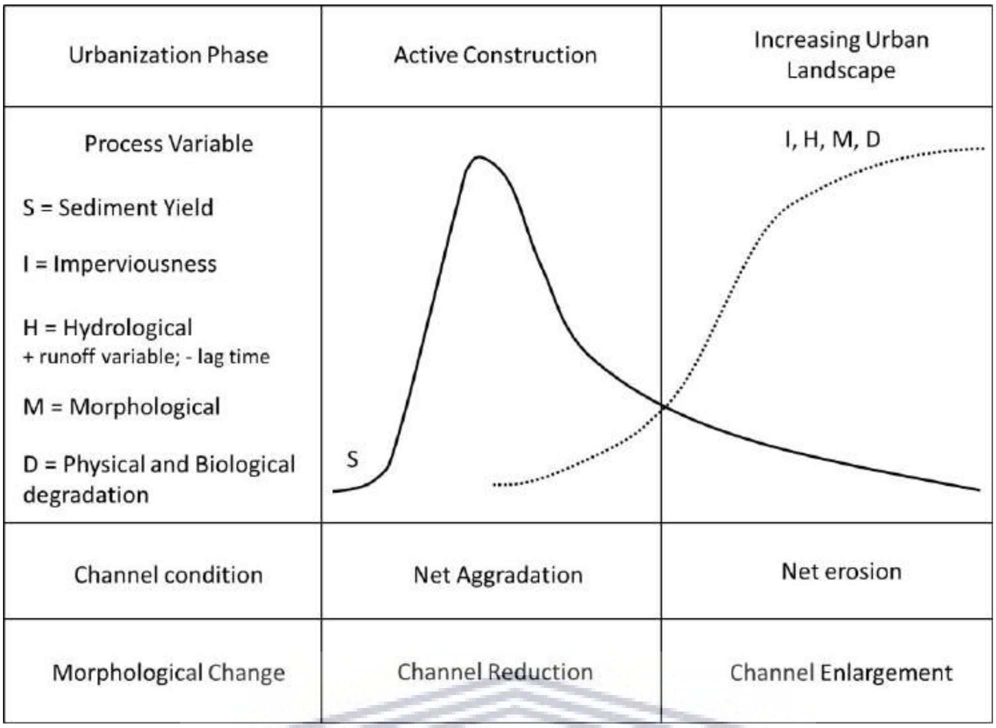

Figure 2.16 **General phases in urbanization with associated changes in geomorphological processes, channel conditions and morphology. Modified from Wolman (1967a) and Chin (2006).**

The impervious surface cover (ISC) in a catchment is an accurate predictor of urbanisation and its impacts on a river's flow regime (Figure 2.17; Paul and Meyer 2001). Relative to forested catchments, surface runoff increases two-fold for an ISC of 10-20%, with concomitant reductions in evapotranspiration and infiltration. The increase is threefold for an ISC of 35-50% ISC and fivefold for 75-100% ISC (Arnold and Gibbons 1996; Paul and Meyer 2001). Paul and Meyer (2001) report, that many thresholds of degradation in rivers are associated with an ISC as low as 10-20%.

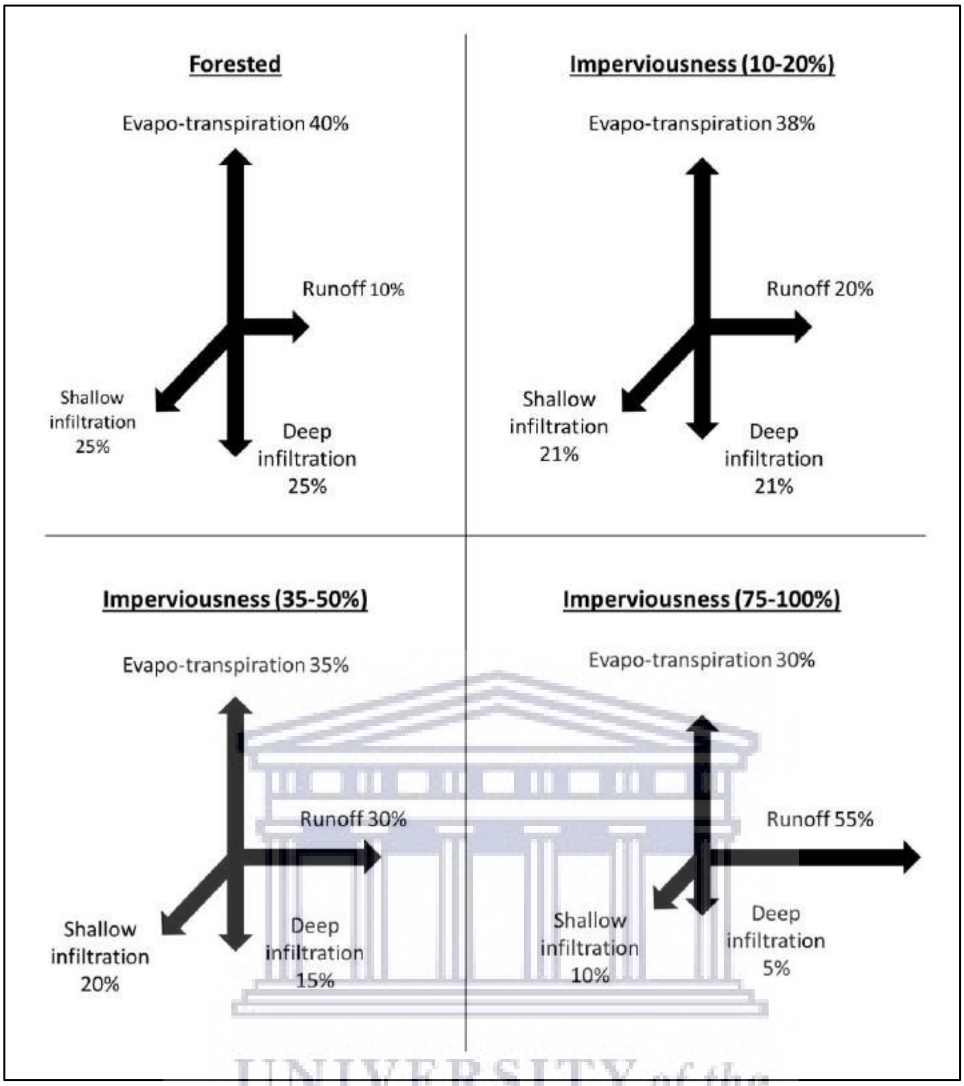

Figure 2.17 Changes in surface runoff, evapo-transpiration and infiltration with increasing imperviousness. Modified from Arnold and Gibbons (1996) and Paul and Meyer (2001).

These indirect impacts are largely a consequence of the hardening of the catchment through development of residential and industrial areas around the river channel as opposed to alterations being made within the river channel itself. Unfortunately, much urban development takes place over the floodplains which are often misinterpreted as being separate from the river system. Other indirect impacts to rivers associated with urbanization include; bank destabilisation, confinement of the river channel, restricted interactions between the river channel and its floodplain, increases in the amount and variety of pollutants, increased water temperatures owing to the loss of riparian vegetation and warming of surface runoff on exposed surfaces (Poff *et al.* 1997; Paul and Meyer 2001; Allan 2004; Cao and Natuhara 2020; Ekka *et al.* 2020). Although many of the impacts of urbanization do not originate from manipulation of the river channel itself, activities such as soil pollution, soil compaction and trampling of surrounding vegetation can elicit changes in channel morphology (Fryirs and Brierley 2013; Cao and Natuhara 2020).

Many changes in river systems due to urbanisation are unintentional, but arise from direct engineering of river channels and floodplains, channelisation, channel diversions, in-channel construction and dredging (Mays 2008; Fryirs and Brierley 2013). Large-scale dams, canals and river diversion schemes are also common (Poff *et al.* 1997, Luger 1998, Wohl, 2000b; Chin 2006; Hughes *et al.* 2014; Duan and Tukara 2020). Channelisation and canalisation are used to increase channel capacity to carry flood water and to stabilize the river banks and transform what would naturally be wide, meandering channels into straight, narrow ones; in so doing reducing their sinuosity and habitat diversity (Harvey and Sing 1989; Fryirs and Brierley 2013). They differ from each other in that canalisation means encasing the river channel in concrete, while channelisation often uses gabions, structures that comprise wire-mesh baskets or mattresses filled with rocks, to stabilise beds and banks (Gore *et al.* 1995; Smith-Adao 2004). Basket gabions are used to protect steep vertical banks, where mattress or blanket gabions offer slope protection (Schultze and Wilcox 1985; Smith-Adao 2004). Canalization seals off the river bed, thereby disconnecting the hyporheos, banks and surrounding floodplains, while channelisation may retain some connections (Gore *et al.* 1995; Smith-Adao 2004; Allan 2004). The impacts of both are exacerbated especially when subjected to an altered flow regime and/or poor water quality (Poff *et al.* 1997; Federal Interagency Stream Restoration Working Group 1998; Malmqvist and Rundle 2002; Walsh *et al.* 2005b; Violin *et al.* 2011; Zahara *et al.* 2016). Engineered river bank stabilization structures such as gabion baskets and mattresses (channelisation), concrete walls (i.e., loffelstein walls or retainer blocks - canalization), or rip-rap, provide protection only for the length of bank covered which is often at the expense of unprotected downstream or upstream areas (Kondolf 1996). Rip-rap is the most commonly used bank stabilization structure and comprises large boulders of different sizes placed on a purposefully shaped slope (Gore *et al.* 1995; Smith-Adao 2004). However, river reaches downstream of any of these modifications are prone to flooding due to an inability to withstand resultant accelerated flows.

According to Fryirs and Brierley (2013), the geomorphic response times following the construction of river engineering works depend on the types of works installed and the extent to which they alter discharge, stream power, sediment supply and vegetation cover. Many of these direct human impacts are site- or reach-specific forms of disturbance that induce an immediate geomorphic response. Feedback loops to such modifications involve a river adjusting its coarse further downstream until an equilibrium state is reached. It may take hundreds of years to attain the new equilibrium. Once channelisation begins, secondary instability and/or channel adjustments elsewhere in the system are often a prompt outcome of the channelisation programme. The accelerated flow through channelized rivers often causes erosion of the river’s bed and banks where it is still un-modified, deepening and widening the river channel and ultimately aggravating longitudinal and lateral migration. Such modifications are typical of river improvement before the concept of river restoration came about.

2.6 River restoration

After decades of uncontrolled anthropogenic influence and the degradation of riparian ecosystems worldwide, the notion emerged that heterogeneity in physical habitat supports diverse biotic assemblages and crucial ecosystem services (Giller 2005; Day *et al.* 2016;

Grizzeti *et al.* 2017; Theodoropoulus *et al.* 2020). Hence, degraded river systems have been engineered to restore their hydrologic, geomorphic and ecological processes and the ecosystem services that they provide (Giller 2005; Wohl *et al.* 2015; Theodoropoulus *et al.* 2020). Over time, focus has shifted from the restoration of benefits and protection of ecosystem services, such as flood prevention, towards the restoration of natural river functioning (Bernhardt *et al.* 2007; Tompkins and Kondolf, 2007; Moore and Rutherford 2017).

2.6.1 Paradigms of river restoration

The science of river restoration emerged approximately 50 years ago in response to the desire to restore degraded ecosystems and has undergone major conceptual development in understanding natural river functioning (Rogers and Bestbier 1997; King *et al.* 2003; Giller 2005; Wohl *et al.* 2015). The field of river restoration has diverged into two opposing philosophies, which restoration ecologists use as the foundation of their approaches; the 'Balance of Nature' (BON) (e.g., Rutherfurd *et al.* 2000) and the 'Flux of Nature' (FON) (e.g., Calow and Pletts 1994; Meier 1998; Wells 1998; Petts *et al.* 2000).

The traditional ideas behind conservation followed the BON philosophy, where river ecosystems are thought to exist in an equilibrium state, provided that they are not subject to human influence (Rutherfurd *et al.* 2000; King *et al.* 2003). Under the BON philosophy, humans are viewed as being separate from natural ecosystems and thus consider any human-related impact to be a non-natural disturbance (Jackson *et al.* 1995; Rutherfurd *et al.* 2000), unless impacts originate from indigenous peoples or hunter-gatherers (King *et al.* 2003). Rutherfurd *et al.* (2000) presents river restoration as projects that restore natural flow, sediment and water quality regimes, channel geometry and stability and aquatic and riparian plant and animal communities. Rutherfurd *et al. (*2000) defines river restoration as return a degraded or impacted ecosystem to a historically natural state – the state prior to any human intervention (Rutherfurd *et al.* 2000). River restoration may only be achieved if, "… the entire stream network and most of the catchment surface are also restored" (Meier 1998; Fogg and Wells 1998). Therefore, on the basis on BON philosophy, it is not possible to restore a catchment that is continuously impacted by anthropogenic influences (Reinecke 2008).

In contrast, FON philosophy recoignizes that ecological systems rarely exist in equilibrium and, that it is no longer possible to restore many of the world's river systems to their natural state given the continued anthropogenic influences they are subjected to (Calow and Pletts 1984; Jackson *et al.* 1995; Rogers and Bestbier 1997; Meier 1998; Fogg and Wells 1998; King *et al.* 2003; Reinecke 2008). Advocates of the FON philosphy define restoration to be, '… an attempt to bring the river back to as high a level of ecological intergrity as possible, taking into account the prevailing socio-economic, political and technological constraints." (Meier 1998). Ecosystem are continously changing; the biological constituents currently present in an ecosystem may not necessarily be the same in the future. One key problem that river managers and engineers are faced with is the difficulty in isolating a section of river from impacts that occur either upstream or downstream. Advocates of FON philosphy see rivers as temporally unique features that are sculpted by isolated climatic events and biological invasions (Calow and Pletts 1984; Jackson *et al.* 1995; Meier 1998; Fogg and Wells 1998).

The emergence of the two opposing philosophies in river restoration demonstrates a shift from the single species approach of looking at population control in a closed ecosystem, to an ecosystem-level approach that considered processes of natural, functioning ecosystems (King *et al.* 2003).

River restoration is often referred to using other terminologies, such as rehabilitation, remediation, enhancement and preservation (Table 2.7). These terms are often used interchangeably to represent the science of restoration as a whole; however, each term represents different degrees to which a rivers condition is improved. The term restoration will be used in this study to describe all activities associated with improving the state of degraded river ecosystems.

Table 2.7 Definitions of various terminology used in defining river restoration.

Terminology	Definition and description	Reference
Restoration	"…return the degraded or impacted ecosystem to a historically natural state…" River restoration may only be achieved if, "… the entire stream network and most of the catchment surface are also restored".	Rutherfurd *et al.* 2000
	"…all activities associated with improving the state of degraded river ecosystems."	Current study
Rehabilitation	"…making the land useful again after a disturbance."	Fogg and Wells 1980
	"…a partial return to a pre-disturbance condition usually linked to fish or wildlife habitat. To return degraded habitats to a pre-existing condition (e.g., dredging backwaters that have filled with sediment; forming riffles, or changing the plan form of channelized reaches; or planting riparian buffer strips)." Acknowledges that neither the entire river network nor the greater part of the catchment can be rehabilitated.	Petts *et al.* 2000
Remediation	"…to improve the ecological condition of the stream, but the end point of that improvement will not necessarily resemble the original state of the stream".	Rutherfurd *et al.* 2000
Enhancements	"…improving the current state of an ecosystem without reference to its initial state…" May be attempted to mitigate the effect of disturbance and to provide optimal conditions for a highly valued species such as game fish (Petts *et al.* 2000).	Calow and Petts 1994 Petts *et al.* 2000
Preservation	"…the maintenance of functions and characteristics of an ecosystem in its desired state…not requiring rehabilitation".	Petts *et al.* 2000

2.6.2 Early “restoration” efforts

The earliest efforts to restore rivers date back to the late-1900’s and consisted of narrow-minded objectives motivated by the interests of fishery boards, water quality and discharge of raw sewage (Uys 2003; Addy *et al.* 2016). Some examples of these early efforts include: the Bronx River Restoration Project that commenced in 1977 to control the discharge of raw sewage into the river and mitigate water quality impacts (Perini and Sabbion 2017); the Mersey River Basin Campaign that was launched in 1985 to clean raw sewage being released into the river (Tippet 2001); and the Anacostia River Restoration Project which started in 1987 and aimed to mitigate water quality impacts and improve riverine habitat for recreational purposes (Chesapeake Bay Program Office 1992).

Many of these earlier ‘restoration’ projects are more accurately described as ‘river improvement’, ‘stormwater control’ and ‘greening of urban areas’ because they did not take all the relevant ecological principles into consideration. Generally having little to do with reinstating natural ecosystem processes, these early projects consequently caused great harm to river ecosystems (Us 2003; Wohl *et al.* 2015). Trial and error were the approach, with a primary focus on river form and pattern (Kondolf *et al.* 1996; Rutherfurd *et al.* 2000; Uys 2003; NCC 2006; Arizpe *et al.* 2008; Addy *et al.* 2016; Yochum 2018). Experiences gained and lessons learnt from earlier ‘restoration’ practices did however contribute to the refinement of the current favoured approach to river restoration (Addy *et al.* 2016).

2.6.3 Process-based restoration

Recent calls for national and international river restoration efforts have necessitated a more holistic approach for managing river systems that address root causes of degradation and restore natural ecosystem processes (Kondolf *et al.* 2006; Palmer and Allan 2006, Roni *et al.* 2008; Beachie *et al.* 2010). This approach promotes the self-recovery of physical habitat through natural processes, which in turn, can restore natural physical habitat and functioning for the benefit of biodiversity and people (Kondolf *et al.* 1996; Beechie *et al.* 2010; Addy *et al.* 2016; Day *et al.* 2016).

Kondolf *et al.* (2006) addressed the need to restore natural river processes and suggested using simple descriptive models as a structured way of investigating changes in ecological processes in rivers over time (Figure 2.18). Although these models are not quantitative, they focus on natural river processes, unlike earlier restoration efforts that over overemphasised form and pattern (Wohl *et al.* 2005; Kondolf *et al.* 2006). According to Kondolf *et al.* (2006), focussing on river form without restoring the processes that maintain it, leads to transformation away from an ideal river. These models serve to reveal relationships between longitudinal, lateral and vertical connectivity and river dynamics. Such models are useful for visualizing the trajectories of different types of human alterations and restoration approaches and to specify constraints associated with flow variability and connectivity.

Process-based restoration is a means of addressing the root causes of degradation and aims to re-establish the physical, chemical and biological processes that create and sustain riverine ecosystems (Beechie *et al.* 2010). Examples of such processes include processes of erosion and deposition, storage and movement of water, plant growth and successional processes, input of nutrients and thermal energy and nutrient cycling in the aquatic food web (Beechie *et al.* 2010). These processes involve the movement of, or changes to, components of the ecosystem (Beechie and Bolton 1999; Beechie *et al.* 2010). The process-based approach focuses on minimizing anthropogenic disruptions to these processes in a manner that allows the river to recover without further corrective intervention (Beechie *et al.* 2010).

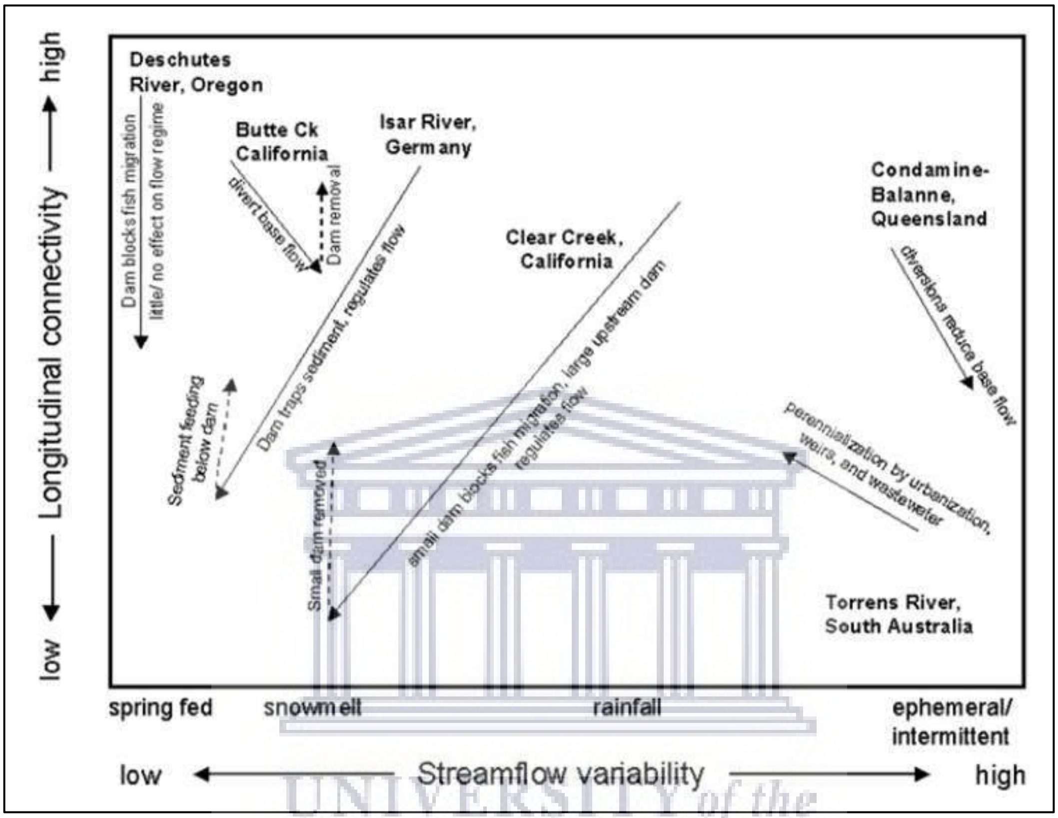

Figure 2.18 An example of a descriptive model used for investigating changes in ecological processes of a river over time. Reproduced from Kondolf *et al.* (2006)

Many engineering techniques such as bank hardening, channel construction and creation of morphological features that provide hydraulic biotopes (i.e., riffles and pools), attempt to control ecological processes and dynamics rather than to restore those (Beechie *et al.* 2010). These techniques continue to dominate the practice of river restoration, despite the many failures to achieve ecosystem recovery (Palmer *et al.* 2005; Beechie *et al.* 2010). Over an extended time period, it is more sustainable to restore river processes by using minimal intervention, which in turn, assists with re-establishing characteristic high-quality habitat (Addy *et al.* 2016). Addy *et al.* (2016) defines river restoration as the re-establishment of natural physical processes (e.g., variation in the movement of flow and sediment), features (e.g., river shape and sediment sizes) and physical habitats in the riparian zone. This definition acknowledges that that is it impossible to restore a river to its state before human intervention and rather encourages the recovery of natural processes. In essence, this aims to create characteristic, dynamic and self-sustaining physical habitat that promotes biological recovery and restores the accrued benefits that people rely upon, i.e., regulation of flood waters (Addy *et al.* 2016).

There are several advantages of restoring the natural processes in riparian ecosystems (Kondolf *et al.* 2006; Newson and Large 2006; Mainstone and Holmes 2010; Beechie *et al.* 2010; Addy *et al.* 2016). These include; 1) it focuses on providing a solution to the root cause of degradation rather than the symptoms, 2) it results in conditions more representative of a natural river system and its characteristic biodiversity, 3) it results in dynamic habitat conditions that are more resilient and sustainable compared to engineered channels or habitats, particularly regarding climate change, 4) construction and maintenance costs are reduced by creating a more self-sustaining system, and, 5) it is more likely to achieve a broader range of ecosystem benefits that address multiple objectives rather than benefiting limited habitat types or species.

2.6.4 Principles of river restoration

River restoration has developed and advanced to a point where national and/or regional guidelines and manuals are being developed, many of which are based on geomorphological and ecological principles and processes (Day *et al.* 2016; Yochum 2018).

Addy *et al.* (2016) recommends six key overarching management principles that guide effective river restoration, which include:

1) Improve overall ecosystem integrity and biodiversity, rather than focusing on the status of single species, by using process-based techniques such as maintaining sinuous low flow channel, maintain natural sequence of morphological units, floodplain reconnection.
2) Engage with the interests and motivations of different stakeholder groups as early as possible. Discuss objectives and identify opportunities and barriers, before planning activities.
3) Understand the connections between natural processes upstream and downstream: work beyond the scale of individual reaches to consider riparian areas, floodplains and the wider catchment.
4) Target measures at the root causes of degradation – not the symptoms – and at the scale at which the pressures exist.
5) Use minimal intervention wherever possible to reinstate natural processes so that rivers can recover by themselves.
6) Evaluate restoration projects using robust monitoring techniques over long timescales (>5 years) to determine outcomes and inform future restoration.

3 Description of the study area

3.1 Location and topography

The Lourens River is a short (~20km), naturally perennial river that originates from deep within the Hottentots-Holland Mountain range in the Diepgat Ravine, known as ‘Watervalkloof’ (Tharme *et al.* 1997, CCA 2000; Smith-Adao 2004; Schaber 2015). The upper part of its catchment is formed by the Helderberg, a part of the mountain range that borders the north and north east of the catchment. Altitudes range from 0 to 1080 m.a.m.s.l. (Somerset West 3418 BB, 1:50 000 topographical map, 4th edition 1995; CCA 2000; Smith-Adao 2004).

The river is located in the municipality of the City of Cape Town Metropolitan and drains an area of of ~106 km^2 (Figure 3.1; Tharme *et al.* 1997, CCA 2000; King *et al.* 2003, Smith-Adao 2004; Schaber 2015). It flows in a south-westerly direction through the town of Somerset West and parts of Strand, before entering False Bay and the Indian Ocean via a small estuary.

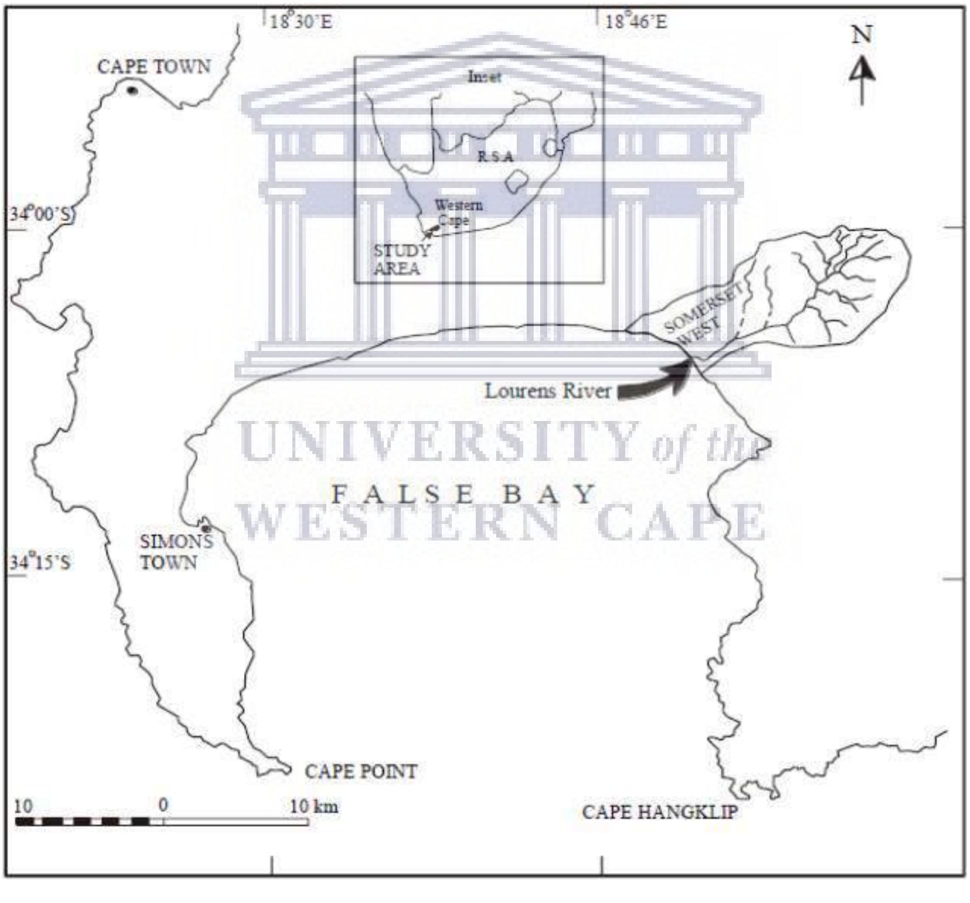

Figure 3.1 The Lourens River catchment near Somerset West, South Africa (Heydorn and Cliff 1982).

3.2 Climate

Most of Western Cape is considered to have a Mediterranean climate, which gives the Lourens River catchment warm, dry summers and mild, wet winters, which is classified as 'Csb[2]' according to the Köppen-Geiger classification scheme (Kottek *et al.* 2006; Schaber 2015; Appx. Figure 1). Monthly average temperatures in Somerset West range from 11.7 °C in winter to 22.1 °C in summer (Schaber 2015). The mean annual precipitation in Somerset West historically ranged from 1500 mm in the upper basin to ~600 mm in the lower reaches (Midgley *et al.* 1994, Tharme *et al.* 1997). The area currently has a mean annual precipitation of 1002 mm (Schaber 2015).

3.2.1 Hydrology

Flooding of rivers in the Western Cape, such as the Lourens River, mostly occurs in winter due to the Mediterranean climate (Kottek *et al.* 2006, Schaber 2015). There are, however, exceptions to this when some of the most severe flood events on the Lourens River occurred during spring and summer months. Flooding during this time of the year is a result of a persistent, strong and usually a dry south-easterly wind that blows along the coast of South Africa from October to March. The wind is affectionately known as the "Cape Doctor" (Deacon *et al.* 2004), as it blows away air pollution and cools the coastal cities in the hot summer months. Occasionally, the south-easterly wind is accompanied by an offshore cut-off low pressure system, particularly in the spring and autumn. In these instances, the wind brings heavy rain to the area, a phenomenon known as the 'Black South-Easter' (Roberts and Alexander 1983; Moir 1993; Pieterson 2018). Under such conditions, the rain laden clouds are pushed up against the Helderberg Mountains and deposit their water into the headwaters of the Lourens River, resulting in massive flooding downstream. Another example of this phenomenon is the flood event that occurred in Laingsburg, Western Cape in 1981, where the black south-easter caused significant amounts of rain to fall within the catchment, which resulted in severe flooding of the area (Pieterson 2018).

The natural mean daily discharge is 1.84 m^3/s, which correspond with a mean annual discharge of about 58.02 million m^3, and a mean annual water depth of 547 mm/year (Table 3.1; Aurecon *et al.* 2017). The present-day MAR is ~59.27% of the natural MAR (Table 3.1), with the highest differences occurring in the dry seasons (Figure 3.2). The MAR with the yearly totals for 1920 to 2009 is presented in Figure 3.3.

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[2] According to Köppen-Geiger classification scheme, 'Csb' is classified by: C = warm temperate climate; s = steppe precipitation; b = warm summer temperature.

Table 3.1 **Simulated naturalized and present-day hydrology at Site (Lou1; Aurecon *et al.* 2017) on the Lourens River from 1920 to 2009. Reproduced from Aurecon *et al.* (2017).**

Month	Natural MAR (MCM)	Present-day MAR (MCM)	% Natural	Natural Mean Q (m^3/s)	Present-day Mean Q (m^3/s)
October	5.31	4.87	91.80	2.19	2.01
November	3.10	1.92	61.92	1.24	0.77
December	1.50	0.45	29.94	0.56	0.17
January	0.73	0.13	17.53	0.28	0.05
February	0.51	0.06	11.05	0.19	0.02
March	0.58	0.12	20.20	0.22	0.05
April	1.87	0.72	38.15	0.70	0.27
May	5.17	2.79	54.05	1.93	1.04
June	9.15	8.15	89.01	3.53	3.14
July	10.76	10.79	100.26	4.02	4.03
August	10.93	10.94	100.09	4.22	4.22
September	8.03	7.81	97.29	3.00	2.92

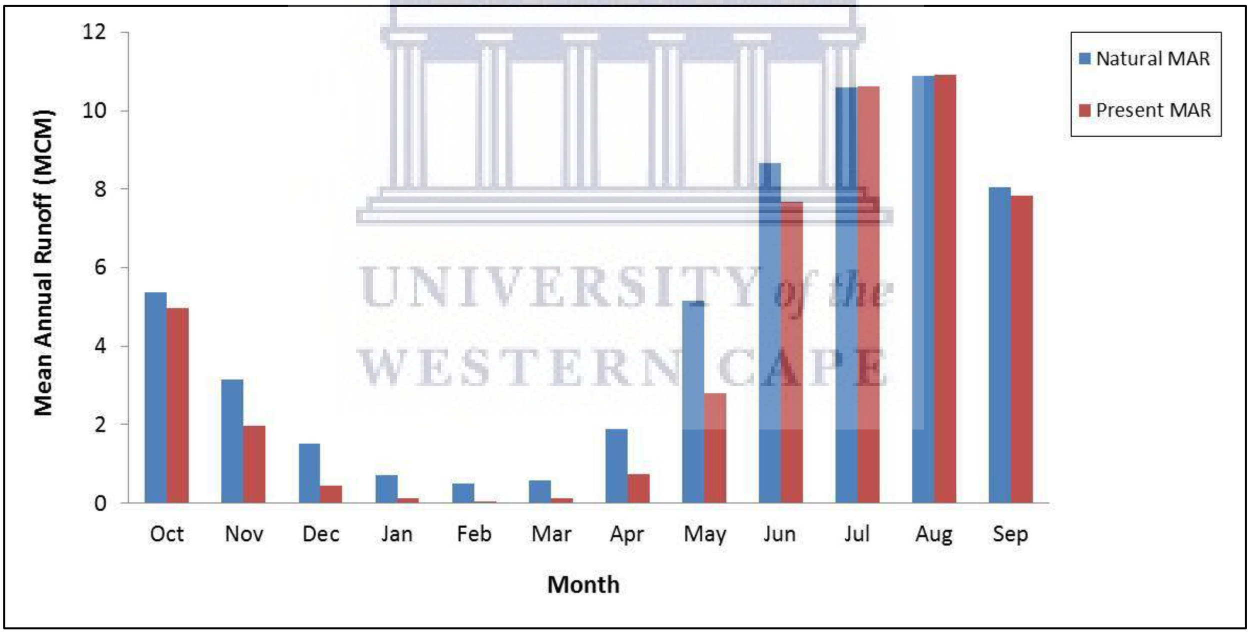

Figure 3.2 **Natural and Present day mean monthly runoff showing for periods 1920 to 2009 (Aurecon *et al.* 2017).**

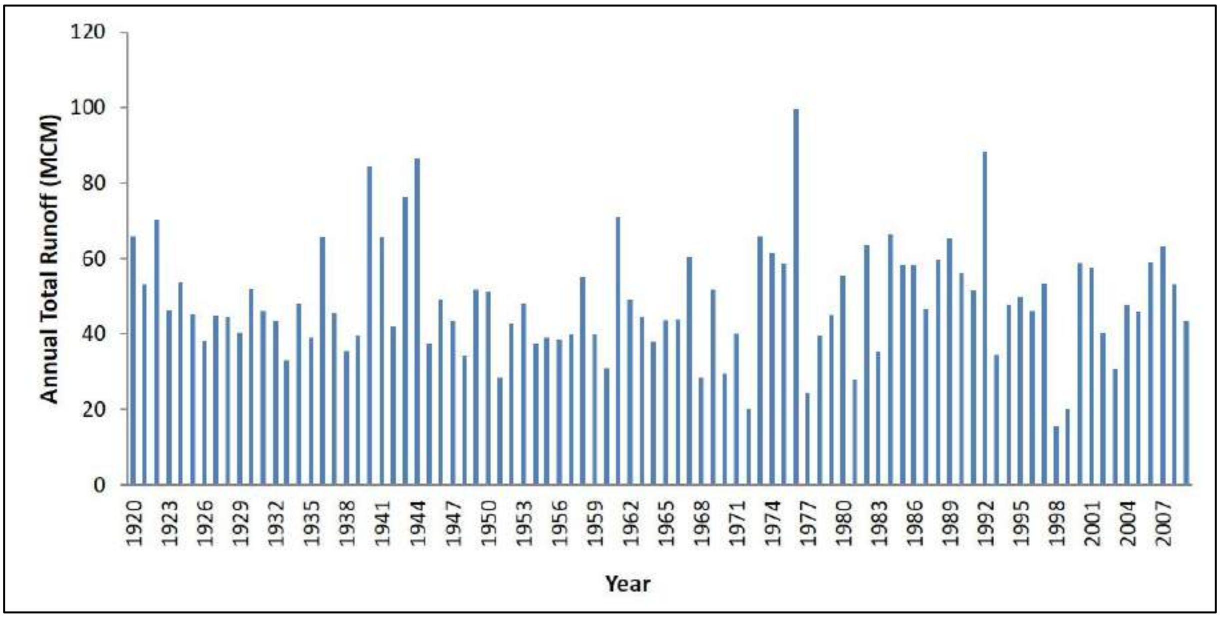

Figure 3.3 Annual total runoff for periods 1920 to 2009 (Aurecon *et al.* 2017).

3.3 Geology

The geology of the catchment can be classified into three major zones (Tharme *et al.* 1997; CCA 2000; Smith-Adao 2004; Schaber 2015; Figure 3.4). The headwaters of the river are situated within the ecoregion underlain by the Table Mountain Group Sandstones, a dominate component of the Cape Fold mountains that includes the Hottentots Holland Mountains. The second zone starts in the mountain stream zone, which comprises the Pre-Cape granites and Malmensbury Group Shales. The foothills of the river pass through a shallow valley that is underlain by tertiary/quaternary alluvial clays and Aeolian sands. This composition results in high surface runoff of acidic, low-salinity water (River Health Programme 2003, Schaber 2015).

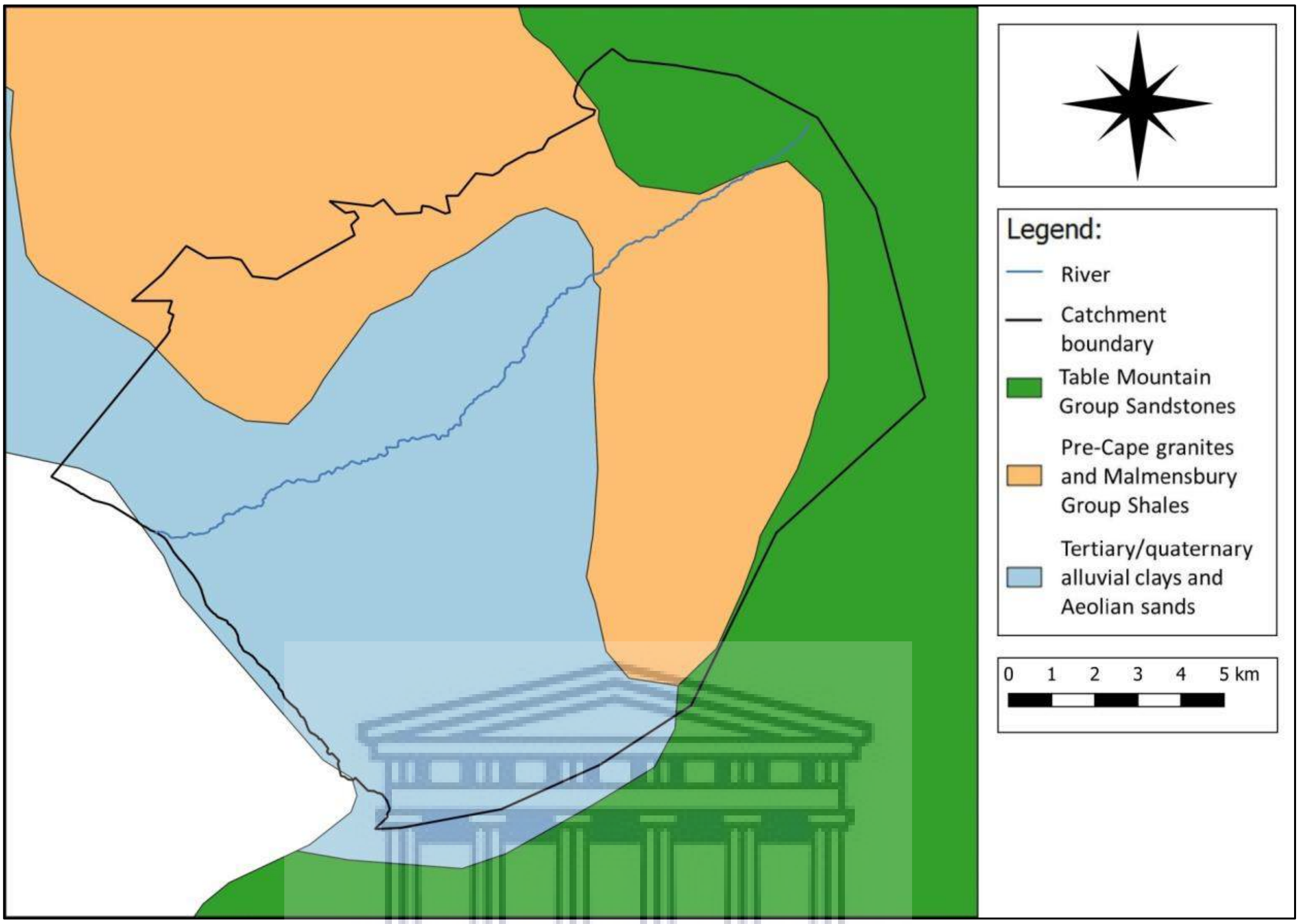

Figure 3.4 Geology and soil formation of the Lourens River catchment (SANBI 2009).

3.4 Vegetation

The Lourens River catchment forms part of the Cape Floral Kingdom (Schaber 2015). Historically, vegetation of the catchment comprised a mixture of natural Fynbos and Renosterveld vegetation (Tharme *et al.* 1997, Smith-Adao 2004; Schaber 2015). The mountainous area of the upper catchment is still vegetated with indigenous vegetation that is classified as Mountain Fynbos (e.g., Kogelberg Sandstone Fynbos and Boland Granite Fynbos; Figure 3.5); however, indigenous vegetation becomes progressively scarcer with distance downstream. While there are some remnant patches of indigenous vegetation, much of the natural vegetation along the river has been removed and altered through plantations, agriculture, urban development and infestation by alien invasive species (Tharme *et al.* 1997).

Indigenous species found along the river are interspersed with large stands of alien species (Lourens River Advisory Board 1988; Tharme *et al.* 1997; CCA 2000), which include: grey poplar (*Populus canescens*), black wattle (*Acacia mearnsii*), port jackson (*Acacia saligna*), eucalyptus (*Eucalyptus camaldulensis*), maritime pine (*Pinus pinaster*), stone pine (*Pinus pinea*) and wide bands of kikuyu grass (*Pennisetum clandestinum*). Some landowners adjacent to the river have implemented their own measures in attempt to control alien species, while others have planted alien plant species for aesthetic purposes and allowed the continued proliferation of alien plants (Tromp, B and Louw, S. pers. comm. Lourens River Advisory Committee, April 2019).

An ecological assessment by Tharme *et al. (*1997), found four main vegetation communities along the banks of the Lourens River; each described according to its dominant species. These include: a) the mountain stream forests community, b) lower mountain slope shrubland community, c) foothill zone shrub forest community and, d) flats shrubland community.

a) *Mountain stream forests community*

This community described as the Bitter Almond (*Brabejum stellatofolium*) – Spoonwood (*Hartogiella schinoides*) community is found on the banks of the upper reaches of the river. The alien trees River red gum (*E. camaldulensis*) and long-leaved wattle (*A. longifolia*) becomes progressively more common along the lower portions of this community.

b) *Lower mountain slope shrubland community*

This community is described as the Bitter Almond (*Brabejum stellatofolium*) – *Othonna quiquidentata* community and is found where the river passes over concave mountain slopes. Much of the indigenous plants in this community have become dominated by alien plants, particularly Acacia and Eucalyptus species.

c) *Foothill zone shrub forest community*

This community is described as the Bitter Almond (*Brabejum stellatofolium*) – Wild millet (*Digitaria sanguinalis*) community and is found where the river passes between the Vergelegen and Rome Estates. This is one of the most alien infested sections of the river with an array of alien tree, shrub and herb species. Among the alien trees in the area are the historically planted Camphor trees (*Cinnamonum camphora*).

d) *Flats shrubland community*

This community is described as the Weeping willow (*Salix babylonica*) – Common reed (*Phragmites australis*) community and is found along the river from immediately above the historic bridge to the estuary. Only a few tolerant indigenous species remain along this section of the river. The only widespread indigenous tree in this portion of the river is the Wild peach (*Kiggelaria africana*).

Towards the Lourens River estuary, species such as *Juncus kraussii*, *Juncus punctorius*, *P. australis* and *Cyperus textilis*, are found along the river banks (Cliff and Grindley 1982; Tharme *et al.* 1997). The low-lying, muddy banks of the estuary are suitable for colonisation by plants that are salt tolerant, such as *Paspalum vaginatum*.

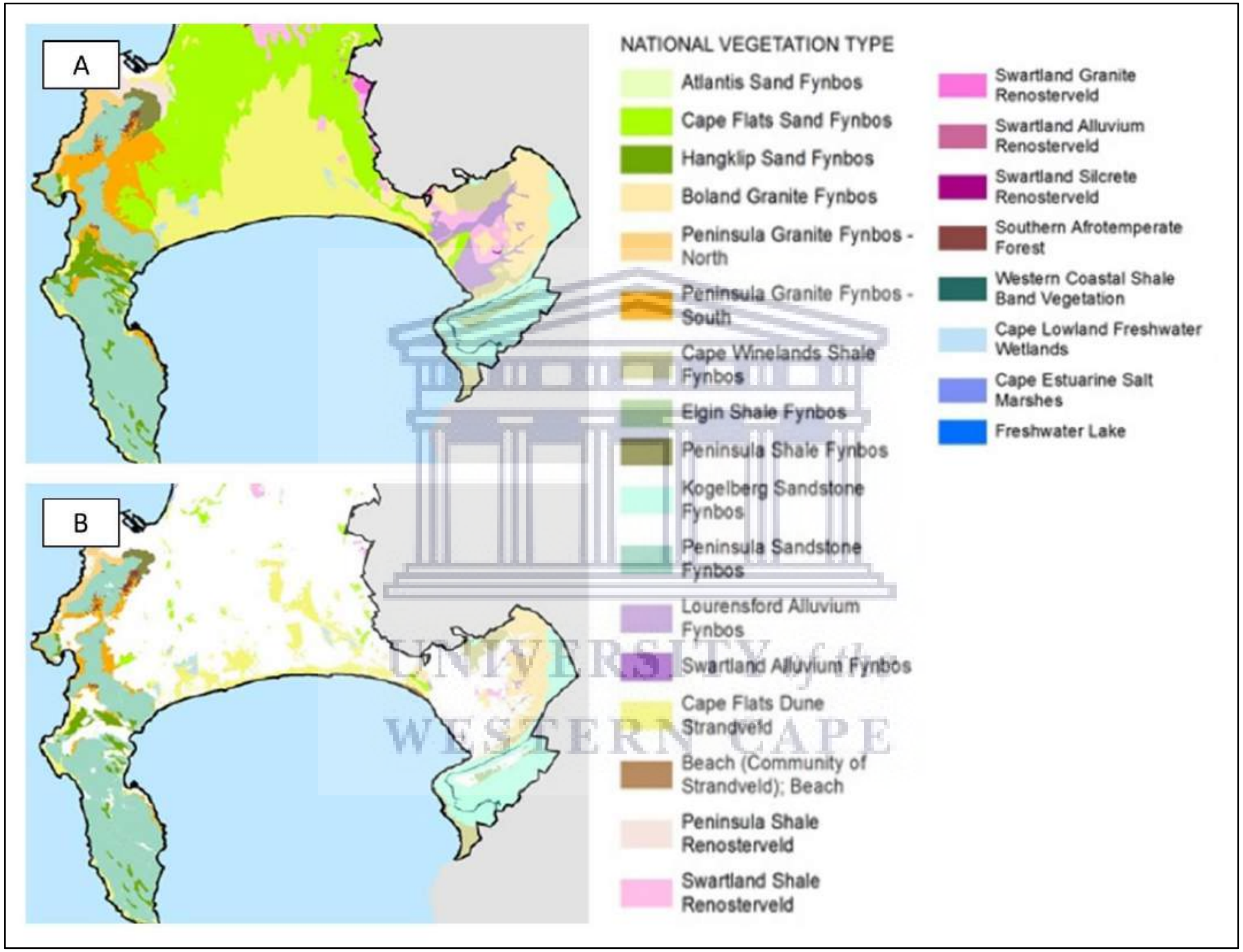

Figure 3.5 Maps illustrating the (a) historical and (b) present distribution of vegetation types in the Lourens River basin. Modified from CoCT 2018.

3.5 Water quality

Water quality in the upper reaches of the Lourens River can be described as cool, clear and high oxygenated with a low pH, few dissolved solids (TDS) and low conductivity (EC) (Table 3.2; Tharme *et al.* 1997; Ollis 2005). At the lower reaches, the water becomes warmer, more alkaline and less oxygenated with more dissolved solids and (Tharme *et al.* 1997; Ollis 2005). Water quality of the Lourens River is impaired by the contaminated runoff from surrounding farms (i.e., fertilizers, insecticides, pesticides), stormwater from urban, industrial and commercial areas (Cliff 1982; Tharme *et al.* 1997; Dabrowski *et al.* 2002; Bollmohr and Schulz 2011; Aurecon *et al.* 2017) and domestic and general waste emanating from the community of homeless people who are resident in the riparian zone (www.Netwerk24.com 2020).

Table 3.2 Average Water quality values during sampling period of the upper, middle and lower reaches of the Lourens River (Tharme *et al.* 1997)

Variable	Upper reach	Middle reach	Lower reach
Temperature (ºC)	12.0	18.7	20.9
pH (pH units)	5.5	6.6	7.5
DO	10.76	9.36	8.99
EC	4.84	15.29	34.70
TDS	25.6	93.1	160.3
Turbidity	Clear	Slightly turbid	Highly turbid

3.6 Anthropogenic activities

Early inhabitants of the Lourens River catchment were pastoralists and hunter-gathers who moved with the seasons (Brown and Magoba 2009). The first permanent settlements along the Lourens River were farms in the early 1700s and the construction of a church which marked the establishment of the town of Somerset West in the early 1800s. The town of Strand - previously known as Mostert's Bay – which borders the river and estuary to the east at the coast, was established on the coast as a holiday and fishing resort in 1714.

Most of the catchment is cultivated particularly in the upper catchment and is subject to an array of agricultural activities such as pine plantations, vineyards, crops, a piggery and a sawmill (Figure 3.6; Brown and Magoba 2009, Schaber 2015). There are many orchards in the catchment including apples, pears, plums, lemons, grapes, kikuyu grass, orchids and pasturelands that are cultivated for sheep and cattle (Tharme *et al.* 1997); however, viticulture is the main farming activity (Schaber 2015). The two biggest farms, Lourensford (4000 ha) and Vergelegen (3200 ha), together cover about 60% of the catchment's area (Schaber 2015). Over 2000 ha of land on both farms is under protection and vegetated with Fynbos. Morgenster farm, a much smaller farm, cultivates olives and wine on 74 ha and the remaining 125 ha of their land is under protection. The Helderberg Nature Reserve (400 ha) covers less than 5%. The middle reach consists of a mixture of residential and recreational areas and the much lower coastal zone is now urban. There is also a Water Works Treatment (WWT) facility situated downstream of the N2 above Paardevlei dam on Beach Road close to the estuary and another in the centre of Strand. According to Schaber (2015), approximately 15% of the catchment comprises urban development.

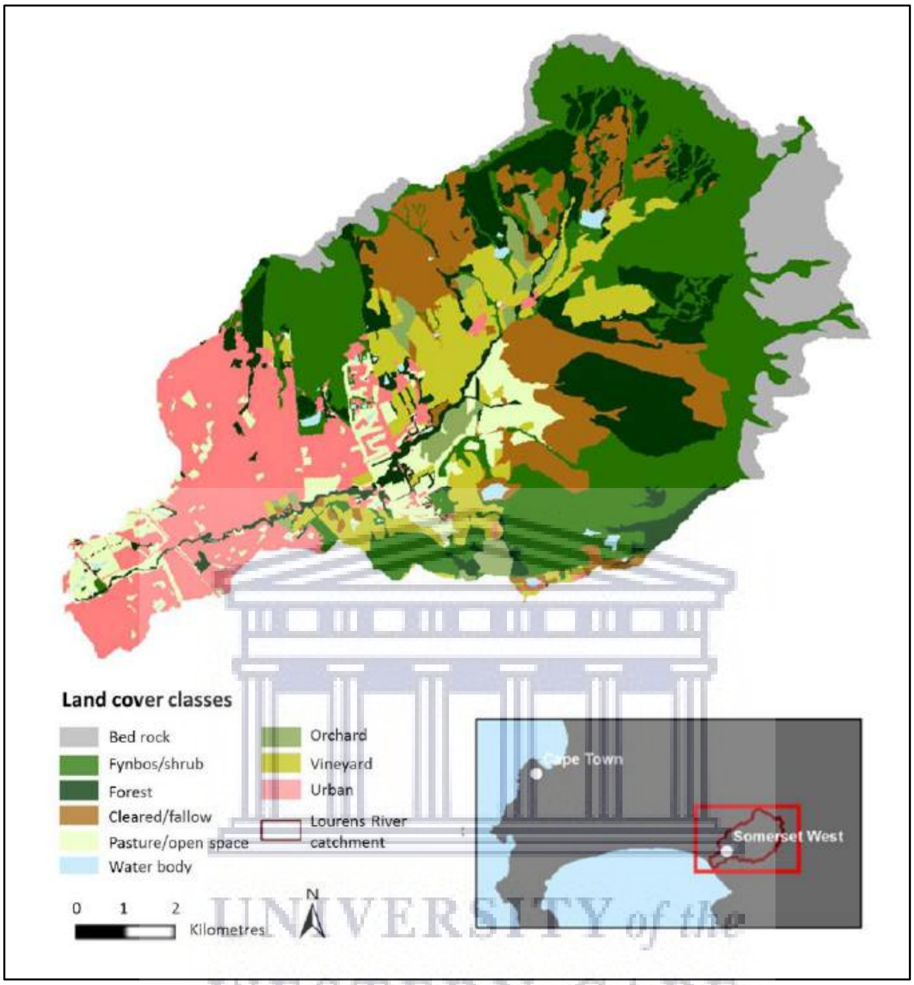

Figure 3.6 Land cover of the Lourens River catchments in 2010. Modified from Schaber (2015).

There are no major impoundments in the catchment; however, several farms have built dams on the tributaries of the river (Schaber 2015). This has enabled farmers to store water during the winter months when there is surplus runoff and use it during the dry summer months for irrigation. This is also sometimes used for domestic purposes even though most of the water demand in Somerset West and Strand is supplied by Steenbras Dam, which is east of the catchment. The total capacity of the farm dams in the catchment was estimated to be approximately 9 million m^3, which is equal to 15% of the total mean annual runoff (RHP 2003; Schaber 2015). Surrounding farms also abstract water directly from the river to water their crops, which has been the case since farming started in the area (Brown and Magoba 2009; Schaber 2015).

Many vagrants have been reported to live along the river on vegetated islands, mid-channel; bars and under bridges. Many of these areas are polluted with raw human waste and litter.

3.7 Channel planform and pattern

The upper reaches of the Lourens River are relatively straight and the river starts to slowly meander in the middles reaches increasing with distance downstream. Prior to extensive urban development of the lower reaches, the river was associated with a wide floodplain and riparian wetlands and probably displayed a tendency to form oxbow lakes, which has been curbed by urban development in the floodplain of the river (CCA 2000; Brown and Magoba 2009).

The Lourens River has no major tributaries; there are a few small ones that drain surface runoff into river (Figure 3.7; Tharme *et al.* 1997). Some of these smaller tributaries are episodic and only flow after precipitation, while others carry a little water over most of the year (Schaber 2015). The river has two channels: the main river channel and a distributary that diverges from the main channel just upstream of the urban development, i.e., residential area and the Vergelegen Medi-Clinic hospital (Tharme *et al.* 1997).

The earliest evidence of the distributary's existence can be found in a historical map dating back to just over two decades ago (Univerzita Karlova 1789; Figure 3.8). Circumstantial evidence suggests that once settlement started in the valley, the distributary was used as an irrigation furrow for agriculture. The historical map shows a distributary flowing below a railway line; however, topographical maps dating back to the mid-1900 show a distributary that starts upstream of the railway. Evidence of the latter can be found in the 1:50 000 topographical maps from 1942 (Figure 3.7; Trigonometrical Survey Office 1944). This is also supported by the direction that the distributary flows, following main road (upstream of railway) for a while before continuing its course to the ocean. Topographical maps after the 1942 edition show the distributary becoming increasingly more fragmented over time. The topographical map of 2010, displays remnants of the distributary that exists downstream of the N2 national highway, passing through urban settlements. What remains of the distributary also seems to have been redirected at some point through stormwater drainage canals as the distributary disappears under the Weltevreden area of Strand and presents itself again just before the coastline (Appx. Figure 3).

There is evidence that the distributary did not flow year-round but rather carried flood waters that exceeded the capacity of the main river channel and thus played a vital part in preventing and controlling flood events through the valley. This is supported by large river boulders, of a size that could only have been carried by large floods that were unearthed during excavations for the foundations of Vergelegen Medi-Clinic hospital in the late 1980s, previously known as the 'Helderberg Medi-Clinic. This is further supported by features in the modern landscape. For instance, the capacity of the historic main road bridge (the oldest bridge in South Africa) across the Lourens River is estimated to be between 70 and 82 m^3/s (Compion and Rooseboom 1995; SSI 1998). This is significantly lower than the magnitude of the 1 in 50 flood which was estimated to be 350 m^3/s (Hill Kaplan Scoot Inc. 1986; Compion and Rooseboom 1995; Pitman 1997; SSI 1998; Pegram 2000), suggesting that when it was built in 1938, the full volume of the 1:50 flood was not carried by the main channel alone.

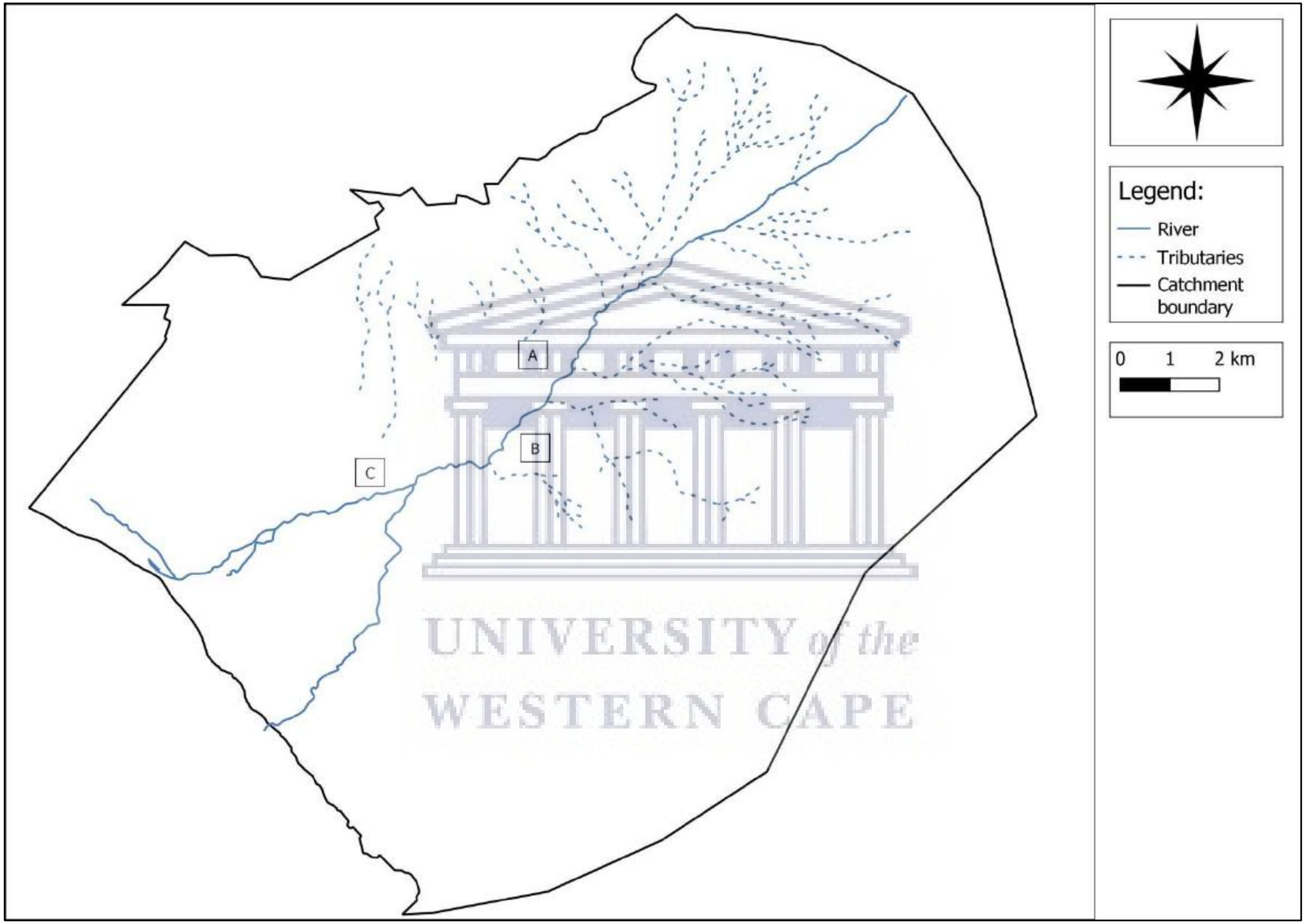

Figure 3.7 Channel planform and pattern derived from 1:50 000 topographic map (1994). A = Lourensford; B = Vergelegen; C = start of urban development (Trigonometrical Survey Office 1944).

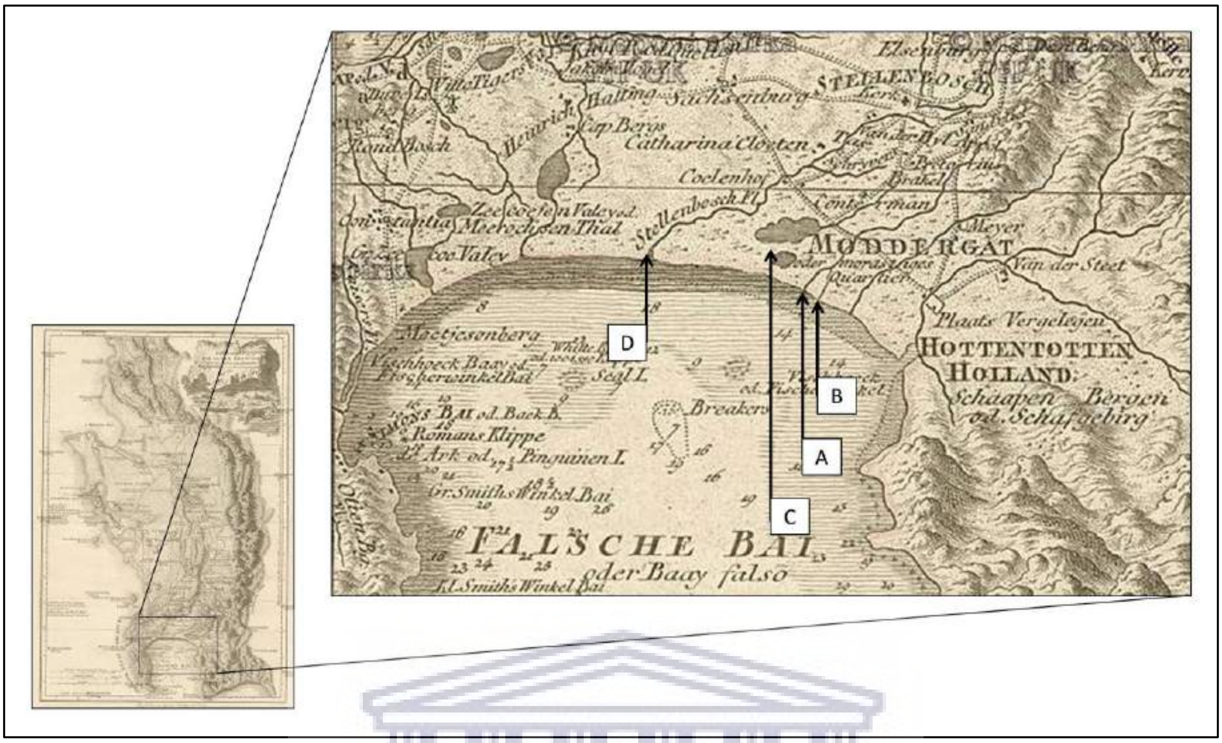

Figure 3.8 **Historic map displaying Cape Floristic Region (Univerzita Karlova 1979), showing: A = the Lourens River; B = Lourens distributary; C = Paardevlei; D =Eerste River. The estimated width at the extreme southern part of False Bay (Falsche Bai) shown in the map is 30 km.**

3.8 The Lourens River: A Protected Natural Environment (PNE)

The Lourens River is promulgated by the Western Cape Province as a Protected Natural Environment (PNE) and listed by NEMA as a protected environment; however, it has no management plan, no protected area manager and regulatory compliance is not always followed by the managing authorities, i.e., City of Cape Town. The reason for the river's proclamation as n PNE is not well documented. However, according to Tromp, B and Louw, (S. pers. Comm) who is a member of the Lourens River Advisory Committee, April 2019, the river was proclaimed a PNE as a result of the high biodiversity that it supports and the dire need to protect this biodiverse riverine ecosystem. Proclamation was achieved through a campaign by two community-based organisations – the 'The Lourens River Conservation Society' and the 'Lourens River advisory board'. A management plan was drafted by the Lourens River Advisory Board in 1988 but was never officially adapted and there has not been much drive form governing bodies to do so since. The Lourens River is under the watchful eye of the Lourens River Conservation Society, a voluntary NPO, which has been working to conserve the river for ~40 years. They monitor river and water conditions, advice on developments, run anti-pollution campaigns, raise funds, clear alien vegetation and represent the river on statutory and other bodies/committees. The declaration of the Lourens River as a Protected Natural Environment (PNE) required the appointment of a Management Advisory Committee (MAC) – The Lourens River Advisory Committee. The Helderberg Municipality has practical control over development within the river corridor and although the Management Advisory Committee (MAC) makes comment, the final adjudication lies with the local municipal authority. There is definitely a need for greater coordination of activities - possibly with the introduction of a management plan, a protected area manager and/or a civil body that must sign-off on any river works and any development within the boundaries of the PNE.

The Lourens River was declared as a Protected Natural Environment (PNE) in 1997 owing to the Lourens River Conservation Society, with a buffer of 45 m on both sides of the entire river (LRSC 1992, Schaber 2015). It is still to this day the only river in South Africa which was declared a PNE through its full length (River Health Programme 2003). In view of the Protected Natural Environment (PNE) status of the river, it was not possible to canalise the river to increase its capacity to cope with the 20- and 50-year flood periods (SSI 1998).

4 The incorporation of ecological principles into the flood alleviation measures on the Lourens River

4.1 Introduction

Floods are among Earth's most common, wide-spread and destructive natural perils (Booij 2005; OECD 2016; Dottori *et al.* 2018), causing widespread hardship for people settled in flooded areas. They result in loss of life and damage to state/municipal and personal property and critical public infrastructure (Booij 2005; Dottori *et al.* 2018). According to UNISDR (2013), floods negatively affect, on average, ~250 million people around the world each year. This is because the practical advantages of living near to rivers, such as access to water, fertile soil, waterborne transport and aesthetic value (Purseglove 1989; OECD 2016) have resulted in significant development in areas prone to flooding (OECD 2016). Population growth and the accumulation of assets in flood-prone areas have led to an increase in developed areas susceptible to flooding and an increase in the severity of the impacts arising from flood disasters (OECD 2016). In urbanized catchments, the capacity of rainfall absorption deteriorates and water runoff increases significantly above what would be expected to occur with natural terrain (Dunne and Leopold 1978; Hugo and De Villiers 1988; Gordon *et al.* 1992; Leopold 1994; Paul and Meyer 2001; White and Greer 2006). While subject to significant uncertainty, climate change is also expected to increase flood risk through changes to precipitation patterns, such as a higher incidence of heavy precipitation events and reducing dry season flows lead to more frequent drought (Booij 2005; Dottori *et al.* 2018; Schumtz and Senzimir 2018).

In common with many cities, Somerset West and Strand in the Western Cape, South Africa, were developed along the banks of a river and its tributaries. Early settlers were drawn to the freshwater and fertile farmland provided by the Lourens River (Luger 1998; Brown and Magoba 2009). Over time, agricultural activities gave way to housing and industrial estates, which hardened the catchment and encroached onto the floodplains. The combination of increases in the intensity of flood events resulting from catchment hardening and loss of river and riparian capacity to transport and store floodwaters caused recurrent flooding of residential and industrial areas and a fear that this could lead to significant loss of human life (Compion and Rooseboom 1996; SSI 1998).

After three significant flood events that occurred in a short succession in 1976, 1980 and 1983 (Figure 4.1), the Lourens River Advisory Board appointed Hill Kaplan Scott Inc. (1986) to conduct a flood study. Hill Kaplan Scott Inc. (1986) were tasked with calculating the magnitude of flood return periods (years) and proposing remedial measures to attenuate future flood events. The flood estimates provided by Hill Kaplan Scott Inc. (1986) for the 20- and 50-year flood-return period was ~209 m^3/s and ~270 m^3/s respectively (Table 4.1). Remedial measures included an attenuation dam, 'soft' and 'hard' canalization of the main river channel and a combination of these options. The study, however, used existing data and was considered preliminary in nature.

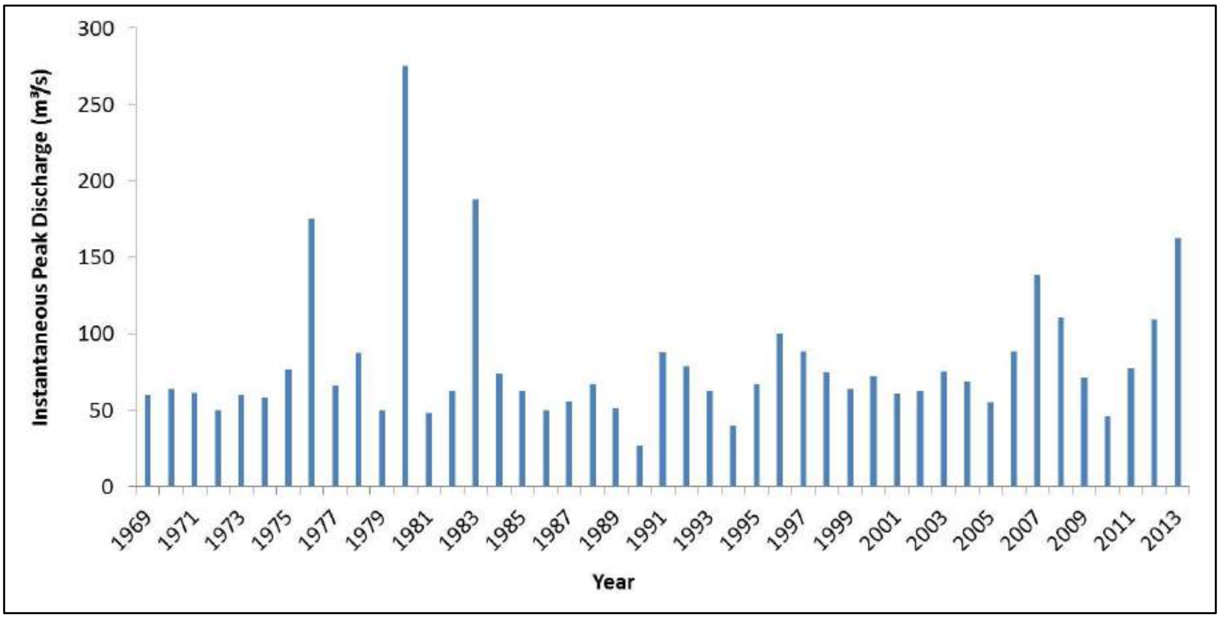

Figure 4.1 **Historical flood peaks recorded at the DWAS gauges (Number) at Main Road between 1969 and 2013 (Adapted from Du Plessis et al. 2013).**

Alleviating the Lourens River floods was only addressed again a few years later in 1996, when Sigma Beta Consultants was appointed by the then Somerset West Municipality to produce a Flood Master Plan (CCA 2000). The study comprised two parts; a hydrological study to determine flood magnitudes (Compion and Rooseboom 1995) and an ecological study (Tharme *et al.*1997) to determine the condition of the river ecosystem. Compion and Rooseboom (1995) calculated the 20- and 50-year flood-return period to be in the region of ~200 m^3/s and ~350 m^3/s, respectively (Table 4.1). The 20-year flood-return period was estimated to spread ~700 m along Main Road (Historic Bridge). The width of the 50-year flood-return was estimated to be ~850 m, achieving a maximum width of ~1 km along the railway line. At this time, three main stormwater engineering schemes were put forward as possible solutions to the flooding problems experienced in Somerset West and Strand: (Option 1) a flood attenuation dam at Radloff Park; (Option 2) canalization of a long section of the river with the removal of major obstructions to flow; and, (Option 3) a flood diversion canal/culvert running outside the main river channel. In the case of Option 3, based on an estimated peak flood discharge of ~350 m^3/s (Compion and Rooseboom 1996), the flood diversion canal would convey ~230 m^3/s with the remaining 120 m^3/s conveyed along the main river channel. Of the options presented, Option 3 was the preferred option from an engineering and ecological perspective, and Option 2, the least desirable approach from an ecological perspective (CCA 2000).

Compion and Rooseboom (1996) demarcated two potential routes to increase the flood carrying capacity of the Lourens River. The first route was a diversion off-take on the southern side of the Lourens River opposite Meadow Lane, which would re-join the main river just upstream of the N2 road bridge (Figure 4.2). The second route was a diversion off-take located immediately downstream of Radloff Park, which would re-join the main river downstream of the railway line bridge. The latter followed an old distributary that had carried floodwaters before agricultural and then urban development reduced it to an irrigation furrow (Compion and Rooseboom 1996, Tharme *et al.* 1997, Schaber 2015). The second route, along the distributary, was considered the best option (Compion and Rooseboom 1996, Tharme *et al.*1997) but it was not implemented and by the late 1990s, urban development (*inter alia*, a hospital and retirement home) had all but eliminated the use of the old distributary as a flood alleviation channel.

Table 4.1 Magnitude of flood return periods in m^3/s (1:10, 1:20, 1:50, 1:100) at Lourens River Main Road (historic bridge), calculated by Hill Kaplan Scott Inc. 1986; Compion and Rooseboom 1995; Sigma Beta 1996; Pitman 1997 and Pegram 2000.

Flood studies	1:10 year flood	1:20 year flood	1:50 year flood	1:100 year flood
Hill Kaplan Scoot Inc. (1986)	173	209	270	326
Compion and Rooseboom (1995)	163	202	350	
Sigma Beta (1996)		200	350	
Pitman (1997)		240	350	
Pegram (2000)		389	518	

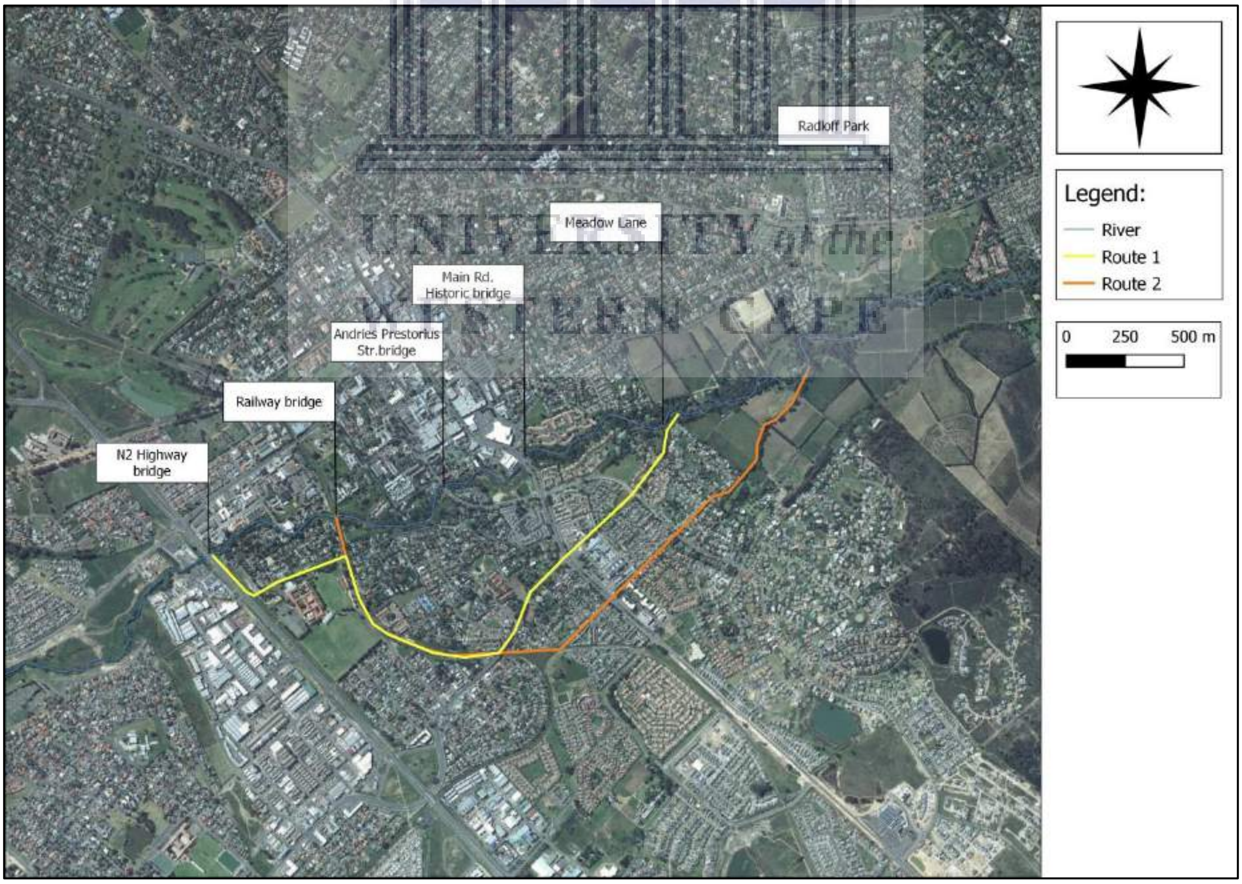

Figure 4.2 Diversion routes demarcated by Compion and Rooseboom (1996). Route 1 follows part of the old distributary.

In 1998, in line with changes in local government (Siddle and Koelble 2016; Binza 2017), Stewart Scott was appointed by Cape Metropolitan Council (CMC) to conduct another flood study (SSI 1998). The purpose of this study was to review the flood study carried out by Compion and Rooseboom (1995) and to comment on their proposed solutions for alleviating the floods. The review by was done by Pitman (1997), who confirmed and supported the assumptions made and conclusions drawn by Compion and Rooseboom (1995), however, they calculated the 20-year return flood period to be ~240 m^3/s instead of ~200 m^3/s (Table 4.1).

In 1999, Crowther Campbell and Associates (CCA) were appointed by Stewart Scott Inc. on behalf of Helderberg Municipality to undertake an Environmental Impact Assessment (EIA) for the flood alleviation measures proposed by Compion and Rooseboom (1995). The final part of the EIA was an Environmental Impact Report (EIR), which included findings of three specialist studies that were undertaken to assess the impacts of the proposed project. The specialist studies included; an independent hydrological study (Pegram 2000), a heritage assessment (Hart 2000), and an ecological report that combined aspects of fluvial geomorphology, freshwater ecology and botany (Brown *et al.* 2000). The purpose of the hydrological study in the EIR was to provide yet another review of the work on which the EIA was based, i.e., Compion and Rooseboom (1995) and Pitman (1997). This was because the flood estimates by Compion and Rooseboom (1995) and Pitman (1997) were disputed by some of the stakeholders as being unrealistically high, particularly when compared to eyewitness accounts of flood events and existing rainfall data for the area (CCA 2000). Pegram (2000) estimated the 20- and 50-year return flood period to be 50% higher (Table 4.1) than previously predicted; however, the difference was attributed to a different methodological approach. Findings of this review were that the flood estimates by Compion and Rooseboom (1995) and Pitman (1997) were based on accepted hydrological engineering practice and represented a realistic estimate of the potential flood magnitudes of the 20- and 50-year return flood periods (CCA 2000).

A three phased approach was proposed to provide protection to Somerset West and Strand from a 1:50 year flood (CCA 2000; SSI 2001). Phase 1 aimed to increase conveyance in the main river channel so that it would a carry a minimum discharge of 120 m^3/s. Phase 2 included a smaller diversion canal to convey an additional discharge of 120 m^3/s. Phase 3 involved an off-channel flood attenuation dam in Radloff Park, which would reduce an expected peak discharge of ~350 m^3/s (CCA 2000) to ~240 m^3/s. According to the final EIA report (CCA 2000) the flood alleviation measures were intended to provide protection from the 1:20 and 1:50 year flood, with no mention of the 1:100 year flood.

At the time the Lourens River was divided into 13 discussion reaches to facilitate planning of flood alleviation measures, some of which were later sub-divided (CCA 2000; Table 4.2 and Figure 4.3). Each discussion reach comprised of chainage points at intervals of 50-m, which were used as the centre points for cross-sections.

Table 4.2 Description of discussion reaches (1-13) and corresponding chainage points (CCA 2000).

Discussion reach:	Chainage points	Location:
Reach 1	1090-1100	Upstream of Morgenster Bridge to Morgenster Bridge
Reach 2	1130-1500	Morgenster Bridge to downstream of housing estate on right bank.
Reach 3	1550-2160	Radloff Park.
Reach 4	2180-2490	Hillcrest Road to downstream of hairpin bend.
Reach 5	2150-3150	Downstream of hairpin bend to upstream of Meadow Lane.
Reach 6	3200-4400	Upstream of Meadow Lane to Andries Pretorius Street.
Reach 7	4440-5350	Andries Pretorius Street to Lourens Street.
Reach 8	5350-6300	Lourens Street to upstream extent of the de Ruyter Rylaan.
Reach 9	6300-7550	Upstream extent of the de Ruyter Rylaan to Broadway.
Reach 10	7550-7850	Broadway to upstream of Kay's Caravan Park.
Reach 11	7850-8150	Upstream of Kay's Caravan Park to Lourens River Road.
Reach 12	8200-8500	Lourens River Road to Fagan Road.
Reach 13	8550-8750	Fagan Road to the estuary.

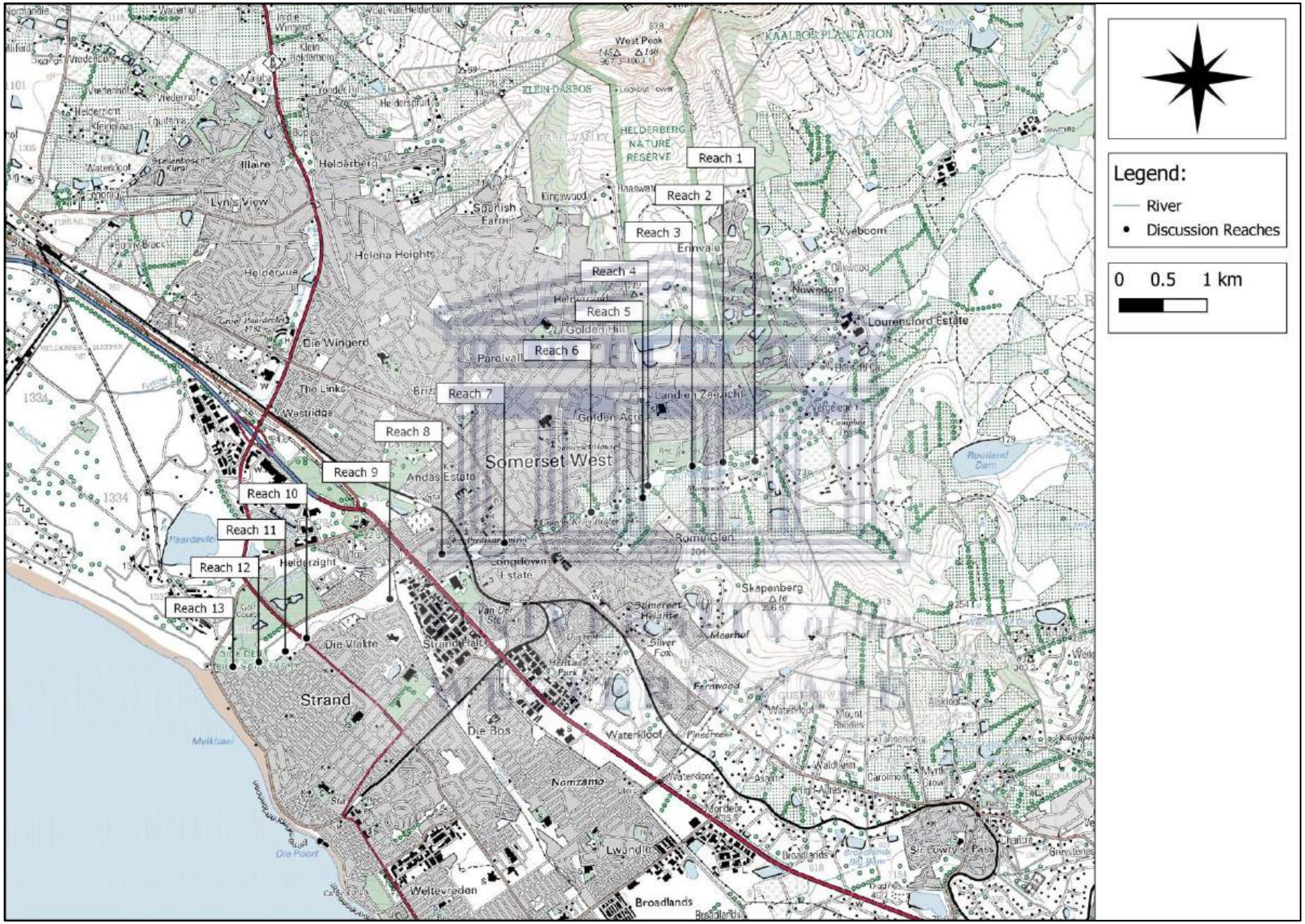

Figure 4.3 Location of discussion reaches 1 to 13 (CCA 2000).

Prior to the 1990s there were few, if any, high-profile river restoration efforts underway in South Africa and almost all river works focused on hard engineering options (Uys 2003; King *et al.* 2003). Examples of rivers in the Western Cape impacted by hard engineering approaches include the Berg (Magoba 2018), Liesbeeck (Luger 1998), Kuils (Thomas *et al.* 2010), Sand, Keyser, Diep and Black Rivers. Many of the urban rivers in Cape Town have been canalised as conduits for stormwater runoff with few remaining ecological attributes (Brown and Magoba 2009). The general canalisation of urban rivers started to change towards the end of the 20th century after implementation of the country's National Water Act (DWAF 1998; Uys 2003; Brown *et al.* 2020) This was around the time that the Lourens River Flood Alleviation scheme was initiated (Brown *et al.* 2000, CCA 2000; Brown and Boucher 2003). In line with the prevailing norms at the time, the first suite of proposed flood alleviation measures for the Lourens River (SSI 2001) focused on hard engineering options and excluded basic ecological considerations (Brown 2000; CCA 2000; Brown and Boucher 2003). The first set of design proposals and drawings recommended increasing the conveyance of the river channel by widening and deepening, reducing the resistance to flood waters by removing vegetation, sand/gravel bars and other obstacles and by straightening and channelising (and in places canalizing) the river channel (Brown *et al.* 2000; CCA 2000; Brown and Boucher 2003).

These initial proposals were queried by river scientists and local residents who were concerned that they would lead to a serious decline in the ecological condition of the Lourens River; similar to what had occurred in other rivers in South Africa and abroad (Brooker 1985; Luger 1998; Brown *et al.* 2000; Day *et al.* 2005; Thomas *et al.* 2010). In response to the concerns raised, the engineering proposals were reviewed and recommendations made to incorporate geomorphological and ecological principles where possible (Brown *et al.* 2000; CCA 2000; Brown and Boucher 2003). The goal was not to develop the ideal ecological rehabilitation plan for the Lourens River but rather to attempt to make better decisions for the river ecosystem given the constraints imposed on it by urban development (Brown *et al.* 2000; CCA 2000). The review process and the subsequent discussions represented one of the earliest engineering-ecological collaborations in river restoration in South Africa (Uys 2003).

Descriptions of work planned in the original suite of hard-engineering flood alleviation measures and the suggested ecological considerations in each discussion reach are presented in Table 4.3. Discussion reaches 6 and 7 were divided into smaller parts based on their extent: Reach 6 into three parts and Reach 7 into two. In an attempt to minimize the impacts of engineering works on the Lourens River and to support the life cycles of as diverse an array of fauna and flora as possible, it was recommended that rehabilitation of the Lourens River should aim for: diverse habitat in the channel and free passage between habitats; an appropriate riparian zone and connectivity with the floodplain; near-natural flow patterns; appropriate water quality and; a near-natural temperature regime (Brown *et al.* 2000; CCA 2000). The ecological recommendations (Brown *et al.* 2000; CCA 2000; Brown and Boucher 2003) included suggestions to implement the required river works from upstream in a downstream direction so that restored reaches were not subject to disturbance from upstream works (Semonin 1989, National Research Council 1992, Uys 2003, Rolls *et al.* 2012, Nepal *et al.* 2014, Yoon *et al.* 2015) and to maintain channel planform, including a meandering low-flow channel and the natural riffle-run-pool sequence (Hunt 1988; National Research Council 1992; Uys 2003; Mihov and Hristov 2011; Yochum 2018). The ecological report also highlighted the importance of features in the channel, such as tree roots, bedrock intrusions and uneven channel margins for providing habitat diversity and hydraulic protection to river life and promoting biodiversity (National Research Council 1992; Madramootoo and Dodds 1994; Doll *et al.* 2003). A major recommendation was to create multi-stage channels to increase conveyance of floodwaters by reshaping river banks and ensuring their stability by maintaining a slope of 1:2 or less if possible (National Research Council 1992; Doll *et al.* 2003). Multi-stage channels are a common engineering practice that allows low flows to be contained in a relatively narrow channel, with higher flows being carried by a wider, leveed floodplain (Brown *et al.* 2000; CCA 2000). Another recommendation to utilise off-channel (floodplain) areas as flood detention areas (National Research Council 1992; Madramootoo and Dodds 1994; Uys 2003), particularly at Victoria Park (Chainage 6150-7450 m; Table 4.2) and the Strand Golf Course (Chainage 8100-8750 m; Table 4.2) so that the river remained connected or could reconnect to its residual floodplain, where some wetlands were still in existence. It was recommended that rip-rap be used where possible and where not possible gabion walls, mattresses and berms be placed as far away from the active channel as possible, that exotic invasive woody vegetation be cleared and that the river banks, gabion walls and mattresses be vegetated with indigenous vegetation based on expected flooding frequencies (Figure 4.4; National Research Council 1992; Madramootoo and Dodds 1994; Uys 2003; Addy *et al.* 2016). Suggestions were also made for toilet facilities in the parks, removal of all fencing that crossed the river and minimizing the need for future mechanical intervention (Brown *et al.* 2000; CCA 2000; Brown and Boucher 2003).

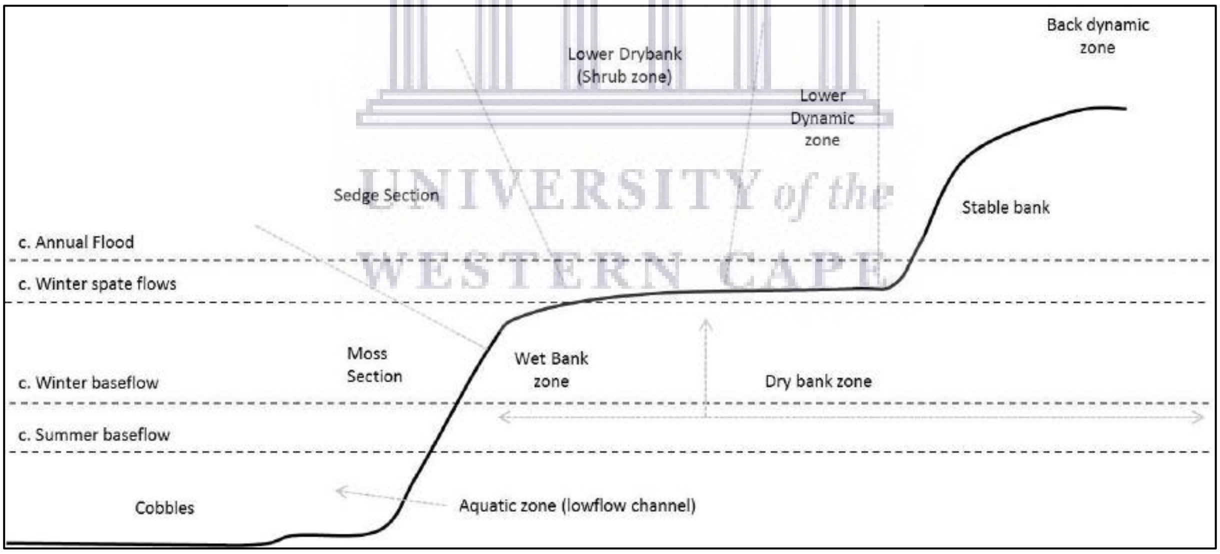

Figure 4.4 Schematic indicating approximate position of vegetation zone relative to river flow. Modified from Brown *et al.* (2000).

Many, but not all, of the ecological recommendations suggested were included in the updated engineering designs for the flood alleviation works. As per Table 4.3, ~75-80% of ecological principles suggested were agreed to be incorporated into the updated designs for the flood alleviation measures. The reasons for excluding some of the suggestions were deemed impracticality, constraints imposed by property ownership, costs associated with river works and the available hydraulic capacity of bridges (CCA 2000). For instance, river deepening was abandoned at all locations, with the exception of discussion reach 8 where deepening was required between the industrial sites below Melcksloot take-off, which was likely to be excavated into rock (Brown *et al.* 2000, CCA 2000). Allowing for and creating multi-stage channels within the existing channel was also not always possible due to property constraining the available space (E.g., Discussion reaches each 7.1, 7.2 and 8). There was, however, mention of possibly expropriating land in discussion reach 7.1 to create the suggested multi-stage channels (Brown *et al.* 2000; CCA 2000). Another example of property constraints was discussion reach 13, where it was suggested that a vegetated berm with a width of 10-m should be used instead of a brick wall. The berm was not considered because it would have taken up the full width of Erf 4 (POS) and blocked access to properties via the east road. The suggestion to utilise the Public Open Space (POS) in discussion reach 7.1 as riparian wetlands/flood detention areas and to surround the area with earth berms was rejected, on the basis that it did not assist the hydraulics and that the conveyance was determined by the capacity of the bridge (Brown *et al.* 2000; CCA 2000). Suggestions to recreate the floodplain in the open area opposite Victoria Park in discussion reach 8 and 9 was considered but also rejected on the basis of costs associated with the extensive earthworks that would be required. The proposed toilet facilities in all parks and POS were rejected as being outside the Scope of Work for the flood alleviation project. In discussion reach 10, the installation of litter traps before the Dick Dent bird sanctuary were proposed, but it was deemed impractical.

Table 4.3 Descriptions of work planned along with ecological considerations in each discussion reach, 1 to 13 (CCA 2000).

Discussion Reach	Chainage (m)	Engineering proposal	Ecological recommendations	Ecological recommendations subsequently into design (Yes/ No)
Reach 1	1090-1100	Channel widening and deepening, construction of gabion mattresses	Low flow channel meander within existing channel	N/A – No longer altering bed of channel
			Allow multistage channels	Yes
			Margins should be irregular	Yes
			Replace bed material after construction	N/A – No longer altering bed of channel
			Plant gabion mattresses with *Cyperus. textilis* and *Pronium serratum*	Yes
			Increase dimension of channel	Yes
			Revegetate with indigenous vegetation	Yes
			Maintain riffle-pool sequences	N/A – no longer altering bed of channel
Reach 2	1130-1500	Channel widening, construction of gabion mattresses and a berm on the right bank	Berm to be located as far away from river as possible and pathways realigned on the river side of the berm	Yes
			Right bank should be stepped to create a multi-stage channel	Yes
			Remove alien vegetation (exotic creepers)	Yes
			Ensure bank elevations are tied upstream and downstream to prevent formation of nick points	N/A – No longer altering bed of channel
			Preserve indigenous stabilizing vegetation	Yes
Reach 3	1650-2160.	No proposed engineering works	Re-shape existing channel to allow for a multistage channel	Yes
			Plant river banks with dense indigenous vegetation (3-5 m wide)	Yes
			Remove alien vegetation from left bank and replant with wet bank zone vegetation	Yes
Reach 4	2180-2490	Remove fill from macro-channel	Remove fence at Chainage 2300	Yes
			Remove concrete berm	Yes
			Re-shape existing channel to allow for a multistage channel	Yes
			Clear alien vegetation, particularly behind concrete (physically remove *Lantana. camara*)	Yes
Reach 5	2150-3150	Construct gabion wall on right bank	Dumped vegetation and litter to be removed from right bank as well as the section below the bridge (Chainage 2860)	Yes

Discussion Reach	Chainage (m)	Engineering proposal	Ecological recommendations	Ecological recommendations subsequently into design (Yes/ No)
			Remove alien species from riparian zone	Yes
Reach 6.1	3200-3420	Construction of gabions mattresses, gabions walls and earth berms	Allow for multi-stage channel within existing channel	Yes – Space constraints due to Erf boundaries will apply
			Maintain pool-riffle sequence (using upstream morphology)	Yes
			Keep channel margins irregular	Yes
			Remove alien vegetation and plant river banks with dense indigenous vegetation	Yes
			Situate berms and gabions as far away from the river as possible	Yes
			Plant gabions mattresses with *C. textilis* and *P. serratum*	Yes
Reach 6.2	3420-4040	Construction of gabions mattresses, gabions walls and earth berms	Allow for multi-stage channel within existing channel	Yes
			Maintain pool-riffle sequence (using upstream morphology)	N/A – No longer altering bed of channel
			Keep channel margins irregular	Yes
			Remove alien vegetation and plant river banks with dense indigenous vegetation	Yes
			Situate berms and gabions as far away from the river as possible	Yes
			Plant gabions mattresses with *C. textilis* and *P. serratum*	Yes
Reach 6.3	4040-4400	Construction of gabions mattresses, gabions walls and earth berms	Allow for multi-stage channel within existing channel	Yes
			Maintain pool-riffle sequence (using upstream morphology)	N/A – No longer altering bed of channel
			Keep channel margins irregular	Yes
			Remove alien vegetation and plant river banks with dense indigenous vegetation	Yes
			Situate berms and gabions as far away from the river as possible	Yes
			Plant gabions mattresses with *C. textilis* and *P. serratum*	Yes
Reach 7.1	4440-5020	Construction of gabion mattresses, gabion walls, earth berms and deepening of channel by ~1 m	Construct a multi-stage channel with sinuous low flow channel.	Yes – will retain present low flow channel, but may need to expropriate some private land
			Hydraulic controls (channel bars) should be left /replaced, particularly at Chainage 4440	N/A – No longer altering bed of channel
			Utilize Public Open Space POS) as riparian wetland/flood detention areas (could be surrounded by berms) OR create backwater channels	? – Does not assist hydraulics as the railway bridge determines the water profile at design flow (120 meters cubed per second)
			Fencing to be removed at bridge	Yes

Discussion Reach	Chainage (m)	Engineering proposal	Ecological recommendations	Ecological recommendations subsequently into design (Yes/ No)
			Toilet facilities to be added in all park areas.	? – Not part of this project
Reach 7 .2	5020-5300	Construction of gabion mattresses, gabion walls, earth berms and deepening of channel by ~1 m	Hydraulic controls (channel bars) should be left /replaced	Yes – Steeper slopes with gabion protection will have to be incorporated
			Sinuosity of low flow should be preserved and within-channel obstacles should be constructed to increase habitat diversity	N/A – No longer altering bed of channel
			Ensure grade of bed materials ties in with upstream and downstream slopes where channel is deepened	N/A – No longer altering bed of channel
			Allow for multistage channel	Yes – To a limited degree
			Remove tress in the middle of the channel	Yes
Reach 8	5350-6300	Construction of gabion mattresses from 5350 to 5550 and deepening of channel by 0.5 -1 m from 5800 to 5900	Remove whole bank (along path line) at chainage 5550 up till the N2	Yes
			Concrete blocks at chainage 5850 to be removed	Yes
			Alien vegetation to be removed	Yes
			Litter trap to be placed of stormwater drain	Yes
			Gabions to be vegetated with wet bank zone vegetation (*C. textilis*)	Yes
			Allow for multi-stage channel	Yes – Where space permits
			Preserve sinuous low flow channel	N/A – Lowering of bed will only take place in section where rock is encountered at bed level
			Remove old weir	Yes
Reach 9	6300-	Construct small earth berm along portion of left side	Berm to be located along PNE Boundary	? – Will be located as far away from the river as is practical
			Recreate floodplain in open area opposite Victoria Park (Chainage 6150)	? – Expensive because of extent of earthworks that would be required
			Maintain meandering pattern in river and create multi-stage channel	Yes
			Replace woody vegetation with marginal vegetation along banks	Yes
			Remove weeping willows during winter	Yes
			Replace kikuyu (gradually) with indigenous grass, shrubs and trees	Yes
			Institute regular manual maintenance of vegetation	Yes
Reach 10	7550-7850	Construct earth berm on left bank	Berm to be on landward side of leveed banks	Yes – Will be on the line of the levee
			Lower terraces on left bank	Yes

Discussion Reach	Chainage (m)	Engineering proposal	Ecological recommendations	Ecological recommendations subsequently into design (Yes/ No)
			Install litter trap before sanctuary	? – Practicality of installing a litter trap within the river is doubtful
			Re-vegetate with indigenous vegetation	Yes
Reach 11	7850-8150	Construct gabion wall on left bank	Straighten river (remove trees on right hand side OR move caravan park on left hand side) rather than constructing gabions	No – The need for a gabion wall is determined by the level of flow at the pipe bridge (a control point) which in turn is determined by the Spring Tide Level
			Remove Weeping willows on right bank	Yes
Reach 12	8200-8500	Construct earth berm on left bank	Berm to be on boundary of open space on left bank (at least along PNE)	Yes
			Prohibit development of undeveloped properties	Yes
			Re-vegetate with indigenous vegetation	Yes
Reach 13	8550-8750	Re-enforce brick wall on the left river bank	Replace wall with vegetated berm	Yes
			Berm to be outside bank of *Phragmites australis* reeds at least 10 m from the top of the left bank	No – The grassed berm takes up the full width of Erf 4 (POS) and the roadway east of this Erf is needed for access to the properties

The flood alleviation works were divided into three phases (CCA 2000): Phase 1 the upgrading of the existing river channel to increase conveyance; Phase 2 the construction of a diversion channel and; Phase 3 the construction of a flood attenuation dam.

Phase 1 was split into nine sub-phases A-J[3], all of which focused on middle and lower reaches of the main river channel, i.e., discussion reaches 6, 7 and 8 (Brown *et al.* 2000, CCA 2000, CoCT 2015; Figure 4.5; Figure 4.6). River works started downstream and moved upstream. The reason for this was that it was felt that starting upstream as recommended by the ecological team may increase flood risk to downstream communities, which was not acceptable from a town planning perspective (Wessel Swart, Project Manager, Royal Haskoning DHV, pers. comm.). Sub-phases 1A-1E was implemented between Main Road and the Melcksloot off-take between 2001 and 2012 and comprised reaches that were between ~50 and ~700 m long (Table 4.4 and Table 4.5). After a major flood event in 2014 (Hutchingson *et al.* 2016), sub-phases 1F, 1G and 1H were implemented at different locations along the river, starting downstream of Vergelegen Avenue and extending to the estuary. Much of the work in 1F and 1G involved repair to existing gabion walls and mattresses along the river and the repairs of irrigation furrows at Morgenster, Riverside Park and downstream of Radloff Park (Royal Haskoning 2014). Sub-phase 1H started in 2015 and was completed in mid-2019 (Wessel Swart, pers. comm.). It comprised the construction of stormwater outlets with litter traps along the river and a flood detention pond on Erf 3308, which is located on the corner of Somerset Street and Marais Street. After completion of river works in each sub-phase, the river banks, gabion walls, mattresses and loffelstein walls were planted with indigenous plants using guidelines provided by Brown *et al.* (2000) and CCA (2000). The last of the Phase 1 sub-phases, 1J, which focused on the reach between the N2 and Beach Road with a few small reaches upstream of N2 highway, commenced in 2020 (Wessel Swart, pers. comm.).

Phase 2 has not yet started, but is planned. Phase 3, the construction of a flood attenuation dam in Radloff Park, was not considered feasible (CCA 2000) and was eventually excluded from the flood alleviation scheme. The reasons being that the dam was designed based on a particular hydrograph and should a storm event differ in its intensity and duration, floods may exceed the capacity of the dam offering no further protection. The perceived negative visual effect of the dam and public reduced access to Radloff Park also played their parts in the decision to exclude Phase 3.

Information based on official documentation and original plan drawings (Appx. Figure 4 to Appx. Figure 13; SSI 2001) does not always portray what actually happened on the field. For instance, two berms were constructed at Radloff Park: one adjacent to Riverside village (Chainage 1150-1450; Appx. Figure 4) immediately below Morgenster Bridge, and the other along Hillcrest Road (in line with Chainage 2150; Appx. Figure 5). These berms formed part the initial engineering proposals but there is no official record of their construction. Another example of the disconnect between planning and implementation is sub-phase 1D at Reitz Park (Chainage 4750-5000). Sub-phase 1D was started in 2009 and completed early 2011 (CoCT 2009, Southern Water 2011). A faunal assessment of the influences of sub-phase 1D on river biodiversity was conducted late-2011 (Southern Water 2011). On the basis of this and

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[3] There is no sub-phase I in Phase 1.

other assessments sub-phase 1D won the 2012 ‘Sali Shield’, a landscaping industries national honour, which was awarded to ‘Blue Wood Landscaping’ (CoCT 2011; CoCT 2012). Yet, Google Earth© imagery shows that this same section of river was redirected and straightened at the same time that sub-phase 1E was being implemented (Appx. Figure 14), although there were no plans tabled to do this. It is not certain whether this redirection and straightening was as a result of engineering works or flood damage although a series of gabions on the left bank (between chainage 4800 to 4850) suggests that it was a result of engineering works.

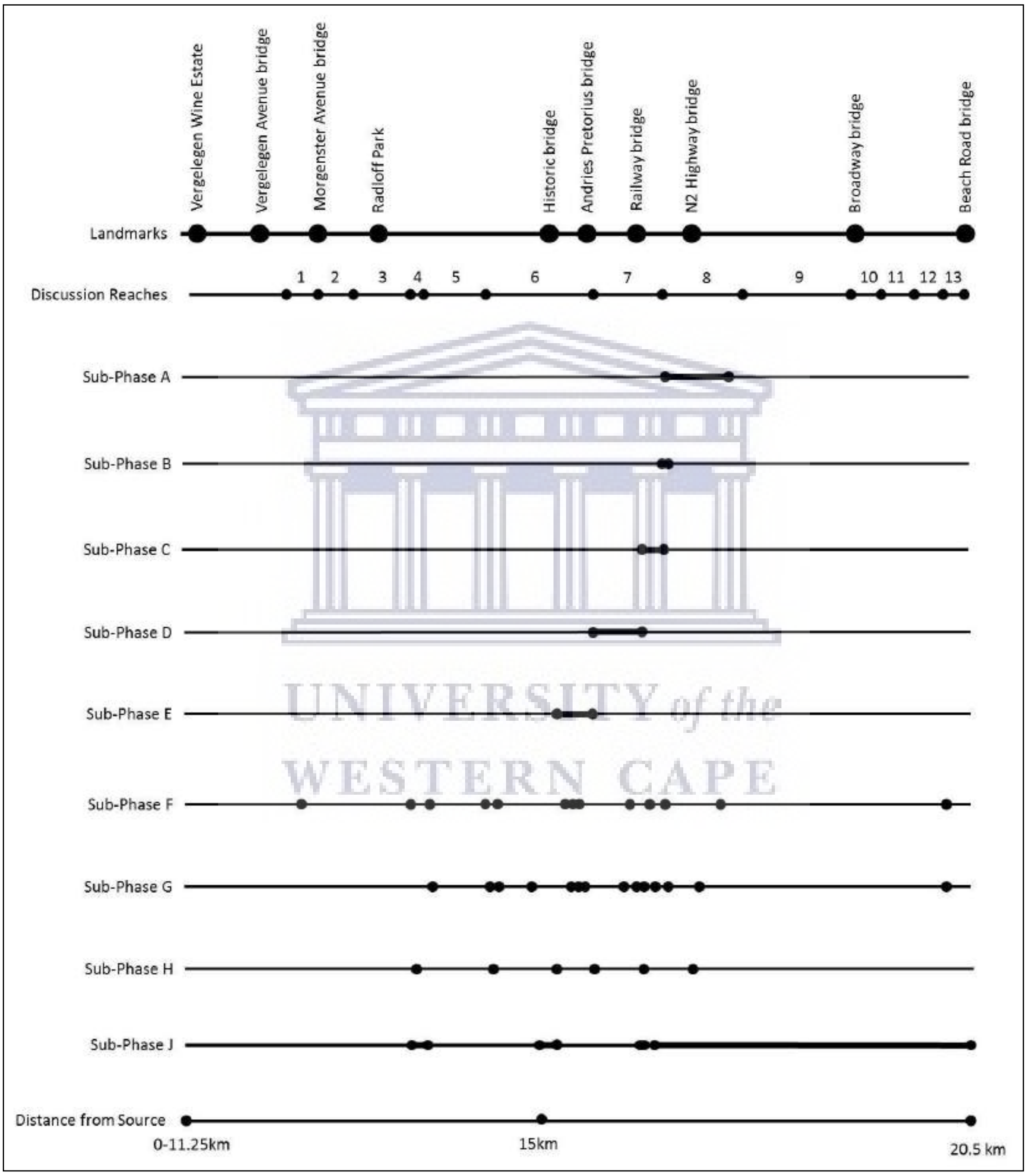

Figure 4.5 **Relative location and extent of key landmarks on the Lourens River, the 13 discussion reaches and river works in Phase 1 A-J.**

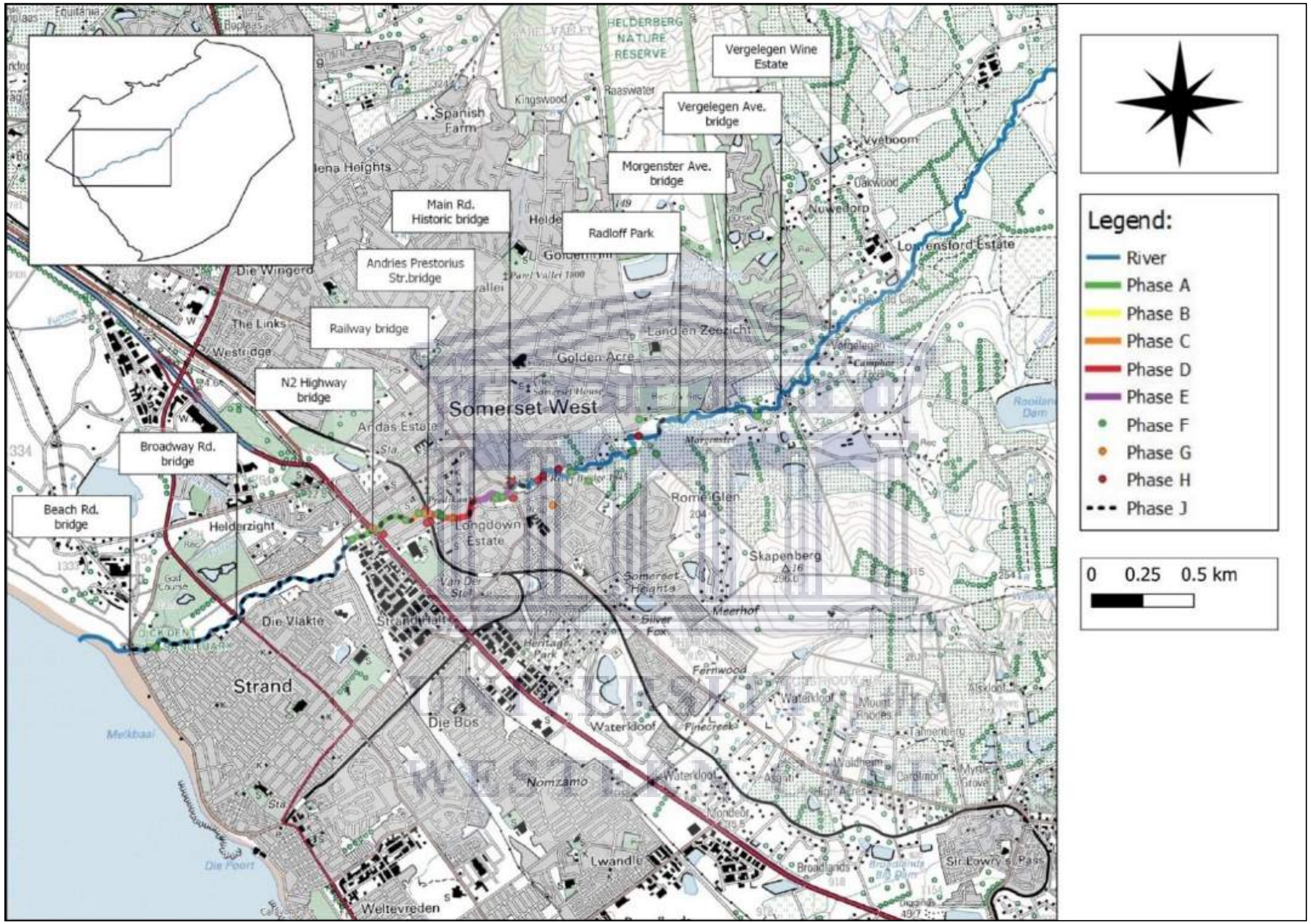

Figure 4.6 Location of landmarks and completed and planned river works (Phase 1 A-J) along the Lourens River[4]. Modified Topographical Map 1:50 000 (NGI 2010).

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[4] Phase 1B is a short reach located between Phase 1A and 1C.

Table 4.4 Date, chainage and location of sub-phases in Phase 1.

Phase	Sub-phases	Chainage	Location	Date of sub-phase
1	A	5300-6000	Sergeant Street bridge to downstream of the N2 national highway.	2001/2002
	B	5250-5300	Vicinity of Sergeant Street Bridge and just upstream.	2002/2003
	C	5000-5250	Railway line to just upstream of Sergeant Street bridge	c. 2003/2009
	D	4400-5000	Andries Pretorius Street bridge to railway line.	2009/2011
	E	4000-4400	Main Road bridge to Andries Pretorius Street bridge	2011/2012
	F	750-8550	Vergelegen Avenue to the estuary.	2014/2015
	G	2500-8550	Hillcrest Road to the estuary.	2015/2016
	H	2200-5000	Hillcrest Road to N2 national highway	2015 to Current
	J	1800-8750	N2 national highway to the estuary.	Commences in 2020

Table 4.5 Date, chainage and location of river works planned and implemented in sub-phases A to J in Phase 1.

Sub-phases	Chainage	Location	Date	Proposed River Works:
A	5300-6000	Sergeant Street bridge to downstream of the N2 national highway.	2001/2002	Excavation of terraces to form multi-stage channels. Slope protection with gabions (boxes or mattresses) and loffelstein walling. Construction of berms and protection walls. Re-vegetation of disturbed areas.
B	5250-5300	Vicinity if Sergeant Street bridge and just upstream.	2002/2003	Additional spanning to Sergeant Street bridge (6.5 Width), which also requires an existing sewer line to be rerouted. Provisional sum allowance for landscaping work along the river banks where construction was carried out under sub-phase A. Excavation of Terraces to form multi-stage channels. Construction of loffelstein walling and mattresses to enable the side slopes of river to be reshaped and the terraces formed. Construction of gabion walling and mattresses along banks, using stones from the existing riverbed. Construction of concrete protection walls along banks; re-enforced either with river stone as a permanent shutter or with terraforce walling blocks. Horticultural Work; clearing of site and felling of trees. Landscaping and re-vegetation of the excavated areas, as well as gabion, loffelstein and terraforce walling.
C	5000-5250	Railway line to just upstream of Sergeant Street bridge.	c.2003/2009	Excavation of Terraces to form multi-stage channels. Slope protection with gabions (boxes or mattresses) and loffelstein walling. Construction of loffelstein walling and gabion mattresses to enable the side slopes of river to be reshaped and the terraces formed, using stones from the existing riverbed.

Sub-phases	Chainage	Location	Date	Proposed River Works:
				Construction of concrete protection walls, reinforced with brick or terraforce walling blocks. Reconstruction of storm water outlets to incorporate litter traps and flaps to prevents reverse flow. Horticultural Work, including felling of marked trees along the river bank and the top soiling of excavated areas and berms.
D	4400-5000	Andries Pretorius Street bridge to railway line.	2009/2011	Excavation of terraces to form multi-stage channels. Constructing berms from excavated material. Construction of gabion mattresses and loffelstein walling, in order to enable the side slopes of the river to be reshaped and terraces formed; using stones from the existing river bed. Construction of concrete protection walls along banks, reinforced with brick or terraforce walling blocks. Reconstruction of storm water outlets to incorporate litter traps and flaps to prevents reverse flow. Horticultural work, including felling of marked trees along the river bank and the topsoiling of excavated areas and berms.
E	4000-4400	Main Road bridge to Andries Pretorius Street bridge.	2011/2012	Excavation of terraces to form multi-stage channels. Constructing berms from excavated material. Construction of gabion mattresses, in order to enable the side slopes of the river to be reshaped and terraces formed; using stones from the existing river bed. Reconstruction of storm water outlets to incorporate litter traps and flaps to prevents reverse flow. Horticultural Work, including felling of marked trees along the river bank and the top soiling of excavated areas and berms.
F	750-8550	Vergelegen Avenue to the ocean.	2014/2015	Construction of gabion and reno mattresses. Construction of loffelstein walling. Construction of earth berms. Repair and re-align existing gabions. Raise existing gabion walls. Removal of trees on banks. Removal of island in the river channel and excessive stones and sand affecting flow. Repair damaged irrigation furrows. Clear river bed of debris and fallen trees.
G	2500-8550	Hillcrest Road to the ocean.	2015/2016	Excavation of terraces to form multi-stage channels. Replacing and rehabilitating existing gabion baskets or mattresses along the banks, in order to enable the side slopes of the river to be reshaped and terraces formed; using stones from the existing river bed. Construction of loffelstein retaining wall. Construction and reconstruction of storm water inlets to incorporate litter traps and flaps to prevent reverse flow. Horticultural work, including felling of marked trees along the river bank and the top soiling of excavated areas and berms.
H	2200-5000	Hillcrest Road to N2 national highway	2015 to 2019	Construction of five storm water outlets wit litter traps. Construction of detention pond.
J	1800-8750	N2 national highway to the ocean.	Commences in 2020	Excavation of terraces to form multi-stage channels. Constructing berms from excavated material. Construction and re-construction of various sewer and storm water structures, including outlet structures, litter traps, manholes, etc. Construction of new or rehabilitation of existing gabion baskets or mattresses; using stones from the existing river bed. Construction of concrete flood protection walls.

Sub-phases	Chainage	Location	Date	Proposed River Works:
				Construction of loffelstein and/or cement block retaining walls. Construction of grass block-lined storm water canals. Possible rehabilitation or alteration to an existing pond in order to accommodate storm water structures. Horticultural Work, including felling of marked trees along the river bank and the top soiling of excavated areas and berms.

The aim of this chapter is to evaluate the extent to which ecological principles, in terms of channel shape, treatment of the bed and banks and landscaping were incorporated into the implemented flood alleviation works on the Lourens River. In order to address this, the study considered the initial engineering plans proposed to address flooding, the suggested adjustments to those plans to incorporate geomorphological and ecological inputs, the resultant plans presented for implementation and finally, the actual channel planform and in-channel and riparian habitats after implementation. Each of these was evaluated in terms of:

- their location along the longitudinal profile;
- channel planform;
- land use;
- lateral extent of floodplain;
- continuity of bankside woody vegetation;
- river works;
- channel shape (cross-sections;
- diversity of hydraulic biotopes and;
- substrate composition.

4.2 Study area

The study focuses on the middle and lower reaches of the Lourens River Somerset West/Strand, South Africa, where the flood alleviation measures are planned or have been completed. The study area starts immediately upstream of Morgenster Bridge, which is ~10 km from the source of the river (Figure 4.7) and ends just upstream of the estuary at ~Beach Road Bridge.

Organization of the study area needed to account for the fact that the historical data were collected at different spatial and temporal scales, in different locations and to serve different purposes (Table 4.6; Appx. Table 1 and Appx. Table 3). For instance, the 13 discussion reaches used to facilitate discussion and planning of the flood alleviation measures were not useful for this study because they matched the original and subsequently altered, engineering proposals (Brown *et al.* 2000, CCA 2000) and because they varied in length, which complicated comparisons between reaches. Furthermore, sites where historical physical and ecological data were available did not consistently correspond with each other. For instance, Ractliffe (1991) studied the effects of suspended sediments on the macroinvertebratre communities in upper reaches of the river, with the last site at Vergelegen Wine Estate, while Tharme *et al.* (1997) described the proportions and character of instream physical habitat at five sampling eco-sites (i.e., ecological sites), four of which fall within the current study's focus area. The locations where cross-sections were surveyed historically also differed, for instance: cross sections by Compion and Rooseboom (1995) start at 'Morgenster' and are at random intervals, whereas those by SSI (2001) start upstream of Vergelegen Avenue and used the chainage points as center points at 50-m intervals.

Table 4.6 Historic data for study reaches (10-16) and eco-sites (1-5).

Type	Date	Reaches/ Sites	Available data	Reference
Topographic Maps	1942	Reaches 1-16	1:50 000 topographical map	Trigonometrical Survey Office 1944
	1959	Reaches 1-16	1:50 000 topographical map	Trigonometrical Survey Office 1962
	1979	Reaches 1-16	1:50 000 topographical map	Surveys and Mapping 1981
	1995	Reaches 1-16	1:50 000 topographical map	Survey and land information 1995
	2000	Reaches 1-16	1:50 000 topographical map	Surveys and Mapping 2003
	2010	Reaches 1-16	1:50 000 topographical map	National Geo-spatial Information 2014
Aerial imagery	1998	Reaches 1-16	Aerial Imagery (0.25 m resolution)	CoCT 1998
	2002	Reaches 1-16	Aerial Imagery (0.25 m resolution)	CoCT 2002
	2005	Reaches 1-16	Aerial Imagery (0.25 m resolution)	CoCT 2005
	2016	Reaches 1-16	Aerial Imagery (0.25 m resolution)	NGI 2016
	2019	Reaches 1-16	Aerial Imagery	CoCT 2019
	2005-2020	Reaches 1-16	Google Earth© - Satellite imagery	Maxar Technologies 2020
Flood Alleviation Measures	2000	Reaches 11-16	Descriptive information of river works and cross sectional profiles for T2	Brown *et al.* 2000
	2000	Reaches 11-16	Cross sectional profiles for T1 and T3 (Chainage 1100-8600)	CCA 2000
	2000	Reaches 11-16	Aerial photographs (1:1000) illustrating planned river works for T3	CCA 2000
	2009	Discussion reaches 1-13	Drawing illustrating planned river works for T3; phase 1D • Chainage 4400-5050	SSI 2009
	2012	Discussion reaches 1-13	Drawing illustrating planned river works for T3; Phase 1E • Chainage 3900-4550	SSI 2012
	2018	Discussion reaches 1-13	Drawings illustrating planned river works for T3; Phase 1J • Chainage 2900-4000 • Chainage 3350-4550 • Chainage 3450-4200 • Chainage 4250-5100 • Chainage 4900-5750 • Chainage 4950-6950 • Chainage 5550-7700 • Chainage 6700-8800 • Chainage 7550-8750 • Chainage 7650-8700	Royal Haskoning 2018
Ecological data	1997	Eco-sites 1, 2, 4 and 5	Proportions of different biotopes in the river Substrate composition of the channel bed	Tharme *et al.* 1997

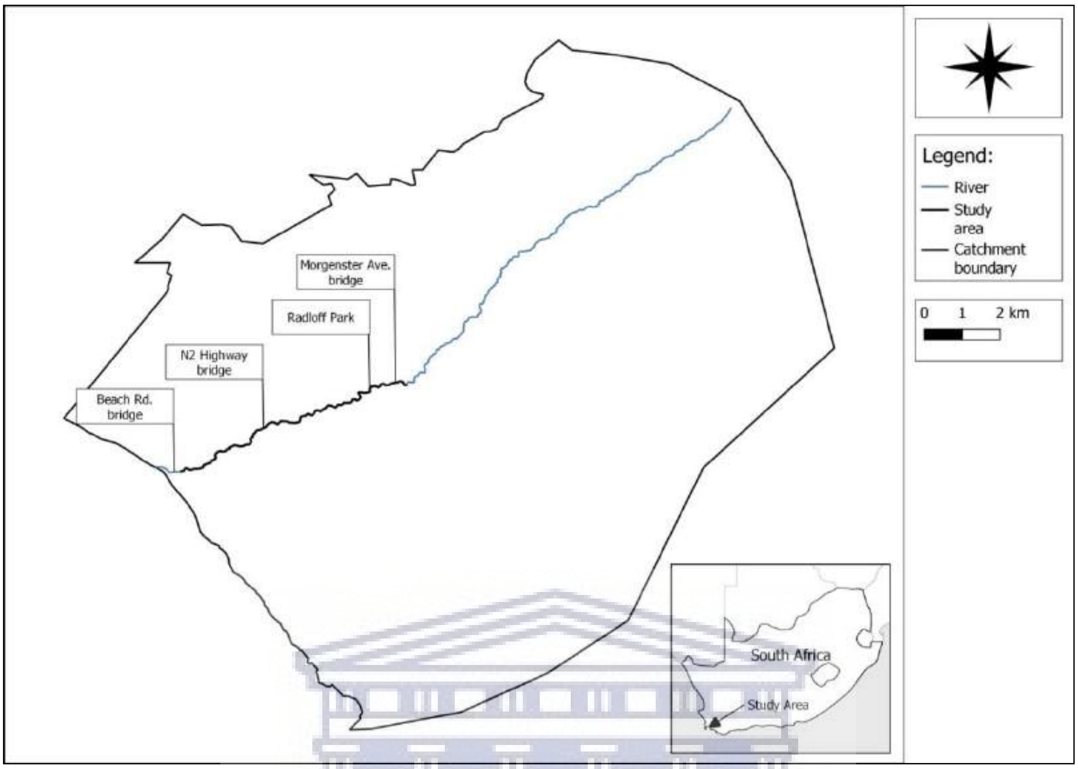

Figure 4.7 Location of study area on the Lourens River where river works were planned and/or have been completed.

Thus, this study was organized into study reaches of equal length, within which there were rivers works planned or done, historical cross-sections and ecological sites where data on habitat and biota had been collected in the past. To do this, the river channel was divided into 17 study reaches at intervals of ~1250 m from source to sea, with a 1-km riparian area on either side of the river channel (Figure 4.8 and Figure 4.9); comprising a ~2.5 km² area. A 2 km buffer zone was used to standardize the size of the area being assessed within each of the 16 study reaches, and to accommodate for the width of the 1:50 year flood line (Compion and Rooseboom 1995). Reach 17 was excluded from the analyses because it was shorter than the others (~500 m) and is in the estuary.

The 16 study reaches were then grouped into two main groups; the upper reaches (1-10) where no river works were planned (code 'NRW'; Table 4.7) and the lower reaches (11-16) where river works were planned. Reaches 11 to 16 were the main focus of this study as they are where flood alleviation works were planned; of which, river works have been completed in reaches 13 and 14. This sub-set of reaches 11 to 16 were divided into three groups: the reaches upstream of completed rivers works (11-12; code 'URW'), reaches where river works have been completed (13-14; code 'RWC') and the reaches downstream of completed works (14-15; code 'DRW').

Table 4.7 Grouping of study reaches (1-16) along the river.

Work planned	Reach group	Reaches (1-16)	Code	Description
No work planned	No river works	1-10	NRW	No river works are planned.
Work planned	Upstream	11-12	URW	River works are planned but have not yet been done.
	River works	13-14	RWC	River work is complete.
	Downstream	15-16	DRW	River works are planned but have not yet been done.

There were five ecological' sites[5] where historic data were available; each comprised a 50-m long length of river (Figure 4.8 and Figure 4.9). Eco-site 1 is situated in reach 10, which is in NRW and is therefore a control site. Eco-sites 2, 3, 4 and 5 are in reaches 12, 13, 14 and 15, respectively. Reaches 13 and 14 are where river works have been completed (RWC). Historical habitat data were collected at eco-sites 1, 2, 4 and 5 but not at eco-site 3; however, eco-site 3 was included in this assessment because it falls within in one of the most extensively modified reaches.

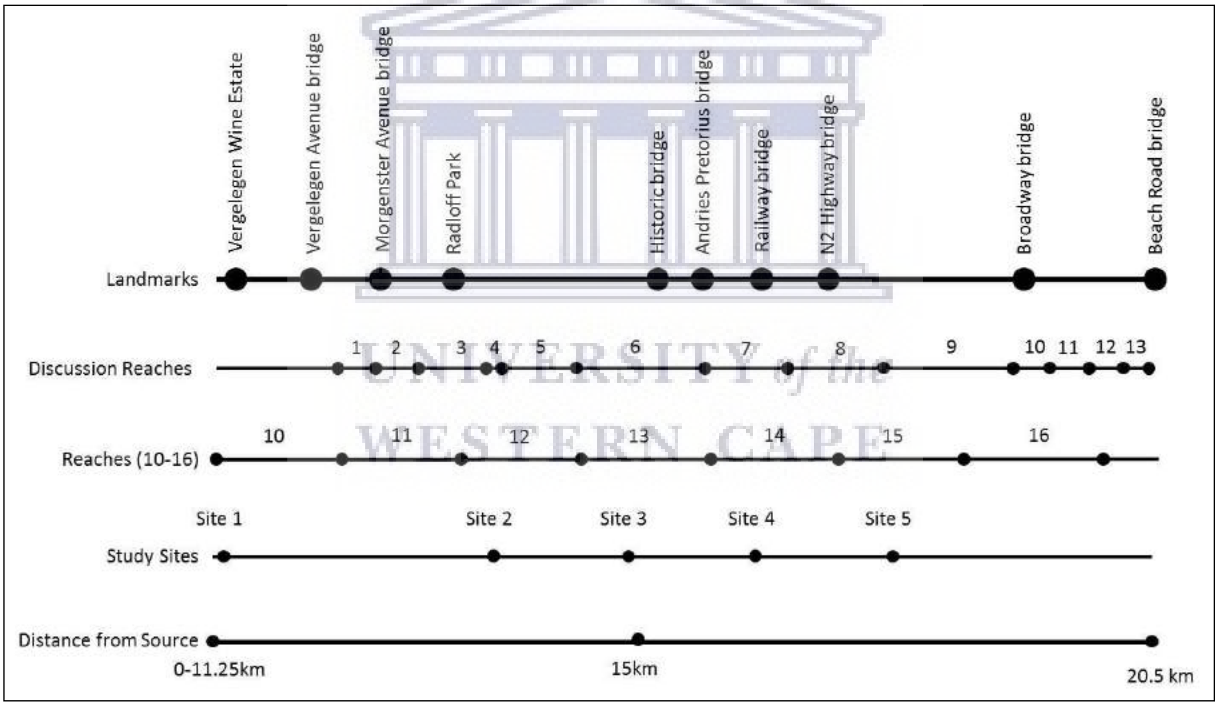

Figure 4.8 Locations of landmarks along the river, discussion reaches (1-13), study reaches (10-16) and eco-sites (1-5) relative to distance from source.

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[5] Site where ecological data have been collected over time are referred to as 'eco-sites' in this study.

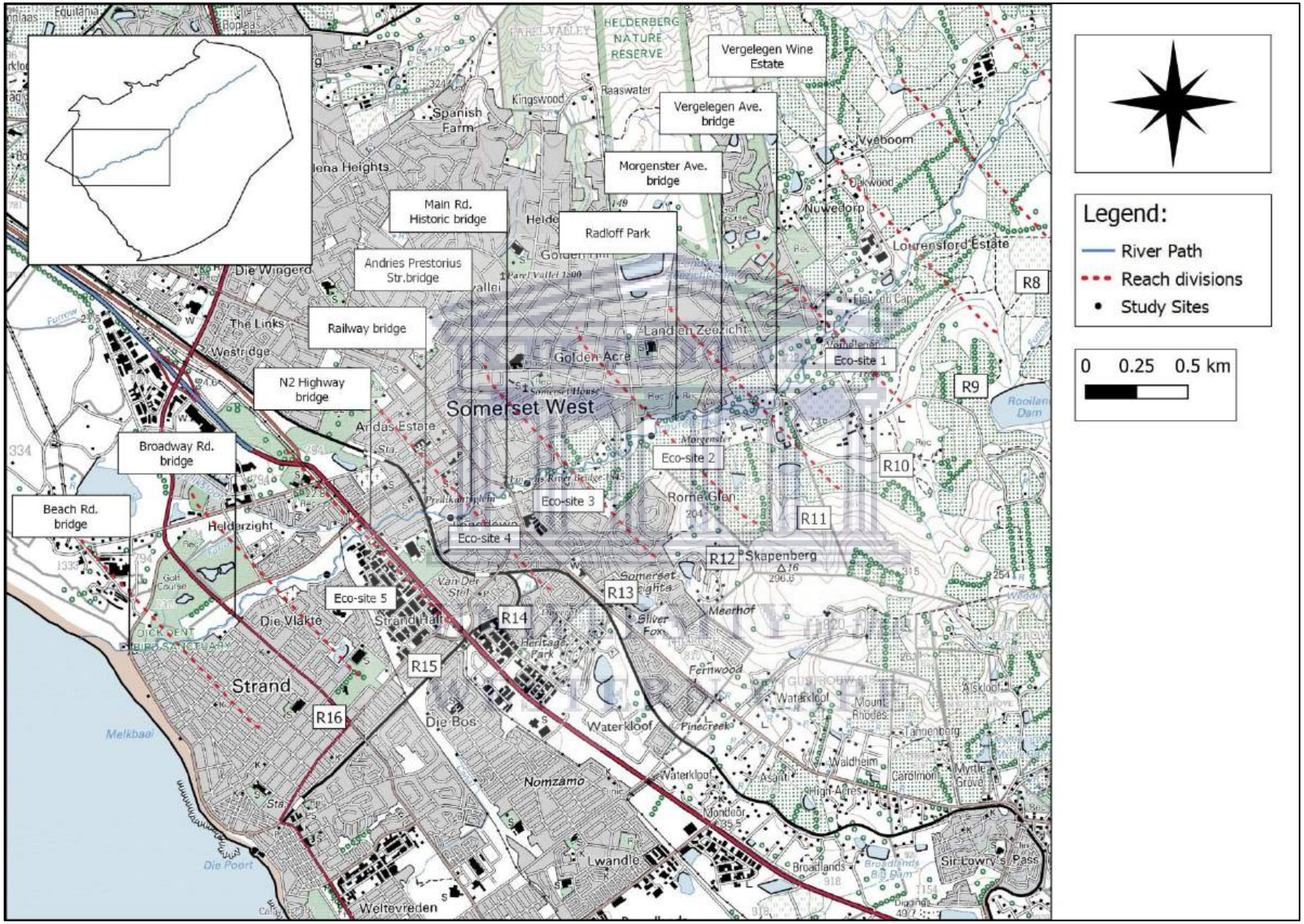

Figure 4.9 The study area showing the location of study reaches (10-16) and eco-sites (1-5).

4.3 Data collection

Quantitative data on the physical character of the river were collected at two scales; a broad scale along the whole length of the river from reach 1 to 16 and at a fine scale where more detailed historic data were available in reaches 10-16. Data collected from topographic maps and aerial imagery provided both broad- and fine-scale data; with the longitudinal profile, channel planform and landuse being assessed at a broad scale, and channel macro-features, lateral extent of available floodplain and continuity of bankside woody vegetation based on field surveys of river channel cross sections at a finer scale. Data on hydraulic biotopes and substrate composition were collected at the eco-sites. To facilitate comparison between different periods, where relevant, the methods used in this study were the same as those used to collect the historic data (Tharme *et al.* 1997; Brown 2000; SSI 2001; del Tanago and de Jalon 2006; Schaber 2015; Magoba 2018).

4.3.1 Longitudinal profile

The original intention was to include an assessment of changes in longitudinal profile in this study, but the contour lines on the available topographic maps were only re-surveyed each year until 1995. The 1995 contours were digitized and vectorized and have been used in subsequent editions of the topographical maps, i.e., no updating of contours since 1995. Although it is unlikely that the long profiles have changed, it was decided to not assess changes in the longitudinal profile of the river over time. Instead, a single longitudinal profile for the river was generated from the 1995 topographic map, where altitude obtained from the contour lines crossing the river was plotted against cumulative distance from source to sea. This was used as a reference for all the periods assessed.

Each study reach (1-16) and eco-site (1-5) was assigned to a geomorphological zone based on mean slope, using the South African classification system (Table 4.8 and Figure 4.10; Rowntree *et al.* 2000). Reaches correspond with the following geomorphological zones: Reaches 1-5 are in the mountain headwater stream and the mountain stream zone; reaches 6 and 7 in the transitional zone and; reaches 8-14 in the upper foothills and 15 and 16 in the lower foothills and in the lowland zones, respectively.

Table 4.8 The location of each reach in the geomorphological zone.

Geomorphological Zone	Gradient	Reach (1-16)	Eco-site (1-5)
Mountain head water stream	>0.1	1-2	
Mountain Stream	0.04 – 0.099	3-5	
Transitional	0.02 – 0.039	6-7	
Upper foothills	0.005 – 0.019	8-14	1, 2 and 3
Lower Foothills	0.001 – 0.005	15	4
Lowland	0.0001 – 0.0009	16	5

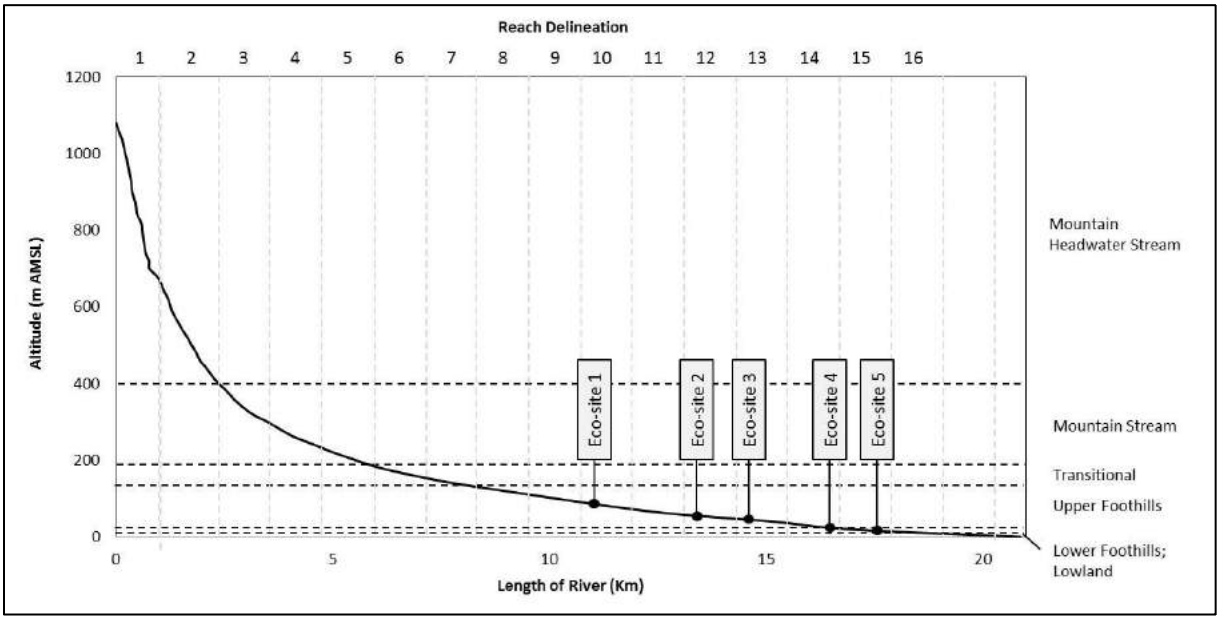

Figure 4.10 **Longitudinal profile of the Lourens River showing the boundaries of study reach (1-16; vertical lines), geomorphological zones (horizontal lines) and the location of eco-sites (S1-5).**

4.3.2 Channel planform

Channel characteristics and features were extracted from topographical maps, aerial photographs and/or GoogleEarthPro© imagery using the methods of Magoba (2018). Topographic maps were available from 1942, 1959, 1979, 1995, 2000 and 2010 and rectified aerial imagery was available for 1998, 2002, 2005 and 2016. The topographical maps were used to provide a long-term overview of channel path(s) for the whole river based on the cartographer's view at the time of generating each map and measure length and sinuosity of the main river channel and the flood channel. The aerial images were used to map and measure changes in sinuosity of the main river channel in each of the 16 reaches. The length of the main river channel and flood channel were measured using the field calculator in QGIS along the river and divided by the length *as the crow flies* to calculate sinuosity (Equation 1; Schumm 1963; Magoba 2018).

$$Sinuosity = \frac{Length\ of\ thalweg}{Length\ as\ the\ crow\ flies} \qquad \text{Equation 1}$$

4.3.3 Landuse

Schaber (2015) assessed changes in landuse in the Lourens River basin over six periods (1993, 1953, 1977, 1988, 2000, and 2010) by mapping and digitizing land cover using orthographic photographs. The same method was used in this study, where land use categories were mapped and digitized using aerial imagery (1998, 2002, 2005, and 2016) and measured using the field calculator in QGIS (2019/2020). Landuse was mapped because it plays a major role in the hydrological changes that has occurred in the catchment over time. The following landuse types were used:

- Urban:
    - roads
    - parking lots
    - residential housing and complexes
    - business parks
    - factories
    - shops and shopping centres
    - hospitals
    - schools
- Crops and livestock:
    - vineyards
    - orchards
    - fields where livestock are kept
- Bare ground:
    - fallow fields
    - bare ground with little vegetation
- Recreational areas/parks:
    - urban parks
    - golf courses
    - school sports fields
- River and riparian vegetation:
    - river channel
    - woody riparian vegetation,
    - reeds
    - pine plantations
- Surface water:
    - ponds
    - reservoirs
    - dams.

4.3.4 Lateral extent of available floodplain

del Tanago and de Jalon (2006) recommend using different riparian buffer widths to assess the lateral width of floodplain based on geomorphological zones (Table 4.9). Buffer widths recommended by del Tanago and de Jalon (2006) were used to delineated the buffer zones in this study. The recommended widths from the top of the macro-channel banks are: 5 m for the upper reaches where the river channel is narrow and steep and with a V-shaped steep valley; 10-15 m for the middle reaches where they valleys becomes progressively broader with distance downstream, with gentle relief and alluvial terraces and floodplains are predominant landforms and; > 50 m for the lower reaches where the river is broader and consists of flat valleys. The channel banks were hidden under the riparian canopy in some places so the buffer widths were started at the thalweg and were thus increased by standard 5 m for the upper and middle zone. The lateral extent of the floodplain, starting at the river's edge, was digitised from the aerial imagery (1998, 2002, 2005 and 2016) using these buffer widths per geomorphological zone and the areas measured using the field calculator in QGIS.

Table 4.9 Widths used to delineate buffers zones for assessing lateral extent of the floodplain and continuity of bankside woody vegetation.

Zone	Geomorphological zone	Reach #	Buffer width from top of bank (del Tanago and de Jalon 2006)	Width from thalweg (this study)
Upper	Mountain headwater Mountain stream Transitional	1-6	5 m	10 m
Middle	Upper and lower foothills	7-14	10-15 m	20 m
Lower	Lowland river	15-16	>50 m	75 m[6]

4.3.5 Continuity of bankside woody vegetation

Continuity of bankside woody vegetation was assessed in the demarcated riparian buffers (Table 4.9) using three continuity categories of del Tanago and de Jalon (2006): (i) good = >75 % cover, (ii) fair = 25-75% cover and (iii) poor = <25% cover[7]. The extent of bankside woody vegetation was digitised from the aerial imagery (1998, 2002, 2005 and 2016) and the area measured using the field calculator in QGIS.

4.3.6 Macro-features of the river channel

The following channel macro-features were mapped in polygons from aerial imagery; lateral bars, mid-channel bars and vegetated islands. The field calculator in QGIS was used to measure the area (km^2) for each macro feature within the 16 reaches in 1998, 2002, 2005 and 2016.

4.3.7 Bank stabilising structures

A hand-held GPS device and a mobile application called ‘Geo-Tracker’ were used to map the location of bank stabilizing structures (e.g., gabions mattresses and walls, loffelstein walls and rip-rap) in reaches 11-16. The lengths of each of these structures were measured in QGIS using a field calculator. A meta-table was then compiled with a description of each bank stabilizing structure (i.e., gabion wall), the bank (left or right) on which the structure was found and the corresponding study reaches (1-16). The number of terraces on each gabion wall was also recorded (i.e., four terraces is called a 4-stage gabion wall).

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[6] The floodplain in the lower reaches is much more than 50 m, ranging between 200-250 m in some areas. A standard 75 m buffer zone was used for comparison between study reaches and over time.

[7] It was not possible to differentiate between alien and indigenous vegetation, so these were grouped in the assessment of bankside woody vegetation.

4.3.8 Cross-sections

SSI (2001) who are independent land surveyors were contracted to survey cross-sections of the river using an electronic theodolite (Total Station) at intervals of 50 m (Chainage 1100-8750) from immediately downstream of Morgenster Avenue to immediately upstream of Beach Road bridge. At that time a decision was made to use the middle of the river channel at low flow as the centre point for each cross-section throughout planning and implementation of the flood alleviation measures although the centre of the channel may have moved over time. The standard practice of using two different scales in presenting the horizontal and vertical axis of the profiles were used with a 1:10 ratio, meaning that the scale used for the x-axis (horizontal) is 1:1000 and the y-axis (vertical) is 1:100.

In 2001, Stewart Scott (Pty) Ltd demarcated 175 chainage points along the river channel starting upstream of Morgenster Bridge of which 153 were surveyed and fall within the study area and 149 are linked to sections of the river where river works were planned. From these a sub-set of 23 cross-sections was selected in reaches 11-16 (Figure 4.11) for this study, of which 13 are located where river works have been completed. The 23 profiles that were selected are representative of their associated reaches and were selected based on their location and on the basis of accessibility and safety. These were used to capture changes in the shape of the river channel bed and banks over time.

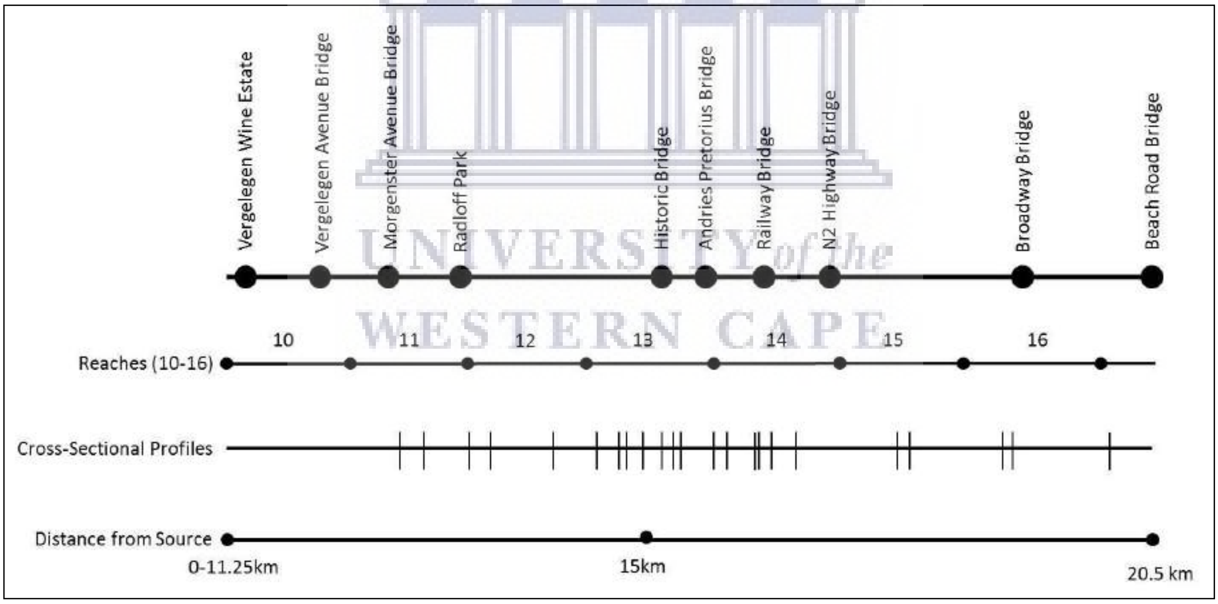

Figure 4.11 **Relative location of study reaches (10-16) and the 23 selected cross-sections.**

Data from cross-sections were collated for the following five periods; T1, T2, T3, T4 and T5, and represent progressive change in the plans of river works and completed thereof (Table 4.10 and Table 4.11). These periods correspond with reaches 11-16 (Table 4.12). T1 are the cross-sections surveyed by SSI (2000) showing the river channel shape prior to any of the plans or river works, the baseline. T2 are the cross-sections showing the original hard engineering proposals. T3 are the cross-sections showing the engineering proposals after incorporation of some ecological recommendations. T4 are the actual cross-sections where works were completed at 2020. T5 are cross-sections showing the envisaged channel shape after future proposed river works are completed.

Table 4.10 The five periods (T1, T2, T3, T4 and T5) with source of cross-sectional data.

Period	Description	Short name
T1	Stewart Scott	"Baseline cross-sections"
T2	Original hard engineering proposals	"Hard-engineered cross-sections"
T3	Engineering proposals incorporating some of the ecological recommendation	"Soft-engineered cross-sections"
T4	Actual river works done	"Current cross-sections"
T5	River works planned but not yet done	"Future cross-sections"

Hard copies of the cross-sections for T1 were obtained from Royal Haskoning (SSI 2001). The original data for the SSI surveys (T1) could not be located, so these were regenerated from the hard copies. The cross-sections were imported in MS PowerPoint and scaled using the profiles from 2020, by lining up the x-axis (distance) and y-axis (height).

For T2, the original data could also not be located, so these profiles were re-constructed with depth and distance values based on the descriptions of engineering proposals in Brown *et al.* (2000). These covered aspects such as the removal of fill from the river bed to deepen the river channel, removal of fill from river banks to widen the channel, grading of the bank slope, and the construction of berms, gabion walls and mattresses, loffelstein walls and protection walls. The descriptions made mention of two levels of channel deepening, 'slight deepening' and 'deepening'. To reconstruct the profiles, it was assumed that 'slight deepening' referred to a 50-cm increase in channel depth and 'deepening' to a 1-m increase in channel depth. Where the descriptions referred to construction of a 'low flow channel', it was assumed that this would be 5 m wide and 25 cm deep. Where a range of slopes was provided for the grading of banks, the mid-point was used. For the removal of fill from channel banks, it was assumed that the bottom of the bank to be removed was at the same depth as the existing thalweg, unless stated otherwise (i.e., construction of low flow channel). A standard base width of 6 m and a height of 1.5 m were used for berms that were to be constructed on the channel banks. Where no measurements were given for gabion walls and mattresses, it was assumed these structures covered the entire bank from the toe of the slope to the top of the bank. It was also assumed that there were no plans to harden the bottom of the channel as the ecological report (Brown *et al.* 2000) mentions the possibility of the formation of knickpoints, which would not occur if the plan was to canalize the river.

The T3 profiles were also generated from hard copies and the T4 profiles were surveyed in March 2020 at the same locations as historic profiles and using the same methods as previous surveys (SSI 2001). To locate the cross-sections in the field, the centre and end points of previously surveyed cross sections were determined by converting cross-sectional lines from a *.cad format into a shapefile/*.kml file, making them compatible with Google Earth. Five points were then plotted along each of the selected cross-sectional lines and saved as a *.kmz file that was converted into a *.gpx file. This *.gpx file was imported into a hand-held GPS and a mobile device called ‘Geo-tracker’ was used to locate each of the points along each cross section. Then, using a measuring tape, a straight line was laid down and the vegetation trimmed to create a clear line of sight. At each location, a benchmark was constructed on each river bank by digging a hole, hammering a galvanized steel rod into the ground and laying down a concrete mixture to stabilize the rod. Where benchmarks from previously surveys were located, these were used as benchmarks in the current study. The cross-sections were surveyed using an electronic theodolite (total station). The entire length of some of the cross-sections could not be surveyed because of changes to property boundaries (Table 4.11). The locations of the edge of the active channel, water’s edge, different hydraulic biotopes and any structures, e.g., top and bottom and details about gabions (five stage gabions wall or two stage gabion walls) were recorded.

With the exception of four cross-sections downstream of N2 highway (Phase J), where the plans for river works differ from those in T3, the T5 profiles are the same as T4 where river works have been done and the same as T3 were not. The 2-D drawings illustrating the T5 planned river works were used to generate representative cross-sections using distance measurements extracted from these drawings and the proposed excavation depth was the same as proposed in T3 profiles.

Data on bank heights, bank slope, width between the bottom and top of channel banks, number of terraces and the presence and absence of engineering structures (gabions matresses and walls, loffelstein walls and earth berms) were calculated from the cross-sections for each period for comparison. The 23 cross-sections were divided into three reach groups based on location and whether river works have been done or not; URW, RWC and DRW (Table 4.12).

Table 4.11 Meta-table of 23 selected cross sections showing cross sections where river works were planned for and those where they were completed, the distance of surveyed T1 and T4 cross-sections[8].

Reach #	Chainage:	River works (None/ Planned/ Completed)	Reach group descriptions	Code name	T1 - Surveyed length (meters) (2001)	T4 - Surveyed length (meters) (2020)
11	1200	Partly	Upstream	URW	90.0	64.0
11	1450	Planned	Upstream	URW	90.0	64.8
12	1850	Planned	Upstream	URW	100.0	58.3
12	2100	Planned	Upstream	URW	230.0	79.7
12	2850	Planned	Upstream	URW	90.0	49.8
13	3300	Completed	River works	RWC	90.0	59.7
13	3550	Completed	River works	RWC	80.0	59.7
13	3600	Completed	River works	RWC	80.0	32.0
13	3750	Completed	River works	RWC	80.0	27.2
13	3950	Completed	River works	RWC	80.0	86.3
13	4050	Completed	River works	RWC	60.0	71.9

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[8] The distances of T2 and T3 are the same as T1.

Reach #	Chainage:	River works (None/ Planned/ Completed)	Reach group descriptions	Code name	T1 - Surveyed length (meters) (2001)	T4 - Surveyed length (meters) (2020)
13	4100	Completed	River works	RWC	60.0	69.6
13	4450	Completed	River works	RWC	60.0	66.1
14	4550	Completed	River works	RWC	60.0	48.2
14	4850	Completed	River works	RWC	60.0	84.4
14	4950	Completed	River works	RWC	60.0	135.4
14	5000	Completed	River works	RWC	60.0	63.9
14	5350	Completed	River works	RWC	60.0	56.8
15	6350	Planned	Downstream	DRW	240.0	262.6
15	6450	Planned	Downstream	DRW	240.0	248.6
16	7350	Planned	Downstream	DRW	240.0	197.2
16	7450	Planned	Downstream	DRW	250.0	206.3
16	8850	Planned	Downstream	DRW	220.0	191.5

Table 4.12 Groups 1 to 3 with associated reaches (11-16) and relevant chainage points.

Group Number	Description	Reach group	Reach #	Chainage
1	Upstream	URW	11	1200, 1450,
			12	1850, 2100, 2850
2	River works	RWC	13	3300, 3550, 3600, 3750, 3950, 4050, 4100, 4450
			14	4550, 4850, 4950, 5000, 5350
3	Downstream	DRW	15	6350, 6450, 7350, 7450
			16	8850

4.3.9 Diversity of hydraulic biotopes

Tharme *et al.* (1997) assessed various physical characteristics at four eco-sites (eco-sites 1, 2, 4 and 5) along the Lourens River, where quantitative data on hydraulic biotopes were generated from a point-by-point visual categorisation of biotopes. The same methods were used to collect comparable data at these locations in this study. In addition, data on hydraulic biotopes were collected by recording the longitudinal extent of biotopes and their frequency of occurrence, with the exception of a ~350 m reach at the end of Reach 14 and the beginning of Reach 15 (Chainage 5650-5700) and a ~200 m reach in Reach 16 adjacent to Kay's Caravan park (Chainage 7900-8100), which were not included due to security risks. The resultant data were used to calculate the proportion of cascades, riffles, runs, pools and marginal vegetation at each eco-site in each reach, *viz.* including at eco-site 3 for which there are no historical data.

4.3.10 Substrate composition

Tharme *et al.* (1997) assessed various physical characteristics at four sites along the Lourens River (eco-sites 1, 2, 4 and 5), where particle size classes of the substrate were estimated by eye for each dominant biotope (riffle, run and pool) using an adapted Wentworth scale (Wentworth 1922) from Tharme *et al.* (1997) and Rowntree and Wadeson (1999) (Table 4.13). The same methods were used to visually estimate proportions of different sediment particles. In addition, cumulative samples of fine sediments (±1kg) were collected using a hand trowel and submitted to a laboratory (Bemlab) for particle-size analysis and stone volume percentages.

Table 4.13 Categories of substratum categories used in previous studies. Adapted from King and Schael (2001).

Class name	Wentworth (1922)	Tharme *et al.* (1997)	Rowntree and Wadeson (1999)	Current study
Mud		<0.00006		<0.00006
Clay	<0.0039	0.00006 - 0.0039	0.00006 - 0.0039	0.00006 - 0.0039
Silt	0.0039 - 0.0625	0.0039 - 0.0625	0.0039 - 0.0625	0.0039 - 0.0625
Sand (Fines)	0.0625 - 0.125	0.0625 - 2	0.0625 - 2	0.0625 - 2
	0.125 - 0.25			
	0.25 - 0.5			
	0.5 - 1			
	1 - 2			
Small gravel	2 - 64	2 - 8	2 - 64	2 - 8
Medium gravel		9 - 32		9 - 32
Large gravel		32 - 64		32 - 64
Small cobble	64 - 256	64 - 128	64 - 256	64 - 128
Large cobble		128 - 256		128 - 256
Boulder	256	256 - 4096	>256	256 - 4096
Bedrock	n/a	>256		>256

4.4 Data analysis

Multivariate statistics were used to test if river works and associated landscaping improved the diversity of physical habitats and thus contributed to a higher Ecological Integrity. Analysis of similarities (ANOSIM; Equation 2) (Clarke and Warwick 2001, Clarke and Gorley 2006), a non-parametric permutation similar to the standard univariate 1- and 2-way ANOVA (analysis of variance) tests, was used to determine if there were significant differences in physical habitat between 16 study reaches, reach groups (URW, RWC and DRW) and the five eco-sites over time (Table 4.7 and Figure 4.8). The ANOSIM test was used to determine whether we can reject the null hypothesis or not. Variables used to compare physical habitat between the 16 study reaches and reach groups (URW, RWC and DRW) comprised: length and sinuosity of the main river channel, land use, lateral extent of available floodplain, and continuity of bankside woody vegetation, macro-channel features, bank stabilising structures and cross-sections. Those used to compare physical habitat between eco-sites 1-5 were diversity of hydraulic biotopes and substrate composition. Where analyses were run to test for significant differences using p-values, data was considered statistically significant at both $p \leq 0.05$ and $p \leq 0.10$ because of the low sample replicates of physical habitat features when using aerial imagery, i.e., 1998, 2002, 2005 and 2016.

$$R\ statistic\ (R^2)^9 = \frac{r_B - r_W}{n\ (n-1)/4} \qquad \text{Equation 2}$$

Where:

- rB is the average rank similarities of pairs of samples (or replicates) originating from different sites,
- rW is the average of rank similarity of pairs among replicates within sites,
- M = n (n – 1)/2, where n is the number of samples.

Calculated from a Bray-Curtis dissimilarity matrix, a similarity percentages routine (SIMPER) analysis was used to distinguish which physical habitat features were responsible for the similarity and dissimilarity between reach groups (URW, RWC and DRW) (Clarke and Warwick 2001, Clarke and Gorley 2006). The analysis was used to show the differences in average abundance of each variable when comparing the 16 study reaches, reach groups and eco-sites, and the percentage that each of these variables contribute to dissimilarity.

A meta-analysis using all the mapped habitat features was used to determine whether there was an overall difference between reaches where no river works were planned (reaches 1-10) and reaches where river works were planned and completed (reaches 11-16) (Table 4.7). Variables used in the overall comparison were length and sinuosity of the main river channel, land use, lateral extent of available floodplain, continuity of bankside woody vegetation, and macro-channel features.

A two-way nested ANOSIM was then used to test for differences in all the habitat features between reaches where no river works were planned (reaches 1-10) and reaches where river works were planned (reaches 11-16) between 1998, 2002, 2005 and 2016 (Clarke and Warwick 2001, Clarke and Gorley 2006). A SIMPER analysis was used to find which habitat features contributed most to differences evident between the upper reaches (1-10) where no work was planned and the lower reaches (11-16) where works were planned (Clarke and Warwick 2001, Clarke and Gorley 2006), in terms of average abundances and the percentage that each variable contributes to dissimilarity.

Most of the other analyses, with some exceptions (i.e., landuse and channel macro-features), focussed on testing for significant differences between the three reach groups where work was planned and completed (Table 4.7): URW (upstream of completed river works; reaches 11 and 12); RWC (competed river works; reaches 13 and 14) and; DRW (downstream of competed river works; reaches 15 and 16).

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[9] $R^2 = \leq 0.5$ (weak correlation); $R^2 = 0.5 \leq \times \leq 0.9$ (weak correlation); $R^2 = 1.0$ (perfect correlation).

4.4.1 Channel planform

A regression analysis (Equation 3) was used to test for significant differences in the length of the main river channel and flood channel between 1942, 1959, 1979, 1995, 2000 and 2010 (©MSExcel 2020). This analysis was used to describe how the changes in length of the main river and flood channel were related to changes in time, and was based on the assumption that both channels decreased over time as a result of urban development and infilling of floodplain.

$$Y = a + bX \qquad \text{Equation 3}$$

Where:

- Y is the dependent variable,
- X is the independent (explanatory) variable,
- a is the intercept (the value of Y when X = 0),
- b is the slope of the line.

A two-way nested ANOSIM was used to test for differences in the length and sinuosity of the main river channel within each reach group (URW, RWC and DRW) in 1998, 2002, 2005 and 2016 (Clarke and Warwick 2001; Clarke and Gorley 2006). A one-way ANOSIM was used to test for differences in the length and sinuosity of the river channel overall between the three reach groups, by using years 1998, 2002, 2005 and 2016 as samples. A SIMPER analysis was used to test how the three reach groups differed in length and sinuosity of the main river channel, in terms of average abundances and the percentage that each variable contributes to dissimilarity.

4.4.2 Landuse

A Hierarchical CLUSTER analysis was used to group landuse categories in each of the 16 study reaches over periods 1998, 2002, 2005 and 2016, based on the similarity in landuse between them. Land use variables included: urban, crops and livestock, bare ground, recreational areas/parks, river and riparian vegetation, and surface water. A two-way nested ANOSIM was used to test for differences in landuse within each reach group (URW, RWC and DRW) in 1998, 2002, 2005 and 2016 (Clarke and Warwick 2001, Clarke and Gorley 2006). A one-way ANOSIM was then used to test for difference in landuse overall between the three reach groups, by using years 1998, 2002, 2005 and 2016 as samples. A SIMPER analysis was used to find out how the three reach groups differed in the terms of landuse categories, in terms of average abundances and the percentage that each variable contributes to dissimilarity.

4.4.3 Lateral extent of available floodplain

A two-way nested ANOSIM was used to test for differences in the lateral extent of available floodplain within each reach group (URW, RWC and DRW) in 1998, 2002, 2005 and 2016 (Clarke and Warwick 2001; Clarke and Gorley 2006). A one-way ANOSIM was then used to test for difference in lateral extent of available floodplain overall between the three reach groups, by using years 1998, 2002, 2005 and 2016 as samples.

4.4.4 Continuity of bankside woody vegetation

A two-way nested ANOSIM was used to test for differences in the proportion of bankside woody vegetation within each reach group (URW, RWC and DRW) in 1998, 2002, 2005 and 2016 (Clarke and Warwick 2001; Clarke and Gorley 2006). A one-way ANOSIM was then used to test for difference in the proportion of bankside woody vegetation overall between the three reach groups, by using years 1998, 2002, 2005 and 2016 as samples. A SIMPER analysis was used to find out how the three reach groups differed in the terms the proportion of bankside woody vegetation, in terms of average abundances and the percentage that each variable contributes to dissimilarity.

4.4.5 Macro-features of the river channel

A two-way nested ANOSIM was used to test for differences in the extent of channel macro-features (i.e., lateral/alternate bars, mid-channel bars and vegetated islands/bars) within each reach group (URW, RWC and DRW) in 1998, 2002, 2005 and 2016 (Clarke and Warwick 2001; Clarke and Gorley 2006). A one-way ANOSIM was then used to test for difference in the extent of channel macro-features overall between the three reach groups, by using years 1998, 2002, 2005 and 2016 as samples. A SIMPER analysis was used to find out how the three reach groups differed in the terms the extent of different channel macro-features, in terms of average abundances and the percentage that each variable contributes to dissimilarity.

4.4.6 Bank stabilising structures

A one-way ANOSIM was used to test for differences in the longitudinal extent of bank stabilizing structures (i.e., gabions mattresses and walls, loffelstein walls and rip-rap) overall between the three reach groups.

4.4.7 Cross-sections

A two-way nested ANOSIM was used to test for differences in bank height, bank slope, bankfull width, channel capacity and number of terraces of cross-section between T1, T2, T3 and T4 periods to determine whether there were significant differences between river channel shapes of the baseline (T1), hard engineered river works (T2), soft engineered river works (T3) and the current day (T4) (Table 4.10; Clarke and Warwick 2001; Clarke and Gorley 2006). A one-way ANOSIM was then used test for differences in bank height, bank slope, bankfull width, channel capacity and number of terraces for each reach group in T2 and T3 and then T1 and T4. A SIMPER analysis was used to identify the features contributing to the differences between T1, T2, T3 and T4 periods, in terms of average abundances and the percentage that each variable contributes to dissimilarity.

A two-way nested ANOSIM was used to test for significant differences in bank height, bank slope, bankfull width, channel capacity and number of terraces of cross-sections in T1, T2, T3, T4 and T5. This was done to determine whether cross-section of T5 differed significantly from what was previously planned in T2 and T3.

4.4.8 Diversity of hydraulic biotopes

A one-way ANOSIM was used to test for differences overall in the proportion of hydraulic biotopes of eco-sites (1, 2, 4 and 5) overall between 1997 and 2020 (Clarke and Warwick 2001; Clarke and Gorley 2006). A one-way ANOSIM was then used test for differences in the proportion of hydraulic biotopes of reach groups (URW, RWC and DRW).

4.4.9 Substrate composition

A one-way ANOSIM was used to test for differences overall in substrate composition of eco-sites (1, 2, 4 and 5) overall between 1997 and 2020 (Clarke and Warwick 2001; Clarke and Gorley 2006). A one-way ANOSIM was then used test for differences in substrate composition of reach groups (URW, RWC and DRW).

4.5 Results

A two-way nested ANOSIM revealed that overall, all mapped habitat features (i.e., river length, sinuosity, land use, lateral extent of floodplain, longitudinal continuity of bankside woody vegetation and channel macro-features) did not significantly differ between any of the reaches (1-16) in 1998, 2002, 2005 and 2016 (Overall ANOSIM R^2=0.06, p>0.05). Despite no significant differences, there were, however, some differences between reaches where no river works were planned (1-10) and those where river works were planned (11-16) that were noted. A SIMPER analysis (Table 4.14) showed that these differences were mainly a result of landuse categories with fynbos, crops and livestock and riparian woody vegetation that were more abundant in reaches 1-10, and urban development, recreational area/parks, surface water and bare ground more abundant in reaches 11-16. Alternate/lateral bars were also more abundant in reaches 1-10 than in reaches 11-16.

Table 4.14 SIMPER - Average dissimilarity in all mapped features between reaches 1-10 (no river works planned) and reaches 11-16 (river works planned).

Reach Groups: ‘No river works planned’ (Reaches 1-10) and ‘River works planned’ (Reaches 11-16)						
Average dissimilarity = 41.01%						
	‘No work planned’(Reaches 1-10)	‘Work planned’ (Reaches 11-16)				
Feature	Average Abundance (km²)	Average Abundance (km²)	Average Dissimilarity	Dissimilarity /Standard deviation	Contribution (%)	Cumulative (%)
Urban	0.35	2.74	10.41	2.78	25.39	25.39
Recreational Area / Park	0.28	1.47	5.55	1.96	13.54	53.84
Riparian Woody Vegetation	1.63	1.23	3.87	1.94	9.44	75.08
Surface Water	0.32	0.88	3.15	1.84	7.67	82.75
Alternate / Lateral bars	0.43	0.28	1.36	1.6	3.31	93.23
Crops and Livestock	1.62	1.02	6.11	1.23	14.9	40.3
Bare ground	1.73	1.82	2.94	1.08	7.17	89.92
Fynbos/Shrub	1.08	0	4.84	0.77	11.8	65.64

4.5.1 Channel planform

The Lourens River historically comprised several tributaries, the main river channel and a flood channel that diverged from the main river channel downstream of Radloff Park. The main river channel did not always flow directly to the ocean as it does today. The 1942 topographic map shows that instead the main channel diverted northwards into a large wetland downstream of Paardevlei. An analysis of topographic maps also revealed progressive fragmentation of the distributary (flood channel) between 1942 and 2010 when only a small disconnected section remained (Figure 4.13). The distributary was subjected to infilling from urban developments such as the Vergelegen Medi-clinic hospital, retirement villages, shopping centres and the township immediately below the N2 highway called ‘Nomzamo/Lwandle[10]’. The distributary flows through several urban suburbs, those upstream of the N2 highway known as ‘Cherrywood Gradens’ and ‘Heritage Mews’ and those downstream, known as ‘Onverwacht’ and ‘Weltervreden’. Stormwater runoff from the distributary enters the ocean through ‘Greenways Golf Estate’ (Appx. Figure 3).

The topographic maps indicate that the length of the main river channel remained stable between 1942 and 2010 (20.3±0.4 km; Table 4.15) while the length of distributary (flood

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[10] Nomzamo and Lwandle are two separate townships, but these names are often used interchangeably to represent both.

channel) decreased by 4.3 km. A negative relationship between length of the flood channel and time was found. (coefficient of determination (R^2) =-0.94, $p<0.05$, Appx. Table 6), where the rate of decrease slowed after 1979 (Figure 4.12). There were no noticeable changes in the sinuosity of the main channel that had a stable average sinuosity index of 1.13±0.04. Sinuosity of the flood channel could only be assessed for the period 1942 and at that stage was similar to the main channel.

Table 4.15 Length and sinuosity of the main river channel and flood channel in 1942, 1959, 1979, 1995, 2000 and 2010.

Period	Length of Main River channel (km)	Sinuosity of Main River channel	Length of Flood Channel (km)	Sinuosity of Flood Channel
1942	20.3	1.1	7.0	1.2
1959	20.8	1.1	6.4	Insufficient length to allow computation
1979	19.9	1.1	3.1	
1995	19.9	1.1	3.0	
2000	19.9	1.1	2.5	
2010	20.8	1.2	2.7	

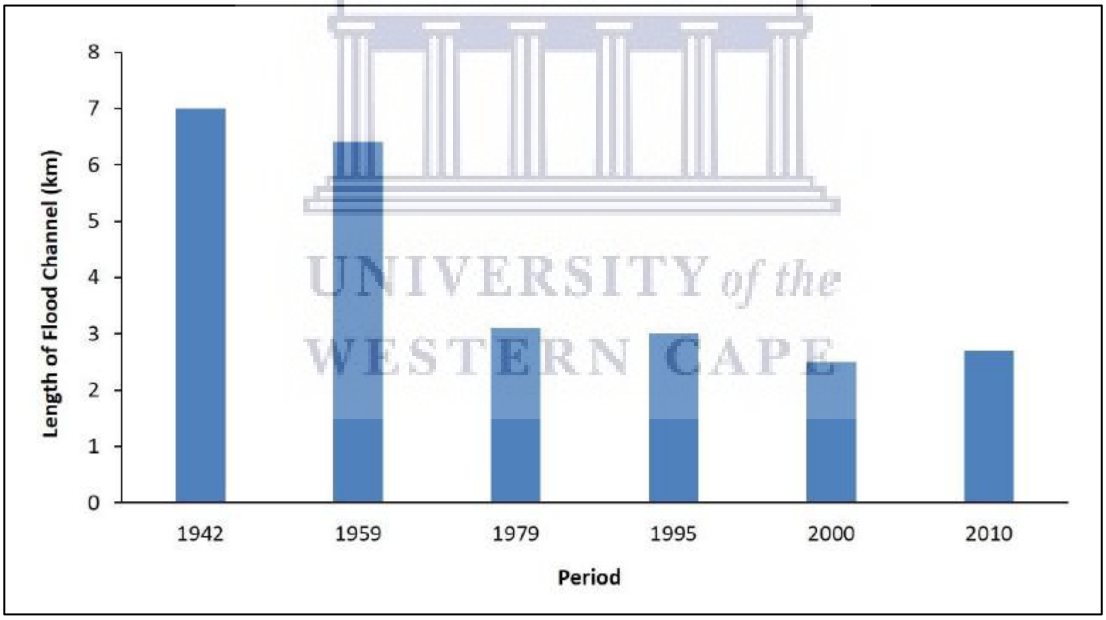

Figure 4.12 **Length of flood channel over time (1942, 1959, 1979, 1995, 2000, 2010)**

The length and sinuosity of the main river channel were measured for 1998, 2002, 2005 and 2016 (Table 4.16), which showed an overall increase in the sinuosity of the river channel over time. A two-way nested ANOSIM showed no significant differences in length and sinuosity of the main river channel within each reach group (URW, RWC and DRW) between 1998, 2002, 2005 and 2016 (ANOSIM R^2=0.272, $p>0.05$). A one-way ANOSIM revealed significant differences when comparing three reach groups to each other (ANOSIM R^2=0.595, $p<0.05$; Table 4.17).

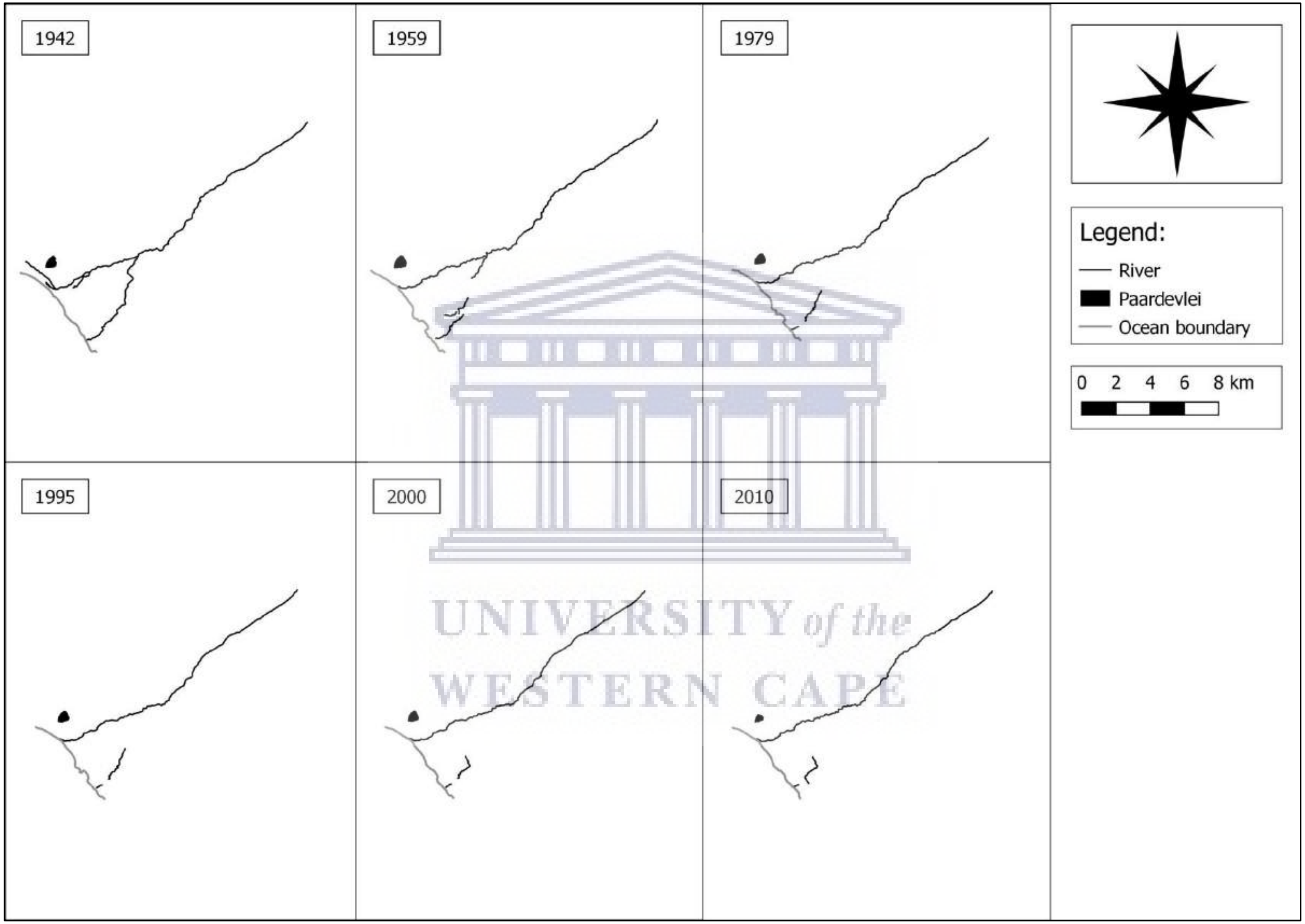

Figure 4.13 Sketches of channel planform and 'Paardevlei' in 1944, 1959, 1979, 1995, 2000 and 2010.

Table 4.16 Sinuosity of the main river channel between 1998, 2002, 2005 and 2016.

Reach	1998	2002	2005	2016
1	1.13	1.13	1.15	1.15
2	1.15	1.17	1.17	1.18
3	1.23	1.22	1.23	1.27
4	1.15	1.04	1.17	1.14
5	1.21	1.22	1.23	1.23
6	1.28	1.11	1.40	1.32
7	1.20	1.21	1.22	1.20
8	1.22	1.25	1.24	1.24
9	1.09	1.09	1.09	1.09
10	1.15	1.22	1.23	1.23
11	1.08	1.11	1.12	1.12
12	1.08	1.12	1.13	1.14
13	1.09	0.93	1.10	1.10
14	1.09	1.12	1.14	1.12
15	0.94	1.11	1.10	1.08
16	1.00	1.08	1.09	1.07

Table 4.17 ANOSIM (One-Way) comparison of sinuosity and length of the main river channel between reach groups (URW, RWC and DRW).

Global Test					
Sample statistic (Global R^2): 0.595					
Significance level of sample statistic: 0.1%					
Number of permutations: 999 (Random sample from a large number)					
Number of permuted statistics greater than or equal to Global R^2: 0					
Pairwise Tests					
	R	Significance	Possible	Actual	Number >=
Pairs	Statistic	Level %	Permutations	Permutations	Observed
URW vs RWC	0.823	0.2	6435	999	0
URW vs DWR	0.772	0.1	6435	999	0
RWC vs DRW	0.242	2.1	6435	999	17

The mean sinuosity of the main river channel in each reach group (URW, RWC and DRW) was presented for 1998, 2002, 2005 and 2016 (Table 4.18). A SIMPER analysis was used to show differences in the length and sinuosity of the main river channel when comparing the three reach groups (Table 4.19). The length and sinuosity of the main river channel were significantly higher in URW than in RWC or DRW. The sinuosity of the main river channel was similar for RWC and DRW, but higher in UWC.

Table 4.18 Mean sinuosity of the reach groups (URW, RWC and DRW) for 1998, 2002, 2005 and 2016.

Reach	Study reaches	Reach Group	1998	2002	2005	2016
Upstream	11-12	URW	1.08	1.12	1.12	1.13
River works	13-14	RWC	1.09	1.02	1.12	1.11
Downstream	15-16	DRW	1.02	1.11	1.12	1.10

Table 4.19 SIMPER - Average dissimilarity of sinuosity and length of the main river channel between reach groups (URW, RWC and DRW).

Groups:			
URW vs RWC; Average dissimilarity = 1.56%			
URW vs DWR; Average dissimilarity = 2.02%			
RWC vs DRW; Average dissimilarity = 0.83%			
	URW	RWC	DRW
Variables	Average Abundance	Average Abundance	Average Abundance
Sinuosity	0.48	0.47	0.46
Length (km)	0.5	0.48	0.48

4.5.2 Landuse

The area of each landuse category in all 16 reaches in 1998, 2002, 2005 and 2016 was calculated (Table 4.20) and the longitudinal distribution of landuse types mapped (Figure 4.15). Collectively across all 16 study reaches over time there was a decrease in Fynbos/shrub, riparian woody vegetation and recreational area/parks between 1998 and 2016, and an increase in urban development, crops and livestock, bare ground and surface water. The most profound changes were the 1476.8 km^2 decrease in the area covered by riparian woody vegetation and a 1217.6 km^2 increase in the area covered by urban development. A regression analysis using the total extent of each landuse categories and comparing it between 1998, 2002, 2005 and 2016 demonstrated significant trends for both riparian woody vegetation (coefficient of determination (R^2) =-0.997; $p<0.05$, Appx. Table 11 and Figure 4.14) and urban development (coefficient of determination (R^2) =-0.996; $p<0.05$, Appx. Table 12).

Table 4.20 Extent of landuse categories in all study reach (1-16) for 1998, 2002, 2005 and 2016.

Land Use (km^2)	1998	2002	2005	2016
Fynbos/ Shrub	6322.73	6342.74	6195.51	6184.81
Riparian Woody Vegetation	4966.42	4612.46	4474.54	3489.65
Urban	7846.82	8204.17	8399.84	9064.36
Crops and Livestock	9101.09	9062.31	9164.33	9438.77
Bare ground	6045.22	6061.04	6035.74	6204.09
Recreational Area/ Park	1343.11	1314.86	1320.54	1310.73
Surface Water	224.30	290.80	291.40	298.08

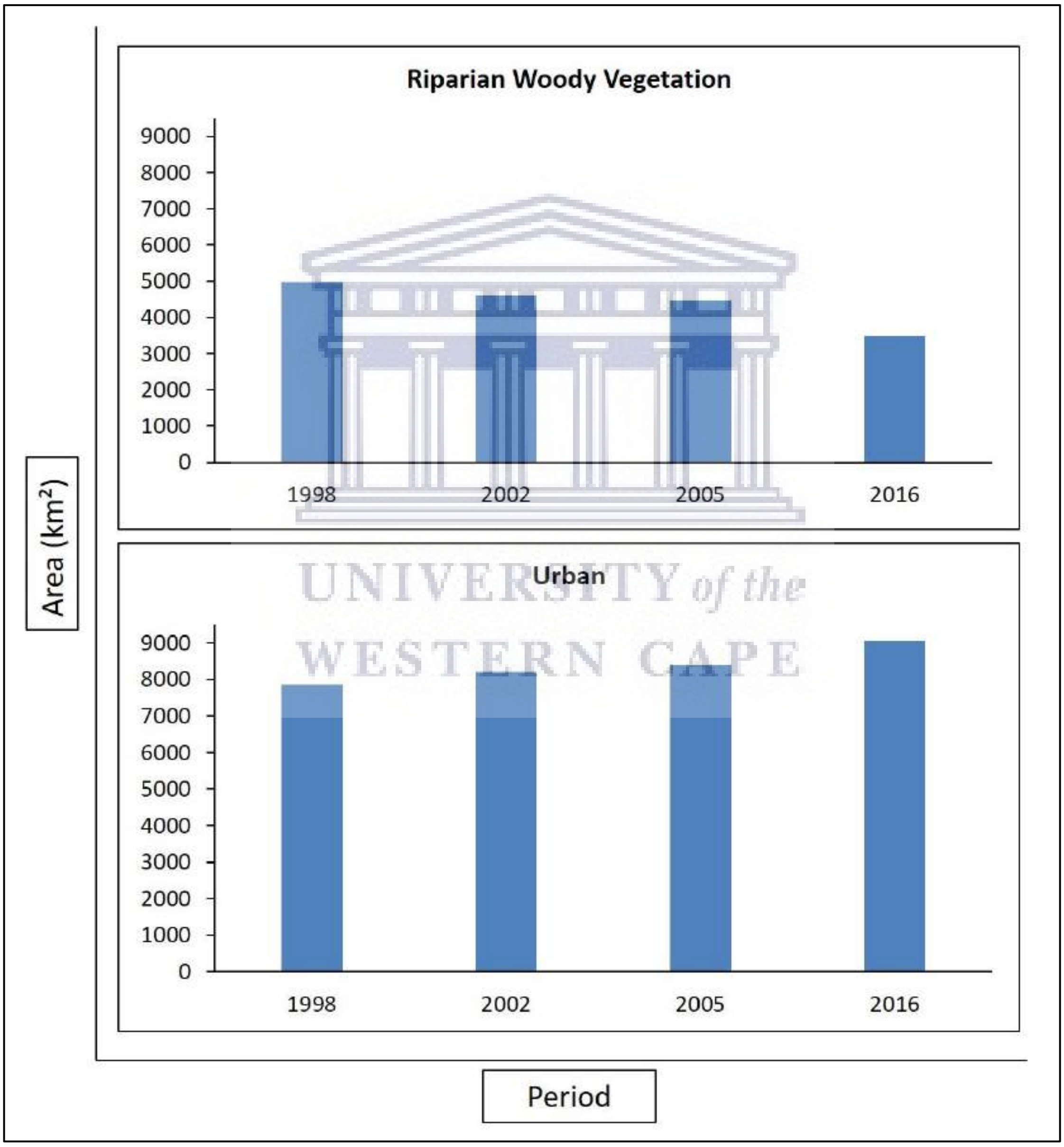

Figure 4.14 Total area of Riparian Woody Vegetation and Urban development in study reaches 1-16 over time (1998, 2002, 2005 and 2016).

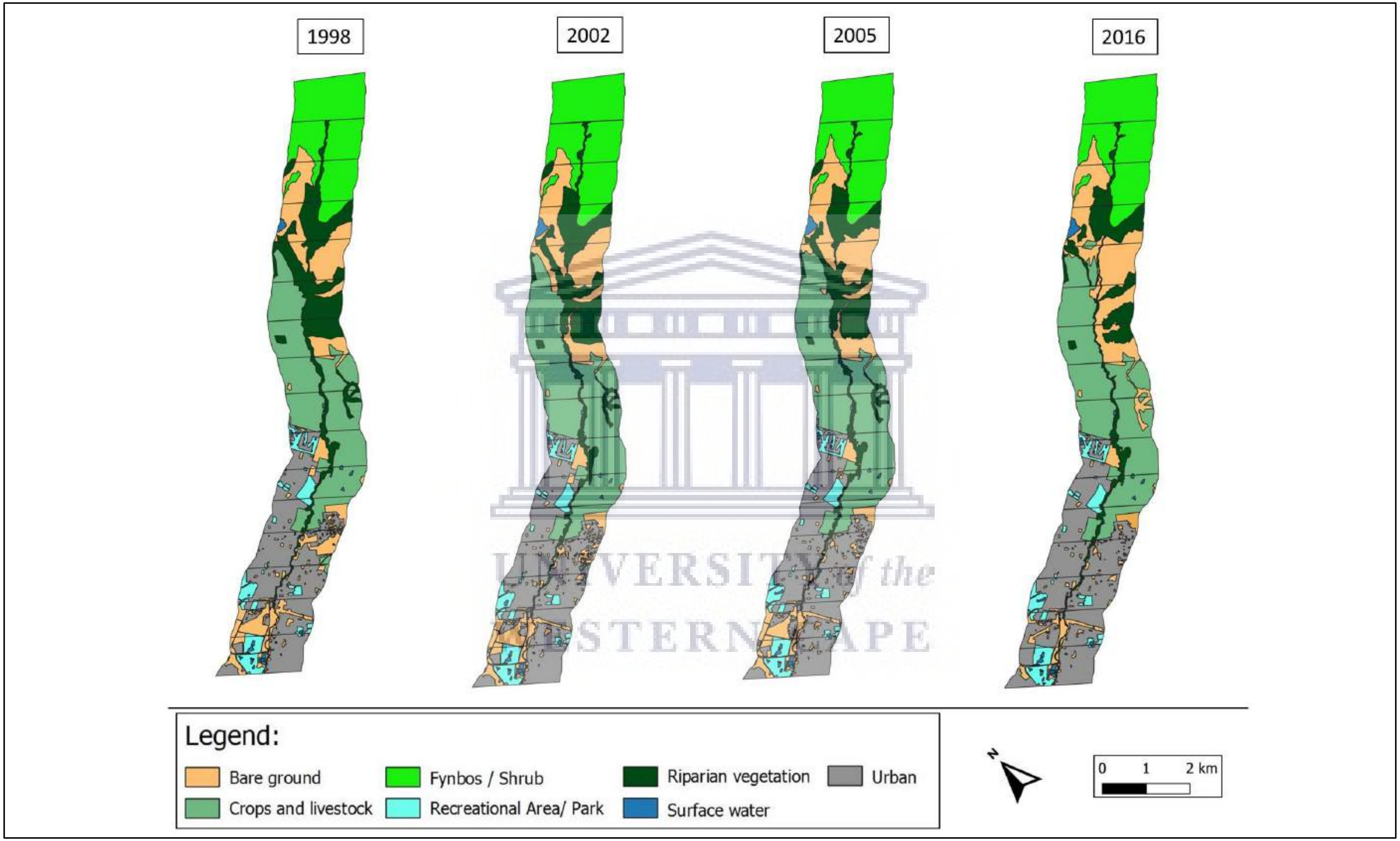

Figure 4.15 Land use in study reaches (1-16) for 1998, 2002, 2005 and 2016.

A Hierarchical CLUSTER analysis was used to group 16 study reaches over periods 1998, 2002, 2005 and 2016 based on their similarity in terms of landuse categories. The cluster analysis revealed four distinct land use groups based on location and the dominant land use category (Table 4.21; Figure 4.16 and Figure 4.17). Group 1 comprised Reaches 1 to 3 where Fynbos/shrub dominated (~84%). Group 2 comprised Reaches 4-7 where there was an even extent of riparian woody vegetation (36%) and bare ground (34%). Group 3comprised Reaches 8 to 12 where crop and livestock dominated (~62%). Group 4 comprised Reaches 13-16 where urban development dominated (~68%).

Table 4.21 Four landuse groups, the corresponding study reaches (1-16), reach groups (NRW, URW, RWC and DRW) and the dominant landuse types.

Landuse group	Reach #	Reach Description	Reach Group	Dominant landuse types
1	1-3	No works planned	NRW	Fynbos/shrub
2	4-7			Riparian woody vegetation and bare ground
3	8-12	Upstream	URW	Crops and livestock
4	13-16	River works and Downstream	RWC and DRW	Urban development

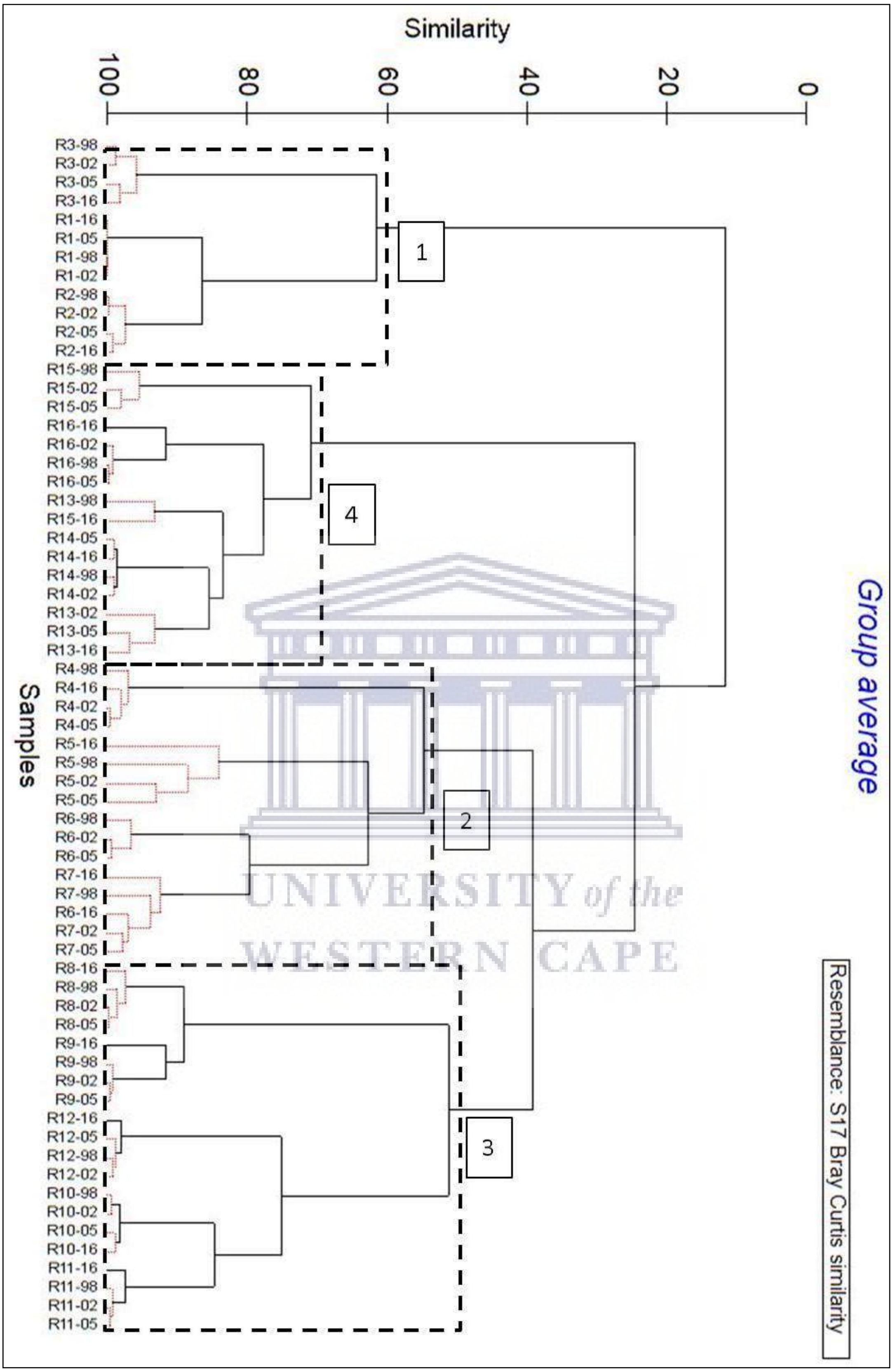

Figure 4.16 Dendrogram of land use proportions in study reaches (1-16) in 1998, 2002, 2005 and 2016. (Group 1 = reaches 1-3; Group 2 = reaches 4-7; Group 3 = reaches 8-12; and Group 4 = reaches 13-16). Samples represent the 16 study reaches for periods 1998, 2002, 2005 and 2016

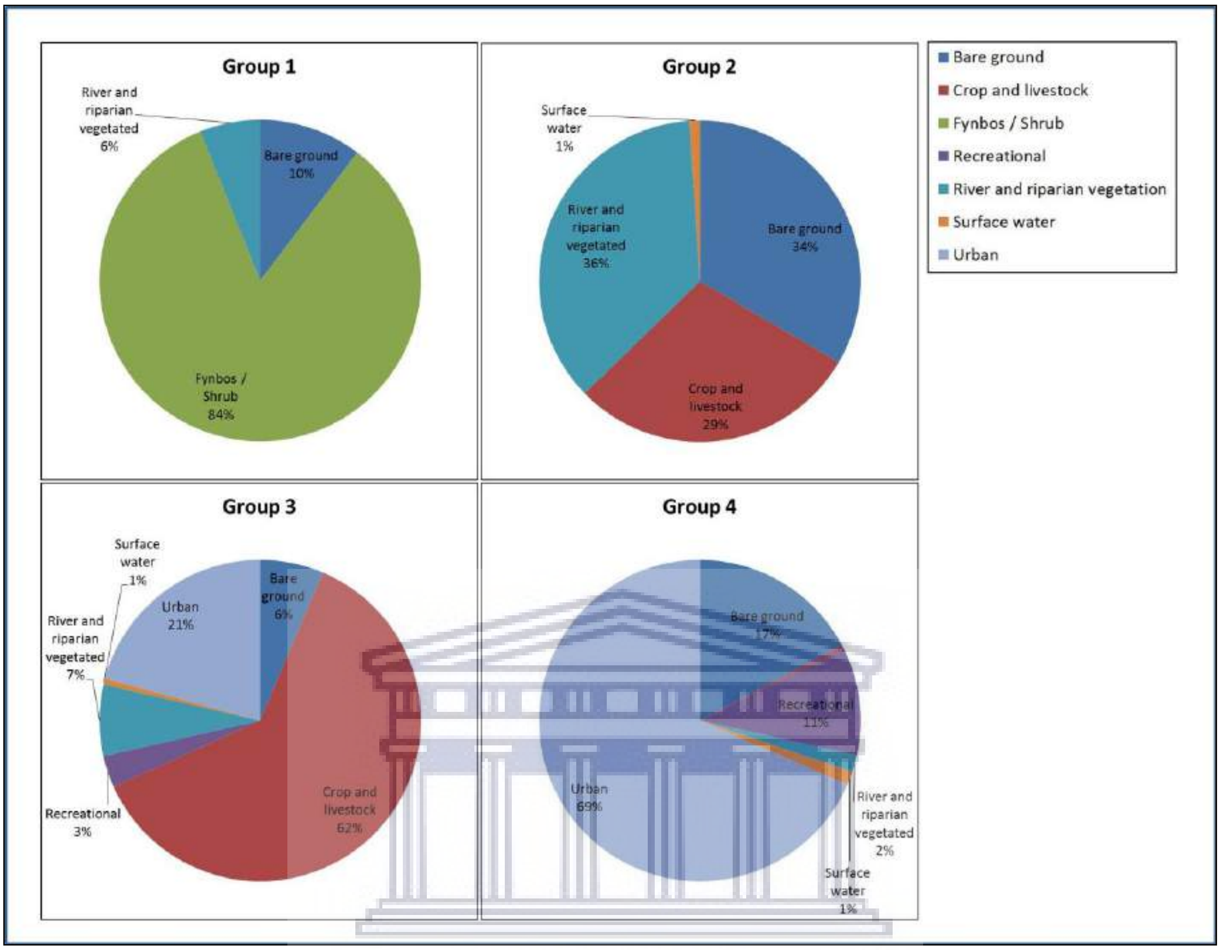

Figure 4.17 **Average proportional landuse in the four landuse groups between 1998, 2002, 2005 and 2016. (Group 1 = reaches 1-3; Group 2 = reaches 4-7; Group 3 = reaches 8-12; and Group 4 = reaches 13-16).**

Using a two-way nested ANOSIM, the comparison that focussed on whether there were changes in landuse categories in each reach group (URW, RWC and DRW) over time 1998, 2002, 2005 and 2016, showed no significant differences (ANOSIM R^2=0.309, $p>0.05$). A one-way ANOSIM revealed that there were, however, significant differences overall when comparing the three reach groups to each other (ANOSIM R^2=0.886, $p<0.05$; Table 4.22). The landuse categories in all three reach groups were significantly different from one another.

Table 4.22 ANOSIM (One-way) - comparing landuse of reach groups (URW, RWC and DRW) to each other.

Global Test					
Sample statistic (Global R²): 0.886					
Significance level of sample statistic: 0.1%					
Number of permutations: 999 (Random sample from a large number)					
Number of permuted statistics greater than or equal to Global R²: 0					
Pairwise Tests					
	R	Significance	Possible	Actual	Number >=
Groups	Statistic	Level %	Permutations	Permutations	Observed
URW vs RWC	0.932	0.1	6435	999	0
URW vs DWR	1	0.1	6435	999	0
RWC vs DRW	0.613	0.1	6435	999	0

The SIMPER analysis was used to distinguish the landuse categories responsible for the dissimilarity between reach groups (URW, RWC and DRW), which showed that crops and livestock, river and riparian vegetation were more abundant in the URW reach when compared with the RWC and DWR reaches (Table 4.23). Urban development, recreational area/parks and bare ground were more abundant in the RWC and DRW reaches than in the URW reach. Surface water was more abundant in the DRW reach than in the URW and RWC reaches.

Table 4.23 SIMPER - Average dissimilarity in landuse (urban, crops and livestock, bare ground, recreational areas/parks, riparian woody vegetation) between reach groups (URW, RWC and DRW).

Groups:			
URW and RWRC; Average dissimilarity = 20.88%			
URW and DRW; Average dissimilarity = 25.69%			
RWC and DRW; Average dissimilarity = 14.72%			
	URW	RWC	DRW
Species	Average Abundance (km²)	Average Abundance (km²)	Average Abundance (km²)
Crops and Livestock	2.53	0.54	0.00
Recreational Area/Park	1.19	1.35	1.86
Urban	2.50	2.97	2.18
Bare ground	1.57	1.71	1.03
Riparian Woody Vegetation	1.46	1.21	1.09

4.5.3 Lateral extent of available floodplain

The lateral extent of the available floodplain of reaches 11-16 was measured for time periods 1998, 2002, 2005 and 2016 (Table 4.24). Using a two-way nested ANOSIM, the comparison that focussed on whether there were changes in the lateral extent of available floodplain in each reach group (URW, RWC and DRW) over time showed no significant differences (ANOSIM R^2=-0.137, $p>0.05$). A one-way ANOSIM revealed that there were, however, significant differences overall when comparing the three reach groups to each other (ANOSIM R^2= 0.365, $p<0.05$; Table 4.25).

Table 4.24 Lateral Extent of available floodplain (km²) in study reaches (11-16) between 1998, 2002, 2005 and 2016.

Reach Name	Reach code	Reach #	1998	2002	2005	2016
Upstream	URW	11	49.29	49.50	49.78	49.30
		12	54.40	54.42	53.33	53.42
River works	RWC	13	45.34	47.68	45.37	46.21
		14	43.71	43.80	44.13	41.82
Downstream	DRW	15	149.19	135.64	136.69	136.11
		16	141.67	139.57	139.67	140.34

Table 4.25 ANOSIM (One-way) - comparing the lateral extent of floodplain between reach groups (URW, RWC and DRW).

Global Test					
Sample statistic (Global R^2): 0.365					
Significance level of sample statistic: 0.1%					
Number of permutations: 999 (Random sample from a large number)					
Number of permuted statistics greater than or equal to Global R^2: 0					
Pairwise Tests					
	R	Significance	Possible	Actual	Number >=
Groups	Statistic	Level %	Permutations	Permutations	Observed
URW vs RWC	0.508	0.2	6435	999	1
URW vs DWR	0.427	0.3	6435	999	2
RWC vs DRW	0.243	3	6435	999	29

All three reach groups showed decreasing trends in the proportion of available floodplain between 1998 and 2016 (Figure 4.18). The proportion of available floodplain in URW decreased by 0.88%, RWC by 1.03% and the DRW reach by 3.54%. Although the DRW has the largest area of available floodplain it had the lowest proportion of floodplain still intact.

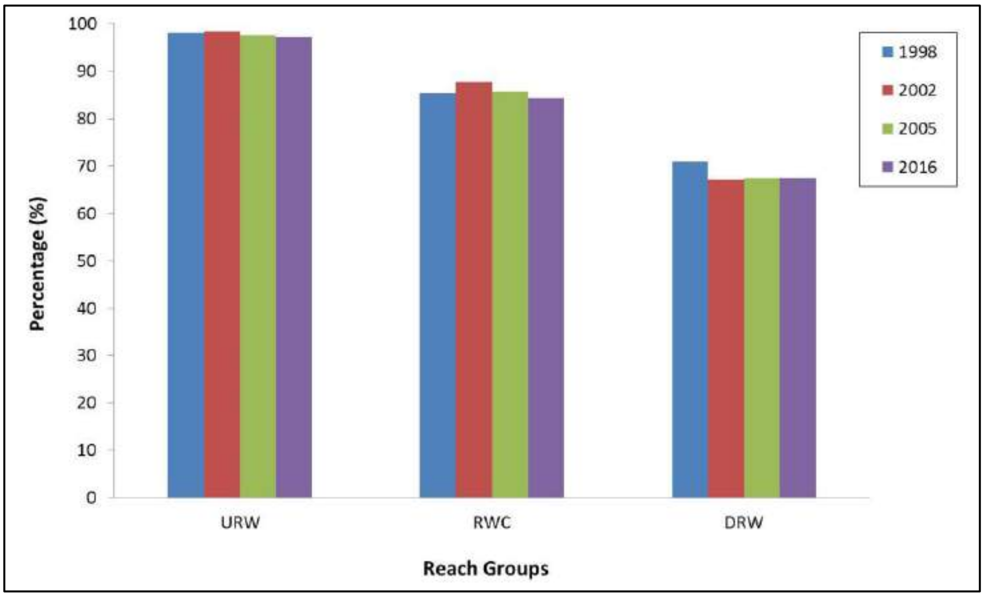

Figure 4.18 Proportion of available floodplain in reach groups (URW, RWC and DRW) for 1998, 2002, 2005 and 2016.

4.5.4 Continuity of bankside woody vegetation

The proportion of bankside woody vegetation of reaches 11-16 was measured for 1998, 2002, 2005 and 2016 using aerial imagery (Table 4.26). Using a two-way nested ANOSIM, the comparison that focussed on whether there were changes in proportion of bankside woody vegetation in each reach group (upstream, river works and downstream reaches) over time, showed no significant differences (ANOSIM R^2=0.031, p>0.05). A one-way ANOSIM revealed that there were, however, significant differences overall when comparing the three reach groups to each other (ANOSIM R^2=0.15, p<0.05) (Table 4.27). The proportion of bankside woody vegetation in URW is significantly different from RWC and DRW. There is a slight decreasing trend in the proportion of bankside woody vegetation in URW and an increasing trend in the RWC and DRW (Figure 4.19).

Table 4.26 Proportion of bankside woody vegetation in study reaches (11-16) for 1998, 2002, 2005 and 2016.

			Period			
Reach group	Reach code	Reach	1998	2002	2005	2016
Upstream	UWR	11	84.10	73.76	75.18	86.61
		12	98.39	96.04	88.25	95.11
River works	RWC	13	63.42	69.20	64.46	71.45
		14	69.01	64.23	56.22	66.02
Downstream	DRW	15	12.09	12.76	12.81	13.36
		16	10.70	12.56	13.71	15.44

Table 4.27 ANOSIM (One-way) - comparing the proportion of bankside woody vegetation (%) between reach groups (URW, RWC and DRW).

Global Test					
Sample statistic (Global R^2): 0.15					
Significance level of sample statistic: 1.3%					
Number of permutations: 999 (Random sample from a large number)					
Number of permuted statistics greater than or equal to Global R^2: 12					
Pairwise Tests					
	R	Significance	Possible	Actual	Number >=
Groups	Statistic	Level %	Permutations	Permutations	Observed
URW vs RWC	0.277	0.6	6435	999	5
URW vs DWR	0.236	1.7	6435	999	16
RWC vs DRW	-0.006	33.4	6435	999	333

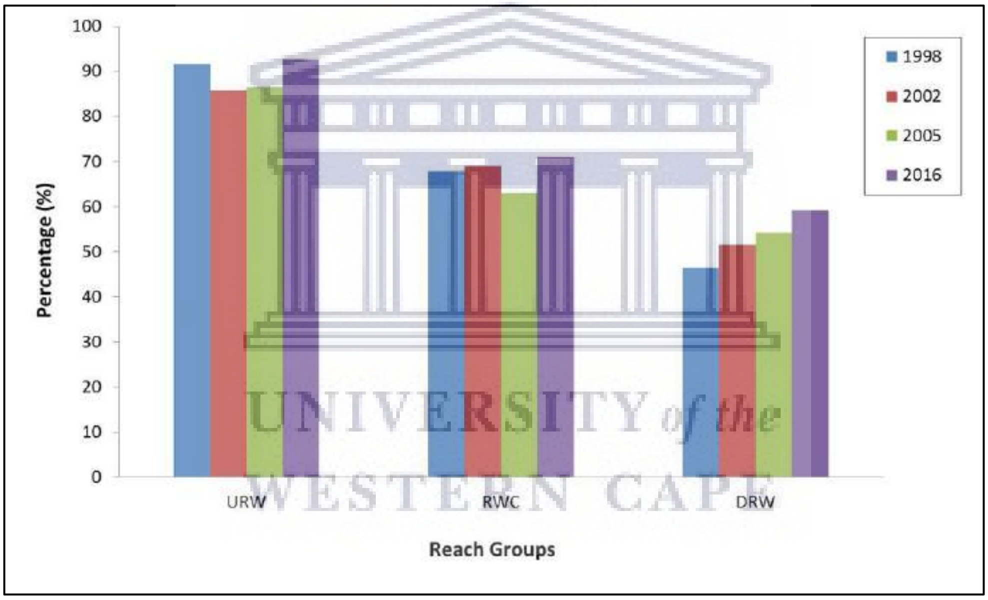

Figure 4.19 Average proportion of bankside woody vegetation in reach groups (URW, RWC and DRW) for 1998, 2002, 2005 and 2016.

4.5.5 Macro-features of the river channel

The extent of channel macro-features of reaches 11-16 was measured for 1998, 2002, 2005 and 2016 using aerial imagery (Table 4.28). Using a two-way nested ANOSIM, the comparison that focussed on whether there were changes in the extent of channel macro-features (i.e., lateral/alternate bars, mid-channel bars and vegetated islands/bars) in each reach group (URW, RWC and DRW) over time showed no significant differences (ANOSIM R^2=0.158, $p>0.05$). A one-way ANOSIM revealed that there were, however, significant differences overall when comparing the three reach groups to each other (ANOSIM R^2=0.475, $p<0.05$) (Table 4.29).

Table 4.28 Extent of channel macro-features in study reaches (1-16) for 1998, 2002, 2005 and 2015[11].

	Mid-channel Bars (km²)				Vegetated islands (km²)				Lateral/Alternate bars (km²)			
Reach	1998	2002	2005	2016	1998	2002	2005	2016	1998	2002	2005	2016
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.02	0.22	0.00	0.00	0.00	0.68	0.00	0.15	0.69	0.87	9.26
6	0.00	0.00	0.11	0.00	0.00	0.24	0.00	1.62	0.41	1.95	1.85	5.54
7	0.39	0.91	0.23	0.26	0.00	0.00	0.00	2.11	0.49	3.72	4.65	10.49
8	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.08	0.56	1.10	5.33
9	0.00	0.00	0.20	0.00	0.00	0.40	0.95	0.00	1.00	0.73	0.69	2.02
10	0.00	0.70	0.20	0.00	0.00	0.00	0.95	0.00	1.02	2.24	0.69	0.96
11	0.00	0.00	0.03	0.03	0.00	0.00	0.00	0.00	2.83	2.55	0.82	1.17
12	0.00	0.12	0.01	0.08	0.00	0.00	0.00	1.30	1.65	2.72	1.74	1.55
13	0.00	0.00	0.04	0.08	0.00	0.00	0.00	1.30	1.19	1.66	1.10	1.55
14	0.01	0.00	0.06	0.18	0.24	0.00	0.24	0.00	0.68	0.89	0.65	0.83
15	0.03	0.00	0.00	0.00	2.19	1.79	0.00	2.06	0.32	0.63	0.14	0.36
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.00	0.47	0.74	0.00
Total area (km²)	0.43	1.74	1.11	0.82	2.43	2.43	2.82	9.07	9.83	18.80	15.03	39.07

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[11] Level of accuracy when measuring channel macro-features (Cell size = 0.5m)

Table 4.29 ANOSIM (One-Way) comparing extent of channel macro-features (i.e., lateral/alternate bars, mid-channel bars and vegetated islands/bars) between reach groups (URW, RWC and DRW).

Global Test					
Sample statistic (Global R^2): 0.475					
Significance level of sample statistic: 0.2%					
Number of permutations: 999 (Random sample from a large number)					
Number of permuted statistics greater than or equal to Global R^2: 1					
Pairwise Tests					
Groups	R Statistic	Significance Level %	Possible Permutations	Actual Permutations	Number >= Observed
URW vs RWC	0.167	5	6435	999	49
URW vs DWR	1	0.1	6435	999	0
RWC vs DRW	0.273	7.1	6435	999	70

A SIMPER analysis was used to show how the three reach groups differed in terms of the extent of channel macro-features (i.e., lateral/alternate bars, mid-channel bars and vegetated islands/bars). The area of alternate/lateral bars made the highest contribution to dissimilarity between the URW, RWC and DRW reaches followed by mid-channel bars (Table 4.30). Channel macro-features were more abundant in URW reach than in the RWC or DRW reaches and more abundant in the RWC than in the DRW reach. Overall, there was a decline in the number channel macro-features with distance in a downstream direction i.e., there were more macro-features in the URW reach than in the RWC or DWR reaches. This is almost entirely attributable to the decline in alternate/lateral bars, and increase in mid-channel bars and vegetated islands over time (Figure 4.20).

Table 4.30 SIMPER - Average dissimilarity the extent of channel macro-features (i.e., lateral/alternate bars, mid-channel bars and vegetated islands/bars) between reach groups (URW, RWC and DRW).

Groups:			
URW vs. RWC; Average dissimilarity = 68.61%			
URW vs. DRW; Average dissimilarity = 100.00%			
RWC vs. DRW; Average dissimilarity = 100.00%			
	URW	RWC	DRW
Species	Average Abundance (km^2)	Average Abundance (km^2)	Average Abundance (km^2)
Lateral/Alternate Bar	0.60	0.24	0.00
Mid-channel Bar	0.22	0.06	0.00
Vegetated Island/Bar	0.18	0.05	0.00

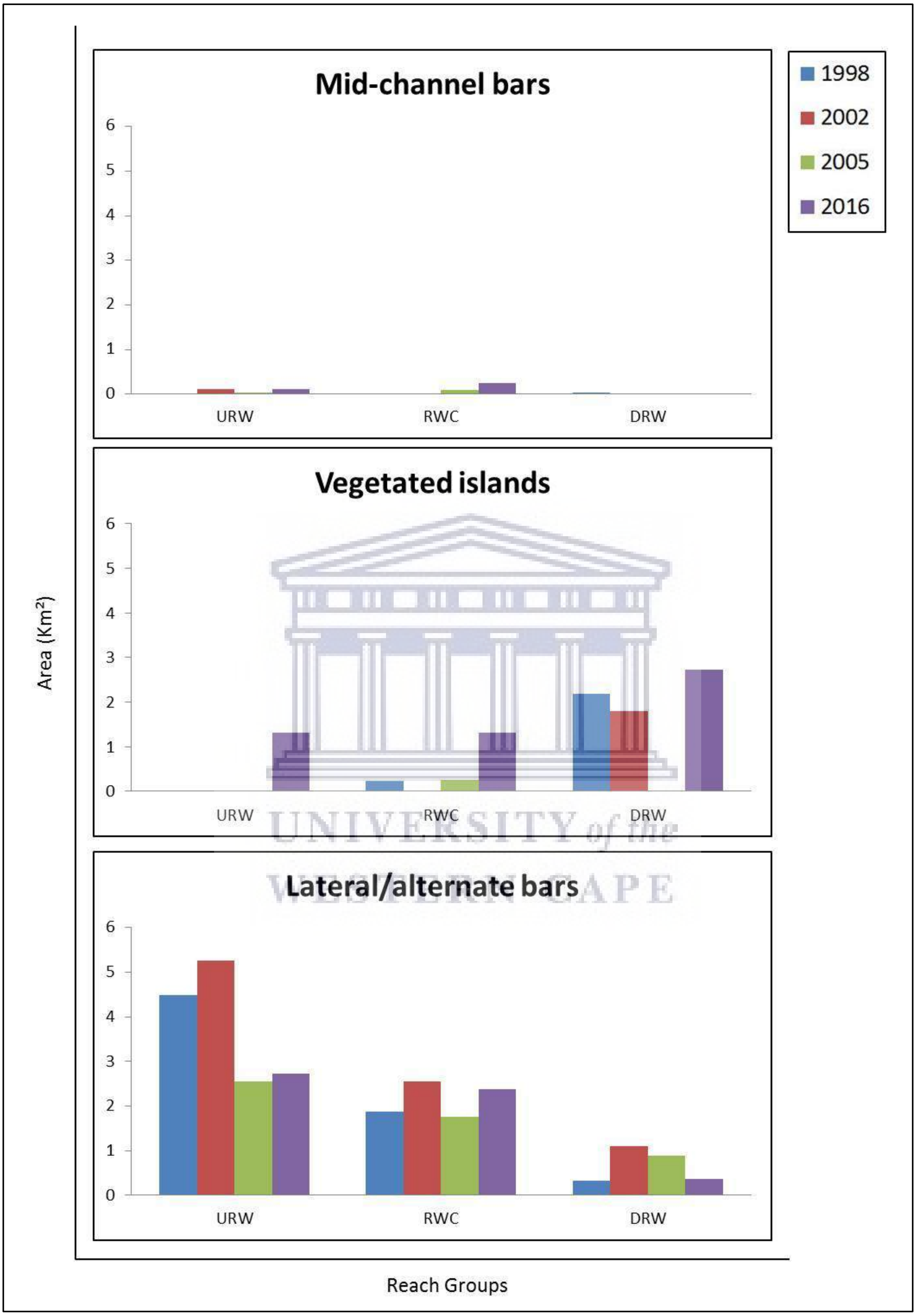

Figure 4.20 **Area of channel macro features (i.e., lateral/alternate bars, mid-channel bars and vegetated islands/bars) in reach groups (URW, RWC and DRW) for 1998, 2002, 2005 and 2016.**

4.5.6 Bank Stabilising structures

The bank stabilizing structures in the river channel were mapped (Figure 4.22) and their length measured (Table 4.31). A one-way ANOSIM was used to test for differences in the longitudinal extent of bank stabilizing structures in each reach group (URW, RWC and DRW), which revealed that were no significant differences (ANOSIM R^2=0.036, $p>0.05$).

Bank stabilizing structures occur in all three reaches but their number and extent is greatest in RWC. The RWC reach had 45 structures, whereas URW and DRW had 18 and 4, respectively (Figure 4.21). Of all the structures located in all three reaches 3.0% of the structures were rip-rap, 86.6% were gabion mattresses and walls and 10.4% were loffelstein walling. Collectively, in RWC, 2.34 km of the river banks were stabilized, of which 76.49% were gabion mattresses and walls and the remainder loffelstein walling.

Table 4.31 The number and total length of bank stabilizing structures in each reach group (URW, RWC and DRW).

		Gabion mattresses and walls		Loffelstein walling		Rip-rap	
Reach group description	Reach #	Number of structures	Total Length (km)	Number of structures	Total Length (km)	Number of structures	Total Length (km)
Upstream	11-12	16	0.77	0	0.00	2	0.03
River works	13-14	38	1.79	7	0.55	0	0.00
Downstream	15-16	4	0.13	0	0.00	0	0.00

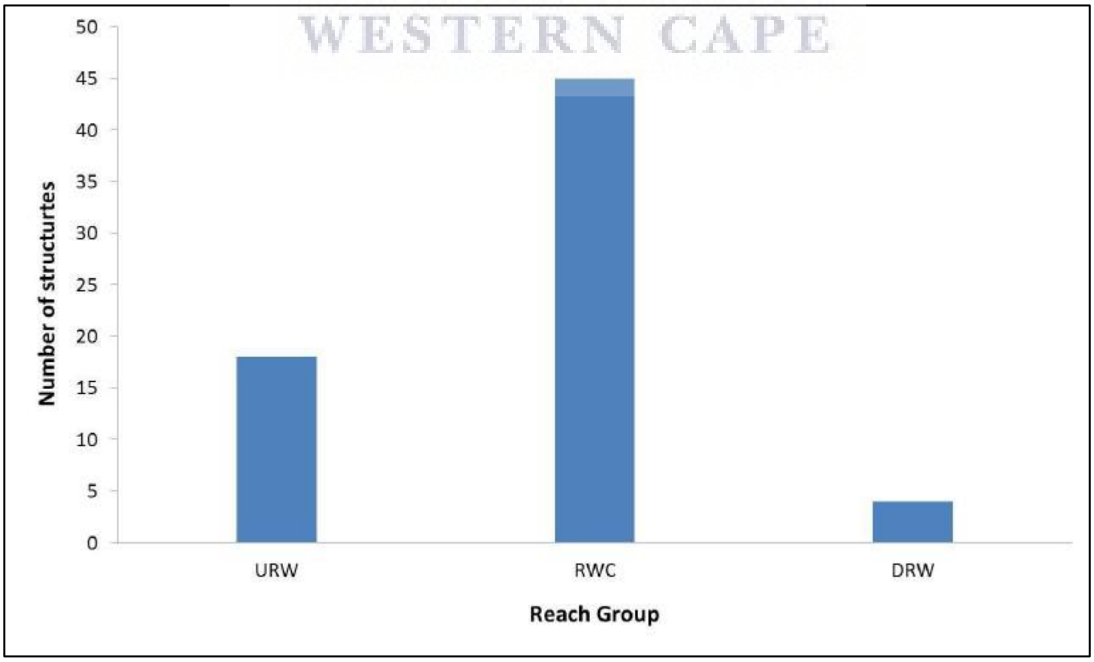

Figure 4.21 Number of bank stabilizing structures in each reach group (URW, RWC and DRW).

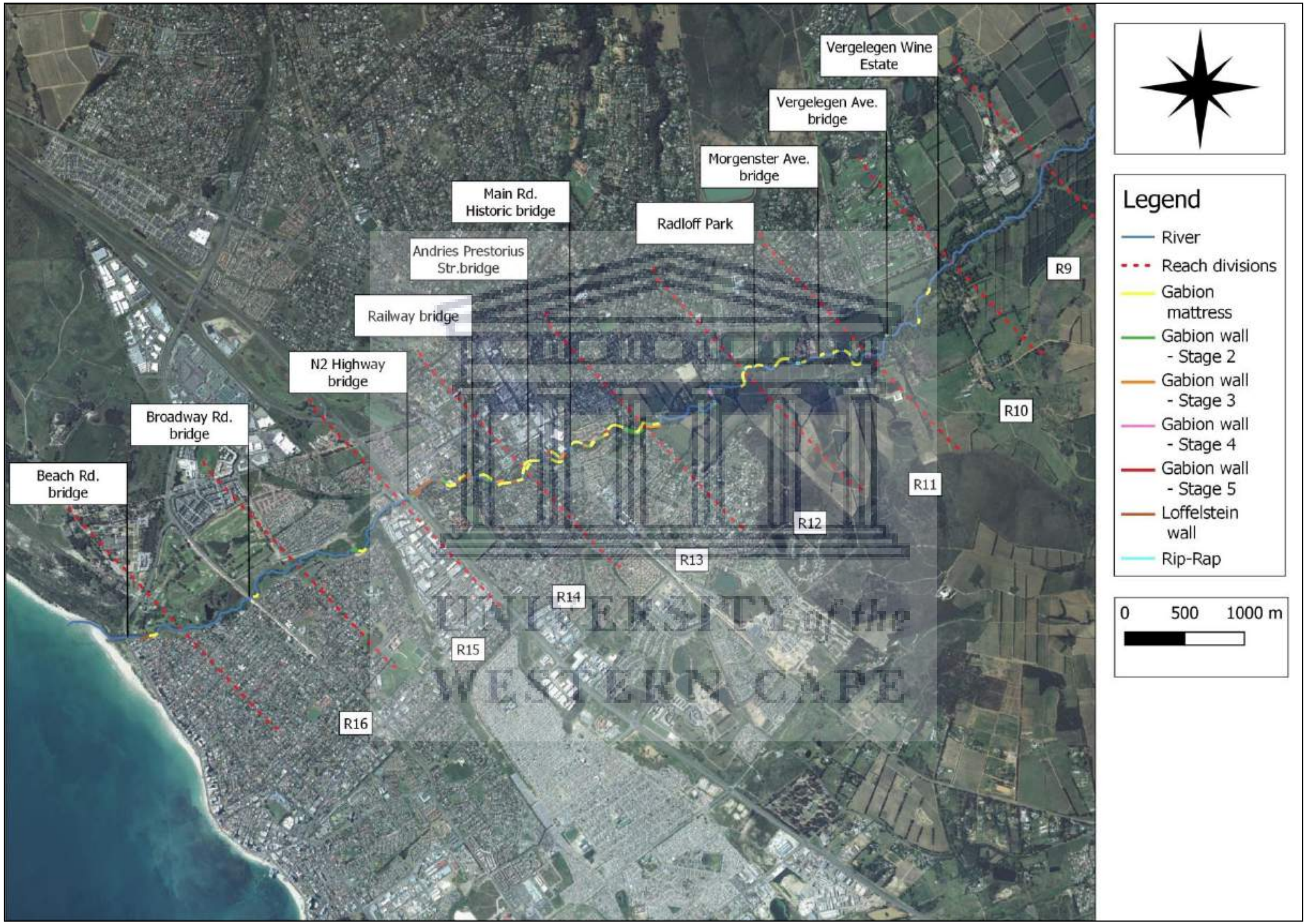

Figure 4.22 Location of banks stabilizing structures in study reaches (11-16).

4.5.7 Cross-sections

A two-way nested ANOSIM was used to compare bank height, bank slope, bankfull width, channel capacity and number of terraces of cross-section of the 23 cross-sections overall between periods T1, T2, T3 and T4, which showed that there was a significant difference (ANOSIM R^2=0.027, $p<0.05$) (Table 4.32). Collectively, the 23 cross-sections in T1 were significantly different from those in T2 and in T3.

Table 4.32 Two-Way ANOSIM - Testing for differences in cross-sections (between T1, T2, T3 and T4.

TESTS FOR DIFFERENCES BETWEEN Period GROUPS					
(Using Chainage groups as samples)					
Global Test					
Sample statistic (Global R^2): 0.027					
Significance level of sample statistic: 4%					
Number of permutations: 999 (Random sample from a large number)					
Number of permuted statistics greater than or equal to Global R^2: 39					
Pairwise Tests					
	R	Significance	Possible	Actual	Number >=
Groups	Statistic	Level %	Permutations	Permutations	Observed
T1, T2	0.09	0.30	Very large	999	2
T1, T3	0.10	0.20	Very large	999	1
T1, T4	-0.02	77.50	Very large	999	774
T2, T3	-0.04	99.20	Very large	999	991
T2, T4	0.01	34.80	Very large	999	347
T3, T4	0.02	17.10	Very large	999	170

A one-way ANOSIM revealed that there was no significant difference in any of the reach groups for T2 and T3, (ANOSIM R^2=-0.168, $p>0.05$) for URW, (ANOSIM R^2=-0.078, $p>0.05$) for RWC (ANOSIM R^2=0.078, $p>0.05$) and (ANOSIM R^2=0.108, $p>0.05$) for DRW.

A one-way ANOSIM showed that there were also no significant differences between T1 and T4 in either the URW reach (ANOSIM R^2=0.04, $p>0.05$) or the DRW reach (ANOSIM R^2=0.116, $p>0.05$). There was, however, a significant difference between T1 and T4 in 13 cross-sections in the RWC reach (ANOSIM R^2=0.107, $p<0.05$; Figure 4.23 to Figure 4.35).

A SIMPER analysis was used to show how the T1 and T4 cross sections in the RWC reach group differed in terms of the bank height, bank slope, bankfull width, channel capacity and number of terraces). The SIMPER revealed that these differences were a result of bankfull width, channel capacity and the number of terraces, which were all greater in T4 and then the height of banks and bank slope, which were lower in T4 (Table 4.33). Bankfull width and channel capacity accounted for >20% of the differences between T1 and T4. The remaining cross-sections where river works were had not been completed are presented in Appx. Figure 16 to Appx. Figure 25**.**

Table 4.33 One Way SIMPER - Average dissimilarity (%) of cross-sections within the RWC reach between T1 and T4.

Groups: T1 cross-sections and T4 cross-sections						
Average dissimilarity = 7.35%						
	Group: T1	Group: T4				
Variables	Average Abundance	Average Abundance	Average Dissimilarity	Dissimilarity / Standard deviation	Contribution (%)	Cumulative (%)
Slope gradient - L	0.75	0.62	0.85	1.45	11.57	68.99
Bankfull width	2.11	2.41	1.68	1.37	22.85	22.85
Channel Capacity	1.75	2.03	1.55	1.24	21.1	43.96
Height - L	1.27	1.24	0.56	1.4	7.63	95.25
No. of Terraces - R	1.17	1.24	0.68	1.15	9.22	87.63
No. of Terraces - L	1.14	1.2	0.69	1.12	9.42	78.41
Slope gradient - R	0.72	0.68	0.99	1.03	13.46	57.42

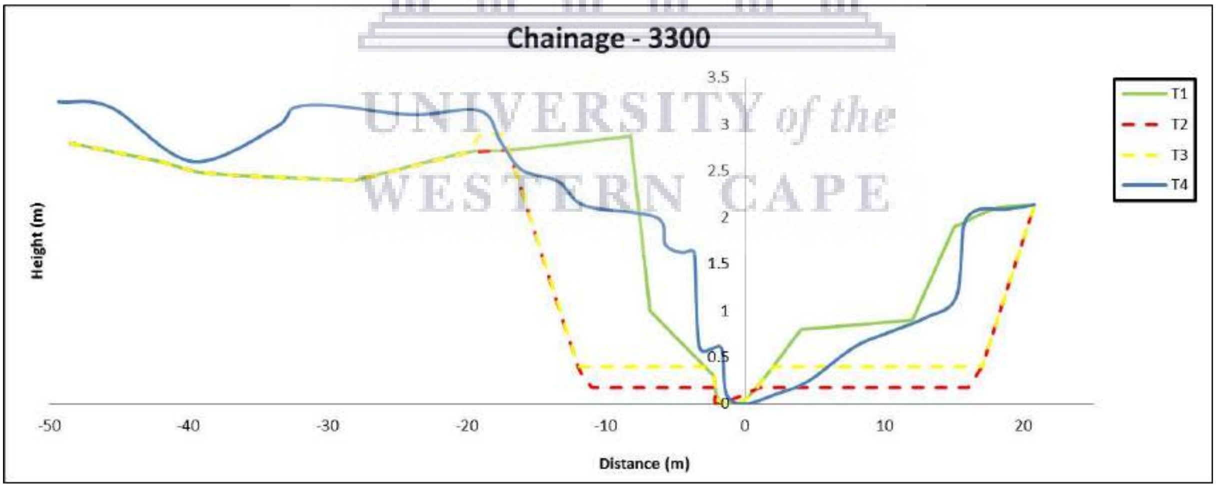

Figure 4.23 Chainage 3300 in T1, T2, T3 and T4.

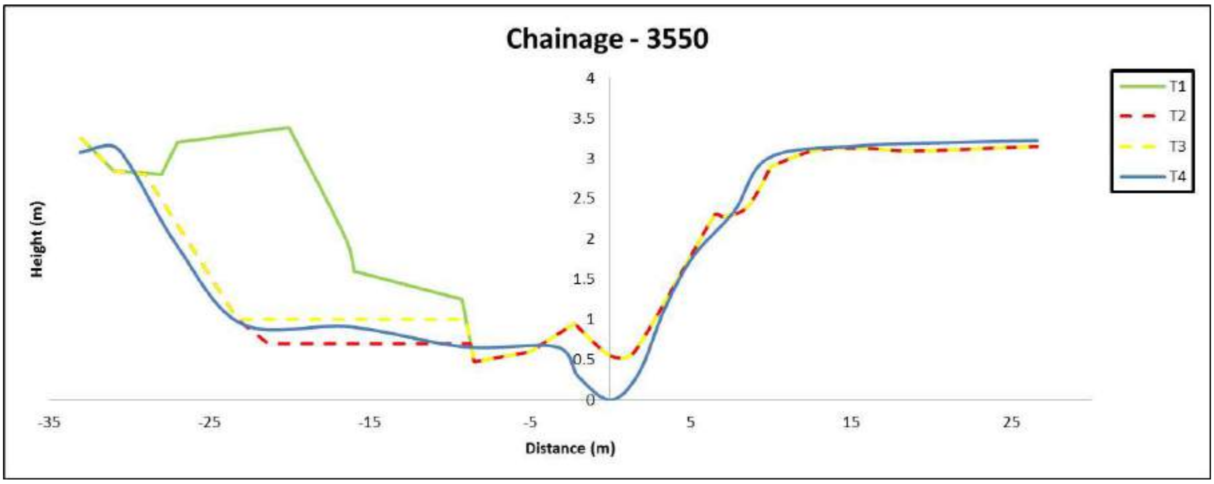

Figure 4.24 Chainage 3550 in T1, T2, T3 and T4.

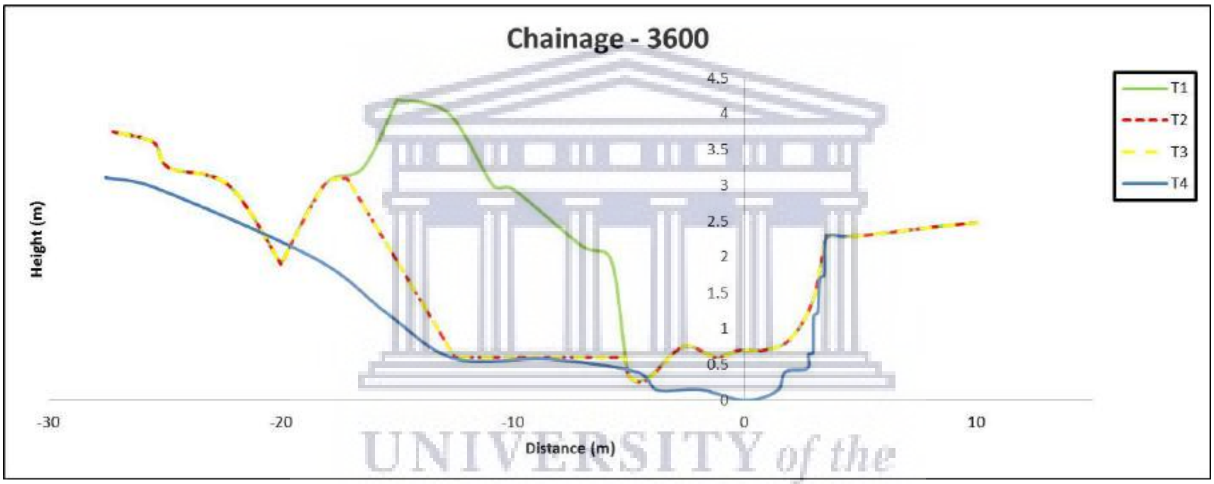

Figure 4.25 Chainage 3600 in T1, T2, T3 and T4.

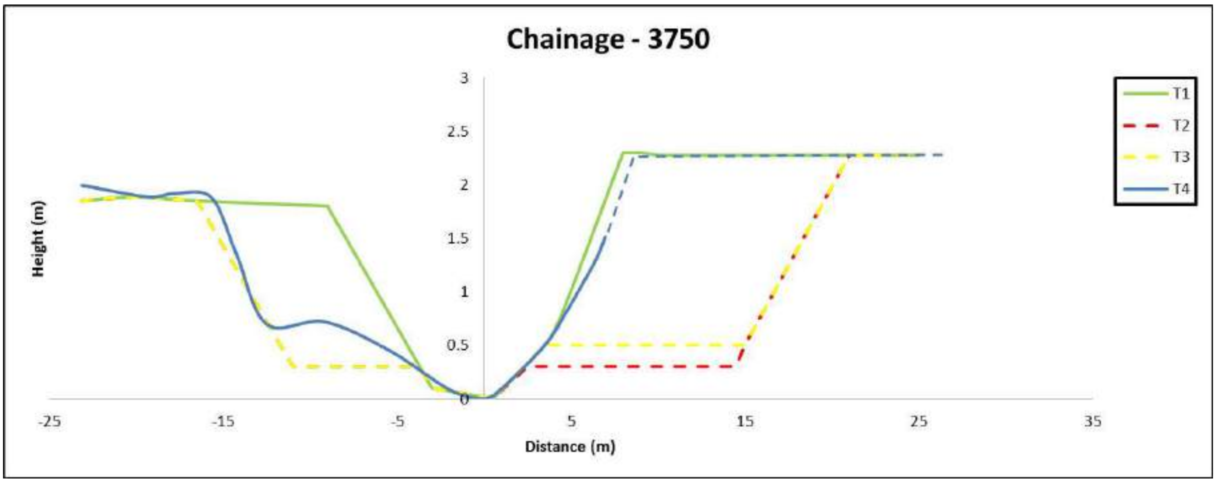

Figure 4.26 Chainage 3750 in T1, T2, T3 and T4.

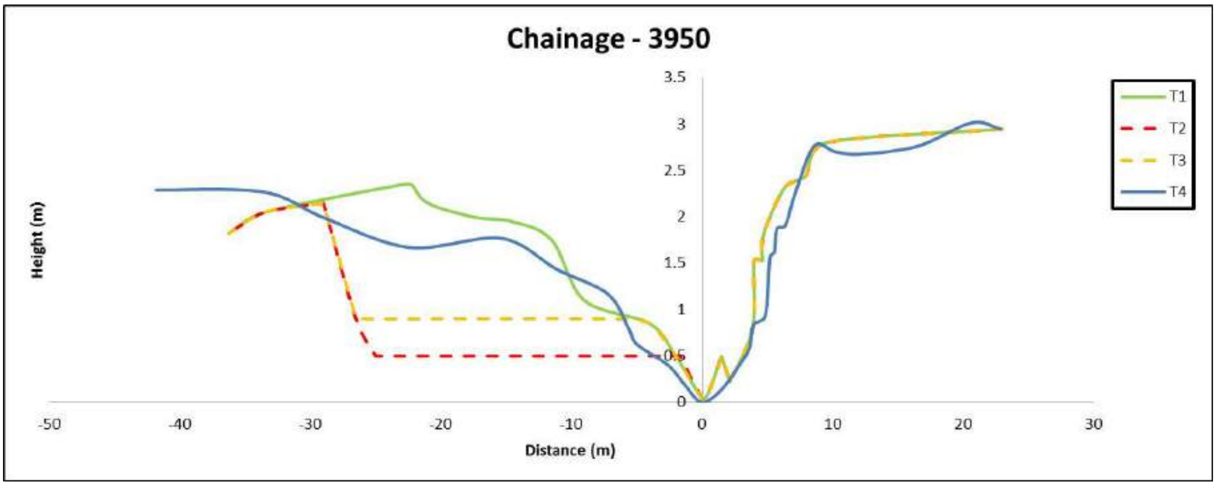

Figure 4.27 Chainage 3950 in T1, T2, T3 and T4.

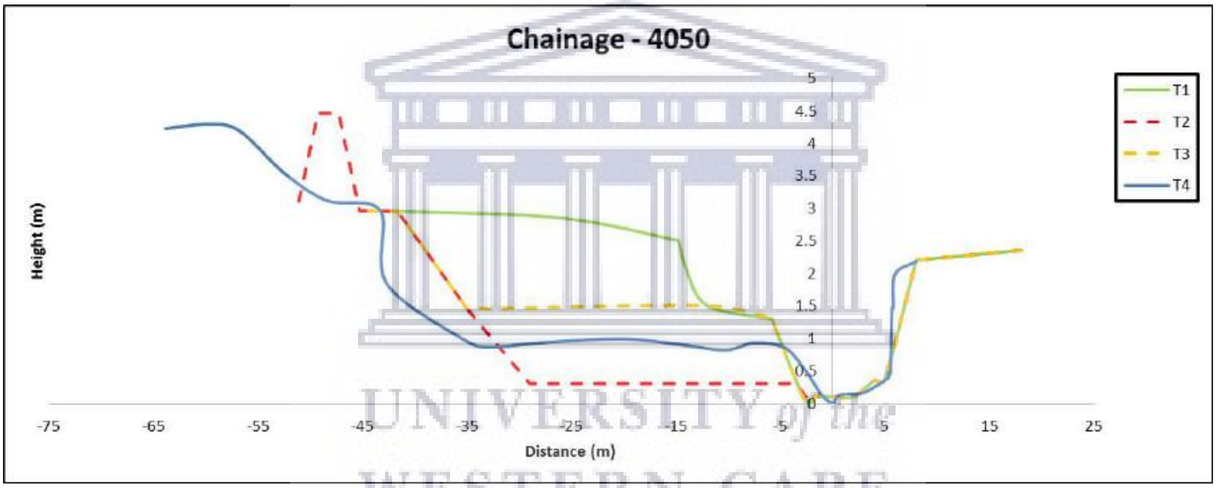

Figure 4.28 Chainage 4050 in T1, T2, T3 and T4.

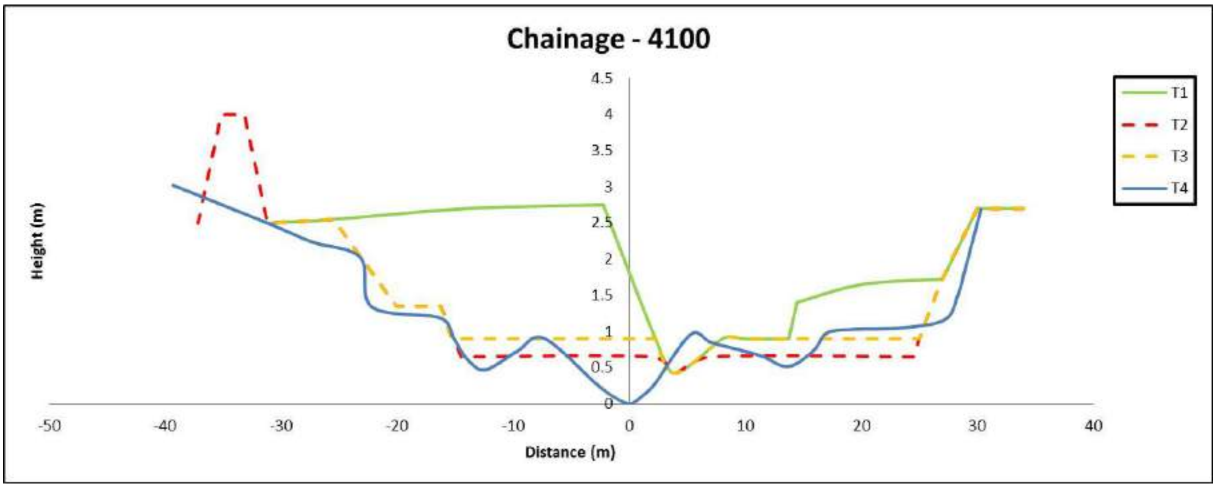

Figure 4.29 Chainage 4100 in T1, T2, T3 and T4.

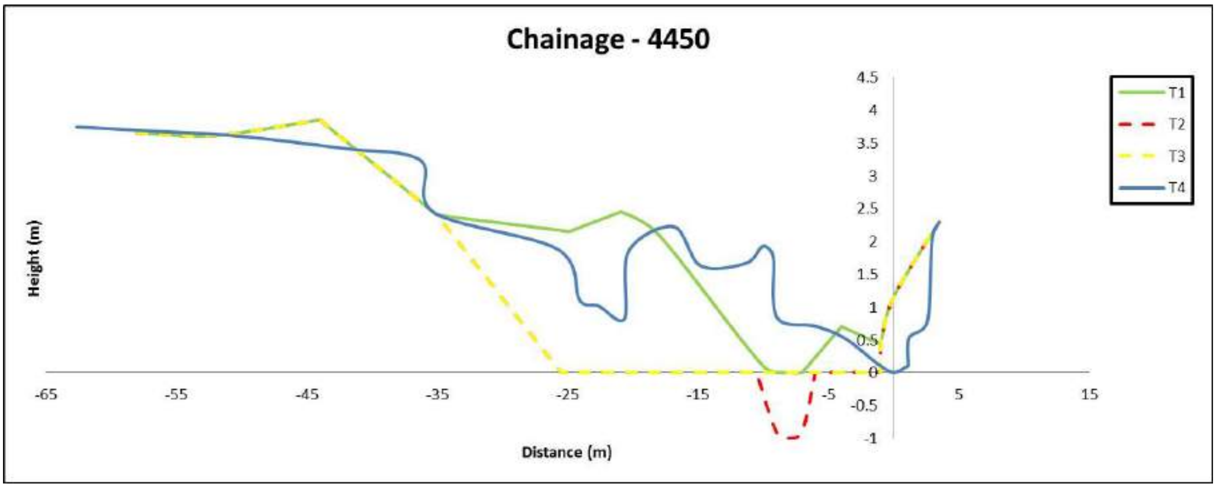

Figure 4.30 Chainage 4450 in T1, T2, T3 and T4.

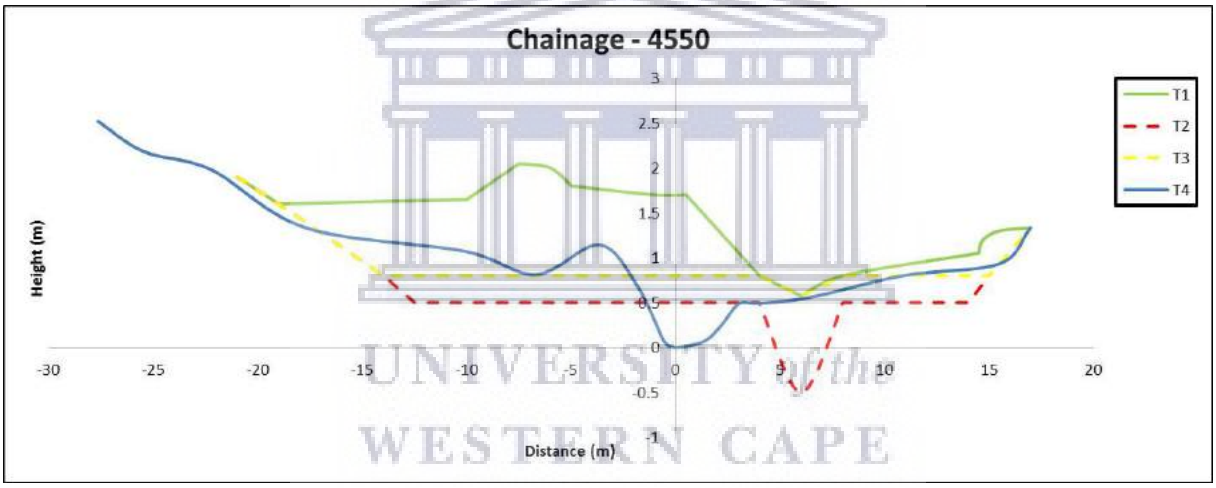

Figure 4.31 Chainage 4550 in T1, T2, T3 and T4.

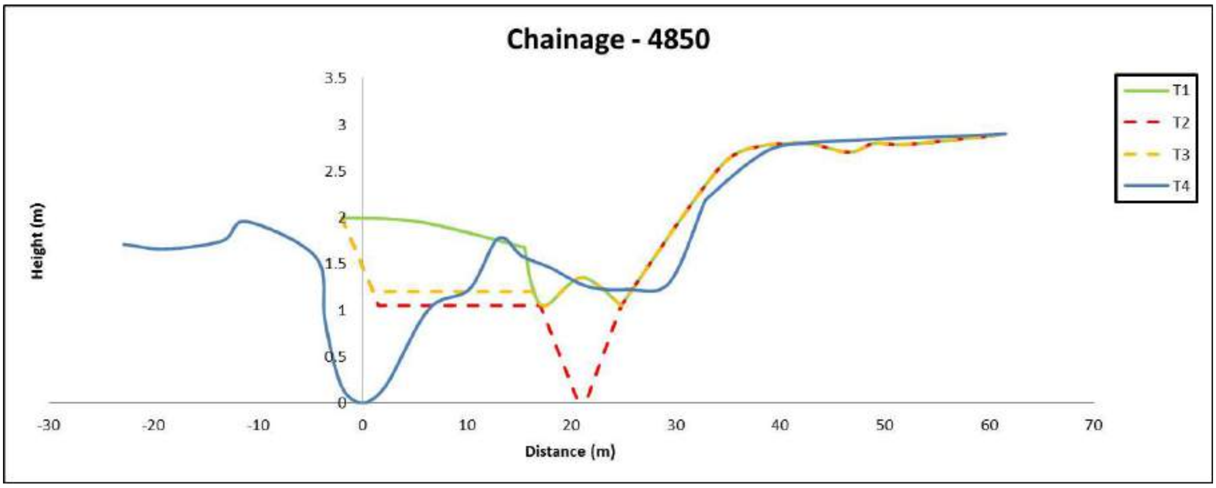

Figure 4.32 Chainage 4850 in T1, T2, T3 and T4.

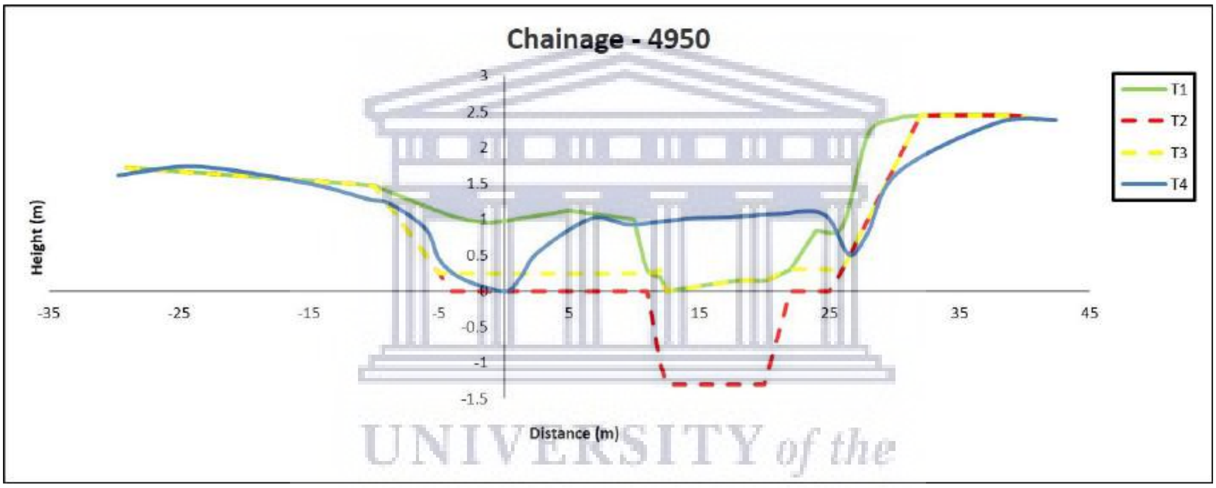

Figure 4.33 Chainage 4950 in T1, T2, T3 and T4.

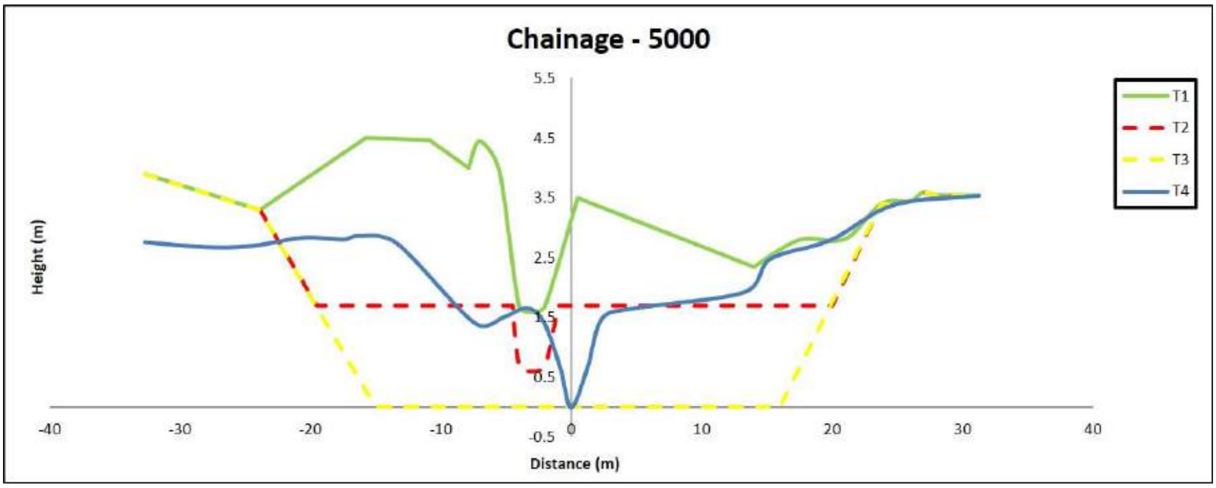

Figure 4.34 Chainage 5000 in T1, T2, T3 and T4.

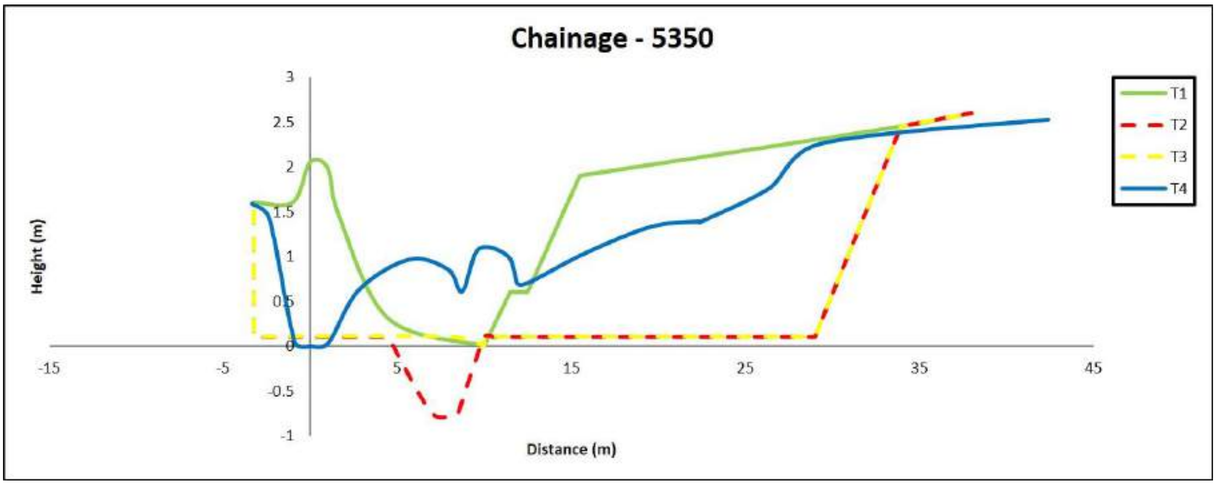

Figure 4.35 Chainage 5350 in T1, T2, T3 and T4.

Using a two-way nested ANOSIM, comparison of the four cross-sections (Chainage 6350, 6450, 7350 and 7450) in DRW where plans in sub-phase 1J (T5) differ from those plans in T3 revealed no overall significant differences (ANOSIM R^2=0.149, p>0.05; Table 4.34). However, comparison of the four cross-sections revealed that T5 was significantly different from T1 and T2. A SIMPER analysis showed that the differences between T1 and T5 cross sections in DRW were a result of bankfull width, channel capacity, number of terraces on the left bank and height of the right bank (Table 4.35). Results for the SIMPER showed that cross-sections in the DRW reach between T1 and T5 were 88.92% similar with bankfull width and channel capacity accounting for ~40% of the difference.

Table 4.34 Two Way ANOSIM - comparing cross-sections (Chainage 6350, 6450, 7350 and 7450) between T1, T2, T3, T4 and T5.

TESTS FOR DIFFERENCES BETWEEN Period GROUPS					
(Using Chainage groups as samples)					
Global Test					
Sample statistic (Global R^2): 0.149					
Significance level of sample statistic: 6.8%					
Number of permutations: 999 (Random sample from a large number)					
Number of permuted statistics greater than or equal to Global R^2: 67					
Pairwise Tests					
	R	Significance	Possible	Actual	Number >=
Groups	Statistic	Level %	Permutations	Permutations	Observed
T1, T2	-0.25	100	35	35	35
T1, T3	-0.125	85.7	35	35	30
T1, T4	-0.188	74.3	35	35	26
T1, T5	0.771	2.9	35	35	1
T2, T3	-0.125	85.7	35	35	30
T2, T4	-0.188	74.3	35	35	26
T2, T5	0.771	2.9	35	35	1
T3, T4	-0.073	57.1	35	35	20
T3, T5	0.167	14.3	35	35	5
T4, T5	0.729	2.9	35	35	1

Table 4.35 One Way SIMPER - Average dissimilarity of cross-sections (Chainage 6350, 6450, 7350 and 7450) within DRW reach group between T1 and T5.

Groups: T1 cross-sections and T5 cross-sections						
Average dissimilarity = 11.08%						
	Group: T1	Group: T5				
Species	Average Abundance	Average Abundance	Average Dissimilarity	Dissimilarity /Standard deviation	Contribution (%)	Cumulative (%)
Bankfull width	2.45	3.56	4.93	1.6	44.48	44.48
Channel Capacity	1.76	2.75	4.42	1.76	39.93	84.41
No. of Terraces - L	1.21	1.19	0.49	1.39	4.39	93.5
Slope gradient - R	0.54	0.42	0.52	0.86	4.71	89.12

4.5.8 Diversity of hydraulic biotopes

Hydraulic biotopes data were collected at the five eco-sites for 1997 and 2020 (Table 4.36). Using a one-way ANOSIM, there were no significant differences in the diversity of hydraulic biotopes overall for eco-sites 1, 2, 4 from 1997 to 2020 (ANOSIM $R^2=0.01$, $p>0.05$). A one-way ANOSIM also revealed no significant difference in the proportion of hydraulic biotopes between reach groups (URW, RWC and DRW; ANOSIM $R^2=0.556$, $p>0.05$). At eco-site 1 and 4 there were fewer pools, runs and cascades in 2020 than in 1997 and more riffles. At eco-site 2, there were more pools and riffles and fewer runs in 2020 than in 1997. Eco-site 5 had more runs and riffles and fewer pools in 2020 than in 1997 (Figure 4.36).

Table 4.36 Proportion of hydraulic biotopes in eco-sites (1-5) for 1997 and 2020.

	Eco-site 1 (%)		Eco-site 2 (%)		Eco-site 3 (%)	Eco-site 4 (%)		Eco-site 5 (%)	
Biotope	1997	2020	1997	2020	2020	1997	2020	1997	2020
Cascade	5.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Riffle	25.00	52.70	34.00	39.53	41.55	25.00	35.34	5.00	17.42
Run	50.00	31.76	57.00	48.84	28.17	53.00	47.37	20.00	38.64
Pool	20.00	15.54	7.00	11.63	30.28	20.00	17.29	65.00	43.94

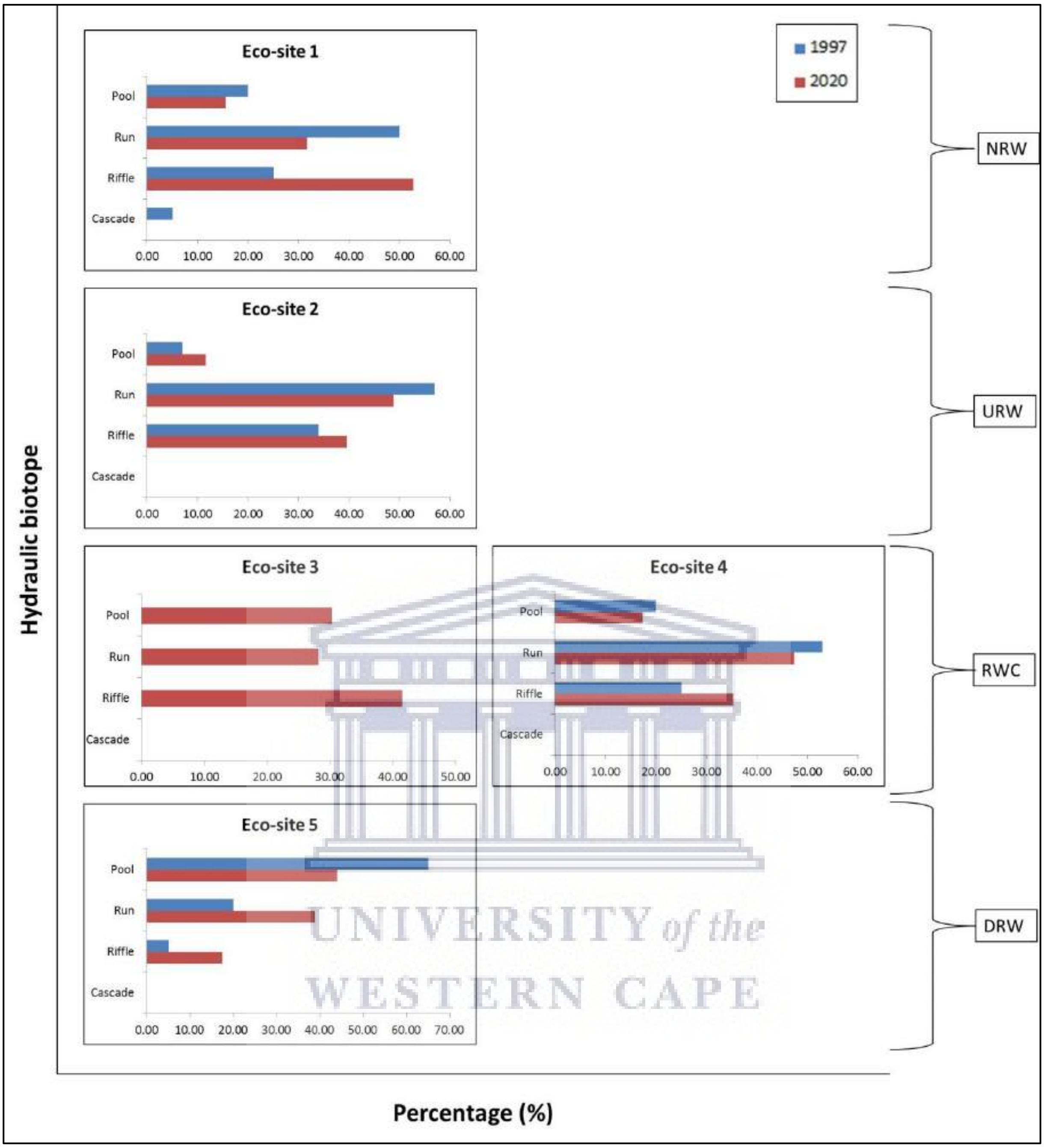

Figure 4.36 **Proportion of hydraulic biotopes in eco-sites (1-5) for 1997 and 2020. Eco-sites are grouped in their corresponding reach groups (NRW, URW, RWC and DRW).**

4.5.9 Substrate composition

Sediment composition data were collected at the five eco-sites in 1997 and 2020 (Table 4.37; Figure 4.37). Using a one-way ANOSIM, there were no significant differences in the substrate composition overall for eco-sites 1, 2 and 4 from 1997 to 2020 (ANOSIM R^2=0.24, $p>0.05$). A one-way ANOSIM also revealed no significant difference in the substrate composition between reach groups (URW, RWC and DRW; ANOSIM R^2=0.167, $p>0.05$).

Table 4.37 Sediment composition for in eco-sites (1-5) for 1997 and 2020.

	Eco-site 1		Eco-site 2		Eco-site 3	Eco-site 4		Eco-site 5	
Substrate Class	1997	2020	1997	2020	2020	1997	2020	1997	2020
Bedrock (unlimited)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Boulder (256-4096)	8.33	5.83	0.00	4.17	5.00	0.00	3.33	0.00	1.67
Large Cobble (128-256)	10.97	23.33	0.00	21.67	26.67	20.93	25.00	0.00	13.33
Small Cobble (64-128)	25.97	31.67	35.13	36.67	40.83	51.27	43.33	60.85	35.00
Large Gravel (32-64)	5.70	5.83	11.70	12.50	5.83	11.30	8.33	0.00	11.67
Medium Gravel (8-32)	9.03	5.83	19.30	10.00	5.83	2.97	6.67	27.50	11.67
Small Gravel (2-8)	2.80	3.33	19.67	9.17	5.83	3.47	5.00	2.50	13.33
Sand (0.06-2)	2.96	5.00	6.03	4.17	6.67	0.87	3.33	5.00	10.00
Mud/Vegetation (<0.06)	34.00	19.17	8.17	1.67	3.33	9.20	5.00	4.15	3.33

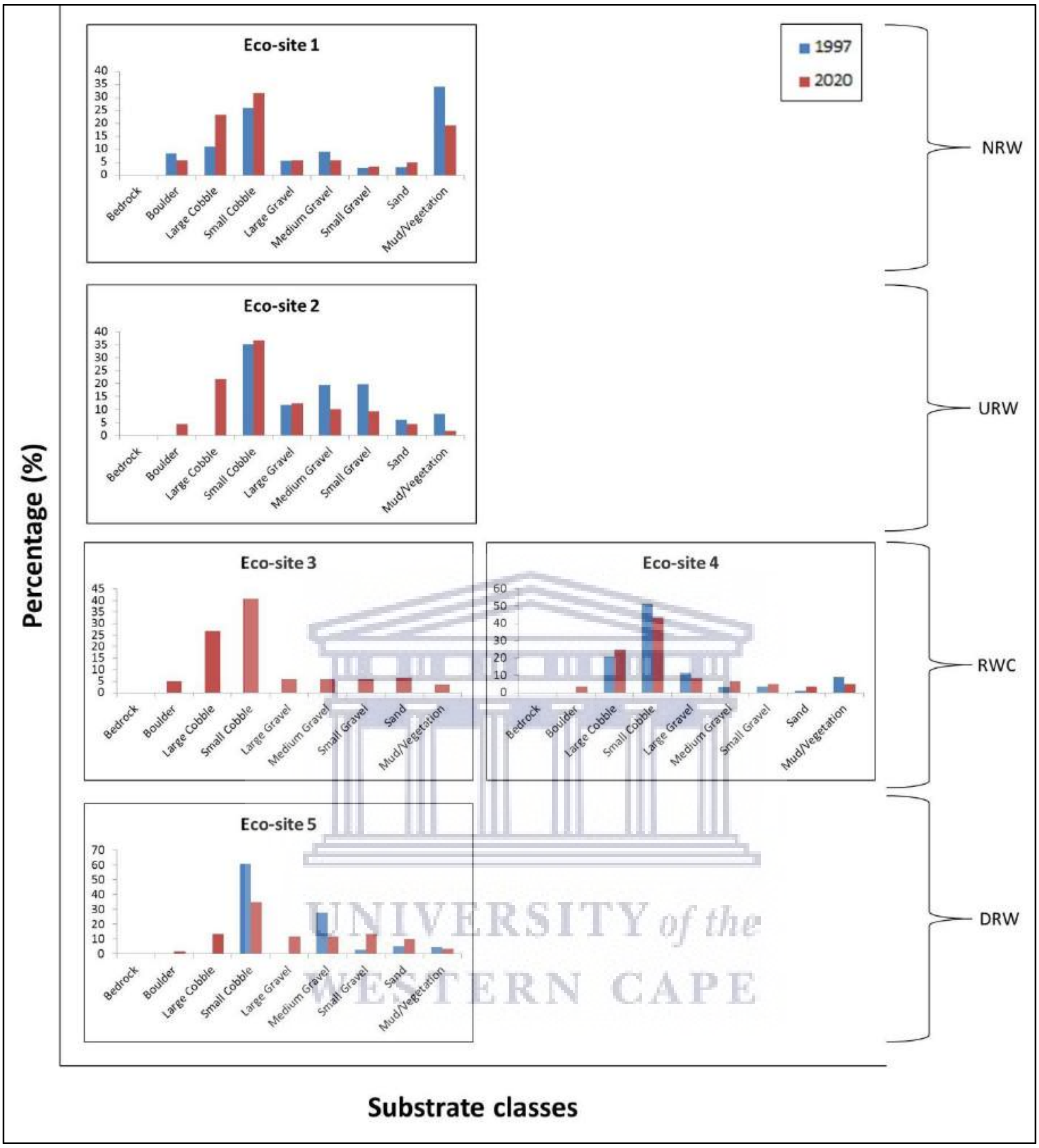

Figure 4.37 **Substrate composition at eco-sites (1-5) for 1997 and 2020. Eco-sites are grouped in their corresponding reach groups (NRW, URW, RWC and DRW).**

Fines sediment samples were collected for each eco-site (1-5) and the proportion of each substrate class calculated (Figure 4.38). The differences between eco-sites were attributed to the proportion of fine, medium and coarse sand. With distance downstream, fine and medium sand decreases and coarse sand increases. The proportions of clay and silt did not change much between the five eco-sites.

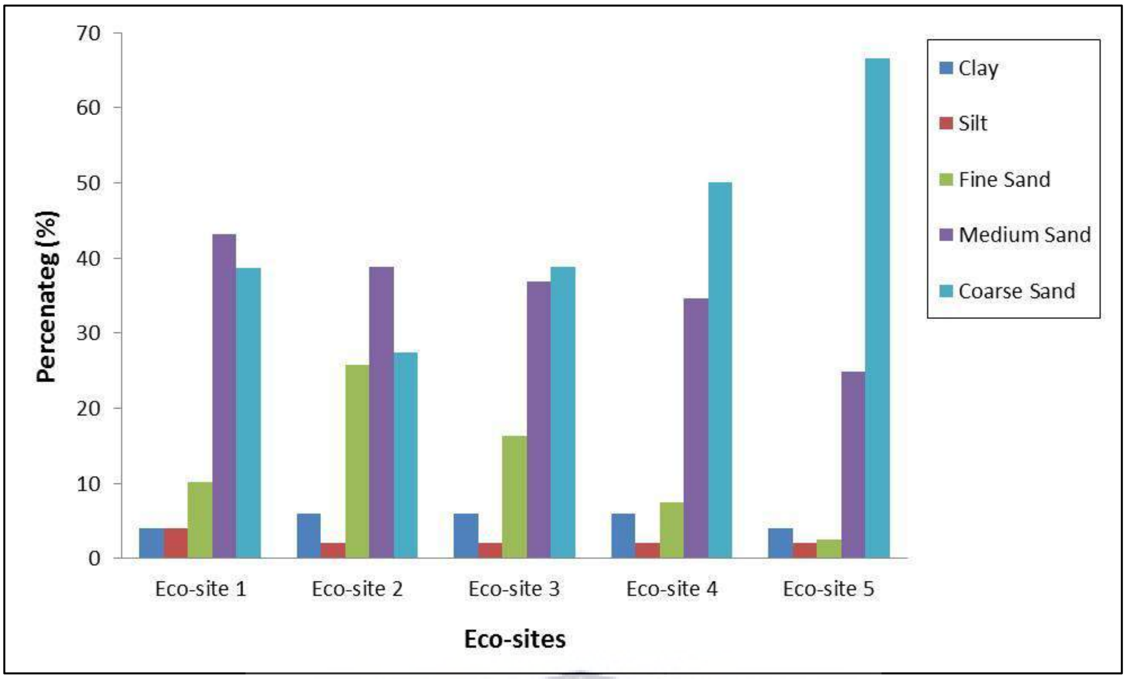

Figure 4.38 **Proportion of fine sediments at each eco-site (1-5).**

4.5.10 Summary of results

A regression analysis showed no major changes in the length of the main river channel over time; however, there was a significant decrease in the length of the flood channel.

A meta-analysis using a two-way ANOSIM showed no significant differences between 1998 and 2016 in river length and sinuosity, land use, lateral extent of floodplain, longitudinal continuity of backside woody vegetation and channel macro-features in reaches 1-16 overall or within any reach group (URW, RWC and DRW) individually. However, a regression analysis of each landuse type showed significant increases in urban and crops and livestock over time with a significant decrease in riparian woody vegetation. Simper analyses revealed that river length and sinuosity were greatest in the URW reach and decrease with distance downstream; crops and livestock, river and riparian vegetation, were most abundant in the URW reach; urban development, recreational area/parks and bare ground were most abundant in RWC and surface water was most abundant in the DRW. The extent of available floodplain was lowest in the RWC reach but the proportion of available floodplain decreased with distance downstream. The extent of bankside woody vegetation was highest in the URW reach and there was a decreasing trend with distance downstream. In URW and RWC bankside woody vegetation decrease from 1998 to 2005 and then increased in 2016.

Channel macro-features were most abundant in the URW reach and were more abundant in the RWC reach than in the DRW reach. Although bank stabilising structures occurred in all reach groups their extent was greatest in the RWC reach.

A two-way ANOSIM for 23 cross sections revealed that T1 were significantly different from T2 and in T3, but not from T4. A one-way ANOSIM comparing cross-section between T2 and T3 showed no significant differences in any of the reach groups (URW, RWC and DRW). A one-way ANOSIM showed that T1 and T4 were significant different in the RWC reach but not in the URW and DRW reaches. SIMPER showed that the differences in RWC were because of the increase in bankfull width, channel capacity and number of terraces and the decrease bank heights and bank slope. For four cross-sections in the DRW there were no significant differences between T3 and T5 but T1 and T5 were significantly different, again because of increase in bankfull width, channel capacity and number of terraces.

A one-way ANOSIM showed no significant differences in the diversity of hydraulic biotopes and substrate composition for eco-sites 1, 2 and 4 overall between 1997 and 2020. There were also no significant differences in diversity of hydraulic biotopes and substrate composition between each reach groups. An assessment of fine sediment showed that fine and medium sand decreased with distance downstream and coarse sand increased.

4.6 Discussion

Urbanization reduces the capacity of a river catchment to absorb rainfall, which significantly increases runoff during rainfall events and thus the intensity of flooding events (Dunne and Leopold 1978; Leopold 1994; Paul and Meyer 2001; White and Greer 2006). Floods cause widespread hardship for people settled in flooded areas in the form of damage to property and loss of life (Baoji 2005, OECD 2016, Dottori *et al.* 2018).

The Lourens River has been subjected to changing landuse since the early 1700s and the natural Fynbos vegetation has given way to agriculture, forest plantations and urban development (Tharme *et al.* 1997 Brown and Magoba 2009; Schaber 2015). According to Schaber (2015), Fynbos/shrub coverage was reduced by more than half its size from 1938 to 2010. Over the last 45 years there have been no major changes in the extent of agriculture although there was a shift from orchards to vineyards (Schaber 2015) in response to the international demand for wine (Anderson and Nelgen 2011; Vink *et al.* 2012; Lubinga *et al.* 2019). Schaber (2015) also found that forest plantations reached their maximum size in the 1970s and 80s and have declined steadily since, whereas urban development has increased by roughly eight-fold over the past eight decades. Areas of grass cover (pasture/open space) have declined over time and cleared areas increased (Schaber 2015). These landuse changes meant that areas with high rainfall absorption capacity, such as Fynbos and forests decreased over time and areas with moderate to low rainfall absorption capacity increased; e.g., agricultural fields, cleared land and urban development) increased (Gregory and Walling 1973; Branson *et al.* 1981; Allan 2004). It is clear that landuse change in the catchment has increased the overall runoff potential, which has led to an increased risk of flooding (Allan 2004; Brown and Magoba 2009; Schaber 2009). This is evident from numerous flood studies conducted on the Lourens River, e.g., CSIR (1982), Compion and Rooseboom (1996), Pitman (1997), SSI (1998), Pegram (2000), IWEE (2014), Du Plessis *et al.* (2014), Schaber (2015) and Hutchings *et al.* (2016). Schaber's (2015) findings are supported by the assessment of landuse from this study, which showed a dramatic decrease in riparian woody vegetation in the upper reaches and increases in agriculture and urban development in the middle and lower reaches respectively. Loss of riparian vegetation as a result of deforestation in the upper catchment is mostly likely because forest plantations are no longer deemed profitable in the Western Cape

(DWAF 1996; van Wilgen and Richardson 2012) and many plantations have been abandoned and/or handed over to conservation agencies that do not have the resources needed to rehabilitate these areas (Kraaij *et al.* 2011; van Wilgen and Richardson 2012).

The risk of flooding along the main Lourens River channel was further exacerbated by the shortening and fragmentation of the old distributary (flood channel), which would have conveyed floodwaters away from the main channel during large flood events to the ocean in the region of modern-day Gordon's Bay (Brown and Magoba 2009; Schaber 2015; Appx. Figure 3). That this and other distributaries carried excess floodwaters is suggested by the 36 m^3/s carrying capacity of the historic bridge on the Main Road in Somerset West (IWEE 2014), which is much too small to have conveyed even naturally-occurring floods with a return-period of >1:5 years. This highlights the necessity for urban planners to understand and consider the wider nature and functioning of rivers flowing through urban areas and incorporate these into urban design (Giller 2005; Wohl *et al.* 2005; Dollar *et al.* 2007; Francis 2014; Day *et al.* 2016) as failure to do so leads not only to increased risk for the residents but also to increased risk to the ecological functioning of rivers and the ecosystem services they support (Wohl *et al.* 2005; Palmer *et al.* 2010; Francis 2014; Vermaat *et al.* 2016). In the case of the Lourens River, failure to identify and protect the old distributary and to include it in the planning of the town's development means that not only is the risk of flooding and flood damage in the main channel increased but that there is the potential that, under a large flood event, the distributary will re-activate. If this were to happen it will put people at risk *inter alia* a newly-constructed hospital, old age home and Nomzamo township. The 162 m^3/s (i.e., ~63% lower than the estimated 1:50 year flood) flood event in November 2013 necessitated the evacuation of patients from the hospital and caused extensive damage to the hospital itself, farms and urban areas in the surrounds (Du Plessis *et al.* 2014). A similar set of events occurred in Bihar, India, where heavy precipitation in the Kosi River catchment caused reactivation of old distributary that had been abandoned for >100 years and mass flooding of a large portion of Bihar (Government of Bihar 2010).

There were no major changes in the extent of available floodplain between 1998 and 2016 but, throughout the study area, the floodplain was smaller than that recommended by del Tanago and de Jalon (2006); particularly in the RWC and DRW reaches. The DWR reach had the largest remnant floodplain, as is expected because floodplains are generally more extensive on the lower parts of the catchment (Schumm 1977; Frissel *et al.* 1986; Vannote *et al.* 1980; del Tanago and de Jalon 2006), but RWC had the lowest remaining floodplain despite it being downstream of URW. RWC is the section of main river channel that flows through the heart of Somerset West where urban development is greatest and the channel is confined, which was why the flood alleviation measures focused on this reach. So extensively confined is RWC that recommendations to incorporate multi-stage channels were rejected on the basis of property constraints and land expropriation was considered to give the river the space it needed (Brown *et al.* 2000; CCA 2000). It was also proposed to use open areas such as Reitz Park in the RWC; and Victoria Park in DWR as flood detention areas (CCA 2000). These recommendations were initially rejected although the Victoria Park option has subsequently been included in sub-phase 1J.

An assessment of bankside woody vegetation showed an apparent anomaly with a decrease in the RWC reach. This is because all invasive alien trees and shrubs and some mature indigenous shrubs and trees were removed during construction, particularly where river banks were excavated to increase conveyance. Post-construction the river banks were extensively re-vegetated with indigenous vegetation but the young trees and shrubs did not show up clearly on the aerial photographs. There was, however, an uptick in bankside woody vegetation in the RWC in 2016, which suggests that the re-vegetation program has been successful and that in five to ten years a similar assessment will show increased woody vegetation in the RWC reach, provided of course that the saplings are cared for (Meek *et al.* 2013; Day *et al.* 2016). Another anomaly is the increase in bankside woody vegetation in the DRW reach, which is difficult to explain in the context of management of the Lourens River. The explanation may be that rivers function as conduits for dispersal of propagules and that positive feedback loops promote the rapid spread of aliens along the riparian corridors through human-induced habitat alteration and increased propagules pressure (Planty-Tabacchi *et al.* 1996; Zavalenta *et al.* 2004; Richardson *et al.* 2007; Meek *et al.* 2013). Thus, it is possible that increased propagation downstream is a result of clearing activities upstream although this would require confirmation and other factors may be at play.

Collectively, the extent of channel macro-features, particularly lateral/alternate bars, increased over time for all study reaches. This may be because loss of riparian vegetation / deforestation in the upper catchment exposed bare ground, increasing soil erosion and thus sediment supply to the river (e.g., Goisan *et al.* 2012; Fryiers and Brierley 2013; Zeraatpishe *et al.* 2013; Restrepo *et al.* 2015; Wohl *et al.* 2015), which may have contributed to the formation lateral/alternate bars (Allan 2004; Habersack and Piegay 2008; Schumtz and Sendzimir 2018). This notion is supported by the data on deforestation and the increase in fine sediment at eco-sites 1, 4 and 5. Added to this, it is possible that the decrease in riparian woody canopy cover meant that the river channel was more visible in the aerial photographs, resulting in the recording of more channel features. Contrary to the natural physical character of river (Vannote *et al.* 1980), fine sediment samples showed a decrease in the proportion of fine and medium sand and an increase in coarse sand with distance downstream, which suggests that the river is in an erosive state and/or there has been an influx of sediment. Another explanation could be that flood alleviation activities, i.e., widening of river channel, grading of banks and bank stabilisation may have led to an increase in sediments in the river channel. The cycle of sedimentation and erosion is often associated with construction and development (Wolman 1967; Roy *et al.* 2009; Gregory 2011). While the deposition of sediments is important for the formation of aquatic habitats, too much sediment can be detrimental to health of the ecosystems (Allan 2004; Brown and Magoba 2009).

As expected, there were considerably more bank stabilising structures in the RWC reach than upstream and downstream. This highlighted the erosive nature of this reach (and thus the need for reliance on bank stabilising structures). This was not unexpected as, apart from the confinement of the channel highlighted by landuse and the lateral extent of available floodplain, the RWC reach is downstream of where the old distributary diverged from the main river channel (Compion and Rooseboom 2009; CCA 2000), which means that it is almost certainly carrying a greater proportion of volume of water during flood events than it would have naturally. The presence of bank stabilizing structures in all three reaches is evidence that the river is in an erosive state. However, these structures also speed up the flow of water, which can lead to bank erosion downstream of them (Schumtz and Sendzimir 2018). Localised erosion was observed on the opposing bank downstream of most gabion mattresses and walls although not where rip-rap was used. Most of these bank structures were gabion mattresses, walls and loffelstein walls with rip-rap only occurring in the URW at Radloff Park. Gabion mattresses and walls also appear more prone to damage from floodwaters and flood debris as highlighted by the repair work to these structured necessitated after the 2013 flood (sub-phases 1G and 1F; IWEE 2014), which did not affect the rip-rap sections. There is other anecdotal evidence of unintended change linked to exceeding channel capacity. According to Schaber (2015), Frans van Moltke (City of Cape Town, pers. comm.) believes that that the main channel of the Lourens River is deepening. If this is so, it is likely also a consequence of the complete closure of the distributary and the confinement of the river channel (e.g., Espito *et al.* 2020).

The differences between the T1 and T2 cross-sections were expected because the T2 cross-sections were the engineering drawings that advocated increasing the conveyance of the river channel by increasing the width and the depth (CCA 2000; Brown *et al.* 2000). Similar differences were evident between the cross-sections in T1 and T3, which represent the altered engineering drawings after inclusion of some ecological principles; chiefly no deepening and multi-stage terraced banks (CCA 2000; Brown *et al.* 2000; SSI 2001). However, the T2 cross-sections were not significantly different from those in T3, even though the one supposedly represents hard engineering approach and the other a softer approach. This is mainly because bankfull width and channel capacity dominate the dissimilarity between cross-sections and neither of these changed substantially between T2 and T3. However, smaller differences between T2 and T3 show that T3 incorporated a higher number of terraces and gentler bank slopes, which is in accordance with the ecological suggestions. This suggests that although the T3 cross-sections were adjusted to incorporate ecological principles these adjustments were not major and that a lot is possible in terms of maintaining functioning ecosystems without changing plans too much. Taken all together, the T1 cross-sections did not differ significantly from those in T4 because large sections of the river had not had any river works done to them. However, there were significant differences T1 and T4 cross-sections in the RWC reach with T4 having significantly greater channel capacity, bankfull width and number of terraces and significantly gentler river bank slopes. Although the river has extensively been engineered the incorporation of ecological principles reduced the visual and ecological impacts relative to T2 with a multi-stage channel design and the extensive re-vegetation.

While the results show that ecological principles were incorporated post initial engineering (T2) into the final product (T4), these did not include the full suite of recommendations. For instance, recommendations to use rip-rap instead of gabions/loffelstein walling was rejected, although there is some evidence that rip-rap may offer a more robust and ecologically-friendly alternative.

In general, record keeping and timelines in the official documentation did not always reflect what was actually done. For instance, the initial engineering proposals included the earth berms at Radloff Park which were constructed but there is no official record of their construction. Another example of the disconnect between planning and implementation is sub-phase 1D, which was awarded the 2012 ‘Sali Shield’ only for the river reach to be redirected and straightened with a series of gabions on the left bank in sub-phase 1E. It is not certain whether this was necessitated by flood damage as the reasons are unclear and undocumented, but it does demonstrate that plans are not always followed and that softer restoration efforts that potentially support ecosystem remain at risk of undoing. For instance, gabions walls (two stages) were constructed in the DRW reach where no river works were planned. Whether this was part of the flood alleviation scheme or a separate contract is uncertain, although given that the materials used to construct the gabions differ from the river cobbles used in the gabions in RWC suggest it was separate. There was also a berm constructed on the left bank of Vergelegen Wine Estate above the wood bridge by CoCT (Eben Olderwagen, Vergelegen Wine Estate, pers. comm.) and several other structures in URW and DRW were installed without due process. It is important to understand that any newly constructed bank structure or modification to the river channel will affect upstream and downstream reaches (Semonin 1989, National Research Council 1992, Uys 2003; Day *et al.* 2016) and these sorts of disconnect between different projects have the ability to undermine the efforts of many involved throughout the flood alleviation scheme – similar to the infilling of the distributary.

In conclusion, urban rivers are important components of urban landscapes and it is crucial that they function as integral parts of urban design (Francis 2014). Ecological-engineering collaborations, such as the Lourens River flood alleviation scheme, enhance our understanding on how to work with rivers to reduces risks and enhance ecological functioning and societal benefits in heavily modified systems.

5 Ecological benefits of flood alleviation measures on the Lourens River

5.1 Introduction

For centuries, rivers have been modified and manipulated to meet the socio-economic needs of society (Petts 1990; Wohl 2005; Richardson *et al.* 2007; Addy *et al.* 2016; Staentzel *et al.* 2019). The range of human-related pressures on rivers include landuse practices such as cultivation, plantations and urbanization, point source and diffuse pollution, water abstraction (e.g., direct abstraction, irrigation furrows), flow regulation (e.g., impoundments, barrages, diversion channels and stormwater conduits), physical modification (e.g., infilling of floodplains, channelisation and canalisation), over-harvesting of river resources and invasive plant and animal species (Nijland and Cals 2000; Day *et al.* 2005; Sabater and Stevenson 2010; Schumtz and Sendzimir 2018). The negative impacts of human activities on the structure and function of rivers are well recognized (Duan and Tukara 2020; Ekka *et al.* 2020) and have resulted in freshwater ecosystems being among the most degraded in the world (Sabater and Stevenson 2010; Schmutz and Sendzimir 2018). Rivers, in particular urban rivers, have experienced significant losses of biodiversity, which have reduced their resilience and productivity and severely impacted the ecosystems services they provide (Giller 2005; Vermaat *et al.* 2016; Ekka *et al.* 2020; Formosa and Kelly 2020), including nutrient cycling and flood regulation.

Accordingly, restoration of river systems within what is possible, given the many changes that have taken place, has become a priority for many water authorities and river managers (Boon *et al.* 2012; Schumtz and Sendzimir 2018; Yochum 2018; Pietersen 2018; SER 2019). Worldwide projects are underway to try to restore river ecosystems and the services they provide (Ralston and Sarr 2017; Hand *et al.* 2018; Mondal and Patel 2018; SER 2019; Staentzel *et al.* 2019; Formosa and Kelly 2020; Korzeniewska and Harnisz 2020). This focus on river rrestoration is in recognition of the importance to humans of intact, resilient and functioning rivers and the societal benefits that accrue from them, even in urban and peri-urban areas (Rutherfurd *et al.* 2000; Ward *et al.* 2001, Giller 2005, Violin *et al.* 2011; Palmer *et al.* 2014; Formosa and Kelly 2020).

Restoring rivers requires an understanding of the life histories of animals and plants that inhabit them and their interaction with the physical environment (National Research Council 1992; Rutherfurd *et al.* 2000; Falk *et al.* 2006; Addy *et al.* 2016; Day *et al.* 2016; Vermaat *et al.* 2016). Each species has unique traits and exploits a set of physical habitats (e.g., riffles, pools and backwaters) and food sources (e.g., algae, leaf-litter and fauna) that may change depending on life stage. For instance, fish may use different habitats and consume different food items during spawning, early-life stages and adulthood (Rutherfurd *et al.* 2000; Rosenfeld and Hatfield 2006; Espirito-Santo *et al.* 2017; Wang *et al.* 2020). Similarly, many insects have an aquatic larval stage and an aerial adult stage (Rutherfurd *et al.* 2000; Gerber and Gabriel 2002; Verberk *et al.* 2008; Khelifa 2019). If one of the habitats or food sources needed to complete a species' lifecycle is missing then the species may die out (Rutherfurd *et al.* 2000; Falk *et al.* 2006; Addy *et al.* 2016). Furthermore, plants and animals in the same ecosystems do not exist in isolation from each other, which means that that the loss or decline of one species invariably has knock-on effects for others (Falk *et al.* 2006). For instance, the loss of macroinvertebrates could result in the decline of fish or birds that eat them (Biggs *et al.* 2000; Nery and Schmera 2016; Hong *et al.* 2020; Gal *et al.* 2020) and loss of predatory fish could also affect macroinvertebrates (Eby *et al.* 2006; Shelton *et al.* 2015; Nery and Schmera 2016). Thus, species diversity is dictated by underlying abiotic conditions, which may have feedback loops that lead to changes in river morphology and the ecosystem (Rutherfurd *et al.* 2000; Addy *et al.* 2016).

Process-based ecological river restoration efforts tend to focus on natural (or quasi-natural) flow and sediment regimes, a diverse array of habitats in the river channel and riparian zone, an appropriate riparian zone, free passage between habitats, connectivity with the floodplain, and appropriate water quality and temperature regimes (Nijland and Cals 2000; Rutherfurd *et al.* 2000; Addy *et al.* 2016; Day *et al.* 2016). This is done on the assumption that near natural physical and chemical processes will encourage and support natural fauna and flora (Rutherfurd *et al.* 2000; Kondlof *et al.* 2006; Addy *et al.* 2016; Beechie *et al.* 2016; Day *et al.* 2016; Ralston and Sarr 2017).

River engineering that considers ecological integrity tends to rely heavily on the re-establishment of vegetation after construction (Vosse *et al.* 2008; Ruwanza *et al.* 2013; Palmer *et al.* 2014; Lapin *et al.* 2016; Weidlich *et al.* 2020). This is mainly because using indigenous plant species to re-vegetate river banks provides a number of advantages (Tabacchhi *et al.* 2000; Rutherfurd *et al.* 2000; Bendix and Stella 2013), such as stabilising the river banks by acting as a form of erosion control (Hicken 1984; Rutherfurd *et al.* 2000; Bendix and Stella 2013); decreasing flow velocity and erosive power by increasing channel margin roughness (Allen and Leech 1997; Tabacchhi *et al.* 2000; Uys 2003; Bendix and Stella 2013); increasing infiltration rates into adjacent river banks, and promoting groundwater recharge and reducing surface runoff (Burgess *et al.* 2001; Hultine *et al.* 2004; Richardson *et al.* 2007; Bendix and Stella 2013). Banks that are well-vegetated with local species also reduce summer water temperatures by providing shade (Richardson *et al.* 2007; Bendix and Stella 2013; Moggridge and Higgit 2014; Addy *et al.* 2016), and ensure that leaf fall, fruiting and flowering of indigenous plants coincide with the food requirements of indigenous fauna (Rutherfurd *et al.* 2000; Richardson *et al.* 2007).

Post-construction evaluation of whether expected improvements in ecosystem functioning and biodiversity actually manifested following physical interventions is an essential component of river restoration. Without evidence of success, river restoration projects are at risk of losing public interest, given the expense associated with these projects (Woosley *et al.* 2007; Lüderitz *et al.* 2011; Coux *et al.* 2016). Lack of post-construction data also forgoes opportunities for education and increases the risks of making the same mistakes in future restoration efforts. Although, it is widely agreed that demonstration of the success of restoration is vital, it is often either not done (Bash and Ryan 2002; Downs and Kondolf 2002; Woosley *et al.* 2007; Coux *et al.* 2016) or lacking in the scientific rigour needed to demonstrate success or failure (Bernhardt *et al.* 2005, Bernhardt and Palmer 2011; Ja¨hnig *et al.* 2011; Vermaat *et al.* 2016). Reasons for this include lack of funding, time constraints, labour shortages, the lack of guidelines for evaluation and failure to set clearly defined project objectives before restoration measures are taken (Bash and Ryan 2002; Woosley *et al.* 2007).

In Somerset West and Strand in the Western Cape, South Africa, recurrent flooding and risk of large-scale damage to property and loss of life (Compion and Rooseboom 1996; Schaber 2015) prompted implementation of a flood alleviation scheme that focussed on increasing channel capacity and off-channel floodplains (CCA 2000). A soft engineering approach was adopted and aspects of river restoration were added to the original design of channel modification (CCA 2000; IMIESA 2011; see Chapter 4). The project objectives were expanded to include promotion of a diverse array of fauna and flora through increasing habitat diversity and improving passage for organisms between the river, its riparian zone and floodplain (Brown *et al.* 2000; CCA 2000; IMIESA 2011). Phase 1 of the Lourens River flood alleviation scheme was divided in nine sub-phases (A-J; CCA 2000, CoCT 2015) and each with two components; 1) a construction component to increase conveyance of floodwaters and promote habitat diversity, and 2) a landscaping component to re-vegetate the river banks and channel margins with low maintenance self-sustaining indigenous species that would provide habitat for local fauna (CCA 2000; CoCT 2009), and create footpaths for recreation along the river.

A nursery was established to propagate indigenous seeds, cuttings and bulbs collected from the river to ensure genetic consistency of the plant species used in the re-vegetation (Brown *et al.* 2000; IMIESA 2011), and based on the premise that local plants are already adapted to the prevailing environment (Rutherfurd *et al.* 2000; Falk *et al.* 2006; Day *et al.* 2016). A list of grasses, herbs, shrubs and trees was provided (for planting in different lateral zones up the river banks based on the velocities that they are able to withstand (CCA 2000; Brown *et al.* 2000; Reinecke 2013; Appx. Table 1). The revegetation plan called for trees and shrubs to be planted in clumps on the upper dry bank (Figure 5.1). Shrubs were to be planted in clumps on the lower dry bank to create open shrubby areas with views of the river and a dense mixture of shrubs, herbs and grasses were to be planted along the dry season's water's edge to stabilise the river banks and protect against erosion. The plan included recommended planting densities (Table 5.1) and the time of the year for planting. In the Western Cape, the best times to plant new vegetation are either spring after the winter rains so that new plants have moisture to establish before summer or autumn, and the onset of winter rains (Grobler, D. pers.comm. Blue Science, Feb 2021). For the Lourens River, the higher portions of the river banks were targeted for replanting in autumn (April and May) and lower parts in spring (September; Figure 5.1). CCA (2000) also recommended that that landscape contractors be tasked with routine maintenance, watering and replacement of plants for the first two years, after which routine maintenance would become the responsibility of the municipality.

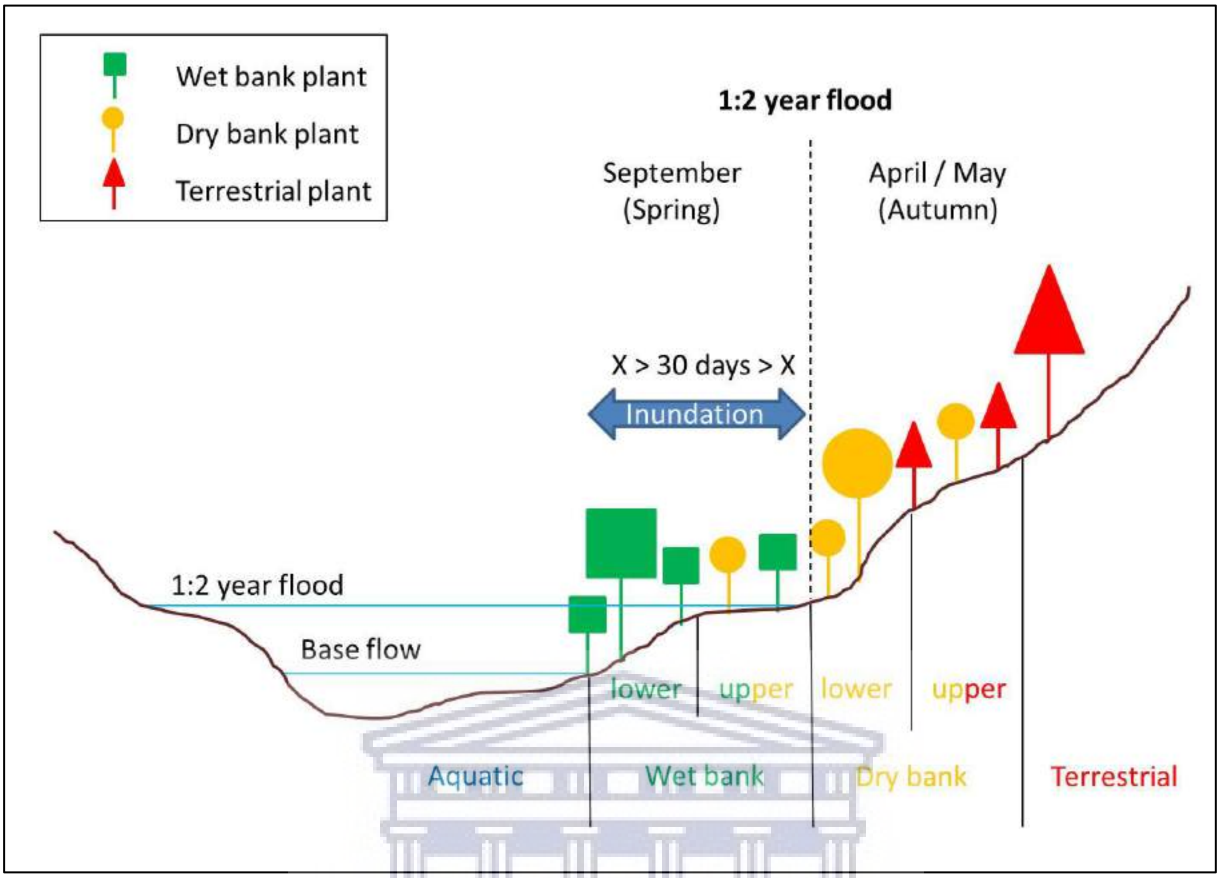

Figure 5.1 **Schematic indicating four main riparian zones (Aquatic, Wet bank, Dry bank and Terrestrial) and recommended planting times (Reinecke 2013).**

Table 5.1 **Recommended planting densities (Brown *et al.* 2000; CCA 2000).**

Growth form	Planting densities
Trees	Plant 1.5 m apart in staggered rows (i.e., ~5 per 6 m²)
Shrubs	~3.5 m² (depending on size and shape)
Herbs in single containers	One plant per 3.5 m²
Ground cover in single containers	One plant per 5-7 m²
Herbs and grounds cover in 6-packs	Six plants per 10 m²
Veld sods	One plant per 3-7 m²
Shrubs and herbs	3 shrubs and 5 herbs per m² = 8 m²
Shrubs and trees	18 shrubs and 5 trees per 6 m²
Trees, shrubs and herbs	18 shrubs and 5 trees and 30 herbs per 6 m²
Palmiet	1-2 m apart
Bulrushes, reeds and sedges	Planted in sods 0.4-0.5 m apart, or as circumstances dictate.

By 2019, the river works and associated landscaping of Phases 1A-H were completed for much of the middle reaches of the Lourens River. In 2011, a faunal assessment of river works in Phase 1D were undertaken by Southern Waters (2011) to determine the extent to which, if at all, species that were resident before construction could return post-construction. The study found that river works resulted in significantly improved marginal and instream habitat, which was manifested by the healthy populations of some species such as the indigenous fish, Cape kurper (*Sandelia capensis*) (Southern Waters 2011). However, the newly created stony substrata appeared to be compromised for some taxa by the growth of macro-algae (mainly the cyanobacterium, *Nostoc* sp.) on the rock surfaces and by an interstitial layer of sand observable below the upper rock layer. The Southern Waters (2011) study assessed aquatic fauna at a reach scale almost immediately after construction. The success of a restoration project needs to be assessed using a large-scale perspective (i.e., catchment) and several years after intervention (Kondolf *et al.* 2006; Woosley *et al.* 2007; Beechie *et al.* 2010; Modal and Patel 2018; Petersen 2019). Until now, there has been no follow up study to assess the efficacy of the rivers works in promoting indigenous biodiversity at a large scale. Thus, the aim of this chapter is to describe and compare riparian and aquatic biota before and after the river works in order to evaluate the success of the river works in providing habitat for indigenous plants and animals.

Two hypotheses are tested:

1. River works and associated landscaping improved the diversity of riparian plant species present and recruiting along the river and thus contributed to a higher Ecological Integrity score.
2. River works and associated landscaping improved the diversity of aquatic invertebrates thus contributing to a higher Ecological Integrity score.

5.2 Study area

The study focussed on the middle and lower reaches of the Lourens River in Somerset West/Strand, South Africa, where flood alleviation measures are planned or have been completed.

The study area is based on the location of completed river works and the points of collection of historic ecological data (Tharme *et al.* 1997; RHP 2003; Ollis 2005; Southern Waters 2011; Appx. Table 14), and is arranged into 16 study reaches (Figure 4.8 and Figure 4.9), four reach groups (NRW, URW, RWC and DRW; Table 4.7) and five eco-sites (Figure 4.8 and Figure 4.9). Eco-sites 1, 2, 3, 4 and 5 are in reaches 10, 12, 13, 14 and 15, respectively. River works have been completed in Reaches 13 and 14 (RWC).

The locations of data collection for previous ecological studies did not always correspond with each other (Figure 5.2; Table 5.2 and Table 5.3). Sites from Tharme *et al.* (1997) correspond with eco-sites 1, 2, 3, 4 and 5 (with no invertebrate sampling at eco-site 3); Ollis (2005) with eco-sites 1, 3 and 5 and; Southern Waters (2011) eco-sites 2 and 4. Tharme *et al.* (1997) and Ollis (2005) studies' took place prior to any river works being undertaken while the assessment of Southern Waters (2011) was done after completion of sub-phase 1D between Andries Pretorius Bridge and Railway Bridge (Table 4.4 and Table 4.5)

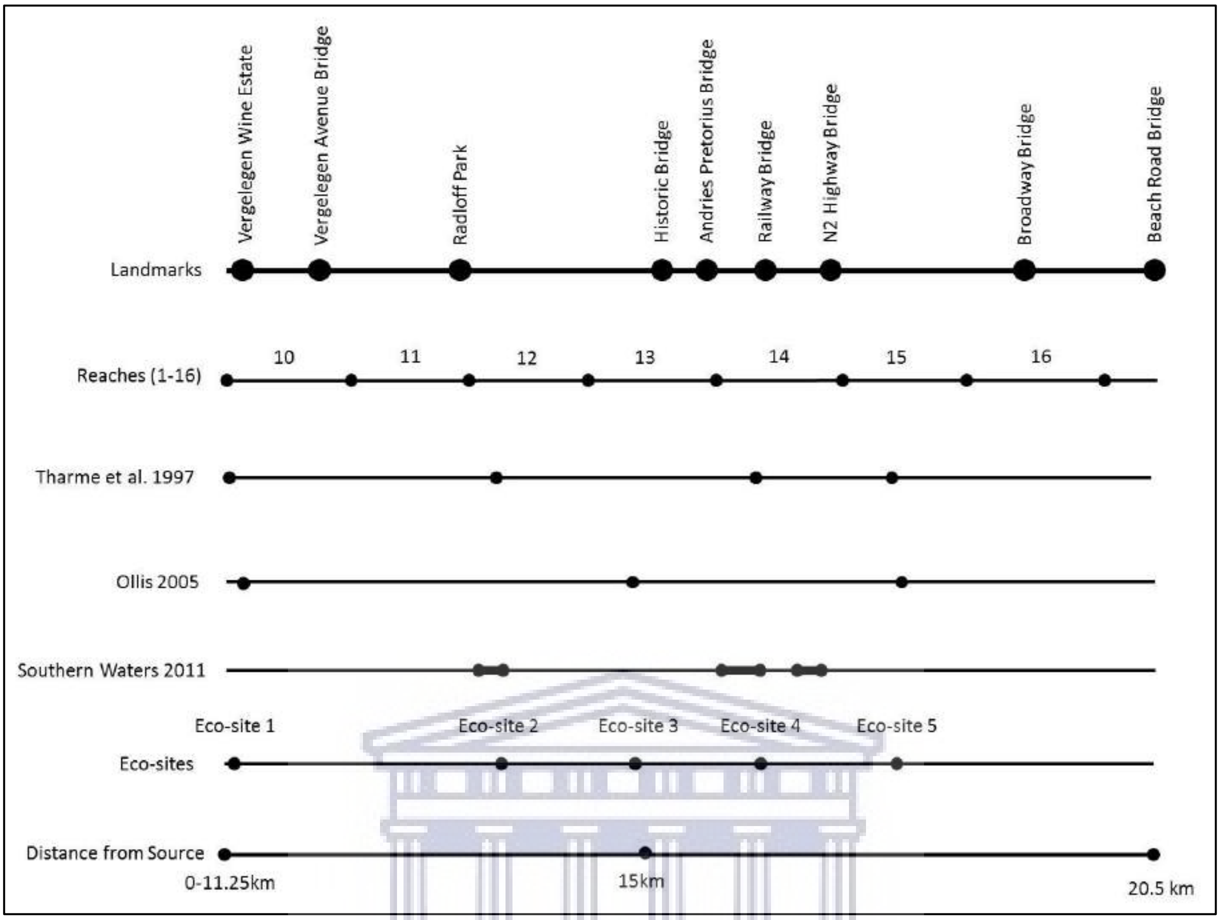

Figure 5.2 **Location of landmarks, discussion reaches (1-13), study reaches (10-16), sites from previous ecological studies (Tharme et al 1997; RHP 2003; Ollis 2005; and Southern Waters 2011) and eco-sites 1-5.**

Table 5.2 **Eco-sites 1-5 and corresponding study site names from previous ecology studies.**

		Corresponding sites from previous ecological surveys			
Eco-sites	Description	Tharme *et al.* (1997)	RHP (2003)	Ollis (2005)	Southern Waters (2011)
1	Vergelegen Wine Estate	Site 2	Site 2	Site 2	
2	Radloff Park	Site 3			Radloff Park
3	Stormhaven Park		Site 3	Site 3	
4	Reitz Park	Site 4			Phase D - REHAB
5	Victoria Park	Site 5	Site 4	Site 4	

Table 5.3 Historic data for Chainage 1100-8750 and eco-sites 1-5

Type	Date	Eco-sites/Chainage	Available data	Reference
Flood Alleviation Measures	2000	Chainage 1100-8750	Descriptive information of flood alleviation scheme	Brown *et al.* 2000
	2000	Chainage 1100-8750	Descriptive information of flood alleviation scheme	CCA 2000
	2008	Chainage 4440-5300	Lourens River flood alleviation measures – Phase 1D Landscaping and horticultural works: Tender report of CONTRACT NO. 314Q/2008/09	CoCT 2008
	2008	Chainage 4440-5300	Lourens River flood alleviation measures – Phase 1D Landscaping and horticultural works: Landscape plan	Megan Anderson Landscape Architects 2008
	2011	Chainage 1100-8750	Descriptive information of flood alleviation scheme	IMESA 2011
	2011	Chainage 4000-4400	Lourens River flood alleviation measures – Phase 1E Landscaping and horticultural works: Landscape plan	Megan Anderson Landscape Architects 2011
	2011	Chainage 4000-4400	Lourens River flood alleviation measures – Phase 1E Landscaping and horticultural works: Typical cross-section profile	Megan Anderson Landscape Architects 2011
Ecological data	1997	Eco-sites 1 to 5	Percentage cover and abundance of vegetation species using the Braun-Blanquet method. Assessment of aquatic macroinvertebrates using SASS 4	Tharme *et al.* 1997
	2003	Eco-sites 1, 3 and 5	Assessment of aquatic macroinvertebrates using SASS 5	RHP 2003
	2005	Eco-sites 1, 3 and 5	Assessment of aquatic macroinvertebrates using SASS 5	Ollis 2005
	2011	Eco-sites 2 and 4	Assessment of aquatic macroinvertebrates using SASS 5 Assessment of ecological condition using the Habitat Integrity Assessment (Kleynhans 1996)	Southern Waters 2011

5.3 Data collection

Quantitative data were collected on the cover of riparian vegetation and macroinvertebrate community structure, and overall habitat integrity at two scales; a broad scale from reaches 10-16 and a fine scale at the five eco-sites. The methods used for collecting these data were kept as close as possible to those used to collect the historic data against which they were to be compared (e.g., Tharme *et al.* 1997, Brown *et al.* 2000, RHP 2003, Ollis 2005 and Southern Waters 2011; Table 5.4 and Appx. Table 14).

Table 5.4 Data collected location and corresponding historical data.

Type	Aspects measured	Location	Method of data collection used historically	Reference
Riparian vegetation	Percentage cover	Eco-sites 1-5	Braun-Blanquet cover-abundance method	Tharme *et al.* (1997)
Macroinvertebrates	Species richness and diversity SASS and ASPT Scores	Eco-sites 1-5	SASS 4	Tharme *et al.* (1997)
			SASS 5	RHP (2003); Ollis (2005); Southern Waters (2011)
Habitat Integrity	Habitat Integrity Scores	Eco-sites 1-5	Habitat Integrity Assessment method of Kleynhans (1996)	Tharme *et al.* (1997); Brown *et al.* 2000)

5.3.1 Riparian vegetation

Vegetation transects, each 50-m long, were laid parallel to the river channel. Fifteen transects were surveyed along the river with three transects in each of the reach groups NRW, URW and DRW, and six transects in RWC (Figure 5.3 and Table 5.5). Each eco-site corresponded with one vegetation transect. The dominant plant species present along each transect in the wet and dry bank zones on both banks were recorded. Cover and abundances data were converted to the Braun-Blanquet scores *post hoc* for the historical comparison (Table 5.6; Tharme *et al.* 1997).

Table 5.5 The location of the 15 vegetation sample transects in relation to the eco-sites (1-5), study reaches (10-16) and reach groups (NRW, URW, RWC and DRW).

Transects	Reach groups code names	Reach group names	Study Reaches (10-16)	Eco-site (1-5)
Plot 1	NRW	No River Works	10	Eco-site 1
Plot 2			10	n/a
Plot 3			10	n/a
Plot 4	URW	Upstream of River Works	11	n/a
Plot 5			11	n/a
Plot 6			12	Eco-site 2
Plot 7	RWC	River Works Completed	13	n/a
Plot 8			13	n/a
Plot 9			13	Eco-site 3
Plot 10			13 and 14	n/a
Plot 11			14	n/a
Plot 12			14	Eco-site 4
Plot 13	DRW	Downstream of River Works	15	Eco-site 5
Plot 14			16	n/a
Plot 15			16	n/a

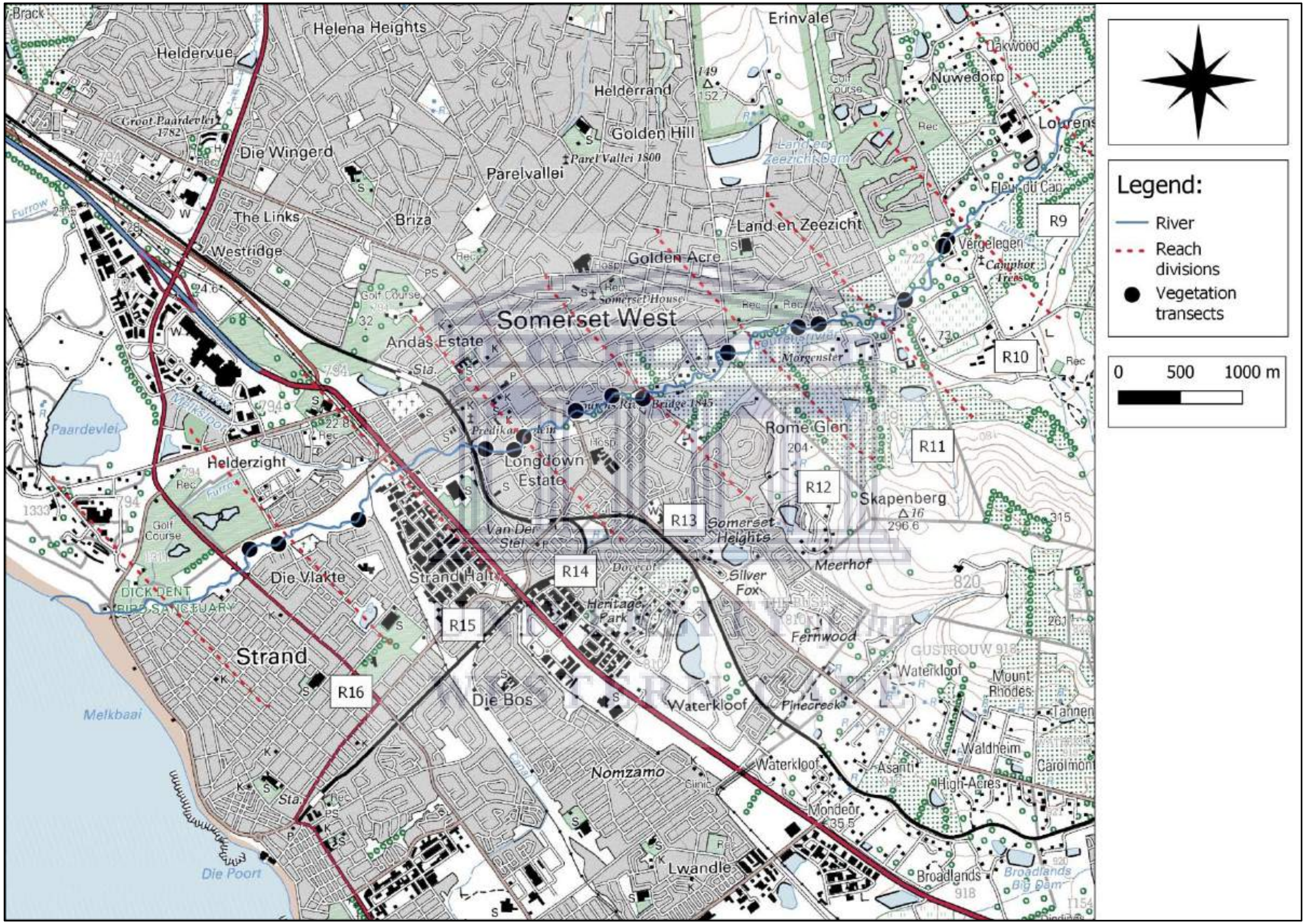

Figure 5.3 Location of fifteen vegetation transects and corresponding study reaches (9-16).

Table 5.6 Braun-Blanquet Scale (Braun-Blanquet 1932)

Braun-Blanquet Scale	Range of cover (%)
r	< 5%; very few individuals
+	< 5%; few individuals
1	< 5%; numerous individuals
2	5-25%
3	25-50%
4	50-75%
5	75-100%

5.3.2 Macroinvertebrate community structure

The macroinvertebrate community was sampled at each eco-site over a 100-m length of river using the SASS 5 (South African Scoring System, Version 5) sampling protocol (Dickens and Graham 2002). Samples were collected from three biotopes, stones (in and out of current), vegetation (marginal and aquatic) and gravel, sand and mud (GSM) using the following procedures:

- kick stones-in-current (SIC) for 2-5 minutes, depending on availability;
- kick stones-out-of-current (SOOC) for one minute;
- sweep marginal vegetation (IC and OOC) for 2m in total;
- sweep aquatic vegetation for 1m and stir and sweep gravel, sand and mud (GSM) for a total of one minute.

Specimens that may have been missed by the net were picked off stones during visual observations for about1 minute. Each sample (biotope) was placed in a separate sample tray for sorting and identification. Excessive debris was carefully removed from the trays ensuring that no organisms were removed in the process. Macroinvertebrates were identified in the field to Family level using an identification guide (Gerber and Gabriel 2002) for a period of 15 minutes or until no additional SASS taxa were identified for 5 minutes.

The standard SASS 5 scoring sheet was filled in (Appx. Table 15) and the abundance of each taxon was estimated as follows: A = 2–10 individuals; B = 11–100 individuals; C = 101–1000 individuals; and D = >1000 individuals. Each taxon was scored on a scale from 1-15 based their tolerances to pollution as follows:

- 1-5 = Highly tolerant to pollution
- 6-10 = Moderately tolerant to pollution
- 11-15 = Very low tolerance to pollution.

The SASS 5 method generates three standard scores; the Total SASS Score (summarised sensitivity score of all taxa present), the number of taxa and the average score per taxon (Equation 4, Dickens and Graham 2002). The three scores were calculated for each biotope and for all the biotope groups combined per eco-site.

$$ASPT = \frac{SASS\ Score}{Number\ of\ taxa} \qquad \text{Equation 4}$$

5.3.3 Habitat integrity

Habitat Integrity (HI) was assessed using the Habitat Integrity Assessment method (HIA; Kleynhans 1996). A HI assessment is based on a qualitative assessment of the assumed impact on river integrity for a number of criteria (i.e., water abstraction, flow and bed modification; Table 5.7).

At each eco-site scores from 0–25 was assigned to each criterion, with zero being no impact and 25 being severely impacted and used to calculate Habitat Integrity (Table 5.8) ranging from A (natural) to F (Equation 5):

$$Habitat\ Integrity = \frac{Rating\ for\ Criterion}{Maximum\ value\ (25)} \times Weight\ (\%) \qquad \text{Equation 5}$$

Table 5.7 Criteria and weights used for the assessment of instream and riparian habitat integrity (Kleynhans 1996).

Instream Criteria		Riparian Criteria	
Water abstraction	14	Indigenous vegetation removal	13
Flow modification	13	Exotic vegetation encroachment	12
Bed modification	13	Bank erosion	14
Channel modification	13	Channel modification	12
Water quality	14	Water abstraction	13
Inundation	10	Inundation	11
Exotic macrophytes	9	Flow modification	12
Exotic fauna	8	Water quality	13
Solid waste disposal	6		
Total (%)	100	Total (%)	100

Table 5.8 Habitat Integrity categories (A-F) and overall ratings (%) (Kleynhans 1996).

Ecological Category	% Score	Description of the habitat
A A/B	92-100% 87-92%	Still in a Reference Condition.
B B/C	82-87% 77-82%	Slightly modified from the Reference Condition. A small change in natural habitats and biota has taken place but the ecosystem functions are essentially unchanged.
C C/D	62-77% 57-62%	Moderately modified from the Reference Condition. Loss and change of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged.
D D/E	42-57% 37-42%	Largely modified from the Reference Condition. A large loss of natural habitat, biota and basic ecosystem functions has occurred.
E E/F	22-37% 17-22	Seriously modified from the Reference Condition. The loss of natural habitat, biota and basic ecosystem functions is extensive.
F	0-17%	Critically/Extremely modified from the Reference Condition. The system has been critically modified with an almost complete loss of natural habitat and biota. In the worst instances, basic ecosystem functions have been destroyed and the changes are irreversible.

5.4 Data analysis

Multivariate statistics were used to test if river works and associated landscaping improved the diversity of aquatic and riparian vegetation and benthic aquatic macro-invertebrates, and thus contributed to a higher Ecological Integrity. Analysis of similarities (ANOSIM; Equation 2) (Clarke and Warwick 2001, Clarke and Gorley 2006), a non-parametric permutation similar to the standard univariate 1- and 2-way ANOVA (analysis of variance) tests, was used to determine if there were significant differences in the composition, diversity and abundance of vegetation and macro-invertebrates between the three reach groups (URW, RWC and DRW) and the five eco-sites over time (Table 4.7 and Figure 4.8), where relevant. The ANOSIM analysis was used to test whether we can reject the null hypothesis or not. Where analyses was run to test for significant differences using p-values, data was considered statistically significant at both $p \leq 0.05$ and $p \leq 0.10$ because of the low sample replicates of both vegetation and macro-invertebrates and varying locations where data is available.

Calculated from a Bray-Curtis dissimilarity matrix, a similarity percentages routine (SIMPER) analysis was used to distinguish the vegetation and macro-invertebrates' species/taxa responsible for the similarity and dissimilarity between reach groups (URW, RWC and DRW) and eco-sites 1-5 (Clarke and Warwick 2001, Clarke and Gorley 2006). The SIMPER analysis showed the differences in average abundance of each species/taxon when comparing the reach groups and eco-sites to each other, and the percentage that each of these variables contribute to dissimilarity.

5.4.1 Riparian vegetation

The cover-abundance of riparian vegetation recorded at eco-sites in 1997 and 2020 were tabulated, and compared by plotting the numbers of indigenous and alien plant species present at each eco-site on a clustered column bar graph. The presence/absence of plant species in 1997 and in 2020 were compared using the statistical analysis package PRIMER V6 (Clarke and Warwick 2001; Clarke and Gorley 2006). A univariate diversity index is a measure of species diversity in a community and provides information about the community composition, and was thus used to compare diversity of plant species at each eco-site between 1997 and 2020 [*Margalef* species richness (Equation 6) and *Shannon diversity index* (Equation 7)]. A one-way ANOSIM was used to test for differences in the species diversity of each eco-site between 1997 and 2020. A SIMPER analysis was used to discern which species contributed to any similarity and differences revealed and these were plotted using tornado graphs.

$$d = \frac{S-1}{\log(N)} \qquad \text{Equation 6}$$

Where:

- d is *Margalef* species richness index,
- S is the total number of species,
- N is the total number of individuals.

$$H = \sum[(p_i) \times \ln(p_i)]$$ Equation 7

Where:

- H is defined as the *Shannon diversity index,*
- P*i* is the proportion of total sample represented by species *i*. Divide no. of individuals of species i by total number of samples.

A one-way ANOSIM was used to look for differences in the cover-abundance of plant species between reach groups (NRW, URW, RWC and DRW). A SIMPER analysis was used to distinguish plant species contributing dissimilarity between reach groups, which were plotted in tornado graphs. The number of indigenous and alien plant species within each reach group was then plotted on a clustered column bar graph for comparison.

The number of seedlings of the most prominent indigenous and alien trees and shrubs for each reach group was plotted on a clustered column bar graph for comparison. A one-way ANOSIM was then used to assess the differences in the abundance of seedlings between reach groups (NRW, URW, RWC and DRW). A SIMPER analysis was used to discern plant species contributing to group similarity and dissimilarity, which were plotted in tornado graphs.

A life history table was compiled for the common and discriminant species describing their growth form, heights, reproductive methods, season of flowering, seed set and preferred habitat. Plants were categorized according to their preferred bank position, i.e., wet bank zone (WB) and dry bank zone (DB).

5.4.2 Macro-invertebrate community structure

The data from Tharme *et al.* (1997), which were collected using SASS 4, were converted from SASS V4 to SASS V5 using a linear regression (Equations 8 and 9; Ollis 2005 and Dallas 2007).

$$\text{SASS 5} = 1.02\ (\text{SASS4 Score}) - 1.64$$ Equation 8

$$\text{ASPT 5} = 0.83\ (\text{ASPT 4 Score}) + 0.78$$ Equation 9

Analyses of macro-invertebrate assemblages at eco-sites over time were done in PRIMER V6 (Clarke and Warwick 2001; Clarke and Gorley 2006). A Hierarchical CLUSTER analysis and Multi-Dimensional Scaling ordinations (MDS) was used to group eco-sites based on the assemblage of macroinvertebrate taxa and their similarities, and was used to show the overall differences in species diversity between 1997, 2005, 2011 and 2020.

A one-way ANOSIM was used to test for differences in the overall macroinvertebrate community composition within each eco-site. A two-way nested ANOSIM was then used to test for differences in the macroinvertebrate community composition within each eco-site over time, where relevant. A SIMPER analysis was used to discern the macroinvertebrate taxa responsible for the dissimilarity between eco-sites between 1997 and 2020, which were plotted in tornado graphs.

The key aspects of the life histories of the macroinvertebrate families' habitat preferences, tolerance to pollution and feeding guilds (i.e., collector, shredder, predator and scrapers or grazers) responsible for differences between the samples were tabulated.

5.4.2.1 Ecological integrity based on SASS scores

Macroinvertebrate data recorded at each eco-site (biotope groups combined) were used to categorise the ecological integrity (A to E/F/) using 'biological bands' of SASS Score vs. ASPT generated from reference sites for the Southern Folded Mountains (Figure 5.4 and Table 5.9; Dallas 2007). The combined scores for 'upper' and 'lower' zones were used because eco-sites were located in both zones of the river.

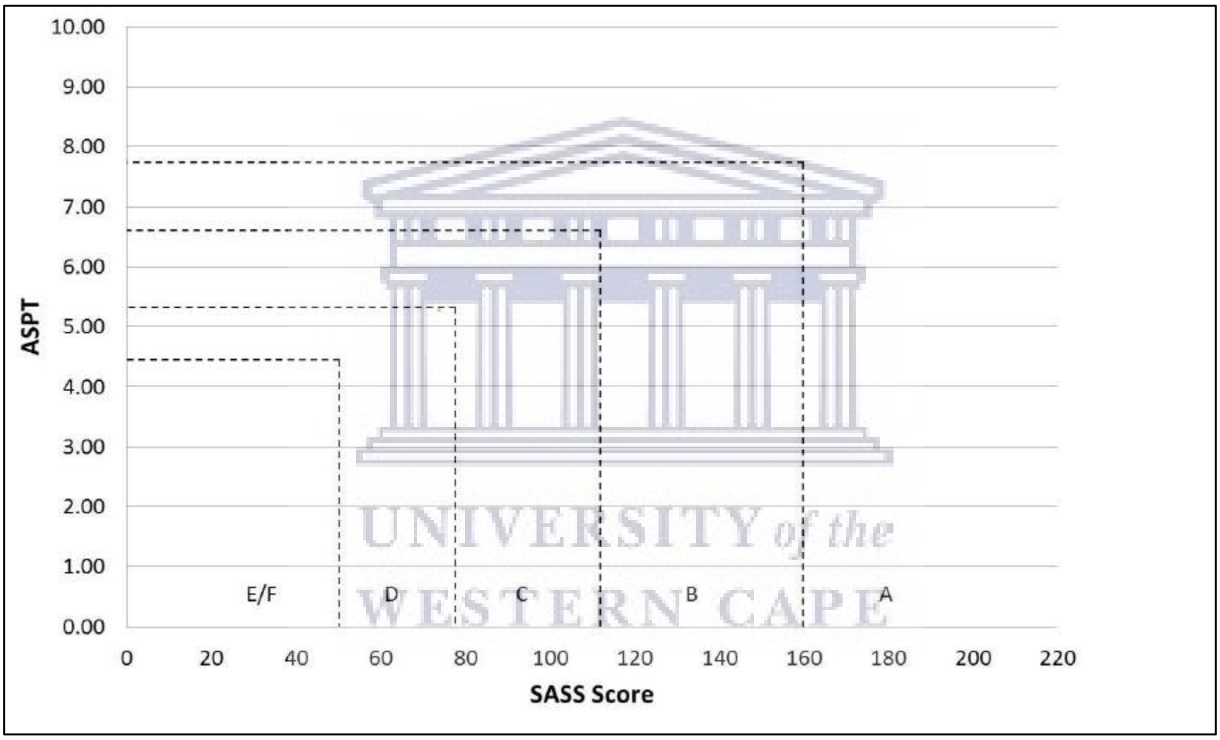

Figure 5.4 Biological bands for the Southern Folded Mountains reference site, Western Cape. Based on Dallas (2007)

Table 5.9 Reference ecological categories (A to E/F) for the Southern Folded Mountains reference site, Western Cape (Dallas 2007).

Biological Bands	SASS Score	ASPT Score
A/B	161	7.9
B/C	114	6.7
C/D	82	5.4
D/EF	54	4.6

5.4.3 Habitat integrity (HI)

The HI scores were tabulated and compared to the historical scores of Tharme *et al.* (1997) and Brown *et al.* (2000).

5.5 Results

5.5.1 Riparian vegetation

The cover-abundance of riparian vegetation recorded at eco-sites in 1997 and 2020 were tabulated (Table 5.10). The comparison showed that relative to 1997, in 2020, there were 47% more species recorded at eco-site 1, no difference in the number of species at eco-site 2, one additional species at eco-site 3, 22% more species at eco-site 4 and 22% fewer species at eco-site 5.

Table 5.10 Braun-Blanquet cover-abundance at eco-sites 1-5 for 1997 and 2020.

	Eco-site 1		Eco-site 2		Eco-site 3		Eco-site 4		Eco-site 5	
Species	1997	2020	1997	2020	1997	2020	1997	2020	1997	2020
Acacia longifolia	3		2	+	1		+	+	1	
Acacia mearnsii	2		1	+	2		R			
Acacia melanoxylon	1	2								
Acacia saligna			+		+		+		1	
Acacia terminalis										
Agapanthus hybrid		+			R					
Ageratina adenophora		2				2		+		1
Arundo donax		2					+		+	
Athanasia trifurcata				R						
Brabejum stellatifolium	2	2	1	1			+			
Brachylena nerrifolia		R								
Camellia japonica		1								
Canna hybrid							+		+	
Canthium inerme		R	+			1				
Carpobrotus edulis						2				
Casuarina equisetifolia				1	+			1	R	2
Chasmanthe aethiopica		+	+			+		2		
Cinnamomum camphora		3	+		+	2		+		
Cliffortia odorata		R		2	1			2	1	+
Cliffortia strobilifera			R	+	R			2		+
Clivia sp.		2								
Coleus neochilus								R		
Colocasia esculenta		+	R		+		R		+	
Crotalaria capensis								R		
Cynodon dactylon				2		1				2
Cyperus longus				+	1	1	+		1	
Cyperus sp.										
Cypress textiles				1	R	2	+	3	+	2
Ekebergia capensis								R	+	
Eucalyptus camaldulensis	2	2	+	2	1		+	1		
Fern Sp. 1 - Narrrow fern		R								
Freylinia lanceolata					1	2	2	2	R	2
Holcus lanatus	R	+	+				R			
Hymenolepis crithmifolia								R		
Ilex mitis			1							
Ipomoea nil			1	+	2	2	+	1		+
Ischyrolepis subverticillata										
Isolepis prolifera	+	R	+	1		2		+		

	Eco-site 1		Eco-site 2		Eco-site 3		Eco-site 4		Eco-site 5	
Species	1997	2020	1997	2020	1997	2020	1997	2020	1997	2020
Juncus effusus	R	+	+	2			+			
Juncus lumatophyllus	+			2		2		1		
Kiggelaria africana	+		1	2	1	1	+	1		+
Lantana camara				2	+					
Leucojum aestivum		R								
Nephrolepis cordifolia						2				
Olea capensis								1		
Olea europaea subsp *africana*									1	
Osteospermum moniliferum								2		
Paraserianthes lophantha				R		R		R		R
Paspalum urvillei	+	R	1	2	1		1	2	1	1
Pelargonium cucullatum								+		
Pennisetum clandestinum	1	2	3	3		3	4	4	4	3
Perisetum macrounum		R					1		2	+
Persicaria lapathifolia			1	2	2	2	1	2	1	1
Phoenix sp.					R		+			
Pinus pinaster			+					+		
Pinus pinea			1		3		3		+	
Pittosporum undulatum		R								
Platanus acerifolia		R	R	1	1	2	+	1	R	2
Podocarpus elongatus								1	+	
Podocarpus falcatus		2	1					2		
Polygala myrtifolia								+		
Populus canescens		1	2	1	3		1	+	2	
Prionium serratum						+		1		
Psoralea aphylla								+		
Psoralea pinnata				+		+	+	1	+	R
Quercus palustris			R							
Quercus robur	3	2	3		2	2	3			
Rubus fruticosus	1			2					+	
Salix babylonica			+		3		2		2	1
Salix mucronata		R		2	R	1	+	2	+	2
Searsia angustifolia										+
Searsia pendulina										1
Senecio angulatus										1
Setaria megaphylla			1		R	2	1	+		
Tecoma capensis					+	2				
Thunbergia alata						1	+	2		
Tree sp2. - Dragon Fruit Tree						2				
Tree sp3. - Old Man Tree				+						
Tropaeolum majus			R	R		1		2	+	
Typha capensis				1		1		1	2	
Zantedeschia aethiopica	1								R	
Number of species	**15**	**28**	**29**	**29**	**27**	**28**	**29**	**39**	**27**	**21**

The number of indigenous and alien species at eco-sites in 1997 and 2020 were plotted on a bar graph for comparison, which showed that there were more alien than indigenous species at eco-sites 1-4 in 1997 and 2000 (Figure 5.5) whereas eco-site 5 had more alien species in 1997 and more indigenous species in 2020. The number of indigenous species was higher in 2020 than in 1997 at all the eco-sites, particularly at eco-sites 3 and 4. The number of alien species was lower or the same (i.e., eco-site 4) with the exception of eco-site 1 where there were more alien species in 2020 than in 1997.

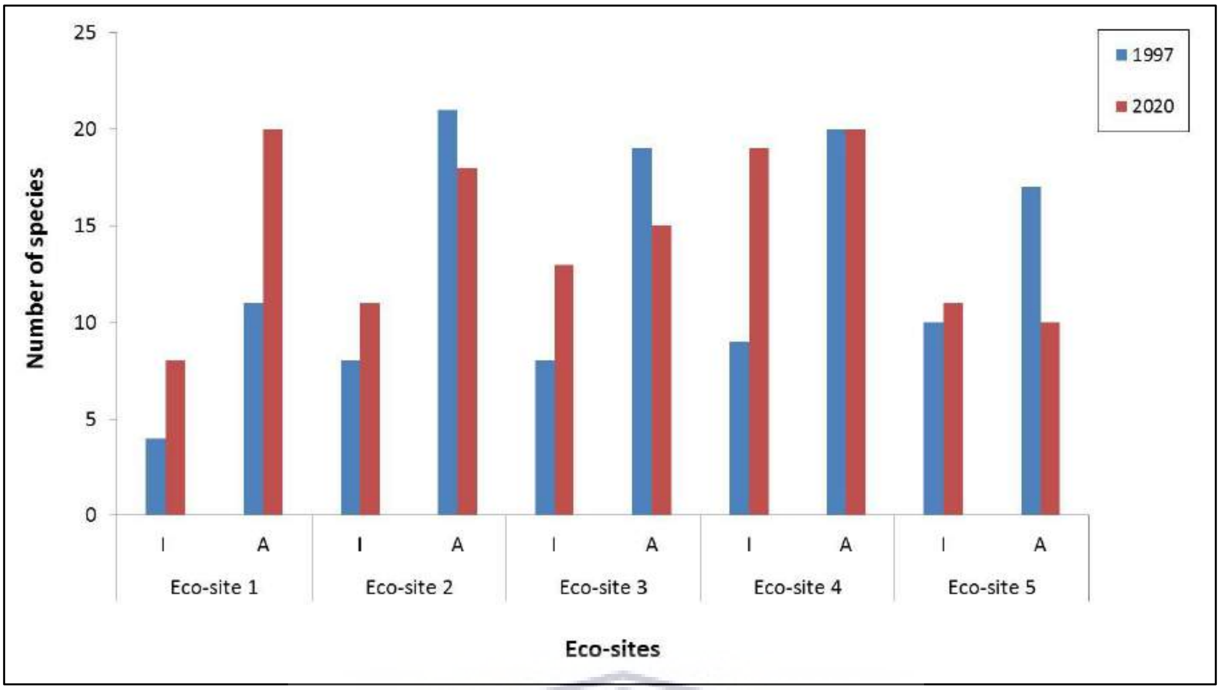

Figure 5.5 **Number of indigenous and alien species recorded at eco-sites 1-5 in 1997 and 2020. I = Indigenous species; A = Alien species.**

The diversity of indigenous plants species was analysed using a univariate diversity index (Table 5.11), which showed that species richness was higher at every eco-site in 2020, reflecting the increase in the number of indigenous plant species present. Eco-site 4 had more indigenous species in 2020 when compared to any of the other eco-sites.

Table 5.11 **Univariate Diversity Index – Comparing indigenous species richness at eco-site 1-5 between 1997 and 2020.**

Eco-sites	Species richness (1997)	Species richness (2020)
Eco-site 1	2.16	3.08
Eco-site 2	3.37	4.17
Eco-site 3	3.37	4.68
Eco-site 4	3.64	6.57
Eco-site 5	3.91	4.17

The most prominent alien species at eco-sites 1-5 in both 1997 and 2020 were *Acacia longifolia, Acacia mearnsii, Eucalyptus camaldulensis, Ipomoea nil , Paspalum urvillei, Persicaria lapathifolia, Pennisetum clandestinum, Platanus acerifolia, Populus canescens and Quercus robur* (Table 5.12). Eco-site 1 had the highest number of newly established alien species, of which many were popular garden plants, e.g., *Agapanthus* hybrid*, Camellia japonica, Clivia* sp.*, Colocasia esculenta, Cinnamomum camphora* and *Leucojum aestivum.* Other newly-established alien species that form a major component of the cover at the eco-sites were *Ageratina adenophora, Canthium inerme, Paraserianthes lophantha* and *Tropaeolum majus.*

A one-way ANOSIM revealed that the plant species composition of all the eco-sites was significant different[12] in 1997 relative to 2020 (ANOSIM R^2=0.232, p=0.063) with an overall Bray-Curtis similarity co-efficient of 42.32% (Figure 5.6). The main species contributing to the differences were alien species *Acacia saligna* and *Pinus pinea* present in 1997 but absent in 2020 and *A. adenophora*, *Cynodon dactylon* and *P. lophantha* in present in 2020 and absent in 1997.

In 2020, relative to 1997, there were increases in the average abundance of the indigenous species *Cliffortia odorata, Chasmanthe aethiopica, Juncus lomatophyllus, Isolepis prolifer, Psoralea pinnata* and *Typha capensis;* all of which were included in the list of recommended species for landscaping (Appx. Table 4). Two indigenous species had lower average abundances in 1997 than in 2020; the tree *Brabejum stellatifolium* and the rush *Juncus effusus.*

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[12] Using a 10% significance level.

Table 5.12 Alien species at eco-sites 1-5 present in both 1997 and 2020 and newly established in 2020. Growth form: T = Tree; S= Shrub; P = Perennial; A = Annual; G = Geophyte.

Eco-sites	Alien species in both 1997 and 2020	Newly established alien species in 2020
Eco-site 1	*Acacia melanoxylon* (T) *Holcus lanatus* (P) *Paspalum urvillei* (P) *Pennisetum clandestinum* (P) *Quercus robur* (T)	*Agapanthus* hybrid (P) *Ageratina adenophora* (S) *Arundo donax* (P) *Camellia japonica* (S-T) *Canthium inerme* (S) *Chasmanthe aethiopica* (G) *Cinnamomum camphora* (T) *Clivia* sp. (P) *Colocasia esculenta* (P) *Leucojum aestivum* (P) *Perisetum macrounum* (P) *Pittosporum undulatum* (S) *Platanus acerifolia* (T) *Populus canescens* (T)
Eco-site 2	*Acacia longifolia* (T) *Acacia mearnsii* (T) *Eucalyptus camaldulensis* (T) *Ipomoea nil* (A) *Paspalum urvillei* (P) *Persicaria lapathifolia* (A) *Platanus acerifolia* (T) *Populus canescens* (T) *Tropaeolum majus* (P)	*Casuarina equisetifolia* (T) *Cyperus longus* (P) *Lantana camara* (S) *Paraserianthes lophantha* (S) *Rubus fruticosus* (P) Tree sp3. - Old Man Tree (T)
Eco-site 3	*Acacia longifolia* (T) *Acacia mearnsii* (T) *Eucalyptus camaldulensis* (T) *Ipomoea nil* (A) *Persicaria lapathifolia* (A) *Platanus acerifolia* (T) *Quercus robur* (T)	*Ageratina adenophora* (S) *Canthium inerme* (S) *Chasmanthe aethiopica* (G) *Nephrolepis cordifolia* (A) *Tropaeolum majus* (P)
Eco-site 4	*Acacia longifolia* (T) *Eucalyptus camaldulensis* (T) *Ipomoea nil* (A) *Paspalum urvillei* (P) *Pennisetum clandestinum* (P) *Persicaria lapathifolia* (A) *Platanus acerifolia* (T) *Populus canescens* (T)	*Ageratina adenophora* (S) *Casuarina equisetifolia* (T) *Chasmanthe aethiopica* (G) *Coleus neochilus* (P) *Paraserianthes lophantha* (S) *Pinus pinaster* (T) *Tropaeolum majus* (P)
Eco-site 5	*Casuarina equisetifolia* (T) *Paspalum urvillei* (P) *Pennisetum clandestinum* (P) *Perisetum macrounum* (P) *Persicaria lapathifolia* (A) *Platanus acerifolia* (T) *Salix babylonica* (T)	*Ageratina adenophora* (S) *Ipomoea nil* (A) *Paraserianthes lophantha* (S)

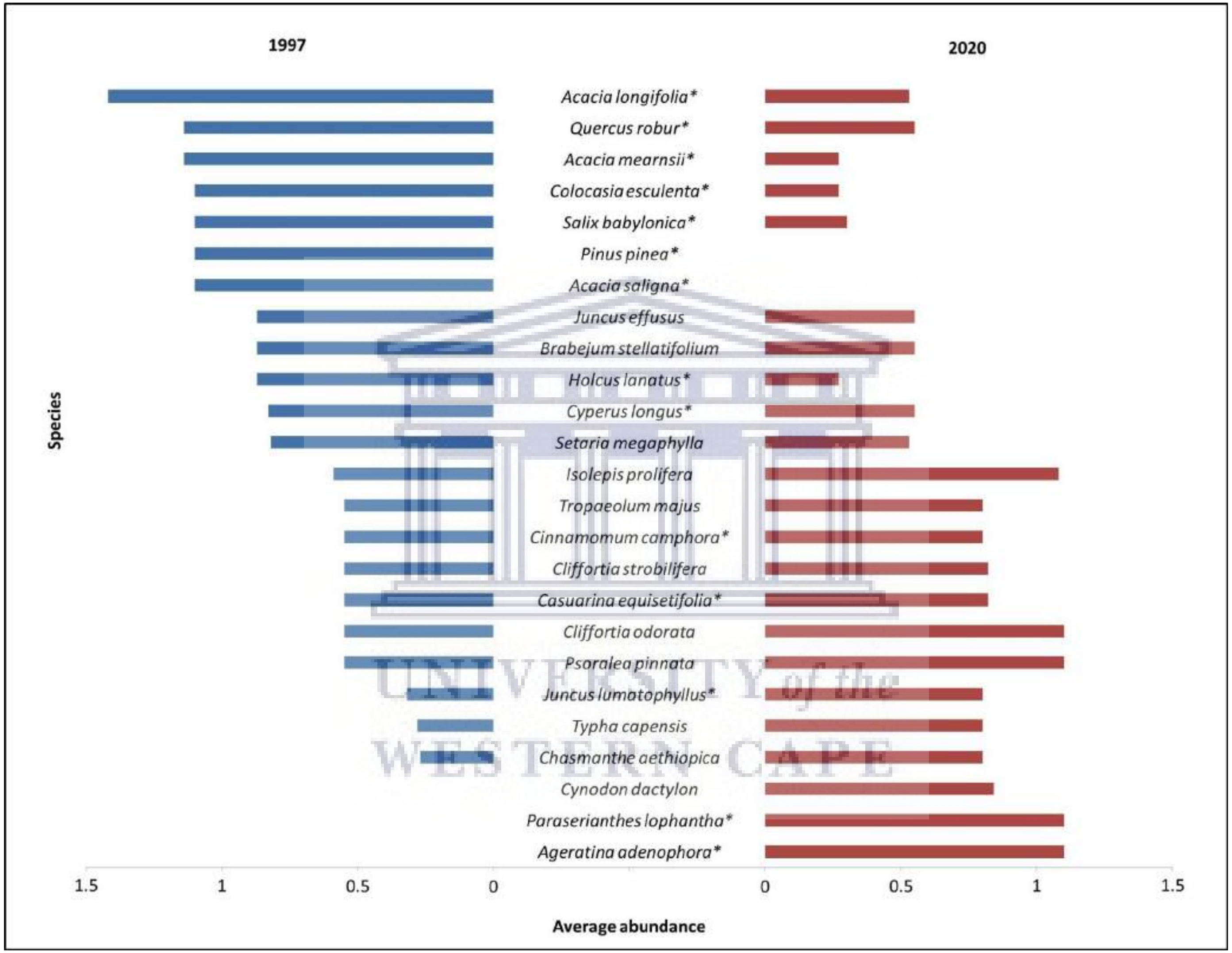


Figure 5.6 Average abundance of the main plant species contributing to dissimilarity in overall species diversity at all for eco-sites (1-5) between 1997 and 2020; * = Alien species. Dissimilarity between 1997 and 2020 is 57.68%.

With respect to the overall differences between reach groups NRW, URW, RWC and DRW in 2020, there were more indigenous than alien plant species present at RWC and more alien species at NRW, URW and DRW in 2020 (Figure 5.7). RWC also had the most indigenous species in all of the reach groups, followed by URW, NRW and DRW. DRW had the least indigenous and alien species out of all four reach groups.

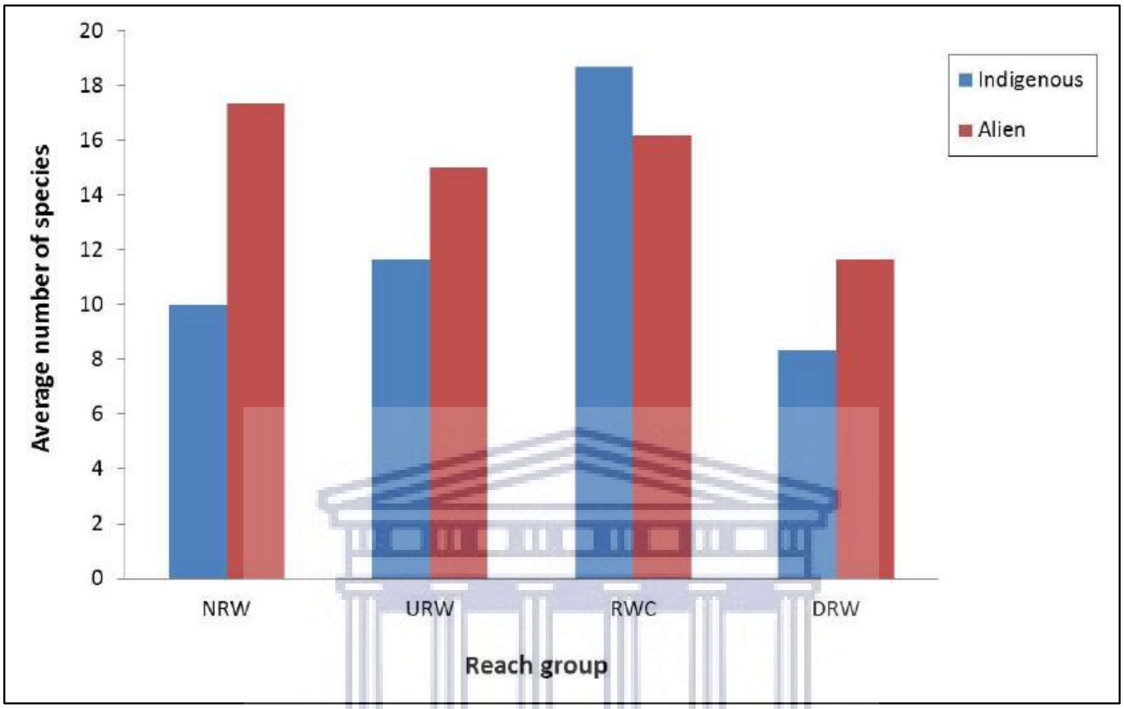


Figure 5.7 Average number of indigenous and alien species in each reach group (NRW, URW, RWC and DRW).

A one-way ANOSIM revealed that, in 2020, the plant species composition at RWC was significantly different from NRW, URW and DRW (ANOSIM R^2=0.645, p=0.001; Table 5.13).

A SIMPER analysis showed that the differences between NRW and RWC were driven by *Acacia melanoxylon, Ischyrolepis subverticillata* and *Zantedeschia aethiopica* that were only present in NRW and *Cypress textilis, C. dactylon, I. nil, Kiggelaria africana, Osteospermum moniliferum, Pelargonium cucullatum, P. lapathifolia, Prionium serratum, Setaria megaphylla* and *T. majus* that were only present in RWC (Figure 5.8)

A SIMPER analysis showed that the differences between URW and RWC were driven by *Lantana camara* only present in URW and *F. lanceolata, O. moniliferum, P. cucullatum and P. serratum* only present in RWC (Figure 5.9). Some indigenous species were more abundant in URW than in RWC, e.g., *B. stellatifolium* and *J. effusus*, while others were less abundant, e.g., *C. aethiopica, S. mucronata and Cypress textilis.* Alien species more abundant in URW were *P. canescens, I. nil* and *A. mearnsii* and those less abundant were *T. alata* and *T. majus.*

Table 5.13 One-way ANOSIM of percentage plant cover between reach groups (NRW, URW, RWC and DRW) sampled in 2020.

Global Test					
Sample statistic (Global R^2): 0.645					
Significance level of sample statistic: 0.1%					
Number of permutations: 999 (Random sample from 1401400)					
Number of permuted statistics greater than or equal to Global R^2: 0					
Pairwise Tests					
	R	Significance	Possible	Actual	Number >=
Groups	Statistic	Level %	Permutations	Permutations	Observed
NRW, URW	0.667	10	10	10	1
NRW, RWC	0.938	1.2	84	84	1
NRW, DRW	1	10	10	10	1
URW, RWC	0.377	2.4	84	84	2
URW, DRW	0.741	10	10	10	1
RWC, DRW	0.549	2.4	84	84	2

A SIMPER analysis showed that the differences between RWC and DRW were driven by *C. aethiopica, J. lomatophyllus, O. moniliferum, P. cucullatum, P. serratum, S. megaphylla* and *T. majus* only present in RWC and *A. saligna* present only present in DRW (Figure 5.10). The indigenous species *Cliffortia strobilifera* was more abundant in RWC than in DRW, while others were less abundant e.g., *F. lanceolata, Salix babylonica, T. capensis* and *Searsia angustifolia.* Some alien species were more abundant in RWC e.g., while other were less abundant e.g., *C. dactylon, I. nil* and *Perisetum macrounum*.

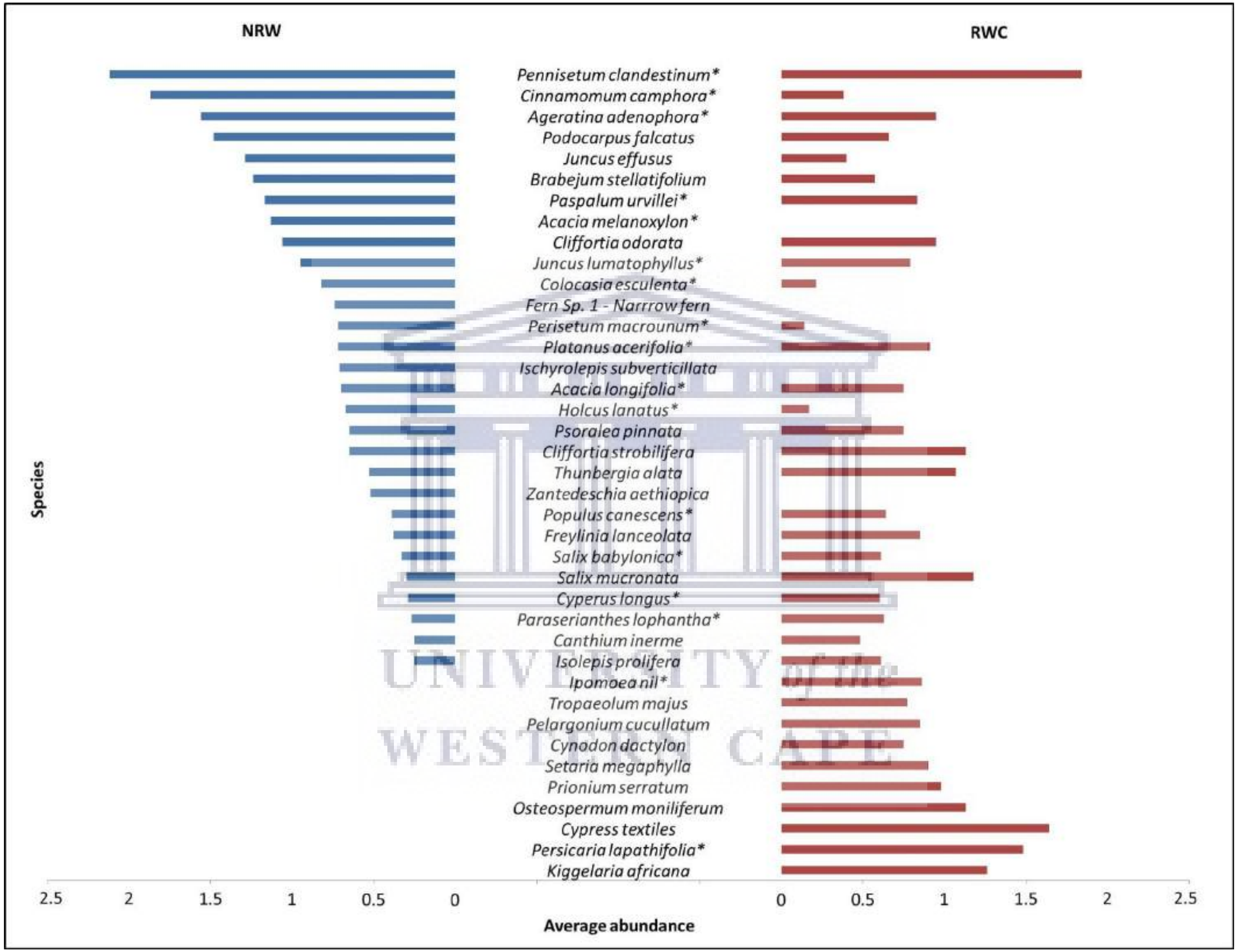


Figure 5.8 Average abundance and percentage contribution of the plant species responsible for differences between NRW and RCW in 2020; * = Alien species. Dissimilarity between NRW and RWC is 66.14%.

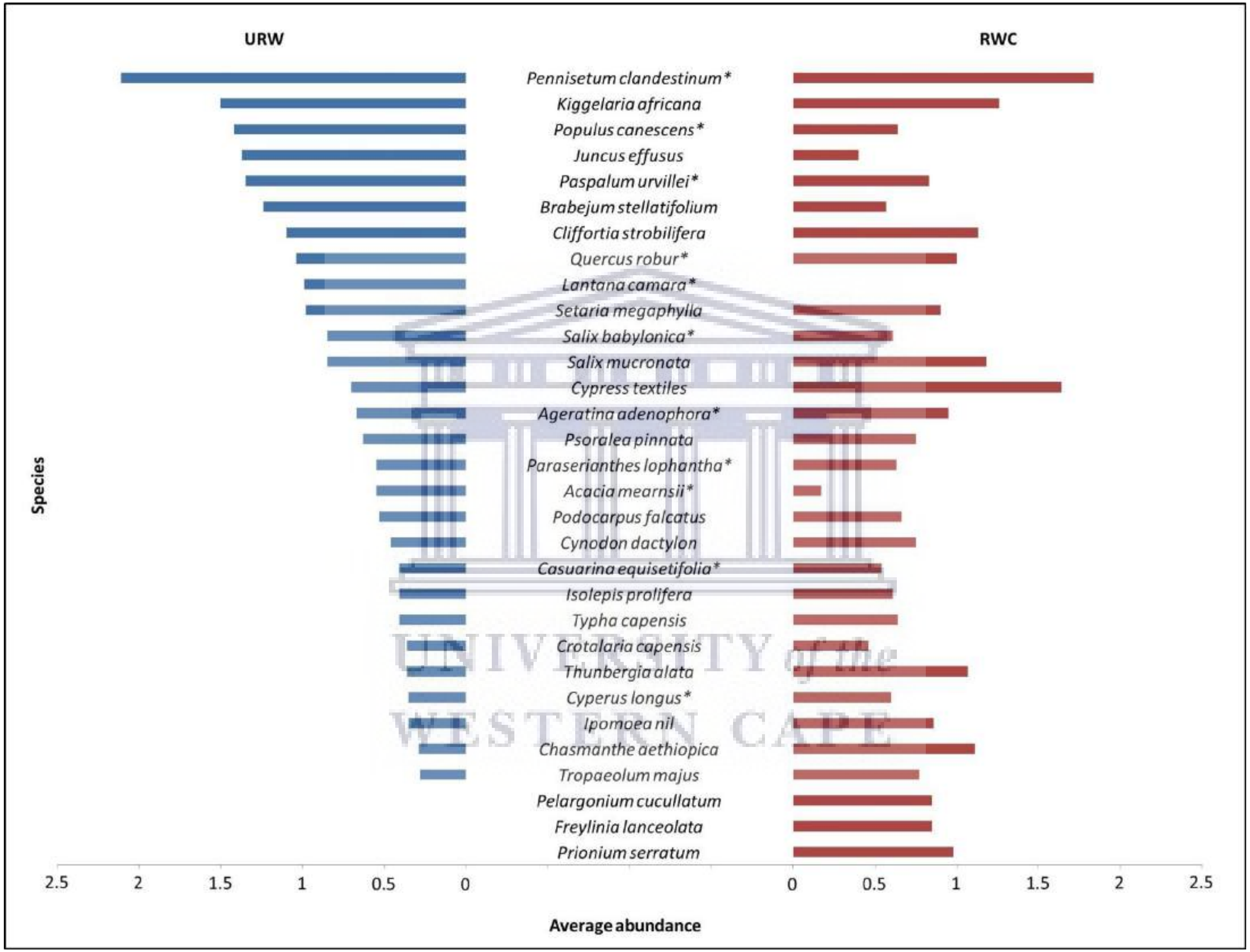


Figure 5.9 Average abundance and percentage contribution of the main plant species contributing to dissimilarity between URW and RCW reach in 2020; * = Alien species. Dissimilarity between URW and RWC is 52.29%.

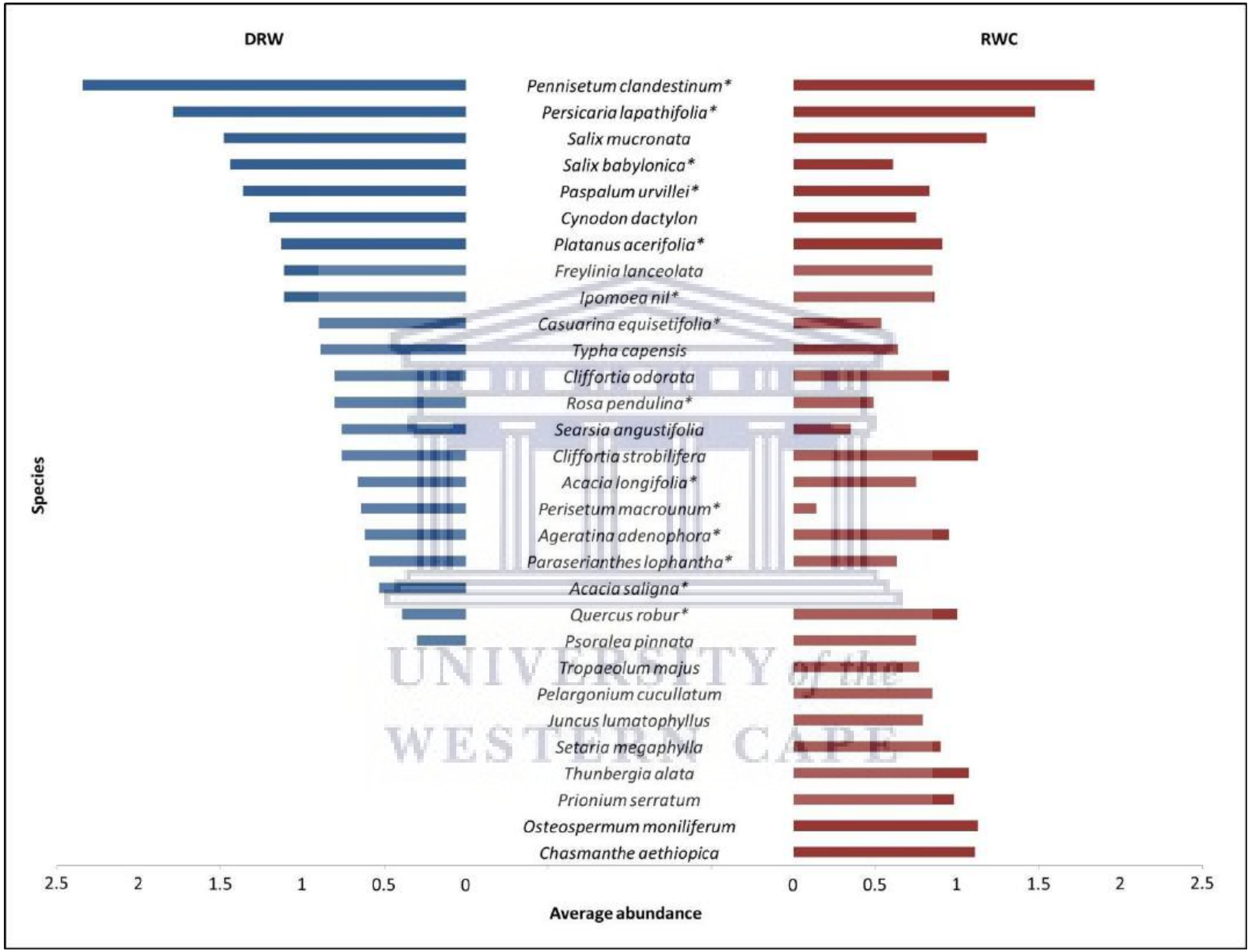


Figure 5.10 **Average abundance and percentage contribution of the main plant species contributing to dissimilarity between RWC and DRW reaches in 2020; * = Alien species. Dissimilarity between RWC and DRW is 54.66%.**

The number of seedlings of the most prominent indigenous and alien trees and shrubs at NRW, URW, RWC and DRW are shown in (Figure 5.11). *B. stellatifolium* had the highest number of seedlings in NRW and *P. falcatus* the highest number in NRW and URW. Seedlings of *B. stellatifolium* and *S. mucronata* were the most abundant seedlings recorded in RWC. Seedlings of *F. lanceolata* were only found at DRW even though there were also adults present upstream at RWC. The species with highest number of seedlings was the alien tree *C. camphora* at NRW. In general, there were more alien than indigenous seedlings and there were fewer aliens recruiting at DRW. Seedlings of the aliens, *A. longifolia, P. lophantha* and *P. acerifolia* were found in all four reach groups. Recruitment of two other aliens, *E. camaldulensis* and *P. canescens* was also evident at URW and RWC.

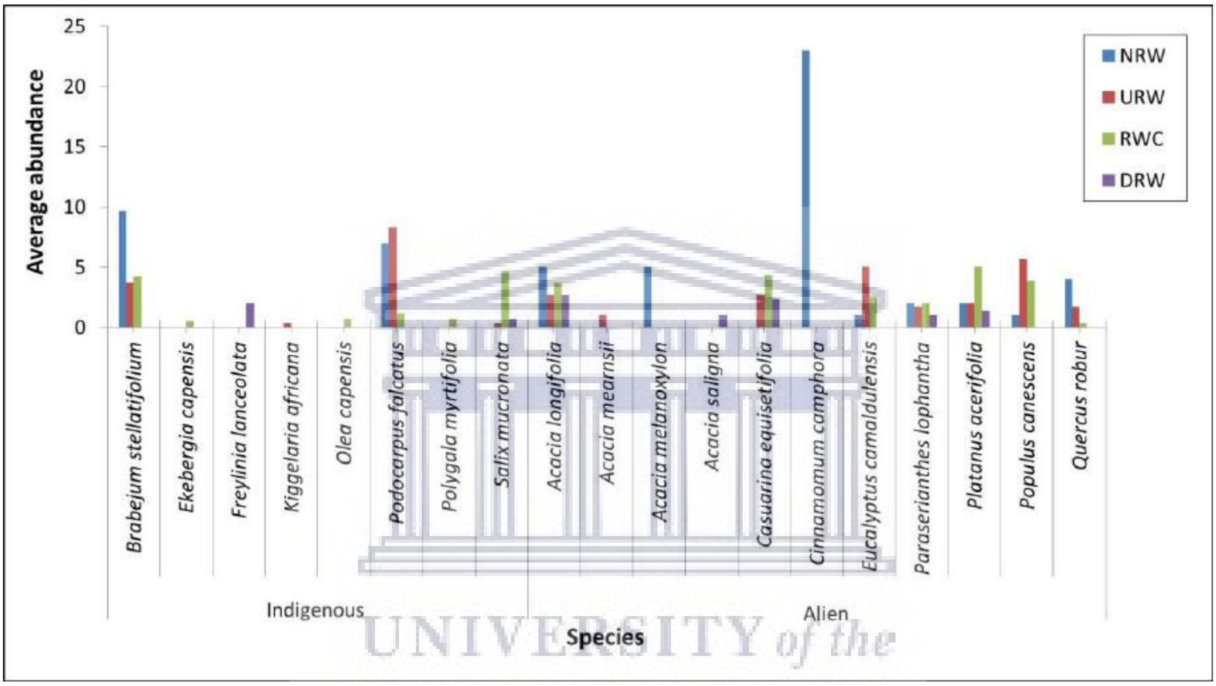


Figure 5.11 **Average number of indigenous and alien seedlings recruiting in each reach group (NRW, URW, RWC and DRW).**

A one-way ANOSIM comparing of the average abundance of seedlings showed that NRW and RWC were most different from one another (ANOSIM R^2=0.42, p=0.036; Table 5.14). These differences were driven by *C. camphora* and *A. melanoxylon,* which were only recorded at NRW (Figure 5.12) and more alien seedlings of *A. longifolia and P. lophantha* at RWC.

Table 5.14 One-way ANOSIM of seedlings abundances between reach groups (NRW, URW, RWC and DRW) sampled in 2020.

Global Test					
Sample statistic (Global R^2): 0.283					
Significance level of sample statistic: 3.3%					
Number of permutations: 999 (Random sample from 1401400)					
Number of permuted statistics greater than or equal to Global R^2: 32					
Pairwise Tests					
	R	Significance	Possible	Actual	Number >=
Groups	Statistic	Level %	Permutations	Permutations	Observed
NRW, URW	0.519	10	10	10	1
NRW, RWC	0.42	3.6	84	84	3
NRW, DRW	0.889	10	10	10	1
URW, RWC	-0.145	73.8	84	84	62
URW, DRW	0.593	10	10	10	1
RWC, DRW	0.127	25	84	84	21

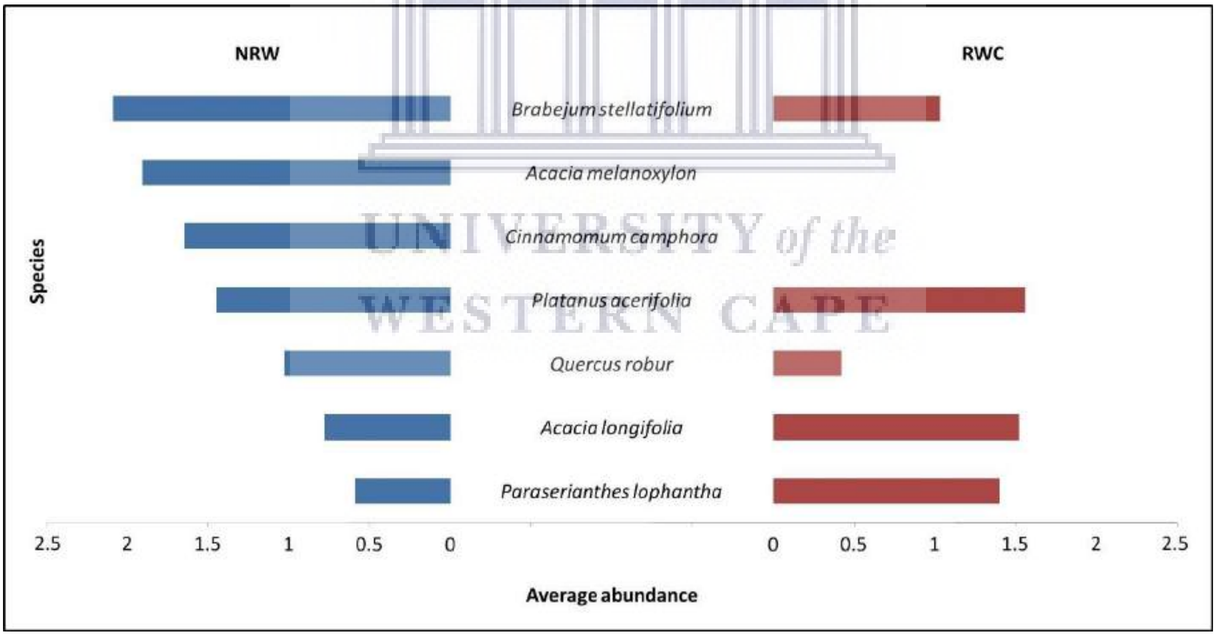


Figure 5.12 Average seedling abundance and percentage contribution of the main plant species contributing to dissimilarity between NRW and RWC reaches. Dissimilarity between NRW and RWC is 70.08%.

Approximately 66% of the plant species identified in this study were dry bank plants, ~14% wet bank plants and ~20% non-specific. Of all species plants recorded, 32% were trees, 17% shrubs and 33% perennial herbs (Table 5.15).

Table 5.15 Preferred bank position and growth forms of plant species recorded in 2020. Habitat: WB = Wet Bank zone; DB = Dry Bank zone. Growth form: T = Tree; S= Shrub; P = Perennial; A = Annual; G = Geophyte. Function: S = Shade; O = Ornamental; C = Cover: E = Erosion control; W = Weed.

Latin name	Common name	Indigenous/ Alien	Bank position	Growth form
Acacia longifolia	Long-leaved Wattle	Alien	WB/DB	T
Acacia mearnsii	Black Wattle	Alien	WB/DB	T
Acacia melanoxylon	Blackwood	Alien	WB/DB	T
Acacia saligna	Port Jackson	Alien	WB/DB	S
Acacia sp. 1		Alien	WB/DB	S-T
Acacia sp. 2		Alien	WB/DB	S-T
Acacia terminalis	Sunshine Wattle	Alien	WB/DB	T
Ageratina adenophora	Sticky snakeroot	Alien	WB/DB	S
Agapanthus hybrid	African Lily	Alien	DB	P
Aloe ferox	Cape Aloe	Indigenous	DB	P
Aloiampelos striatula	Climbing Aloe	Alien	DB	P
Arundo donax	Spanish Reed	Alien	WB	P
Athanasia trifurcata	Samphire-leaf Athanasia	Indigenous	DB	P
Bougainvillea glabra	Bougainvillea	Alien	DB	S
Brabejum stellatifolium	Wild Almond	Indigenous	WB/DB	S
Brachylena nerrifolia	Cape Silver Oak	Indigenous	WB/DB	S-T
Camellia japonica	Tama Electrea	Alien	DB	S-T
Canna hybrid	Canna Lilly	Alien	DB	T
Canthium inerme	Turkey-berry Milkwood	Indigenous	DB	S
Carpobrotus edulis	Sour Fig	Indigenous	DB	P
Casuarina equisetifolia	Beefwood	Alien	WB/DB	T
Chasmanthe aethiopica	Small Chasmanthe	Alien	DB	G
Cinnamomum camphora	Camphor	Alien	DB	T
Cliffortia odorata	Wild Vine	Indigenous	DB	S
Cliffortia strobilifera	Cone Rice-bush	Indigenous	WB/DB	S
Clivia sp.		Alien	DB	S
Coleus neochilus	Smelly Coleus	Alien	DB	P
Colocasia esculenta	Elephant Ear	Alien	WB	P
Crotalaria capensis	Cape rattle pod	Indigenous	DB	S
Cynodon dactylon	Bermuda grass	Indigenous	WB/DB	P
Cyperus longus	Galingale Sedge	Alien	WB	P
Cyperus sp.			WB	P
Cyperus textilis	Umbrella Sedge	Indigenous	WB/DB	P
Dicerothamnus rhinocerotis	Rhinoceros Bush	Indigenous	DB	P
Ekebergia capensis	Cape Ash	Indigenous	DB	T
Eucalyptus camaldulensis	River Red Gum	Alien	DB	T
Euryops virgineus	Honey Euryops	Indigenous	DB	A
Fern sp. *1 - Narrrow fern*			WB/DB	
Freylinia lanceolata	Honey Bell-bush	Indigenous	DB	S
Grass sp. *1 - Speargrass*			WB	
Harpephyllum caffrum	Wild Plum	Alien	DB	T
Holcus lanatus	Common Velvet Grass	Alien	DB	P
Hymenolepis crithmifolia	Coulter-bush	Indigenous	DB	S
Ilex mitis	African Holly	Indigenous	DB	T
Ipomoea nil	Morning-glory	Alien	DB	P
Ischyrolepis subverticillata	Broom Restio	Indigenous	DB	P
Isolepis prolifera	Proliferating Bulrush	Alien	WB	P
Juncus effusus	Common Rush	Indigenous	WB	P
Juncus lumatophyllus	Galingale Sedge		WB	P
Kiggelaria africana	Wild Peach	Indigenous	DB	T
Lantana camara	Common Lantana	Alien	DB	S

Latin name	Common name	Indigenous/ Alien	Bank position	Growth form
Leonotis leonurus	Wild Dagga	Indigenous	DB	B
Leucojum aestivum	Summer Snowflake	Alien	DB	P
Liquidambar styraciflua	Sweet Gum	Alien	DB	T
Nephrolepis cordifolia	Fishbone Fern	Alien	WB/DB	A
Olea capensis	Black Ironwood	Indigenous	DB	T
Olea europaea subsp africana	Wild Olive	Indigenous	DB	T
Osteospermum moniliferum	Bitou Bush	Indigenous	DB	S
Paraserianthes lophantha	Stinkbean	Alien	DB	S
Paspalum urvillei	Vasey's Grass	Alien	WB	P
Pelargonium cucullatum	Hooded-leaf Pelargonium	Indigenous	DB	P
Pennisetum clandestinum	Kikuyu Grass	Alien	DB	P
Perisetum macrounum	African feather Grass	Alien	WB	P
Persicaria lapathifolia	Pale persicaria	Alien	WB	A
Phoenix sp.	Palm	Alien	DB	T
Phyllostachys aurea	Fishpole Bamboo	Alien	WB/DB	A
Phyllostachys edulis	Chinese Bamboo	Alien	DB	P
Pinus pinaster	Maritime Pine	Alien	DB	T
Pinus pinea	Stone Pine	Alien	DB	T
Pittosporum undulatum	Australian Cheesewood	Alien	DB	S
Platanus acerifolia	London Plane	Alien	DB	T
Podocarpus elongatus	Breede River Yellowwood	Indigenous	DB	T
Podocarpus falcatus	Outeniqua Yellowwood	Indigenous	DB	T
Podocarpus henkelii	Henkel's Yellowwood	Indigenous	DB	T
Polygala myrtifolia	September Bush	Indigenous	DB	S
Populus canescens	Grey Poplar	Alien	WB/DB	T
Prionium serratum	Palmiet	Indigenous	WB	P
Psoralea aphylla	Blue Broom Bush	Indigenous	WB/DB	S
Psoralea pinnata	Fountain Bush	Indigenous	WB/DB	S
Pteridium aquilinum	Bracken Fern	Indigenous	DB	P
Quercus palustris	Pin Oak	Alien	DB	T
Quercus robur	English Oak	Alien	DB	T
Rosa pendulina	Mountain Rose	Alien	DB	P
Rubus fruticosus	Bramble Bush	Alien	DB	P
Salix babylonica	Weeping Willow	Alien	WB/DB	T
Salix mucronata	Cape Willow	Indigenous	WB	T
Schinus terebinthifolius	Brazilian Pepper	Alien	DB	T
Searsia angustifolia	Willow Karee	Indigenous	DB	T
Searsia pendulina	White Karee	Indigenous	DB	T
Senecio angulatus	Creeping Groundsel	Indigenous	DB	P
Seriphium plumosum	Silver Stoebe	Indigenous	DB	P
Setaria megaphylla	Broad leaf britle Grass	Indigenous	WB/DB	P
Tecoma capensis	Cape Honey Suckle	Indigenous	DB	S
Thunbergia alata	Black-eyed Susan	Indigenous	DB	P
Tree sp. *1 - Butterfly Tree*		Alien	DB	T
Tree sp. *2 - Dragon Fruit Tree*		Alien	DB	T
Tree sp. *3 - Old Man Tree*		Alien	DB	T
Tree sp. *4 - Ribbed Oak Tree*		Alien	DB	T
Tree sp. *5 - Spikey Bark Tree*		Alien	DB	T
Tropaeolum majus	Nasturtium	Alien	DB	P
Typha capensis	Bull Rush	Indigenous	WB	P
Widdringtonia nodiflora	Mountain Cypress	Alien	DB	T
Zantedeschia aethiopica	Arum Lily	Indigenous	DB	G

5.5.2 Macroinvertebrate community structure

A Hierarchical Cluster and MDS analyses grouped macroinvertebrate assemblages based on their similarity, which showed that the macroinvertebrate taxa from 1997 were different from recorded in 2005, 2011 and 2020 (Figure 5.13 and Figure 5.14). A one-way ANOSIM showed that the macroinvertebrates recorded in 1997 and those recorded in 2005, 2011 and 2020 were significantly different (ANOSIM R^2 = 0.577, $p<0.05$; Table 5.16). A two-way nested ANOSIM showed that there were, however, no differences between eco-sites when year groups were tested independently (ANOSIM R^2 =-0.027, p=0.541).

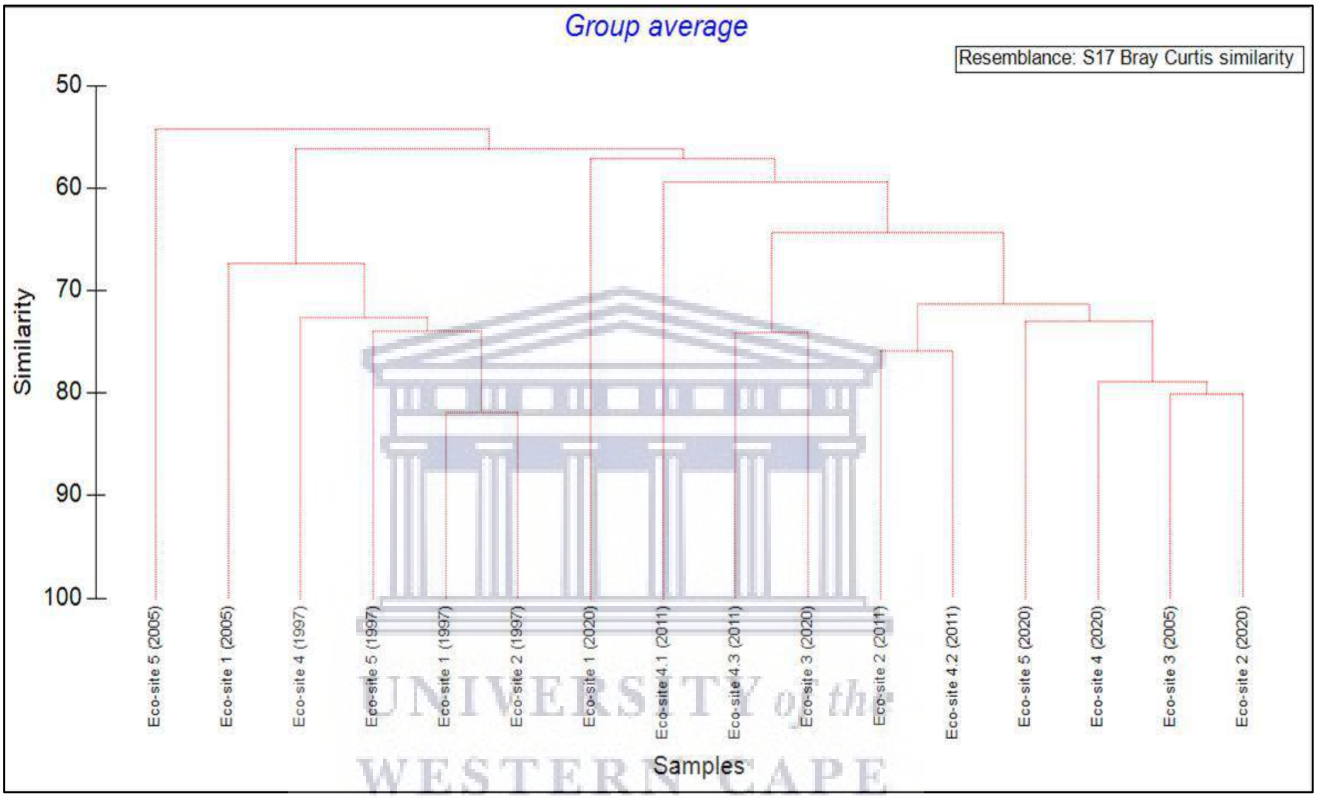


Figure 5.13 Cluster plot showing groupings of eco-sites 1-5 for 1997, 2005, 2011 and 2020 based on the similarity macro-invertebrate diversity.

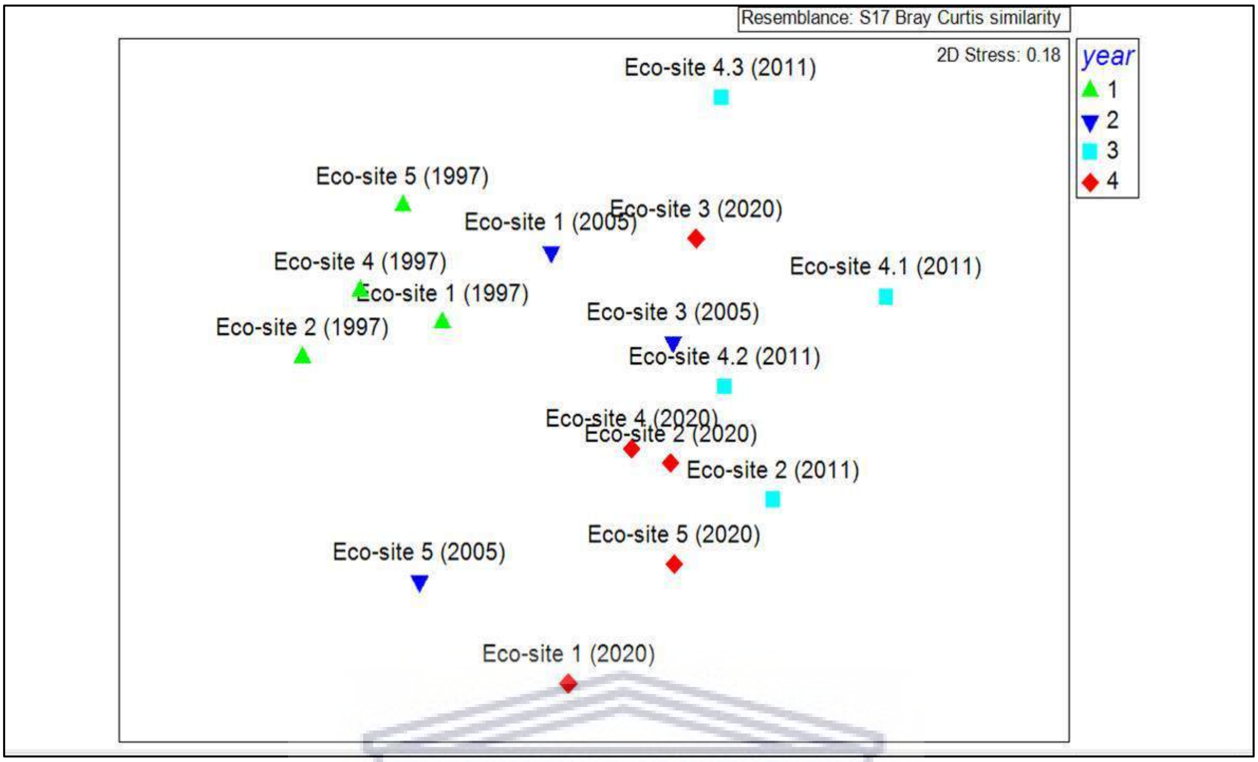


Figure 5.14 MDS plot showing groupings of eco-sites 1-5 for 1997, 2005, 2011 and 2020 based on the similarity macro-invertebrate diversity.

Table 5.16 One-way ANOSIM of differences in macroinvertebrates families between 1997 and those in 1005, 2011 2020.

Global Test					
Sample statistic (Global R^2): 0.577					
Significance level of sample statistic: 0.1%					
Number of permutations: 999 (Random sample from 25225200)					
Number of permuted statistics greater than or equal to Global R^2: 0					
Pairwise Tests					
Groups	R Statistic	Significance Level %	Possible Permutations	Actual Permutations	Number >= Observed
1997, 2005	0.657	2.9	35	35	1
1997, 2011	0.823	2.9	35	35	1
1997, 2020	0.941	0.8	126	126	1
2005, 2011	0.269	5.7	35	35	2
2005, 2020	0.349	5.4	56	56	3
2011, 2020	0.303	3.2	126	126	4

Since not all sites were sampled each year, SIMPER tests were run to determine families responsible for the differences between year groups:

- Eco-sites 1 and 5 sampled in 1997 and 2005.
- Eco-sites 2 and 4 sampled in 1997 and 2011.
- Eco-sites 1, 2, 4 and 5 sampled in 1997 and 2020.

A SIMPER analysis showed that the macroinvertebrate families differed between 1997 and 2005, with caenids, cullicids, philopotamids, gerrids, gomphids and corixids only present in 2005 and a greater average abundance of turbellarians in 1997 (Figure 5.15). Families differed between 1997 and 2011, with turbellarians only present in 1997 and caenids and hirudinids only present in 2011. There were more caenids in 2011 than in 1997 (Figure 5.16). Families differed between 1997 and 2020, with notonectids, libellulids, hydracarinids, dytiscids, pleids, cullicids, gomphids, caenids only present in 2020 and more Gyrinids and less turbellarians (Figure 5.17).

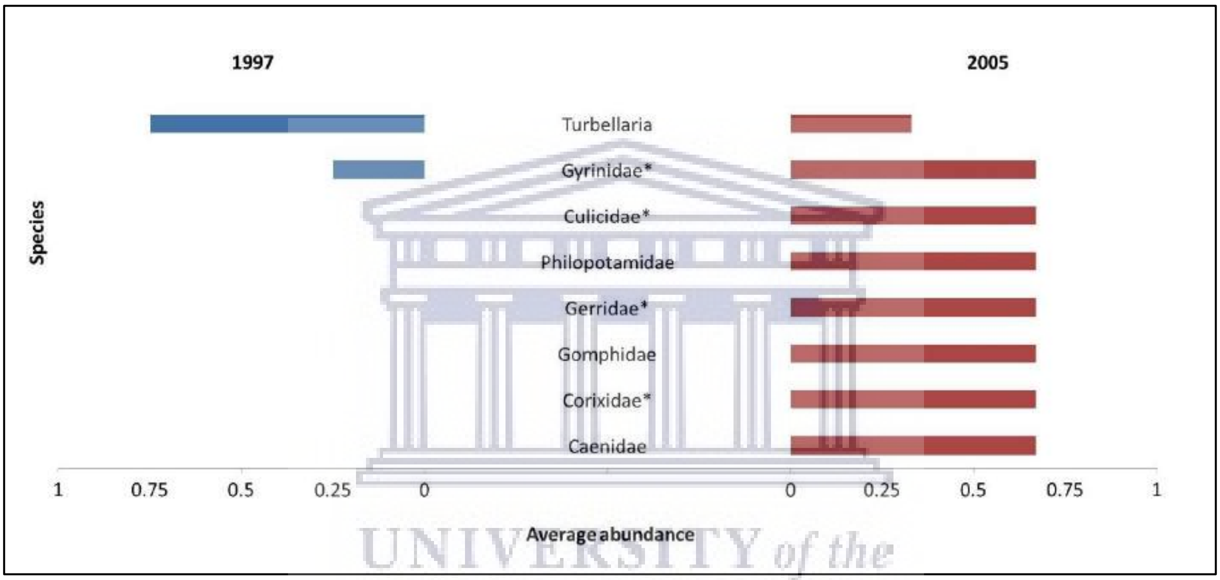


Figure 5.15 **Average abundance of the main macroinvertebrate taxa contributing to dissimilarity of eco-sites 1 and 5 between 1997 and 2005; * = Air breathing. Dissimilarity between 1997 and 2005 = 39.90%.**

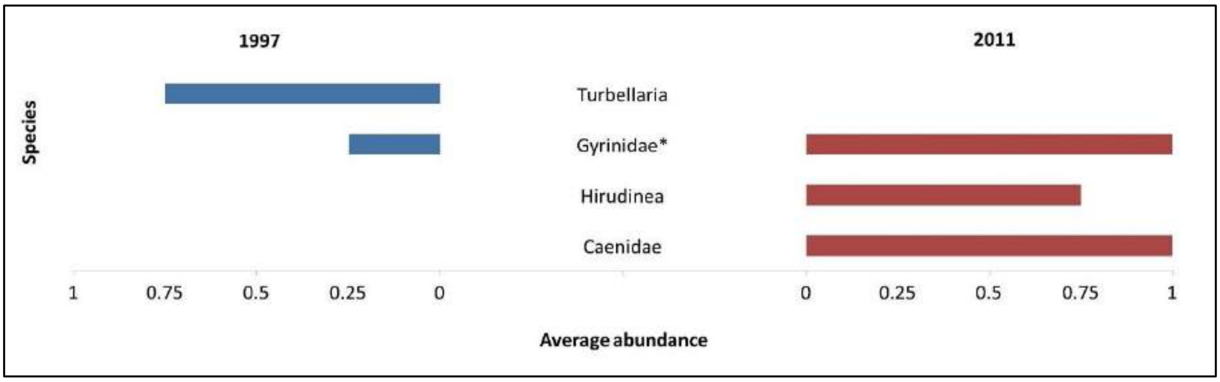


Figure 5.16 **Average abundance of the main macroinvertebrate taxa contributing to dissimilarity of eco-sites 2 and 4 between 1997 and 2011; * = Air breathing. Dissimilarity between 1997 and 2011 = 47.95%.**

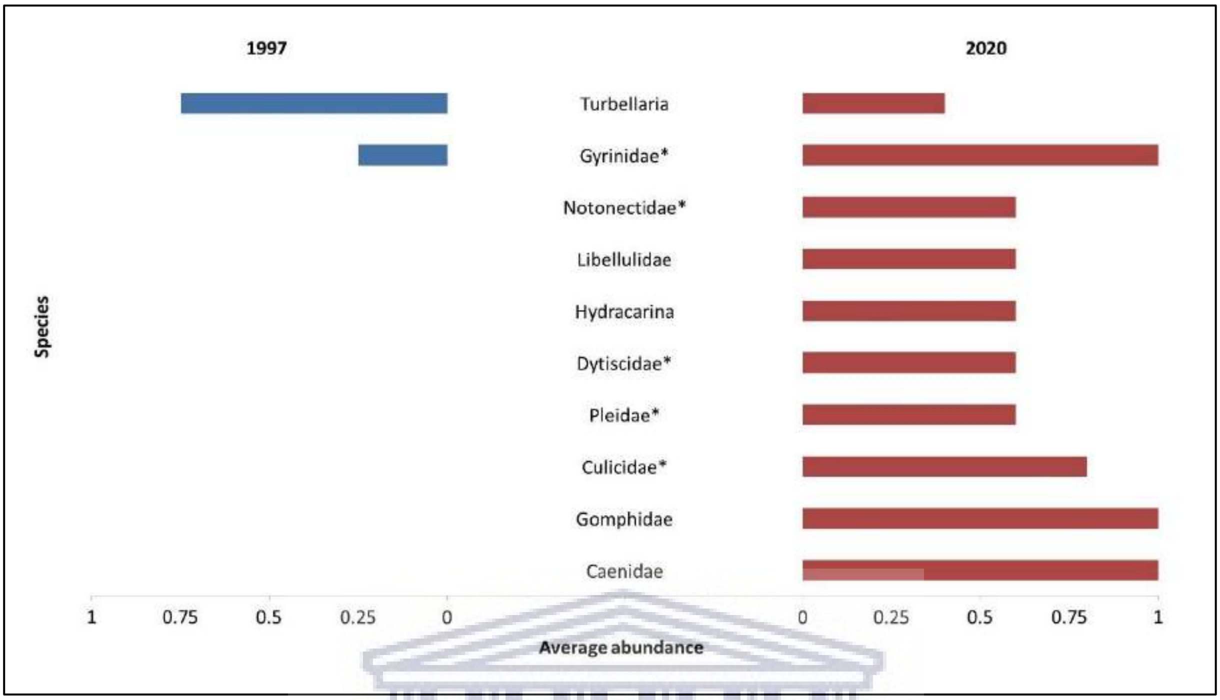
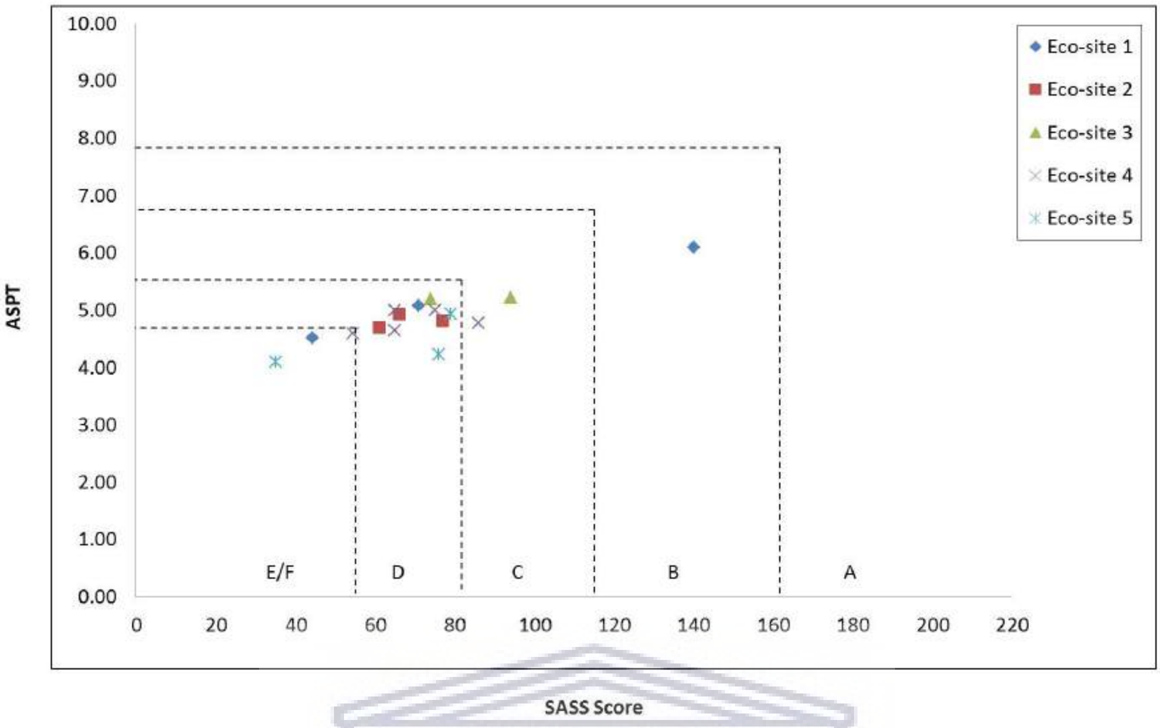


Figure 5.17 **Average abundance of the main macroinvertebrate taxa contributing to dissimilarity of eco-sites 1, 2, 4 and 5 between 1997 and 2020; * = Air breathing. Dissimilarity between 1997 and 2020 = 44.07%.**

Using the method suggested by Dallas (2007, Figure 5.18) for extrapolating ecological integrity from SASS scores:

- Eco-site 1 was category B in 1997 and category D/E in 2020.
- Eco-site 2 was category D in 1997, 2011 and 2020.
- Eco-site 3 was category C in 2005 and category D in 2020.
- Eco-site 4 was category D/E in 1997 and category C in 2020.
- Eco-site 5 was category E in 1997 and category D in 2020.



Eco-sites	Eco-site 1			Eco-site 2			Eco-site 3	
Year	1997	2005	2020	1997	2011	2020	2005	2020
SASS Score	44	71	140	66	61	77	94	74
ASPT	4.52	5.07	6.09	4.93	4.69	4.81	5.22	5.19
Ecological condition	B	D	D/E	D	D	D	C	D

Eco-sites	Eco-site 4					Eco-site 5		
Year	1997	2011a	2011b	2011c	2020	1997	2005	2020
SASS Score	54	65	75	65	86	35	79	76
ASPT	4.60	4.64	5.00	5.00	4.78	4.10	4.94	4.22
Ecological condition	D/E	D	D	D	C	E	D	D

Figure 5.18 Scatter plot showing the ASPT and SASS-Scores of eco-sites relative to relevant biological bands (Combined upland and lowland zone) and corresponding ecological categories (Dallas 2000; Dallas 2007).

Key aspects of the life histories of the macroinvertebrate taxa recorded at eco-sites 1 to 5 in 2020 are presented in Table 5.17. Of the 32 taxa present at the eco-sites, 59% are considered to be highly tolerant to pollution, 37.5% are moderately tolerant and only one taxon, teloganodids had a low tolerance to pollution. Twelve of the 32 taxa were air breathers. The functional feeding groups of aquatic macroinvertebrate taxa found in this study were 43% were predators, 23% were collector/gatherers, 17% were scrapers, 11% were collector/filterers, 3% were shredders and 3% were predators/parasites[13].

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[13] Certain families belong to more than one functional feeding group.

Table 5.17 Preferred habitat and feeding guilds of macroinvertebrate taxa sampled in 2020. SWC = South Western Cape; * air breathers.

Taxon	Common names	Tolerance level to pollution (1-15)	Habitat	Feeding guild
Aeshnidae	Hawkers and Emperors	8	Under stones; slow or fast streams	Predator
Ancylidae	Limpets	6	On rocks or any solid submerge substrate; all stream country-wide (RSA)	Scraper
Athericidae	Water snipe flies	10	Leaf pockets; mountains streams	Predator
Baetidae	Mayflies	4-12	Rocks, plants or coarse sand; moderately fast flowing streams	Collector/Gatherer; Scraper
Caenidae	Squaregills/Cainfle	6	Stone and muddy areas; slow or very slow streams	Collector/Gatherer
Ceratopogonidae	Biting midges	5	Sand, mud; edges of streams	Predator; Collector/Gatherer; Scraper
Chironomidae	Midges	2	Silk tubes on any type of substrate, pools, streams; any container filled with water	Collector/Gatherer
Coenagrionidae	Sprites and blues	4	Vegetation; edges of streams	Predator
Corixidae*	Water boatmen	3	Shallow pools; quiet muddy areas of streams.	Predator; Scraper
Corydalidae	Fishflies and Dobsonflies	8	Under stones; fast flowing streams; mountainous areas	Predator
Culicidae*	Mosquitoes	1	Pools; Any temporary puddle	Collector/Filterer
Dytiscidae/Noteridae*	Diving beetles	5	Amongst plants on the edges of ponds/pools; backwater areas	Predator
Elmidae/Dryopidae*	Riffle beetles	8	Stones or any solid substrate; fast streams	Scraper/Shredder
Gerridae*	Pond skaters/Water striders	5	On surface of ponds or streams; shaded areas	Predator
Gomphidae	Clubtails	6	Sand banks, muddy patches; edges of streams	Predator
Gyrinidae*	Whirligig beetles	5	As adults: on the water surface; quiet ponds or slow flowing water. As larvae: under stones or solid substrate, on vegetation; in slow to moderately fast streams	Predator
Hirudinae	Leech	3	Among plants, under rocks, sticks and logs and attached to organic debris	Predator/Parasite
Hydracarina	Water mites	8	Submerged vegetation or bottom debris; slow streams or quiet pools	Predator
Hydropsychidae	Net-spinning caddisflies	4-12	Under stones, living in shelters made from sand grains; fast flowing streams	Collector/Filterer; Scraper
Leptophlebiidae	Prongills	9	Stones or submerged pieces of wood; gentle flowing streams	Collector/Gatherer
Libellulidae	Darters	4	Stones, muddy patches; backwater areas, very slow streams	Predator
Nepidae*	Water scorpions	3	Vegetation, trash or mud; shallow pools or slow streams	Predator
Notonectidae*	Backswimmers	3	Pools; Backwater of streams	Predator
Oligochaeta	Aquatic earthworms	1	Mud or bottom substrates; pools or quiet area of the stream	Collector/Gatherer
Philopotamidae	Finger-net caddisflies	10	Fast-flowing portions of rivers and streams	Collector/Filterer
Planorbinae*	Orb snails	3	Gravel beds or aquatic vegetation; flowing streams	Scraper
Pleidae*	Pygmy backswimmers	4	Dense vegetation; shallow, clear water	Predator
Potamonautidae*	Crabs	3	Under or among rocks	Shredder
Simuliidae	Blackflies	5	Stones, plants, any solid surface; shallow, rapid streams	Collector/Filterer
Teloganodidae SWC	Teloganodid Mayflies	12	Stones or dense vegetation; fast streams	Collector/Gatherer
Turbelleria	Flatworms	3	Under stones or any other solid surface	Collector/Gatherer
Veliidae*	Ripple bugs	5	Pools; however, some species may prefer riffles in small streams.	Predator

5.5.3 Habitat integrity

HI scores for NRW, URW, RWC and DRW were recorded and compared to previous HI assessments from 1997 and 2000, and tabulated for comparison (Table 5.18). In 2020, HI was in a C category for NRW and in a D category for all the other reach groups. The HI scores of for latter three reach groups were all in a category C for 1997, 2000 and 2020.

Table 5.18 Estimated HI criteria scores for NRW, URW, RWC and DRW in 2020 and HI categories for 1997 (Tharme *et al.* 1997), 2000 (Brown *et al.* 2000) and 2020.

	Criteria	NRW	URW	RCW	DRW
Instream Criteria	Water abstraction	7.0	7.0	7.0	10.5
	Flow modification	6.5	6.5	6.5	9.8
	Bed modification	3.3	4.9	4.9	4.9
	Channel modification	6.5	6.5	9.0	9.8
	Water quality	7.0	7.0	8.8	12.3
	Inundation	0.0	0.0	0.0	0.0
	Exotic macrophytes	3.4	4.5	4.5	5.6
	Exotic fauna	0.0	0.0	0.0	0.0
	Solid waste disposal	0.0	0.0	2.7	3.8
Riparian Criteria	Indigenous vegetation removal	2.5	8.1	6.5	8.1
	Exotic vegetation encroachment	3.0	6.0	6.0	9.0
	Bank erosion	1.5	8.8	8.8	8.8
	Channel modification	1.5	6.0	8.3	9.0
	Water abstraction	2.0	6.5	6.5	9.8
	Inundation	0.0	0.0	0.0	0.0
	Flow modification	2.0	6.0	6.0	9.0
	Water quality	2.0	6.5	8.1	9.8
Overall HI Score		60.3	57.9	52.9	40.1
HI category	Tharme *et al.* 1997	-	D	D	D
	Brown *et al.* 2000	-	D	D	D
	2020	C	D	D	D

5.6 Discussion

On the Lourens River in Somerset West, soft-engineering works designed to alleviate flooding resulted in mixed effects on plant and macroinvertebrate communities and, thus, on the ecological condition of the river. There were increases in the biodiversity of the river, particularly where river works were completed, but there were also signs that the system is not self-sustaining and further intervention may be required to secure long-term gains in biodiversity.

The assessment of riparian vegetation along the river provided evidence that post-construction landscaping improved plant species diversity. This is supported by changes in vegetation species at eco-sites where river works were completed, with a noticeable increase in the number of indigenous species and a decrease in alien species between 1997 (pre-construction) and 2020 (post-construction). The corresponding reach group, RWC, also had the highest number of indigenous species of the four study reach groups and was the only one where there were fewer alien species present than indigenous species. Many of the indigenous species observed in RWC were on the recommended planting list (Appx. Table 4; CCA 2000) such as P. serratum and C. textilis (Appx. Figure 26). There were also serveral indigenous species present that were not listed, including: *C. dactylon, S. megaphylla, O. moniliferum* and *P. cucullatum.* It is tempting to suggest that these recovered naturally but the presence of *O. moniliferum* and *P. cucullatum* in a recently completed river work reach (Phase H) suggests that they may have been planted as part of the landscaping activities ().

There were unexpected changes in plant diversity observed at eco-sites 1, 2 and 5, where no river works have occurred, such as an increase in in indigenous species and a decrease in alien species (excluding eco-site 1). It may be that alien clearing activities in the upper parts of the catchment (See section 4.5.2) and at Vergelegen Wine Estate (www.vergelegen.co.za; van Rensburg 2017) and landscaping activities post-construction (CCA 2000; Southern Waters 2011) led to reduced propagule pressure of alien species and promoted the establishment and recovery of indigenous species (Ricardson *et al.* 2007; Fourie 2012). The tremendous effort by Vergelegen Wine Estate to clear alien plant species, predominantly *Acacia, Eucalyptus* and Pine, should be noted as it has aided in rehabilitation and increased the extent of indigenous vegetation on the property from 928 ha to 2673 ha (van Rensburg 2017).

The recovery of indigenous plants species in an urbanized catchment such as the Lourens River Catchment and the success thereof has been found to be variable (Blanchard and Holmes 2008; Ruwanza *et al.* 2013; Moore and Rutherfurd 2017; Nsikani *et al.* 2020). There is clear evidence that landscaping improved species diversity, increased indigenous species and reduced alien species, however, alien vegetation continues to proliferate along the river and in places seems to outcompete replanted indigenous species (Nsikani *et al.* 2018). For instance, there were decreases in the abundance of several alien species that were recommended for removal such as *A. longifolia, A. saligna, A. mearnsii, Q. robur* and *S. babylonica* (CCA 2000) yet they and others are still prominent along the river. Some species such as the *Q. robur or Pinus sp.* have many negative impacts in that they either inhibit the survival of indigenous species or do not bind the soil sufficiently well (CCA 2000). The latter leads to bank instability that not only has several ecological implications, but it also poses a higher flood risk by potentially blocking bridge openings, thus reducing flow capacity of the river and causing increased risk of flooding. The persistence of alien plant species may be because of the continued propagule pressure in a river system subjected to urbanization and other human-induced disturbances in the catchment (Ricardson *et al.* 2007; Fourie 2012; Lorenz and Feld 2013; Pattison 2016; Moore and Rutherfurd 2017; Cao and Natuhara 2020; Nsikani *et al.* 2020). It may also very well be a result of the methods used to clear alien species and the design of the project (Holmes *et al.* 2008; Ruwanza *et al.* 2013; Moore and Rutherfurd 2017; Hall *et al.* 2020; Nsikani *et al.* 2020), and the lack of appropriate routine maintenance (Moore and Rutherfurd 2017; Cao and Natuhara 2020), or a combination of these.

It is widely accepted that the dynamic nature of riparian ecosystems and ease with which they transport propagules make them highly prone to invasion by alien plant species (Blanchard and Holmes 2008; Fourie 2012; Nobis *et al.* 2018; Pattison *et al.* 2019; Nsikani *et al.* 2020; Ruwanza and Mhlongo 2020). This is why a routine recommendation for river restoration is to work from upstream to downstream. Flood alleviation measures on the Lourens River, however, were implemented in a downstream-to-upstream direction. This was done because authorities were concerned that by starting upstream the river engineering activities would exacerbate downstream flooding. Newly completed river works were therefore subject to disturbances from upstream river works, which disrupted flows, disturbed sediments and may have released seeds of alien species alien downstream (Gioria *et al.* 2014; Nsikani *et al.* 2018; Nsikani *et al.* 2020). Areas that are newly cleared of aliens create opportunities for recolonization because competition between species is reduced while the availability of resources is increased (Buckley *et al.* 2007; Nsikani *et al.* 2020), and may be recolonised through alien propagules that were already present in the seed bank before clearing took place (Gioria *et al.* 2014; Nsikani *et al.* 2018; Nsikani *et al.* 2020). This offers an explanation to the secondary invasion by alien species at eco-site 4 (Table 5.12) and to the dominance of alien seedlings versus indigenous seedlings in all four reach groups. To reduce alien species and achieve a more resistant ecosystem, alien propagules first need to be reduced in an upstream-to-downstream manner and a community of indigenous species that resemble a natural ecosystem must to be established. Once this happens, the rehabilitated vegetation would have a stronger ability to repel invasion by alien plants (Fourie 2012). Until such time, however, ongoing clearing of alien seedlings is needed to safeguard the restoration efforts made to date.

Plant species diversity is strongly linked to habitat conditions, which are directly affected by urbanization and human disturbances in the catchment (Richard *et al.* 2007; van Rensburg 2017; Cao and Natuhara 2020; Nsikani *et al.* 2020). Deforestation, grazing and trampling, urban development, recreation and water abstraction contribute to high alien plant propagule input and increased nutrient availability (Cao and Natuhara 2020). Such activities occur in conjunction with existing alien plant proliferation but can also trigger the establishment of alien communities (Cao and Natuhara 2020), which may explain the continued establishment of alien saplings along the Lourens River where river works were done. The reach, in which most of the urban development over the past two decades occurred, RWC, recorded the second highest number of alien species despite ongoing efforts to remove alien vegetation. This lends support to Richardson *et al.'s* (2007) contention that the removal of alien plant species in rivers subjected to continued human interference, are often futile and potentially counter-productive with respect to maintaining ecosystem function and overall ecological integrity.

The techniques and treatments used to control invasive alien species are known to vary in their success (Galatowitsch and Richardson 2005; Blanchard and Holmes 2008; Pretorius *et al.* 2008; Ruwanza *et al.* 2013; Hall *et al.* 2020; Nsikani *et al.* 2020). On the Berg River in the Western Cape, Ruwanza *et al.* (2013) found that both clearing and thinning methods increased species richness and diversity, but much of this increase was a result of re-invasion by alien herbaceous and graminoid species. Poor maintenance has meant that many restoration projects fail to produce their desired outcomes, even when using best practice (Moore and Rutherfurd 2017; Cao and Natuhara 2020; Nsikani *et al.* 2020; Theodoropoulos *et al.* 2020). On the Lourens River, routine maintenance, i.e., watering and replanting of vegetation was first conducted by landscape contractors, after which these tasks were to become the municipality's responsibility (CCA 2000). The presence of well-established alien plants in RWC and newly recruited aliens in all reach groups suggest that ongoing maintenance activities, if they are indeed occurring, are ineffective. Moore and Rutherfurd (2017) suggest that even self-sustaining interventions, such as revegetation of the Lourens River and the gabions control structures, require maintenance after major disturbances (i.e., flood events). Maintenance was done in Phase F and G after the flood in 2014 (See Chapter 4) but the presence of alien species, in combination with broken gabion structures, suggests that it has either not been sustained or that it is insufficient to protect the integrity of restored reaches of the river.

Macroinvertebrate diversity also increased following river works in the Lourens, but there was a paucity of sensitive species. Plants support a diverse array of macroinvertebrates by providing food, habitat, nursery and oviposition sites and refugia during disturbances such as flood events (Cyr and Downing 1988; Humphries 1996; Harper *et al.* 1997; Harrison 2000; Feldman 2001; Dallas 2007; Tessier *et al.* 2008; Samways *et al.* 2011; Thirion 2016; White and Walsh 2020). For example, aquatic plants create a distinct environment reducing the flow velocity and thus shelter for species that are poorly adapted to fast flowing water, e.g., most Coleoptera (Harper *et al.* 1997) and provide protection against predators (Cyr and Downing 1988; Feldman 2001; Tessier *et al.* 2008). Any changes in plant community composition may therefore result in changes in macroinvertebrate community composition and functional organisation (Allan 2004; Jayawardana and Westbrook 2010; Magoba and Samways 2010; Duan *et al.* 2011; da Silva *et al.* 2015; White and Walsh 2020). Changes in the assemblages at eco-site 3 and 4 suggest that river works and associated landscaping activities improved the river's physical character and supported improved biodiversity. Numerous macroinvertebrate taxa recorded in 2020 were not recorded before the river works, including caenids, corixids, cullicids, dytiscids, gerrids, gomphids, gyrinids, hirudinids, hydracarinids, libellulids, notonectids and pleids. Many of these taxa lay their eggs on indigenous macrophytes (Wetzel 2001; Verblerk *et al.* 2008; SANBI 2011; Thirion 2016), and require these to complete their life cycles (DWS 2002; Gerber and Gabriel 2002; Thirion 2016). Although caenids are most often associated with stones and muddy areas with slow flowing water and feed on fine particulate detritus and periphyton (Gerber and Gabriel 2002), they use vegetation as oviposition sites. Thus, it is likely that the improvement in macroinvertebrate diversity is a result of indigenous macrophytes that were planted as part of the restoration efforts.

Macroinvertebrates are also dependent on the stability of the physical habitat, particularly at a reach scale and are known to be affected by the riverbed's stability and substrate composition (Minshall and Minshall 1977; Reice 1980; Statzner *et al.* 1988; Wallace and Webster 1996; Verdonschot 2001; Duan *et al.* 2011). Caenids, corixids, gomphids and libellulids are strongly associated with gravel-sand-mud biotopes (Gerber and Gabriel 2002; Thirion 2016) and so their presence at eco-site 3 and 4 suggests an increase in lateral and mid-channel bars and gravel areas post-construction (White and Walsh 2020).

The macroinvertebrate taxa recorded in the Lourens River are moderately to highly tolerant to pollution (Dickens and Graham 2002), and the paucity of sensitive taxa suggests that habitat quality may be slightly impaired (Cliff 1982; Tharme *et al.* 1997, Schultz 2001, Schultz *et al.* 2001; Dabrowski *et al.* 2002; RHP 2003; Ollis 2005), particularly in the middle reaches where river works have been completed and are close to densely built urban areas. Tharme *et al.* (1997) reported severe deterioration of water quality with distance down the river with a decrease in dissolve oxygen and increases in temperature, pH, conductivity, TDS, TSS and nutrient concentrations. The increase in temperature is mainly due to reduction in bankside woody vegetation, which allows for more sunlight to penetrate the river channel (See Chapter 4). The life cycle requirements of many macro-invertebrates are cued with temperature which affects rates of development, reproductive periods and emergence times (Kosnicki and Burian 2003, Dallas 2004a; Thirion *et al.* 2016). The changes in water quality may be a result of reduced baseflows (Poff *et al.* 1997), reduced riparian plant cover, contaminated runoff from farms adjacent to the river, stormwater (urban, industrial and commercial areas) (Cliff 1982; Tharme *et al.* 1997; Ollis 2005) and domestic and general waste emanating from communities of homeless people residing in the riparian zone (Appx. Figure 28; www.Netwerk24.com 2020). Around the time when the Lourens River flood alleviation was implemented, contaminated runoff into the Lourens River after rainfall events exceeded national guidelines and toxic thresholds (Schultz 2001, Schultz *et al.* 2001, Dabrowski *et al.* 2002; Ollis 2005). The City of Cape Town recently warned the public to avoid drinking or swimming in the Lourens River citing water quality concerns (www.Netwerk24.com 2020). This is by no means an unusual situation since urban runoff is a primary cause of river degradation because of hydraulic disturbances arising from more concentrated high-flow events and the polluted nature of the runoff (Walsh *et al.* 2005b, Somers *et al.* 2013; White and Walsh 2020).

The integrity of the river ecosystem at RWC, based on the macroinvertebrates community (Dallas 2000, 2007) at eco-site 3 and 4, showed conflicting results. The ecological integrity of eco-site 3 decreased while that of eco-site 4 increased. The decrease at eco-site 3 may be a result of recent river works upstream (Gal *et al.* 2020) or simply that improved macroinvertebrate assemblages are yet to become established. A bio-monitoring assessment, such as SASS 5, in five or ten years might yield a different outcome at eco-site 3 similar to that of eco-site 4. The differences in assemblages between the years sampled may also be a result of differences in sampling technique between SASS 4 and SASS 5 or in sampling effort. A more comprehensive data set (several sampling occasions throughout all four seasons) is required for a better understanding on the changes in macroinvertebrate assemblages over time and space.

In conclusion, this study demonstrated that incorporating geomorphological and ecological principles into flood alleviation measures improved riverine biodiversity and, as a result, ecological integrity. However, the results also suggest that the newly-established communities of plants and animals are not yet self-sustaining as per original objectives (Brown *et al.* 2000; CCA 2000). This is likely a combination of having targeted restorations efforts on small reaches of the river and not addressing key issues at the catchment scale, such as agriculture, urbanization and deforestation (Alberts *et al.* 2018; White and Walsh 2020). It is clear from the results that constant management is required to sustain the gains made from the 'soft' ecological approach (Richardson *et al.* 2007; White and Walsh 2020) and without this, the Lourens River ecological integrity will deteriorate despite the money and time put into restoration efforts. Such efforts should include regular removal of alien plants, replanting of indigenous vegetation, maintaining bank stabilization structures and establishing a river buffer along the length of the river to protect it from catchment activities (Rutherfud *et al.* 2000; Petts *et al.* 2000; Richardson *et al.* 2007). The success of restoring rivers is dependent not only on project design and implementation but also on maintenance (White and Walsh 2020). Some rivers require decades of post-restoration maintenance before they reach a self-sustaining state (Moore and Rutherfurd 2017) and the evidence from this study suggests that the Lourens River is one such river.

6 Conclusion

The overarching aims of this dissertation were to assess the extent to which ecological principles were incorporated into the flood alleviation initiatives on the Lourens River and whether their incorporation improved the suite of ecological benefits.

The conclusions drawn from this study were that ecological principles were incorporated into flood alleviations measures and the result was an improved suite of ecological benefits.

The softer approach taken by the Lourens River flood alleviation project is an example of how engineering and ecological objectives can be integrated to improve river management. In the Lourens River, the capacity of the main channel to transport water was increased, while at the same time improving physical habitat, the riparian vegetation and macro-invertebrate assemblages. This is unlikely to have happened if ecological principles had not been integrated into the river works. The resultant flood alleviation measures were still founded on engineering objectives and it is reasonable to assume that an even greater inclusion of ecological directives would have led to greater gains in terms of river functioning and re-establishment of important regulatory functions and processes, i.e., regulation of floodwaters.

Despite these positive outcomes, there are many indications of continued degradation such as unstable river banks and broken gabions, proliferation of alien vegetation and lack of continued management. This is combined with alterations that push against the natural function of the river ecosystem, risking undesirable outcomes from both an ecological and town-planning perspective. Specifically, the in-filling of the Lourens River distributary that would naturally have conveyed the largest floods and failure to maintain adequate buffers along the river continue to place the people and the river under threat of destruction of major flood events. These persistent issues demonstrate the need for addressing river restoration at the scale of the catchment, where the large-scale functioning of the river ecosystem and the full spectrum of anthropogenic and environmental influences acting thereon, should be taken into consideration.

This study highlights the fact that once river systems have been modified, they require continued management and monitoring to maintain a balance between engineering and ecological objectives. At this point, the trajectory of the Lourens River is dependent on the next management decision. The decision may to either implement restoration efforts that are sympathetic to the function of the system and remain on a trajectory towards improved function, or take no action and the system will continue to degrade undermining the restoration works that have been implemented.

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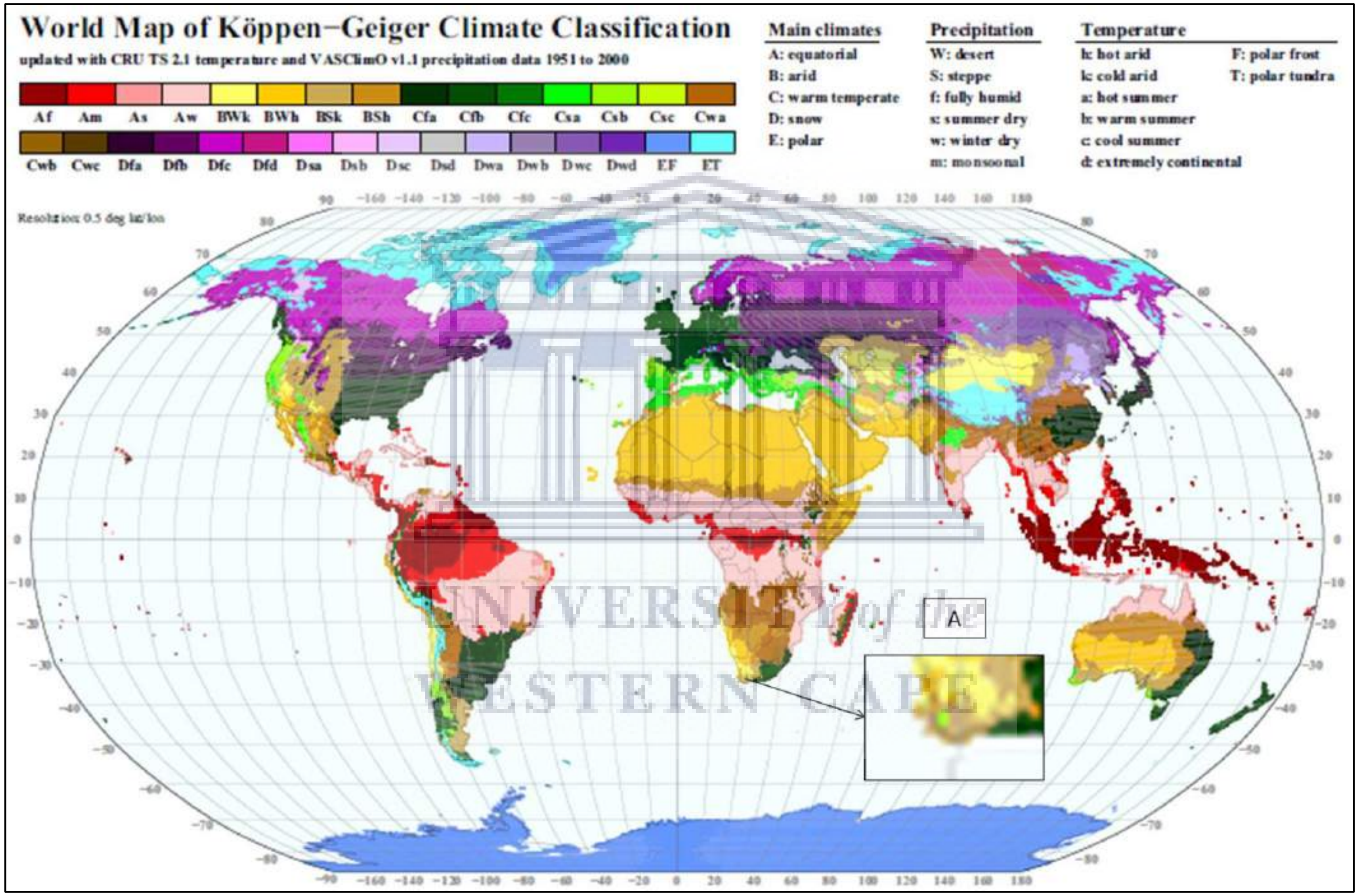
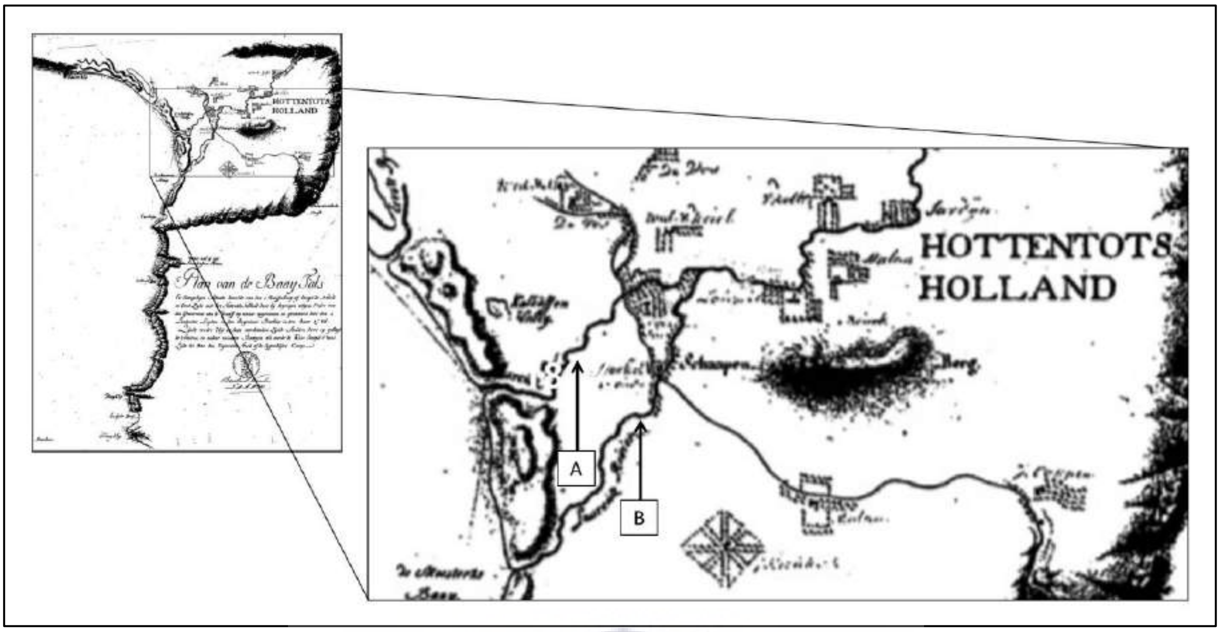
APPENDICES

APPENDIX A. CLIMATE



Appx. Figure 1: World map of Köppen-Geiger climate classification. Green colour in zoomed image (A) shows that Western Cape is classified as 'Csb' where: C = warm temperate climate; s = steppe precipitation; b = warm summer temperature.

APPENDIX B. MAPPING AND SPATIAL IMAGERY



Appx. Figure 2 - Hand drawn sketch of the Hottentots Holland mountain and the Lourens River catchment c. 1850, showing: A = the main river channel; B = distributary (Adapted from Brown and Magoba 2009).

Appx. Table 1: Historic spatial information/data used in the study.

Type	Date	Description	Reference
Historical[14]	1789	Historical map	Univerzita Karlova 1789
	1850	Historical map - Lourens River	Brown and Magoba 2009
Sketch	1935	Compilation sketch - Lourens River	Government Land Surveyor 1935
Topographical Maps	1942	1:50 000 topographical map	Trigonometrical Survey Office 1944
	1955	1:250 000 topographical map	Army Map Service 1955
	1959	1:50 000 topographical map	Trigonometrical Survey Office 1962
	1979	1:50 000 topographical map – Electronic version	Surveys and Mapping 1981
	1995	1:50 000 topographical map – Electronic version	Survey and land information 1995
	2000	1:50 000 topographical map – Electronic version	Surveys and Mapping 2003
	2010	1:50 000 topographical map – Electronic version	National Geo-spatial Information 2014
	2019	1:50 000 topographical map – Printed version	City of Cape Town 2019
Aerial photograph	1999	1:10 000 Aerial photography. Location: Railway to Waste Water Works	Chief Directorate: Surveys and Mapping 2002
	2015	1:10 000 Aerial photography. Location: Bluegum Dam	Chief Directorate: Surveys and Mapping 2015
	2015	1:10 000 Aerial photography. Location: Lourensford Estate to Andre Pretorius Street	Chief Directorate: Surveys and Mapping 2015
	2015	1:10 000 Aerial photography. Location: Railway to Waste Water Works	Chief Directorate: Surveys and Mapping 2015

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[14] Anything before 1900 was considered as historical records.

Type	Date	Description	Reference
	2015	1:10 000 Aerial photography. Location: Waste Water Works to ocean	Chief Directorate: Surveys and Mapping 2015
Aerial Imagery[15]	1938	Aerial imagery	NGI 1938
	1953	Aerial imagery	NGI 1953
	1977	Aerial imagery	NGI 1977
	1989	Aerial imagery	NGI 1989
	1998	Aerial imagery (0.25 m resolution)	CoCT 1998
	1999	Aerial imagery – Does not cover the whole Lourens River catchment.	NGI 1999
	2000	Aerial imagery	NGI 2000
	2002	Aerial imagery (0.25 m resolution)	CoCT 2002
	2005	Aerial imagery (0.25 m resolution)	CoCT 2005
	2010	Aerial imagery	NGI 2010
	2016	Aerial imagery (0.25 m resolution)	NGI 2016
	2019	Aerial imagery	CoCT 2019[16]
	2005-2019	Satellite imagery – Google Earth ©	Maxar Technologies 2020
Flooding and Flood Alleviation	1996	Sketch of 1: 20 and 1:50 year flood line map	Compion and Rooseboom 1996
	2001	Satellite images with proposed engineering drawings (Maps 10 out of 10)	SSI 2001
	2001	1:1000 Aerial photograph Drawing (Drawing No. 1 out of 10). Project No. WA154176 Chainage 1050 to 1800	SSI 2001
	2001	1:1000 Aerial photograph Drawing (Drawing No. 2 out of 10). Project No. WA154176 Chainage 1800 to 2900	SSI 2001
	2001	1:1000 Aerial photograph Drawing (Drawing No. 3 out of 10). Project No. WA154176 Chainage 2900 to 3650	SSI 2001
	2001	1:1000 Aerial photograph Drawing (Drawing No. 4 out of 10). Project No. WA154176 Chainage 3700 to 4600	SSI 2001
	2001	1:1000 Aerial photograph Drawing (Drawing No. 5 out of 10). Project No. WA154176 Chainage 4500 to 5350	SSI 2001
	2001	1:1000 Aerial photograph Drawing (Drawing No. 6 out of 10). Project No. WA154176 Chainage 5300 to 6050	SSI 2001

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[15] Aerial imagery from NGI was not used in this study because of time constraints, however, is listed for record purposes.

[16] There was delay in receiving the '2019 Aerial Imagery' because of COVID-19, however, is listed for record purposes.

Type	Date	Description	Reference
	2001	1:1000 Aerial photograph Drawing (Drawing No. 7 out of 10). Project No. WA154176 Chainage 6000 to 6700	SSI 2001
	2001	1:1000 Aerial photograph Drawing (Drawing No. 8 out of 10). Project No. WA154176 Chainage 6700 to 7450	SSI 2001
	2001	1:1000 Aerial photograph Drawing (Drawing No. 9 out of 10). Project No. WA154176 Chainage 7450 to 8100	SSI 2001
	2001	1:1000 Aerial photograph Drawing (Drawing No. 10 out of 10). Project No. WA154176 Chainage 81d00 to 9000	SSI 2001
	2014	1: 20 and 1:50 year flood line map	Royal Haskoning 2014
Biological	2009; 2018	Map of past and present historical vegetation	Brown and Magoba 2009; CoCT 2018
GIS Shapefiles	2009	Geological – soil type shapefile	SANBI 2009
	2018	Vegetation type shapefile.	SANBI 2018

Appx. Table 2: Data and seasons of Google Earth satellite imagery for the period 2005-2020 (Maxar Technologies 2005-2020)

Year	Date	Season
2005	23/03/2005	Autumn
2006	22/11/2006	Spring
2007	21/01/2007	Summer
2009	12/02/2009	Summer
2010	30/11/2010	Spring
2011	28/02/2011	Summer
	05/04/2011	Autumn
	28/12/2011	Summer
2012	28/04/2012	Autumn
	17/07/2012	Winter
	28/10/2012	Spring
2013	21/02/2013	Summer
	28/02/2013	Summer
	28/06/2013	Winter
	03/08/2013	Winter
	18/10/2013	Spring
	19/10/2013	Spring
	04/11/2013	Spring
	28/11/2013	Spring
2014	13/09/2014	Spring
	11/10/2014	Spring

Year	Date	Season
	26/12/2014	Summer
2015	11/01/2015	Summer
	14/01/2015	Summer
	19/01/2015	Summer
	22/01/2015	Summer
	28/01/2015	Summer
	01/03/2015	Autumn
	09/03/2015	Autumn
	17/03/2015	Autumn
	25/03/2015	Autumn
	22/06/2015	Autumn
	06/08/2015	Autumn
	11/08/2015	Autumn
	19/08/2015	Autumn
	27/11/2015	Spring
	27/12/2015	Summer
2016	10/01/2016	Summer
	31/01/2016	Summer
	05/02/2016	Summer
	11/02/2016	Summer
	28/02/2016	Summer
	03/03/2016	Winter
	23/03/2016	Winter
	04/09/2016	Spring
	23/10/2016	Spring
	28/10/2016	Spring
	03/12/2016	Summer
	11/12/2016	Summer
2017	31/01/2017	Summer
	24/02/2017	Summer
	21/03/2017	Autumn
	24/04/2017	Autumn
	25/04/2017	Autumn
	03/05/2017	Autumn
	07/05/2017	Autumn
	27/09/2017	Spring
	29/10/2017	Spring
	16/11/2017	Spring
	30/12/2017	Summer
2018	01/03/2018	Autumn
	28/03/2018	Autumn
	30/08/2018	Winter
	09/11/2018	Spring
	14/11/2018	Spring

Year	Date	Season
	15/12/2018	Summer
2019	16/01/2019	Summer
	04/02/2019	Summer
	28/02/2019	Summer
	06/03/2019	Autumn
	03/04/2019	Autumn
	28/05/2019	Autumn
	14/06/2019	Winter
	19/06/2019	Winter
	02/08/2019	Winter
	10/08/2019	Winter
	04/09/2019	Spring
	25/09/2019	Spring
	05/11/2019	Spring
	21/11/2019	Spring
	13/12/2019	Summer
	12/01/2019	Summer
	15/01/2019	Summer
	23/01/2019	Summer
2020	24/01/2020	Summer
	23/02/2020	Summer
	19/03/2020	Autumn
	08/04/2020	Autumn
	18/04//2020	Autumn
	21/04//2020	Autumn
	27/04/2020	Autumn
	30/04/2020	Autumn
	23/06/2020	Winter
	01/07/2020	Winter
	12/07/2020	Winter
	16/07/2020	Winter
	23/07/2020	Winter

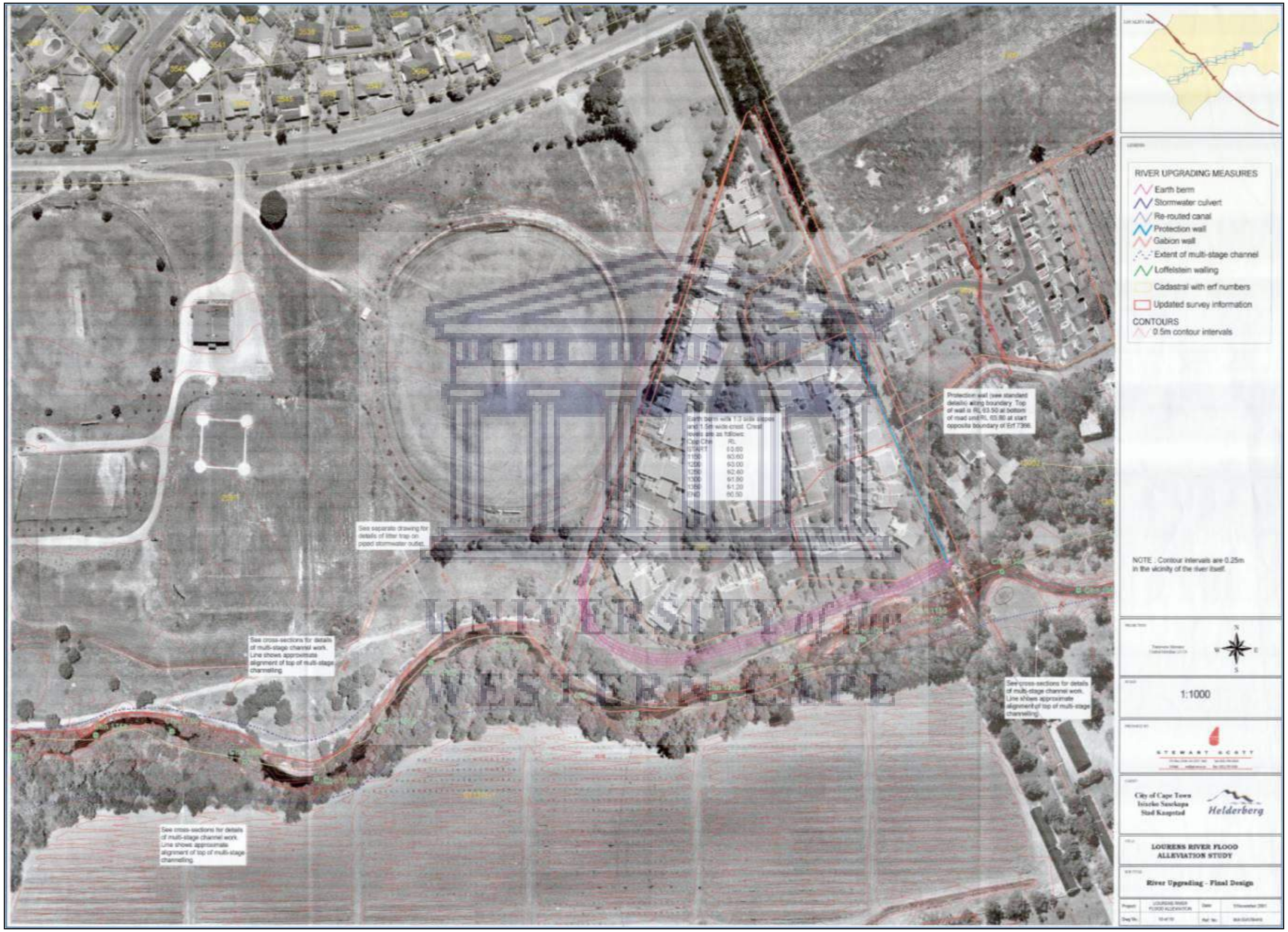
Appx. Figure 3: Distributary flowing through Greenways Golf Estate and entering the ocean by Gordon Bay (Maxar Technologies 2021).

Appx. Table 3: Studies, reports, proposals, plans and drawings for Lourens River Flood alleviation.

Type	Date	Timescale (1-4)	Description	Reference
Studies and Reports	1986	T1	Lourens River Flood Lines, Somerset West.	Hill Kaplan Scott Inc. 1986
	1996	T1	'Vloedmeesterplan' vir die Lourens Rivier deur Somerset-Wes en die Strand'.	Compion and Rooseboom 1996
	1997	T1	Lourens River flood study.	Pitman 1997
	2000	T1	Specialist review of hydrology for the Lourens River Catchment Somerset West and Strand.	Pegram 2000
	2000	T1	Heritage Impact Assessment of proposed Lourens River flood alleviation measures.	Hart 2000
	2000	T1	Lourens River flood alleviation: Ecological considerations	Brown *et al.* 2000
	2000	T1	Environmental impact Report (EIR) for the proposed Lourens River flood alleviation measures.	CCA 2000
	2014	T4	Lourens River Flood Study.	IWEESU 2014
	2015	T4	Proposed Lourens River stormwater outlets, litter traps and detention pond, Somerset West – Final basic assessment report	CoCT 2015
	2016	T4	Lourens River Flood Study.	Hutchingson *et al.* 2016
Contract documents	2001-2002	T3	Contract Tender Document - Lourens River Upgrading Phase 1A River Works (Civil) - CONTRACT NO. H4-2001/2002.	CoCT 2001
	2002-2003	T3	Contract Tender Document - Lourens River Upgrading Phase 1B River Works (Civil) - CONTRACT NO. BH17:2002/2003.	CoCT 2002
	n.d.	T3	Contract Tender Document - Lourens River Upgrading Phase 1C River Works (Civil) – CONTRACT NO. (Not found)	CoCT n.d.
	2008-2009	T3	Contract Tender Document - Lourens River Upgrading Phase 1D River Works (Civil) - CONTRACT NO. 315Q/2008/09	CoCT 2009
	2011-2012	T3	Contract Tender Document - Lourens River Upgrading Phase 1E River Works (Civil) - CONTRACT NO. – 100Q/2011/12. Chainage 4350 to 5300 - Andries Pretorius Street to Sergeant Street bridge.	CoCT 2011
	2014-2015	T3	Contract Tender Document - Lourens River Upgrading Phase 1F River Works (Civil) – CONTRACT NO. (Not found)	CoCT 2014
	2015-2016	T3	Contract Tender Document - Lourens River Upgrading Phase 1G River Works (Civil) - CONTRACT NO.W080150124	CoCT 2015
	2015-2019	T3	Contract Tender Document - Lourens River Upgrading Phase 1H River Works (Civil) - CONTRACT NO. 165Q/2015/16	CoCT 2015
	2018-2019	T3	Contract Tender Document - Lourens River Upgrading Phase 1J River Works (Civil) - CONTRACT NO. 285Q/2018/19.	CoCT 2018
Proposals, plans and drawings	2001-2002 fo	T4	Contract Tender Document - Lourens River Upgrading Phase 1A River Works (Landscaping and Horticultural Works) – CONTRACT NO. (Not found)	CoCT 2001
	2002-2003	T3	Contract Tender Document - Lourens River Upgrading Phase 1B River Works (Landscaping and Horticultural Works) – CONTRACT NO. (Not found)	CoCT 2002
	n.d.	T3	Contract Tender Document - Lourens River Upgrading Phase 1C River Works (Landscaping and Horticultural Works) – CONTRACT NO. (Not found)	CoCT n.d.
	2008-2009	T3	Contract Tender Document - Lourens River Upgrading Phase 1D River Works (Landscaping and Horticultural Works) - CONTRACT NO. 314Q/2008/09.	CoCT 2008
	2011-2012	T3	Contract Tender Document - Lourens River Upgrading Phase 1E River Works (Landscaping and Horticultural Works) - CONTRACT NO. 182Q/2011/12	CoCT 2011
	2014-2015	T3	Contract Tender Document - Lourens River Upgrading Phase 1F River Works (Landscaping and Horticultural Works) – CONTRACT NO. (Not found)	CoCT 2014

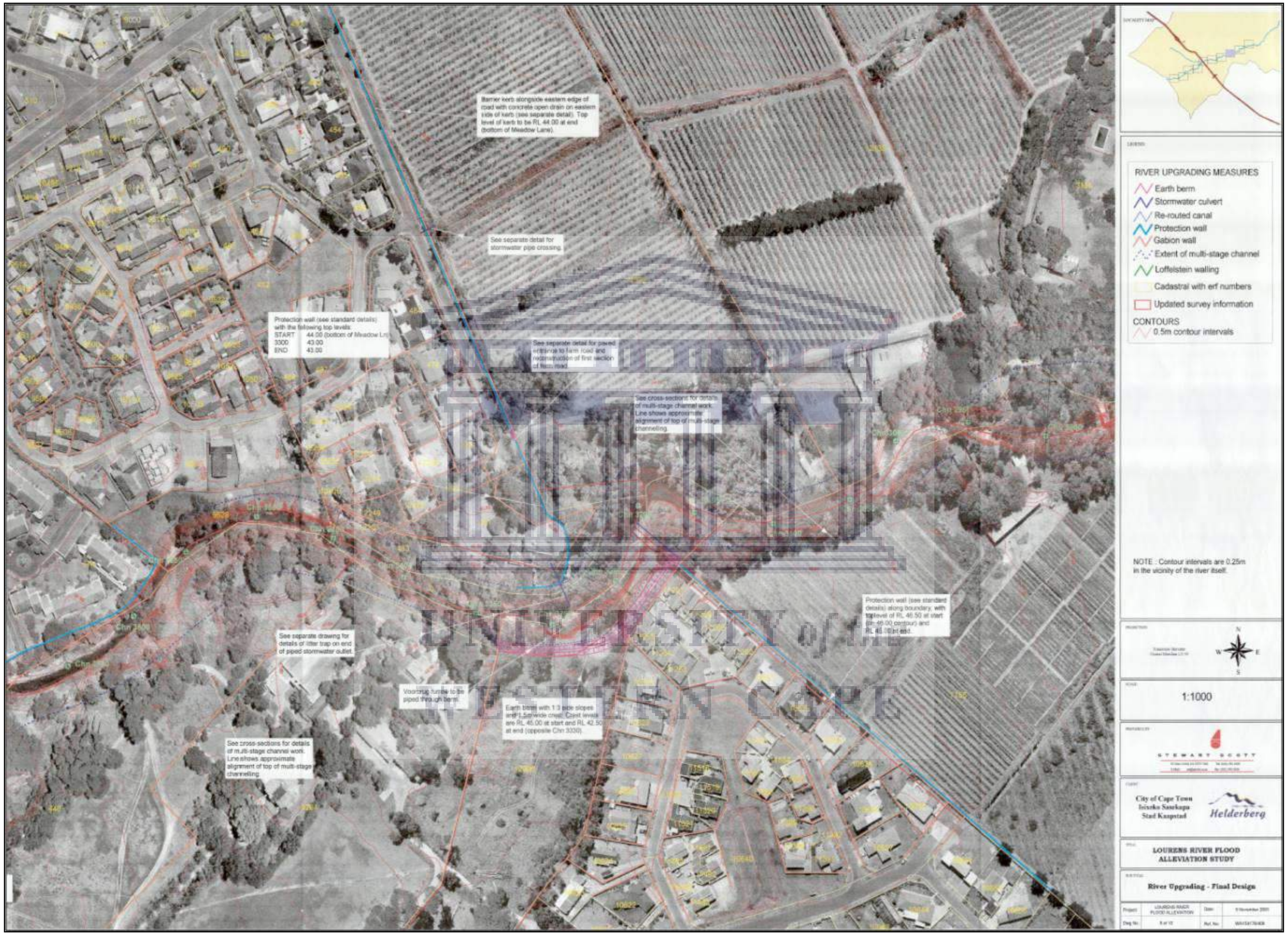
Type	Date	Timescale (1-4)	Description	Reference
	2015-2016	T3	Contract Tender Document - Lourens River Upgrading Phase 1G River Works (Landscaping and Horticultural Works) – CONTRACT NO. (Not found)	CoCT 2015
	2018	T4	Contract Tender Document - Lourens River Upgrading Phase 1H River Works (Landscaping and Horticultural Works) – CONTRACT NO./2018/19	CoCT 2018
	2001	T1	1:1000 Aerial photograph Drawing (Drawing No. 1 out of 10). Project No. WA154176 Chainage 1050 to 1800	SSI 2001
	2001	T1	1:1000 Aerial photograph Drawing (Drawing No. 2 out of 10) .Project No. WA154176 Chainage 1800 to 2900	SSI 2001
	2001	T1	1:1000 Aerial photograph Drawing (Drawing No. 3 out of 10). Project No. WA154176 Chainage 2900 to 3650	SSI 2001
	2001	T1	1:1000 Aerial photograph Drawing (Drawing No. 4 out of 10). Project No. WA154176 Chainage 3700 to 4600	SSI 2001
	2001	T1	1:1000 Aerial photograph Drawing (Drawing No. 5 out of 10). Project No. WA154176 Chainage 4500 to 5350	SSI 2001
	2001	T1	1:1000 Aerial photograph Drawing (Drawing No. 6 out of 10). Project No. WA154176 Chainage 5300 to 6050	SSI 2001
	2001	T1	1:1000 Aerial photograph Drawing (Drawing No. 7 out of 10). Project No. WA154176 Chainage 6000 to 6700	SSI 2001
	2001	T1	1:1000 Aerial photograph Drawing (Drawing No. 8 out of 10). Project No. WA154176 Chainage 6700 to 7450	SSI 2001
	2001	T1	1:1000 Aerial photograph Drawing (Drawing No. 9 out of 10). Project No. WA154176 Chainage 7450 to 8100	SSI 2001
	2001	T1	1:1000 Aerial photograph Drawing (Drawing No. 10 out of 10). Project No. WA154176 Chainage 8100 to 9000	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 1100 to 1950	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 2000 to 2300	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 2350 3050	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 3100 to 3800	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 3850 to 4550	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 4600 to 5300	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 5350 to 6250	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 6300 to 6650	SSI 2001
	2001	T1	Drawing	SSI 2001

Type	Date	Timescale (1-4)	Description	Reference
			Cross sectional profile. Project No. WA154176 Chainage 6100 to 6500	
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 6700 to 7050	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 7100 7350	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 7400 to 7550	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 7650 to 8000	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 7900 to 8750	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 7650 to 8000	SSI 2001
	2001	T1	Drawing Cross sectional profile. Project No. WA154176 Chainage 8050 to 8400	SSI 2001
	2010	T3	Drawing (Drawing No.WA154176/08). Phase 1C and 1D– Survey Layout and proposed plans “As-built”. CONTRACT NO.315Q/2008/09. Chainage 4425 to 5000 - Andries Pretorius Street to Sergeant Street bridge	Royal Haskoning 2010
	2010	T3	Drawing (Drawing No.WA154176/02) Phase 1C and 1D - Cross-sectional profile “As-built”. – CONTRACT NO. (Not found) Chainage 4350 to 5300 - Andries Pretorius Street to Sergeant Street bridge.	Royal Haskoning 2010
	2011	T3	Drawing (Drawing No.LR1E001TD) Phase 1E – Landscape Plan	Anderson 2011
	2011	T3	Drawing (Drawing No.LR1E002TD) Phase E – Typical cross section	Anderson 2011
	2011	T3	Drawing (Drawing No.LR-PH2-IRR-NOV2011) Phase E – Irrigation reticulation	Arid Earth Solutions 2011
	2013	T3	Drawing (Drawing No.WA154176/1E/02). Phase 1E– Survey Layout and proposed plans CONTRACT NO. 100Q/2011/12. Chainage 3900 to 4550 - Andries Pretorius Street to Sergeant Street bridge.	Royal Haskoning 2013
	2013	T3	Drawing (Drawing No.WA154176/1E/03) Phase 1E– Cross-sectional profile “As built”. CONTRACT NO.100Q/2011/12. Chainage 3850-4550 – Main Road to Andries Pretorius street.	Royal Haskoning 2013
	2014	T3	Drawing (WA154176.1G/00) Phase G – Urgent flood remedial works	Royal Haskoning 2014
	2019	T3	Drawing (Drawing No.W01 C 154176 C 102) Phase H - Cross sectional profile “As Built”. CONTRACT NO.165Q/2015/16 Chainage 3050 to 3450 - Historic Bridge to Hathersage	Royal Haskoning DHV 2019
	2019	T3	Drawing (Drawing No.W01 C 154176 C 102) Phase H - Cross sectional profile “As Built”. CONTRACT NO. 165Q/2015/16 Chainage 3575 to 3950- Historic Bridge to Hathersage	Royal Haskoning DHV 2019

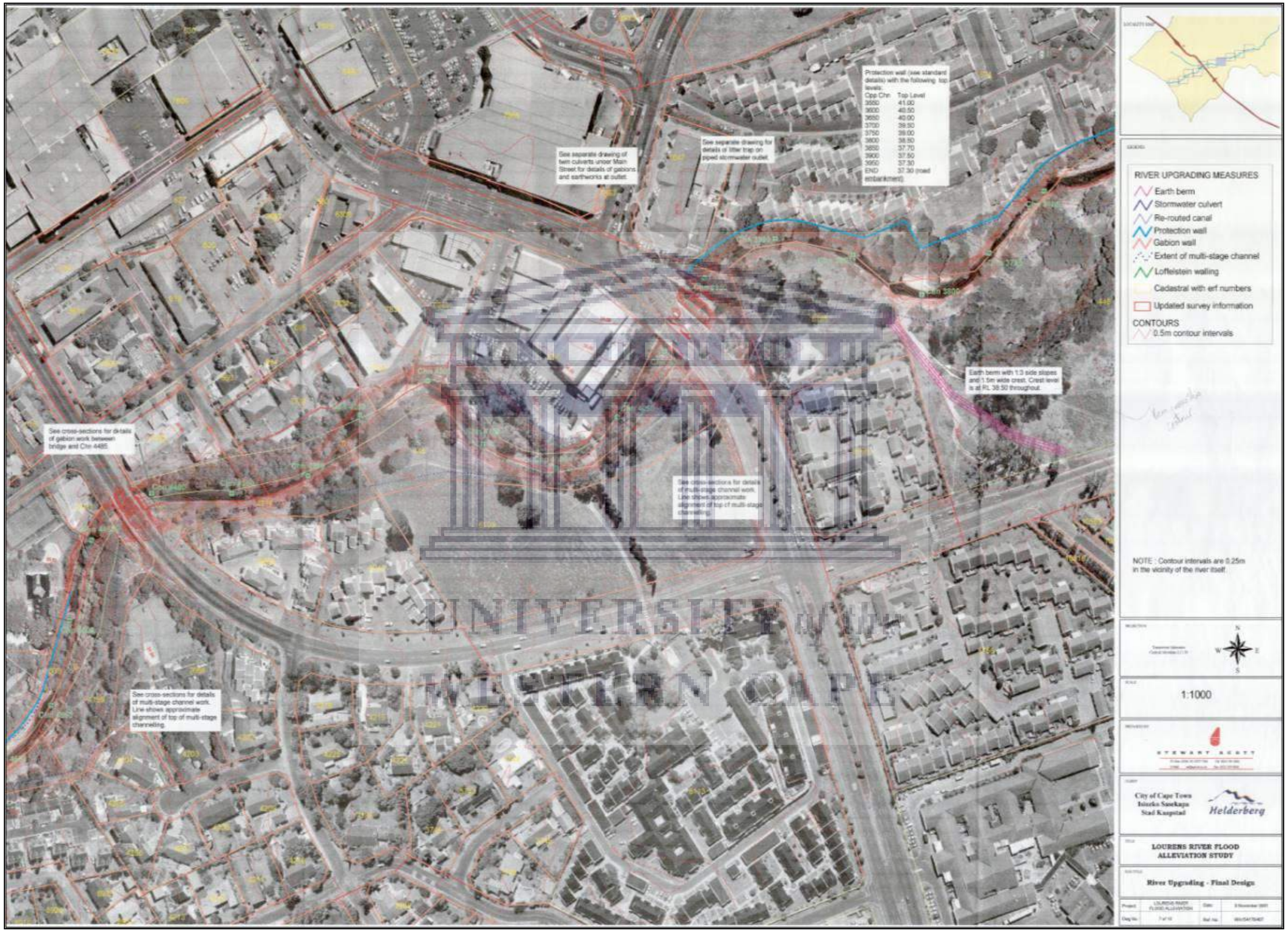


Appx. Figure 4: Aerial photographs of engineering proposals, Map 1 out of 10 (SSI 2001).

Appx. Figure 5: Aerial photographs of engineering proposals, Map 2 out of 10 (SSI 2001).



Appx. Figure 6: Aerial photographs of engineering proposals, Map 3 out of 10 (SSI 2001).



Protection wall (see standard details) with the following top levels:

Opp Chn	Top Level
3550	41.00
3600	40.50
3650	40.00
3700	39.50
3750	39.00
3800	38.50
3850	37.70
3900	37.50
3950	37.30
END	37.30 (road embankment)

See separate drawing of twin culverts under Main Street for details of gabions and earthworks at outlet.

See separate drawing for details of litter trap on piped stormwater outlet.

Earth berm with 1:3 side slopes and 1.5m wide crest. Crest level is at RL 38.50 throughout.

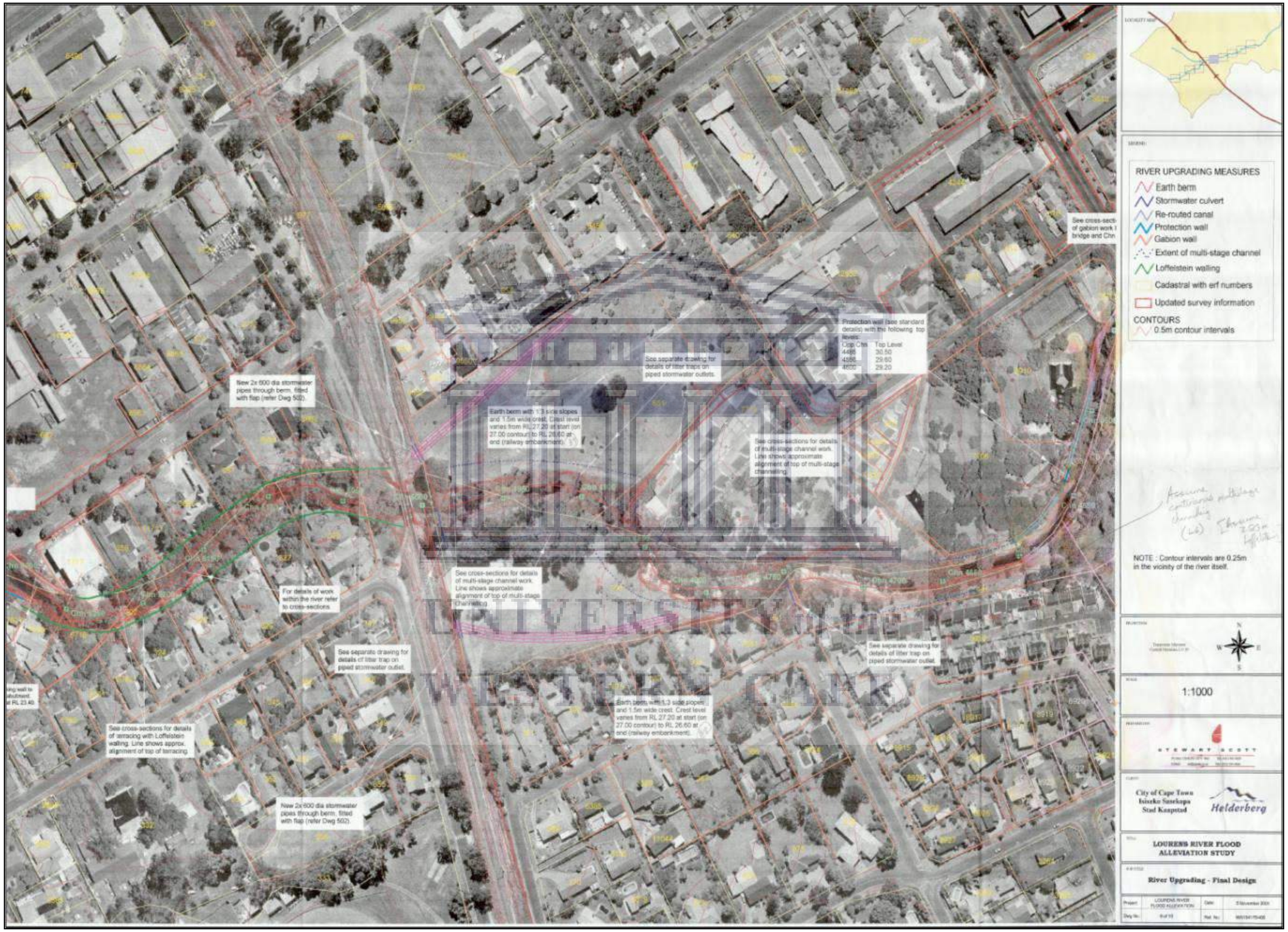
See cross-sections for details of gabion work between bridge and Chn 4485.

See cross-sections for details of multi-stage channel work. Line shows approximate alignment of top of multi-stage channelling.

See cross-sections for details of multi-stage channel work. Line shows approximate alignment of top of multi-stage channelling.

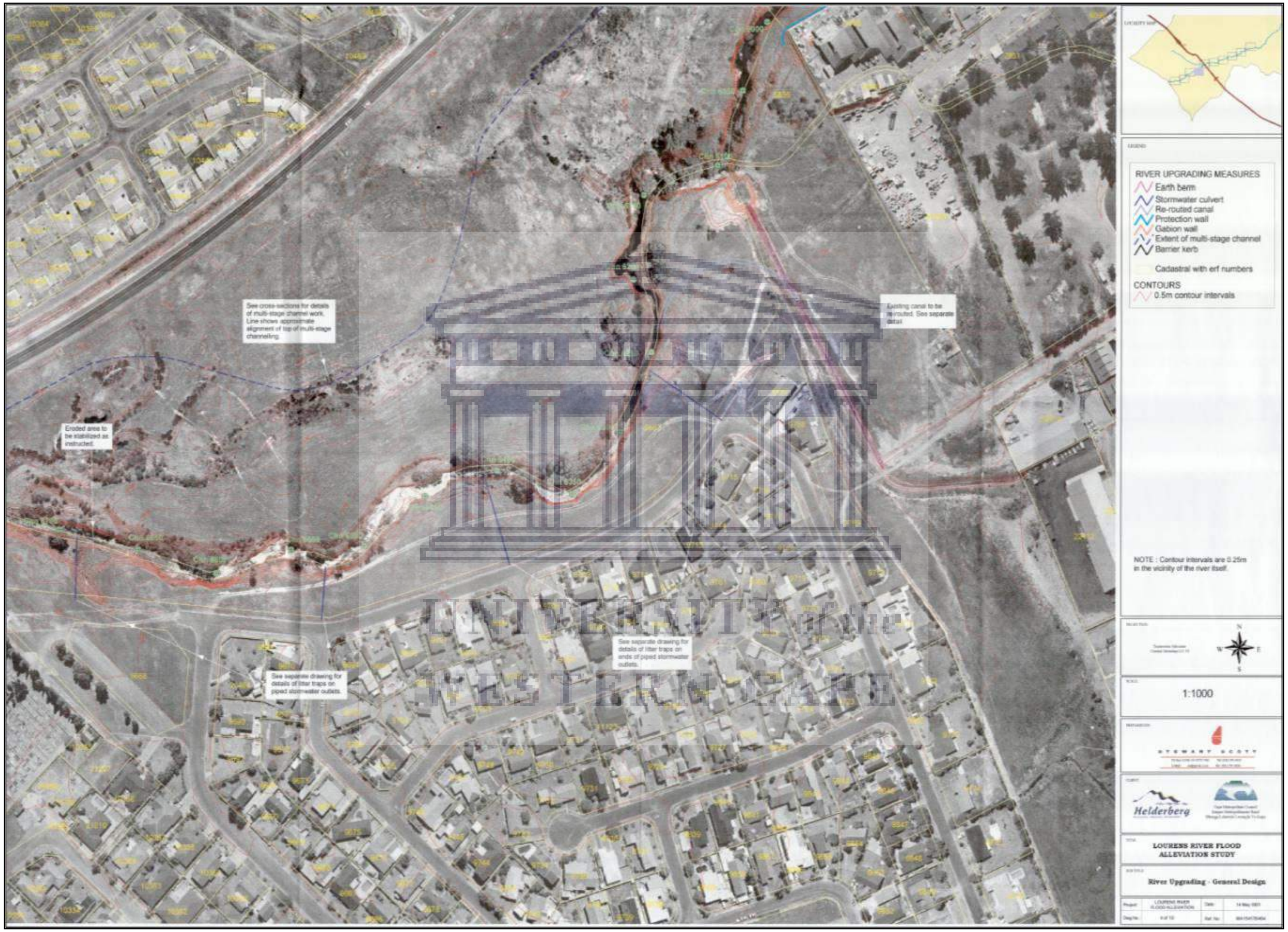
NOTE : Contour intervals are 0.25m in the vicinity of the river itself.

Appx. Figure 7: Aerial photographs of engineering proposals, Map 4 out of 10 (SSI 2001).

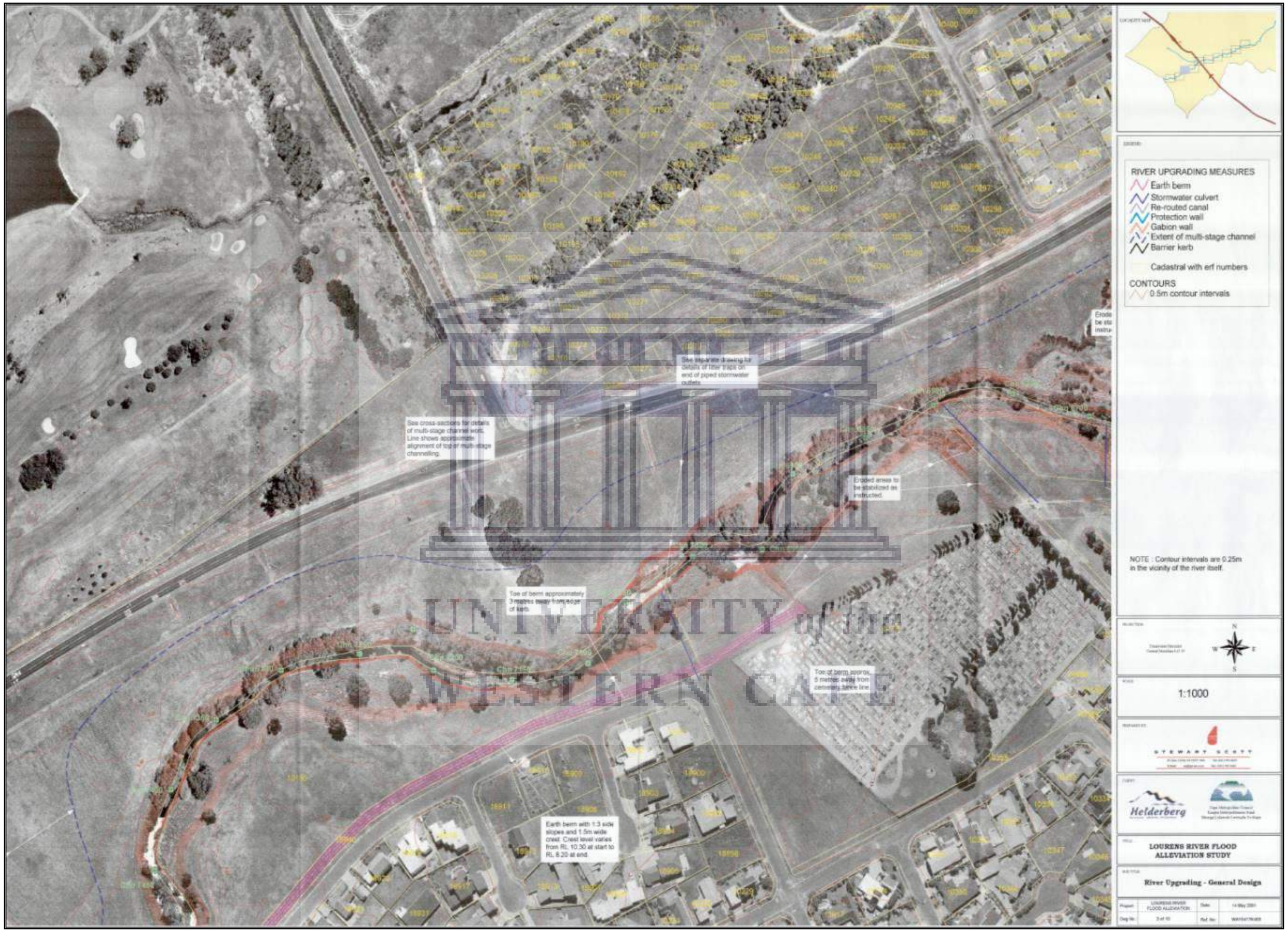


Appx. Figure 8: Aerial photographs of engineering proposals, Map 5 out of 10 (SSI 2001).

Appx. Figure 9: Aerial photographs of engineering proposals, Map 6 out of 10 (SSI 2001).

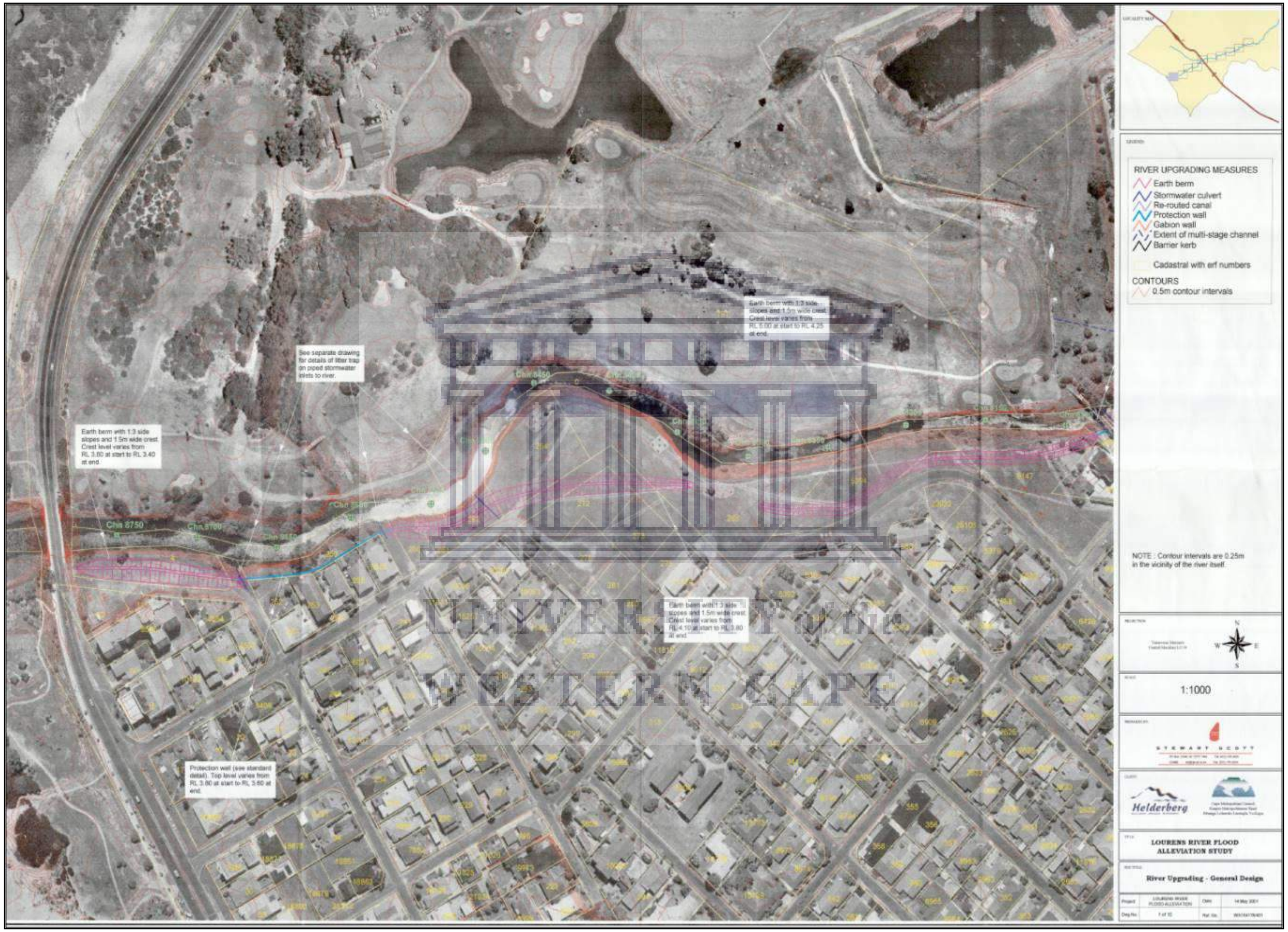


Appx. Figure 10: Aerial photographs of engineering proposals, Map 7 out of 10 (SSI 2001).

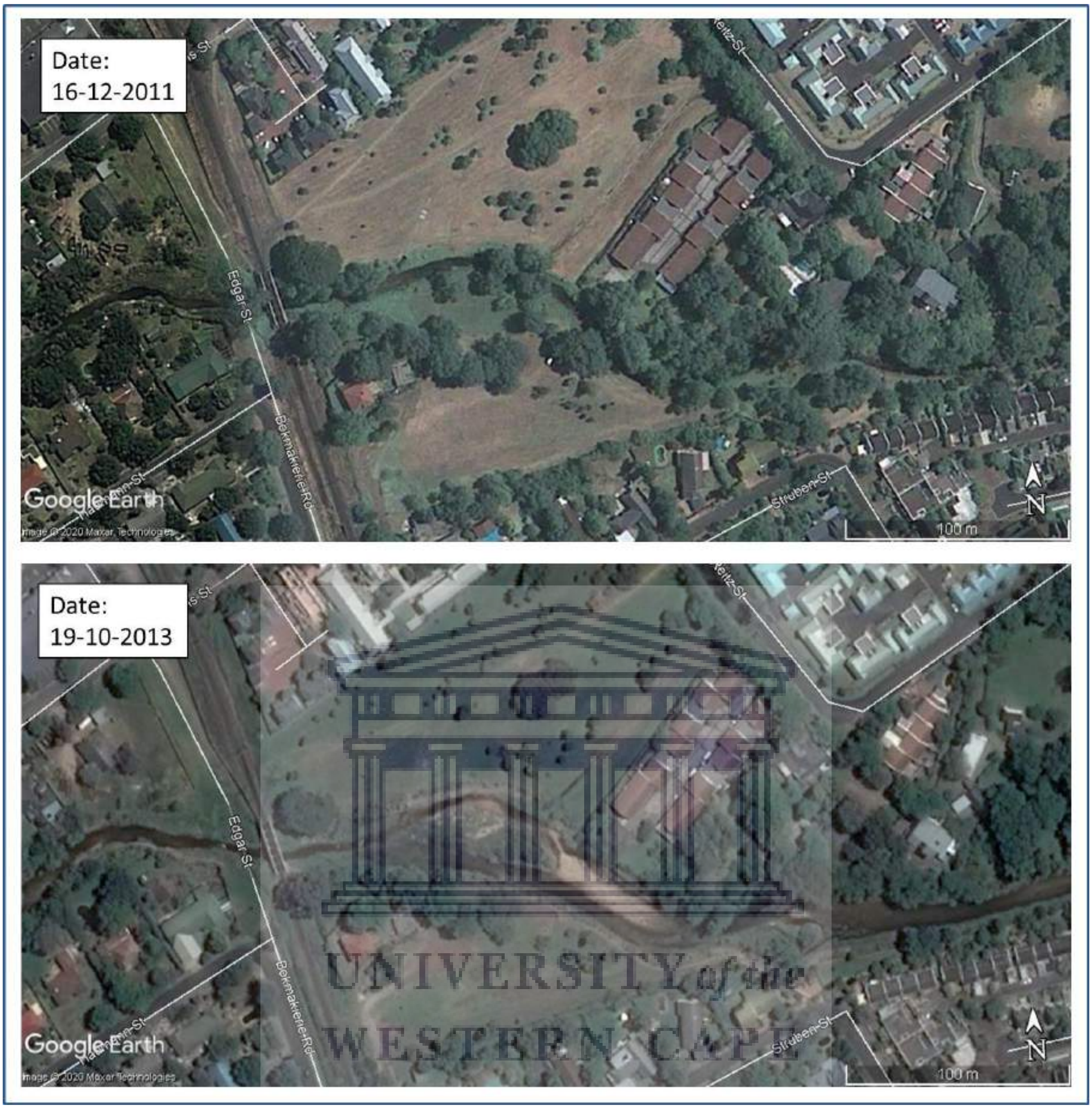


Appx. Figure 11: Aerial photographs of engineering proposals, Map 8 out of 10 (SSI 2001).

Appx. Figure 12: Aerial photographs of engineering proposals, Map 9 out of 10 (SSI 2001).



Appx. Figure 13: Aerial photographs of engineering proposals, Map 10 out of 10 (SSI 2001).



Appx. Figure 14: Section of the Lourens River at Reitz Park (Chainage 4600-5150) pre- and post-sub-phase 1D.

Appx. Table 4: Life history table of plant species present along the Lourens River.

Species	Common name	Months in flower and seed	Habitat	Section of river	Growth form	Function	Importance	Prorogation	Plant spacing per 1 sq m.
Agathosma ovata	False buchu	1-2	DB	A	SM	O	*	S	4
Agrostis lachnantha	Bent grass	11-2	WB	B, C	HT	O, E	*	V, S	5
Amaryllis belladonna	March lily	2-4	DB	A, B	GD	O	**	S	8
Aponogeton distachyos	Waterblommetjie	7-12	AQ	B, C	HP	O	*	SV	4
Aristea macrocarpa	Suurkanol	11-1	DB	A	GE	O, C	*	S	5
Aparagus racemosus	Wild asparagus	1-6	DB	C, D	GE	C	*	V	5
Asparagus suaveolens sensus	Katdoring	4-9	DB	A-C	GE	C	*	V	5
Asplenium sp.	Mother fern	-	DB	A	HP	C	*	V	4
Blechnum attenuatum	Hard fern	-	WB	A	HP	O, C	*	V	4
Blechnum punctulatum	Hard fern	-	WB	B	HP	O, C	*	V	4
Brabejum stellatifolium	Cape bitter almond	2-3	WB/DB	A-C	TS-ST	S, O, C	***	S	0.8
Brachylaena nerifolia	Water white alder	2-3	WB	A, B	TS-ST	O, C	***	S	0.8
Buddleia saligna	Bastard Olive	8-1	DB	B	ST	O	*	S	3
Calopsis paniculata	Besemriet	5-8	WB/DB	A-C	HT	O, E	***	V	3
Canthium inerme	Turkey berry	9-12	DB	B, C	TS	O, C	**	S	0.8
Chasmanthe aethiopica	Suurknaol	4-7	DB	A-D	GD	O, C	**	V, S	8
Cliffortia odorata	Wilde wingerd	5-2	DB	B, C	SM	C	**	V	3
Cliffortia strobilifera	Bof rice-bush	1-4	WB/DB	B, C	SM	FC, FE	**	V	4
Commenlina benghalensis	Blouselblommetjie	11-4	WB	C	HP	C	*	V	6
Commelina diffusa subsp. diffusa	Wandering jew	11-6	WB	B, C	HP	C	*	V	6
Crotalaria capensis	Cape laburnum	8-12	DB	B, C	SM	O	***	S	4
Cryptocarya angustifolia	Blue laurel	11-12	DB	A, B	TS, ST	O	***, rare	S	3
Cunonia capensis	Butterspoon tree	2-5	DB	A-C	TT	S, O, C	***	S	0.8
Curtisia dentata	Assegai wood	5-6	DB	A	TT	C	*	S	0.8
Cyperus brevis	Sedge	10-3	WB	A, B	HP	E	*	V	7
Cyperus longus	Water sedge	10-3	WB	B, C	HP	E	**	V	7
Cyperus textilis	Giant cape sedge	10-3	WB	B, C	HP	E, C, O	***	V	5
Diospyros glabra	Blueberry bush	10-3	DB	A-D	SM	C	***	S, V	4
Diospyros whyteana	Blackbark	8-11	DB	A, B	TS	O, C	***	S, V	0.8
Eheharta calycina	Rooisaadgras	7-12	DB	A-D	HT	C	*	S, V	10
Eheharta delicatula	Watergrass	7-12	DB	A-C	HA	C	O	S	10

Eheharta erecta	-	9-12	DB	A-C	HP	C	O	S	10
Eragrostis curvula	Blue seed grass	1-12	DB	B, C	HT	C	O	S	5
Erica caffra	Sweet scented heathS10	7-12	WB	A, B	ST	C	***	S	3
Festuca scabra	Munniks gras	9-12	DB	A-C	HT	C	O	S	10
Freylinia lanceolata	Honey-bell MSbush	1-12	DB	B, C	ST	O, E, C	***	S, V?	3
Gnidia oppositifolia	GonTSnasbos	1-12	DB	A, B	SM	O, C	**	S	4
Halleria elliptica	Bush TMhoneysuckle	10-4	DB	A, B	SM	O, C	***	SV	4
Halleria lucida	MoSGuntain fuchsia	5-12	DB	A	TS	O, C	**	S, V	0.8
Hartogiella schinoides	Spoonwood	8-1	DB	A	TM	O, C	**	S	0.8
Helichrysum crispum	Hottentotskooigoed	10-1	DB	A-C	SG	C	**	S	5
Helichrysum cymosum	Everlasting	10-3	DB	A	HP	C	*	S	5
Hypodiscus aristatus	Cape reed	1-12	DB	A	HT	C	*	SV	5
Ilex mitis	Cape holly	9-12	DB	A-C	TM	O, C	***	S	0.8
Ischyrolepsis subverticillata	Cape reed	7-3	DB	A-C	HT	E, C, O	***	S, V	3
Isolepis prolifer	Sedge	10-3	WB	A-D	HT	E, C	***	V	10
Juncus capensis	Rush	11-4	WB	A	HT	C	*	V	7
Juncus lomatophyllus	Sedge	10-4	WB	A-C	HP	E, C	**	V, S	7
Juncus punctorius	Rush	10-2	WB	D	HT	C	*	V	7
Kiggelaria africana	Wild peach	9-12	DB	A-C	TS	O, C	***	S	0.8
Knowltonia capensis	Katjiedrieblaar	6-9	DB	A	HP	O	*	S	5
Leucospermum conocarpodendron,	Pincushion	8-1	DB	A	ST	O	*	S	1
Lobelia erinus	Wild lobelia	1-12	WB	A	HA	O	O	S	7
Maurocenia frangularia	Hottentots cherry	7	DB	A	TS	C	**	S	0.8
Maytenus acuminata	Silky bark	5-11	DB	A, B	TM	S, O, C	***	S	0.8
Maytenus lucida	Cape maytenus	5-9	DB	A, B	ST	C	**	S	1
Maytenus eleoides	Rock candlewood	11-1	DB	A-C	TS	S, O, C	***	S	0.8
Metrosideros angustifolia	Lance-leaved myrtle	11-1	DB	A, B	ST	E, C	***	S	3
Myrsine africana	Cape myrtle	10-7	DB	A, B	SM	O, C	***	S, V	4
Myrsiphyllum scandens	Creeping asparagus	8-1	DB	A, B	G,HC	C	**	S	5
Olea capensis subsp. macrocarpa	Ironwood	9-3	DB	A	TS	C	*	S	0.8
Olea europaea subsp. africana	Wold olive	10-5	DB	A-D	TM	S, O, C	***	S	0.8
Olinio ventosa	Hard pear	12-6	DB	A	TM	S, O, C	**	S	0.8
Othonno quiquedentata	5-point daisy	1-12	DB	A, B	SM	C	*	S	4
Panicum schinzil	Sweet buffalo grass	11-5	WB	A, B	HP	E	*	S	5
Passerina vulgaris	Gonnabos	12-4	WB	A-D	HT	C, O	***	S	3

Pellaea dura	Hard fern	-	DB	A	HP	C	*	S, V	6
Pentaschistis ampla	Tassel grass	11-4	DB	A	HT	E	*	S, V	5
Persicaria serrulata	Snake root	1-12	WB	B-C	TM	E	*	V	7
Phragmites australis	Common trees	12-6	WB	C, D	ST	E	***	V, S	4
Platylophus trifoliatus	White alder	12-2	DB	A	TM	S, C	**	S	0.8
Podalyria calyptrata	Water blossom pea	7-10	DB	A, B	SS	O	**	S	3
Podocarpus elongatus	Breede river yellowwood	1-5	DB	A-C	SM	S, O, C	***	S	0.8
Prionium serratum	Palmiet	9-3	WB	A, B	ST	E, C	***	V	5
Protea repens	Sugar bush	1-5-12	DB	A, B	TM	O	**	S	4
Psoralea pinnata	Fountain bush	1-12	WB	A-C	SM	O	**	S	3
Rapanea melanophloeos	Cape beech	6-12	WB/DB	A-C	TM	S, O, C	***	s	0.8
Rhus angustifolia	Willow currant	10-11-4	DB	A-C	SM	C	**	S	4
Rhus rosmarinifolia	Rosemary wild currant	4-9	DB	A, B	SS	C	**	S	6
Rhus tomentosa	Wooly berry	5-2	DB	A-C	SM	C	***	S	4
Salix mucronata	Cape willow	9-10	WB	B, C	TS, ST	E	***	V	5
Schoenoxiphium lanceum	Forest sedge	6-11	WB	A	HT	C	*	S, V	7
Secamone alpinii	Monkey rope	10-1	DB	A	SC	C	*	S	3
Selago sp.	-	-	WB	B, C	HP	O	*	S	5
Setaria megaphylla	Ribbon bristle grass	9-5	DB	B, C	HT	E, C	***	V	5
Stoebe plumosa	Slangbos	4-10	DB	A-C	SS	C	*	S	4
Typha capensis	Bulrush	12-3	WB	C-D	HT	E	**	V, S	5
Zantedeschia aethiopica	Arum lily	6-2	DB	A-D	GE, GD	O, C	***	V, S	5

Key to Appx. Table 4

Habitat:

AQ	Aquatic
WB	Wet Bank Zone
DB	Dry Bank Zone

Growth form:

Note: growth form is related to size and would influence planting densities.

TT	Tree - Tall
TM	Tree - Medium
TS	Tree -Short
ST	Shrub - Tall
SM	Shrub - Medium
SS	Shrub - Short
SG	Shrub – Ground cover
SC	Shrub - Climber
HT	Herb - Tall
HP	Herb - Perennial
HA	Herb - Annual
HG	Herb – Ground cover
HC	Herb - Climber
GE	Geophyte - Evergreen
GD	Geophyte – Deciduous

Function:

O	Ornamental
C	Cover
E	Erosion control
S	Shade
W	Weed

Importance:

Note: It is important that plants marked as essential are propagated for rehabilitation.

***	Essential
**	Useful
*	Immaterial
O	Not recommended

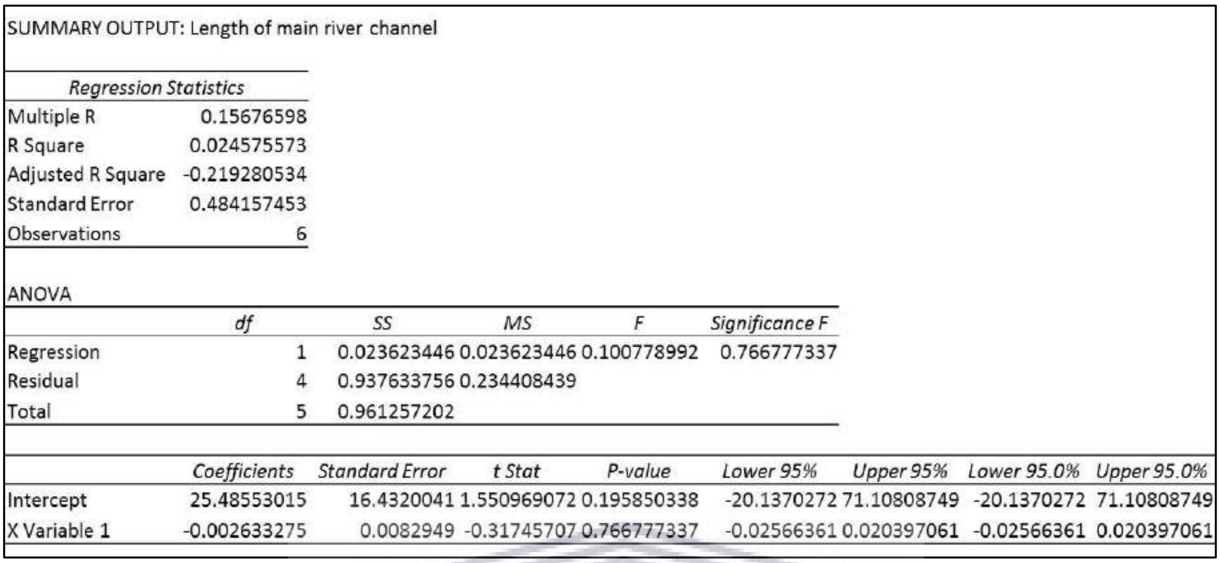
Propagation:

Note: The propagation methods are simply suggestion. For instance, some horticulturalists may prefer to use mainly cutting sand other mainly seed.

S	Seed
V	Vegetative (e.g. cuttings)

Appx. Figure 15: Key to Appx. Table 4

Appx. Table 5: Regression analysis of length of the main river channel between periods 1942, 1959, 1979, 1995, 2000 and 2010.



SUMMARY OUTPUT: Length of main river channel

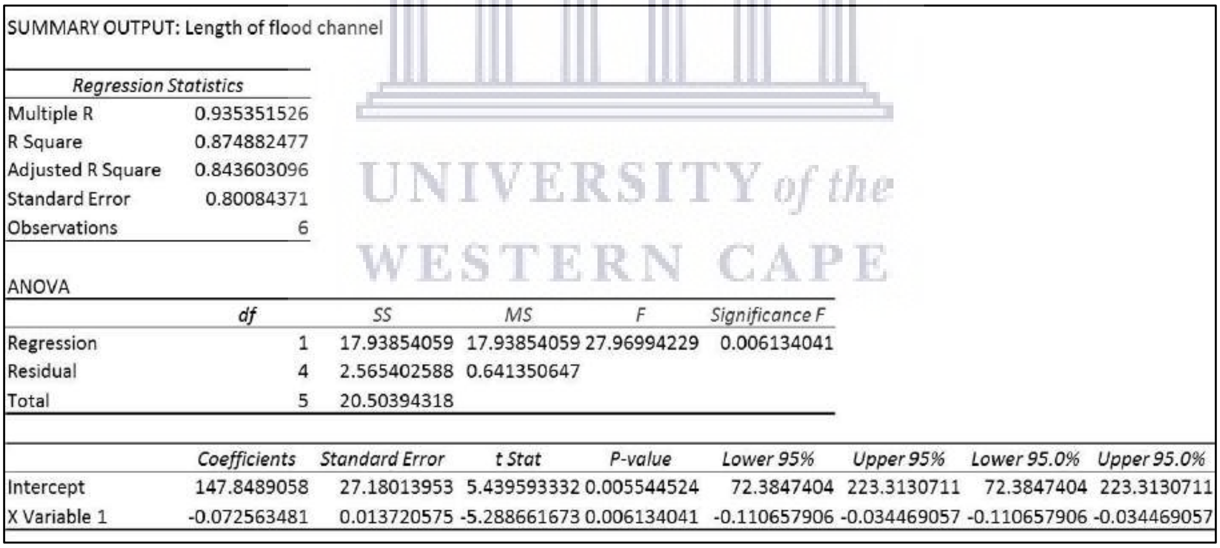
Regression Statistics	
Multiple R	0.15676598
R Square	0.024575573
Adjusted R Square	-0.219280534
Standard Error	0.484157453
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.023623446	0.023623446	0.100778992	0.766777337
Residual	4	0.937633756	0.234408439		
Total	5	0.961257202			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	25.48553015	16.4320041	1.550969072	0.195850338	-20.1370272	71.10808749	-20.1370272	71.10808749
X Variable 1	-0.002633275	0.0082949	-0.31745707	0.766777337	-0.02566361	0.020397061	-0.02566361	0.020397061

Appx. Table 6: Regression analysis of length of the flood channel between periods 1942, 1959, 1979, 1995, 2000 and 2010.



SUMMARY OUTPUT: Length of flood channel

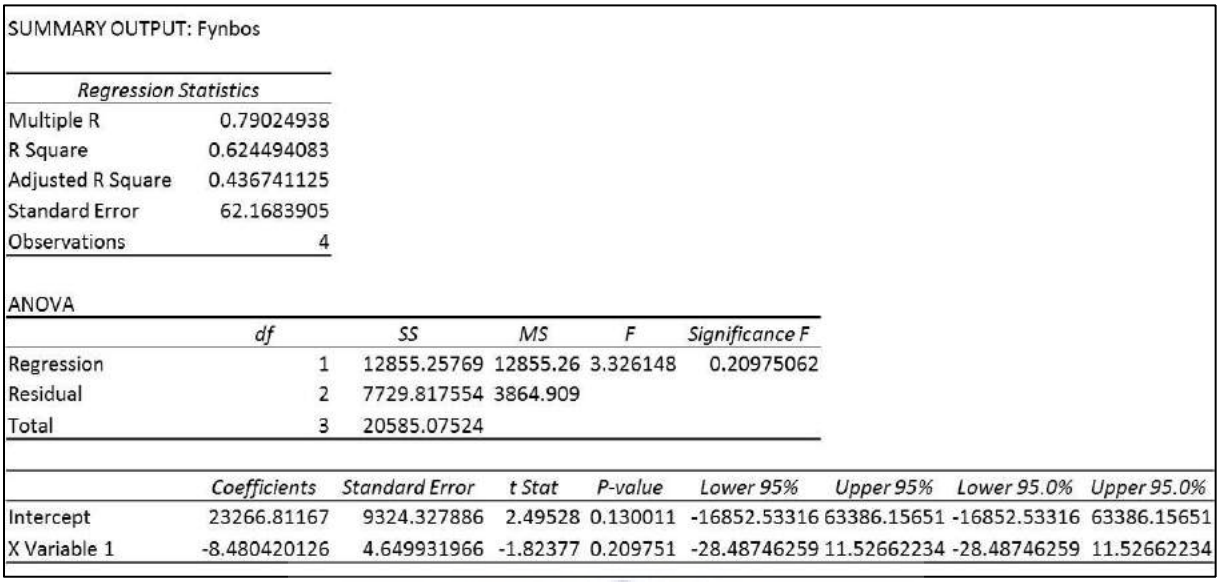
Regression Statistics	
Multiple R	0.935351526
R Square	0.874882477
Adjusted R Square	0.843603096
Standard Error	0.80084371
Observations	6

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	17.93854059	17.93854059	27.96994229	0.006134041
Residual	4	2.565402588	0.641350647		
Total	5	20.50394318			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	147.8489058	27.18013953	5.439593332	0.005544524	72.3847404	223.3130711	72.3847404	223.3130711
X Variable 1	-0.072563481	0.013720575	-5.288661673	0.006134041	-0.110657906	-0.034469057	-0.110657906	-0.034469057

Appx. Table 7: Regression analysis of landuse type ‘Fynbos’ for all study reaches (1-16) between periods 1998, 2002, 2005 and 2016.



SUMMARY OUTPUT: Fynbos

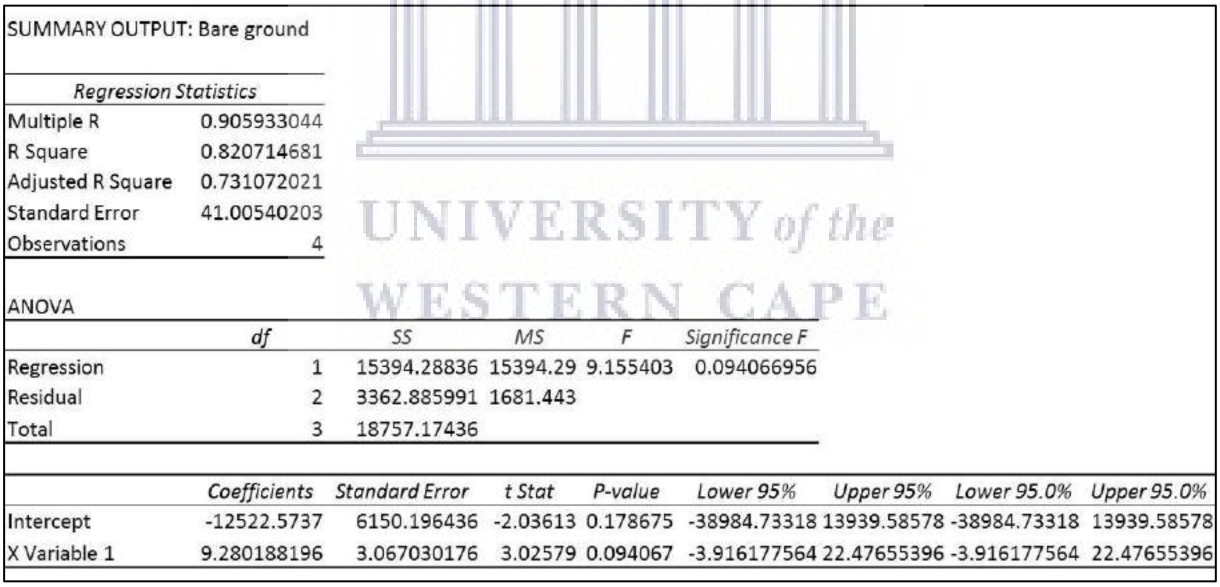
Regression Statistics	
Multiple R	0.79024938
R Square	0.624494083
Adjusted R Square	0.436741125
Standard Error	62.1683905
Observations	4

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	12855.25769	12855.26	3.326148	0.20975062
Residual	2	7729.817554	3864.909		
Total	3	20585.07524			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	23266.81167	9324.327886	2.49528	0.130011	-16852.53316	63386.15651	-16852.53316	63386.15651
X Variable 1	-8.480420126	4.649931966	-1.82377	0.209751	-28.48746259	11.52662234	-28.48746259	11.52662234

Appx. Table 8: Regression analysis of landuse type ‘Bare ground’ for all study reaches (1-16) between periods 1998, 2002, 2005 and 2016.



SUMMARY OUTPUT: Bare ground

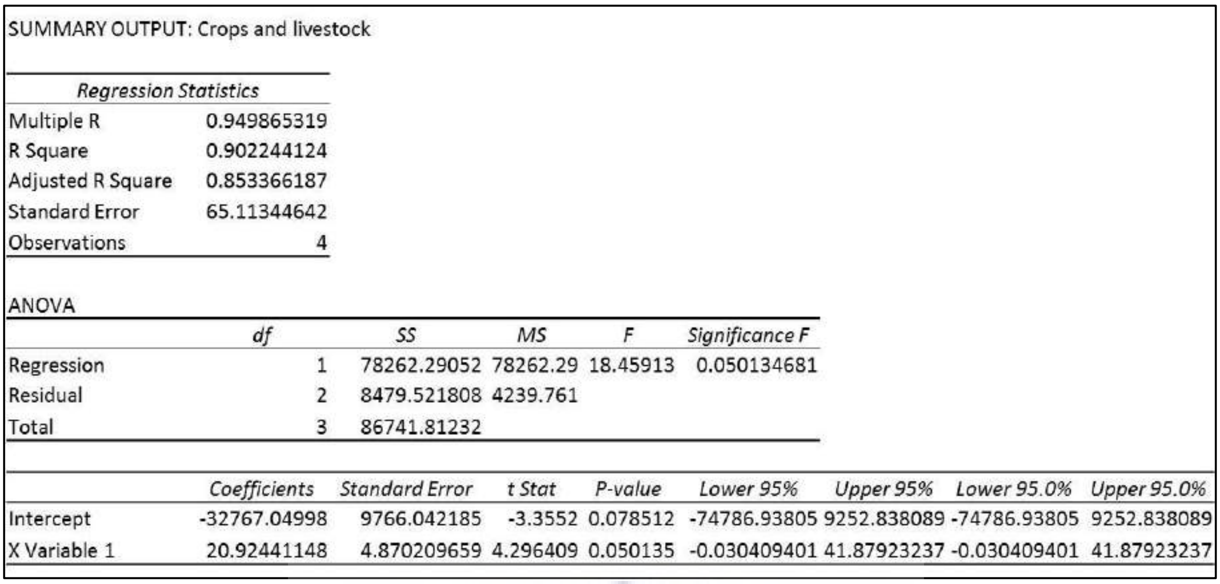
Regression Statistics	
Multiple R	0.905933044
R Square	0.820714681
Adjusted R Square	0.731072021
Standard Error	41.00540203
Observations	4

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	15394.28836	15394.29	9.155403	0.094066956
Residual	2	3362.885991	1681.443		
Total	3	18757.17436			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-12522.5737	6150.196436	-2.03613	0.178675	-38984.73318	13939.58578	-38984.73318	13939.58578
X Variable 1	9.280188196	3.067030176	3.02579	0.094067	-3.916177564	22.47655396	-3.916177564	22.47655396

Appx. Table 9: Regression analysis of landuse type ‘Crops and livestock’ for all study reaches (1-16) between periods 1998, 2002, 2005 and 2016.



SUMMARY OUTPUT: Crops and livestock

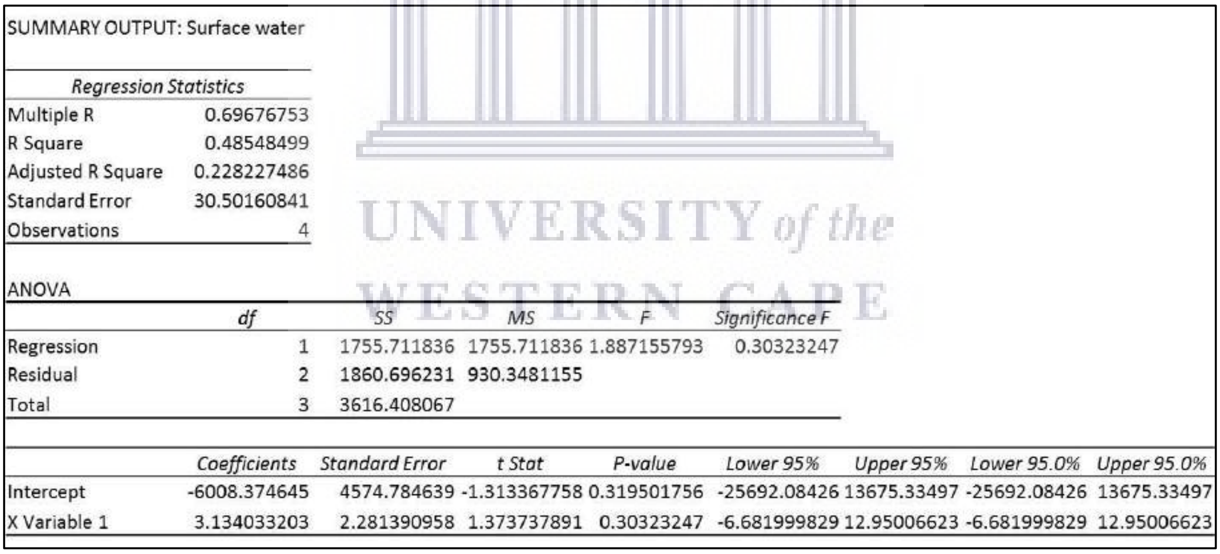
Regression Statistics	
Multiple R	0.949865319
R Square	0.902244124
Adjusted R Square	0.853366187
Standard Error	65.11344642
Observations	4

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	78262.29052	78262.29	18.45913	0.050134681
Residual	2	8479.521808	4239.761		
Total	3	86741.81232			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-32767.04998	9766.042185	-3.3552	0.078512	-74786.93805	9252.838089	-74786.93805	9252.838089
X Variable 1	20.92441148	4.870209659	4.296409	0.050135	-0.030409401	41.87923237	-0.030409401	41.87923237

Appx. Table 10: Regression analysis of landuse type ‘Surface water’ for all study reaches (1-16) between periods 1998, 2002, 2005 and 2016



SUMMARY OUTPUT: Surface water

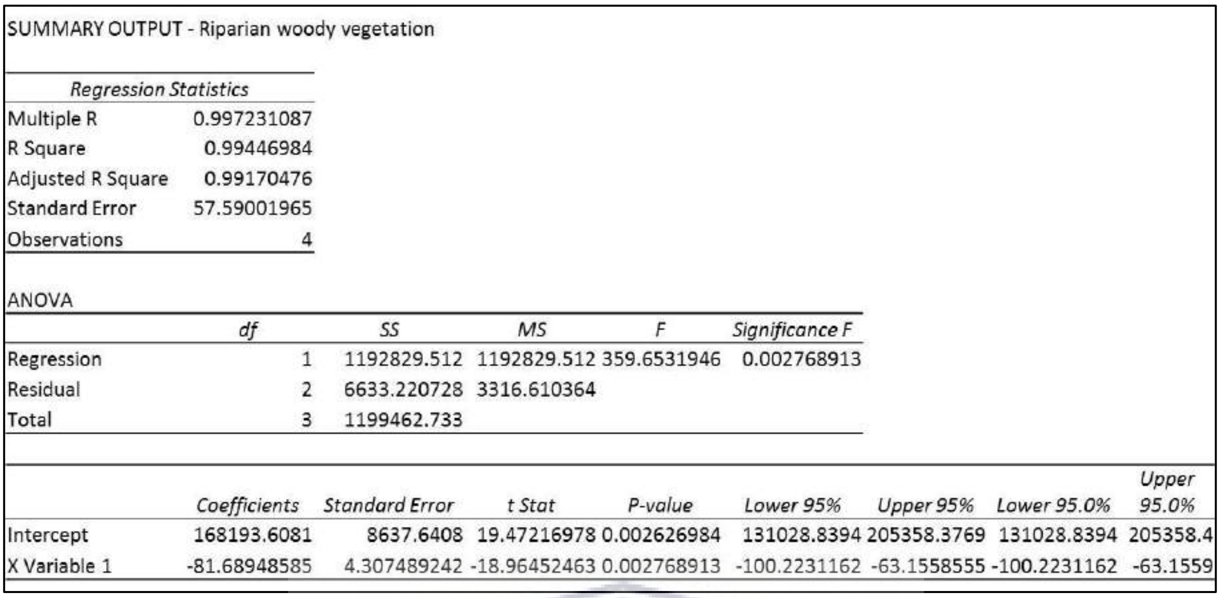
Regression Statistics	
Multiple R	0.69676753
R Square	0.48548499
Adjusted R Square	0.228227486
Standard Error	30.50160841
Observations	4

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1755.711836	1755.711836	1.887155793	0.30323247
Residual	2	1860.696231	930.3481155		
Total	3	3616.408067			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-6008.374645	4574.784639	-1.313367758	0.319501756	-25692.08426	13675.33497	-25692.08426	13675.33497
X Variable 1	3.134033203	2.281390958	1.373737891	0.30323247	-6.681999829	12.95006623	-6.681999829	12.95006623

Appx. Table 11: Regression analysis of landuse type ‘Riparian woody vegetation’ for all study reaches (1-16) between periods 1998, 2002, 2005 and 2016.



SUMMARY OUTPUT - Riparian woody vegetation

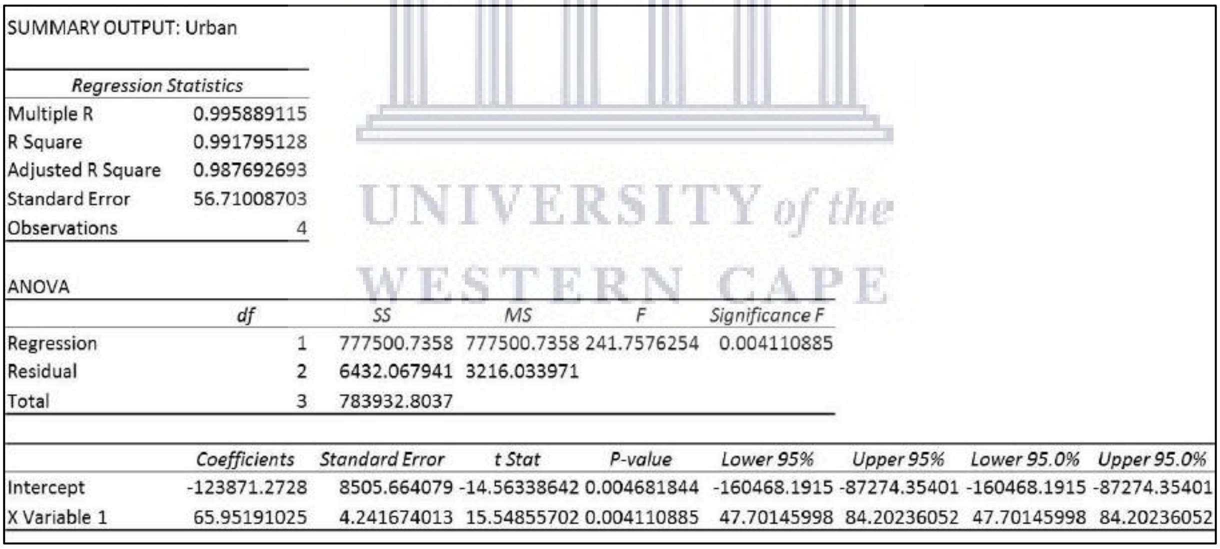
Regression Statistics	
Multiple R	0.997231087
R Square	0.99446984
Adjusted R Square	0.99170476
Standard Error	57.59001965
Observations	4

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1192829.512	1192829.512	359.6531946	0.002768913
Residual	2	6633.220728	3316.610364		
Total	3	1199462.733			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	168193.6081	8637.6408	19.47216978	0.002626984	131028.8394	205358.3769	131028.8394	205358.4
X Variable 1	-81.68948585	4.307489242	-18.96452463	0.002768913	-100.2231162	-63.1558555	-100.2231162	-63.1559

Appx. Table 12: Regression analysis of landuse type ‘Urban’ for all study reaches (1-16) between periods 1998, 2002, 2005 and 2016.



SUMMARY OUTPUT: Urban

Regression Statistics	
Multiple R	0.995889115
R Square	0.991795128
Adjusted R Square	0.987692693
Standard Error	56.71008703
Observations	4

ANOVA

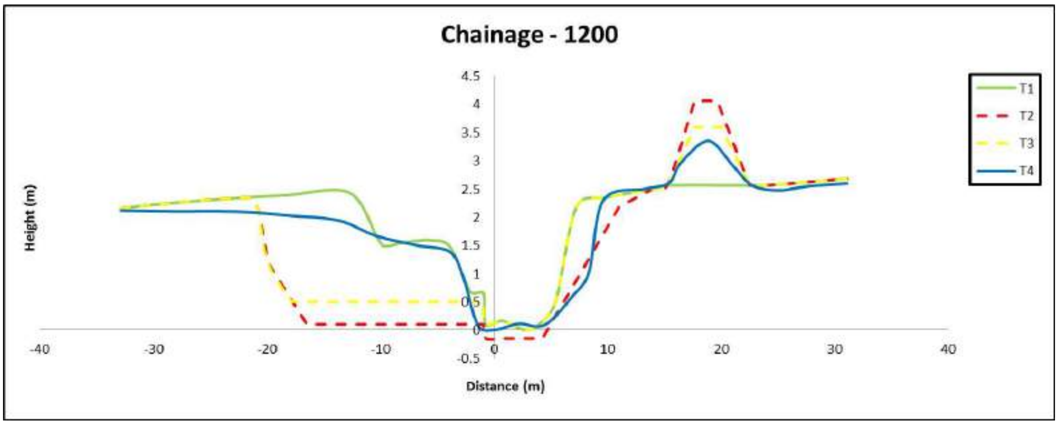
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	777500.7358	777500.7358	241.7576254	0.004110885
Residual	2	6432.067941	3216.033971		
Total	3	783932.8037			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-123871.2728	8505.664079	-14.56338642	0.004681844	-160468.1915	-87274.35401	-160468.1915	-87274.35401
X Variable 1	65.95191025	4.241674013	15.54855702	0.004110885	47.70145998	84.20236052	47.70145998	84.20236052

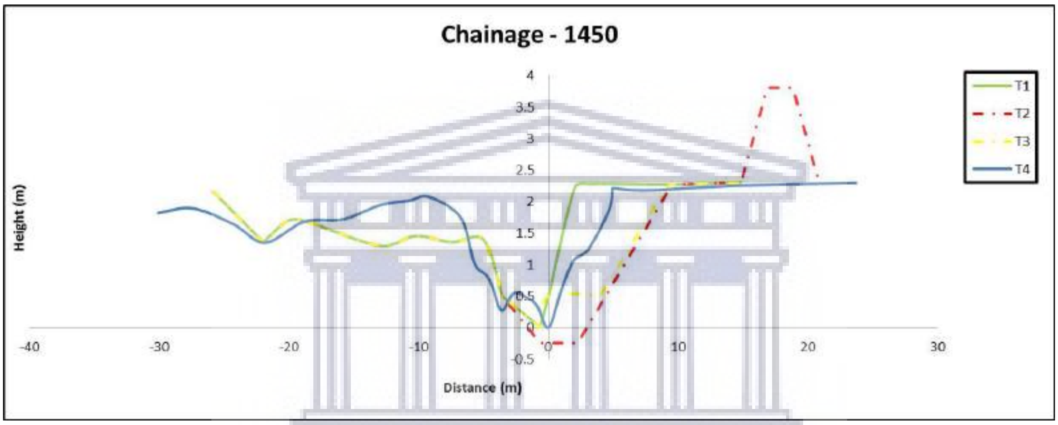
Appx. Table 13: Geographical co-ordinates of the 23 cross-section end points of left and right bank.

		Geographical Co-ordinates (DMS)	
Reach #	Chainage:	Left bank	Right bank
11	1200	34° 4'53.56"S; 18°52'40.83"E	34° 4'49.82"S; 18°52'40.42"E
11	1450	34° 4'53.64"S; 18°52'30.84"E	34° 4'50.87"S; 18°52'32.18"E

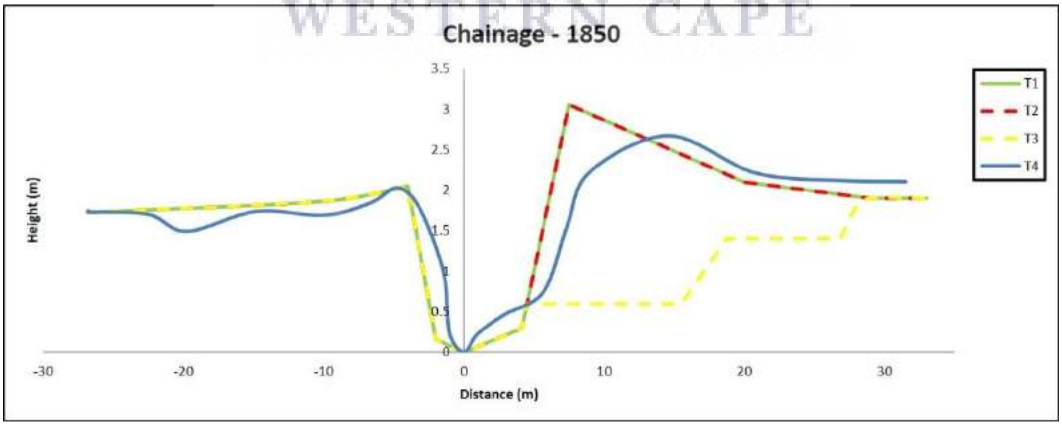
		Geographical Co-ordinates (DMS)	
Reach #	Chainage:	Left bank	Right bank
12	1850	34° 4'55.63"S; 18°52'20.20"E	34° 4'53.86"S; 18°52'17.73"E
12	2100	34° 5'1.56"S; 18°52'12.46"E	34° 4'57.87"S; 18°52'13.21"E
12	2850	34° 5'8.32"S; 18°51'57.73"E	34° 5'5.89"S; 18°51'56.70"E
13	3300	34° 5'12.40"S; 18°51'42.74"E	34° 5'10.10"S; 18°51'42.47"E
13	3550	34° 5'10.63"S; 18°51'34.94"E	34° 5'9.00"S; 18°51'33.03"E
13	3600	34° 5'11.85"S; 18°51'33.96"E	34° 5'10.36"S; 18°51'31.87"E
13	3750	34° 5'14.36"S; 18°51'29.42"E	34° 5'13.08"S; 18°51'27.23"E
13	3950	34° 5'14.93"S; 18°51'22.65"E	34° 5'13.62"S; 18°51'20.16"E
13	4050	34° 5'17.68"S; 18°51'20.15"E	34° 5'16.27"S; 18°51'18.11"E
13	4100	34° 5'18.85"S; 18°51'16.89"E	34° 5'16.54"S; 18°51'16.92"E
13	4450	34° 5'19.80"S; 18°51'7.80"E	34° 5'19.15"S; 18°51'5.13"E
14	4550	34° 5'23.31"S; 18°51'6.21"E	34° 5'22.01"S; 18°51'4.00"E
14	4850	34° 5'23.37"S; 18°50'52.75"E	34° 5'20.79"S; 18°50'55.06"E
14	4950	34° 5'23.27"S; 18°50'52.48"E	34° 5'20.08"S; 18°50'51.74"E
14	5000	34° 5'23.43"S; 18°50'48.15"E	34° 5'20.20"S; 18°50'48.31"E
14	5350	34° 5'24.12"S; 18°50'37.16"E	34° 5'21.48"S; 18°50'38.59"E
15	6350	34° 5'41.10"S; 18°50'15.08"E	34° 5'37.13"S; 18°50'6.12"E
15	6450	34° 5'42.76"S; 18°50'10.29"E	34° 5'35.21"S; 18°50'9.35"E
16	7350	34° 5'49.16"S; 18°49'40.71"E	34° 5'44.91"S; 18°49'36.76"E
16	7450	34° 5'49.90"S; 18°49'39.19"E	34° 5'50.39"S; 18°49'32.67"E
16	8850	34° 6'4.10"S; 18°49'3.99"E	34° 6'0.77"S; 18°49'3.54"E



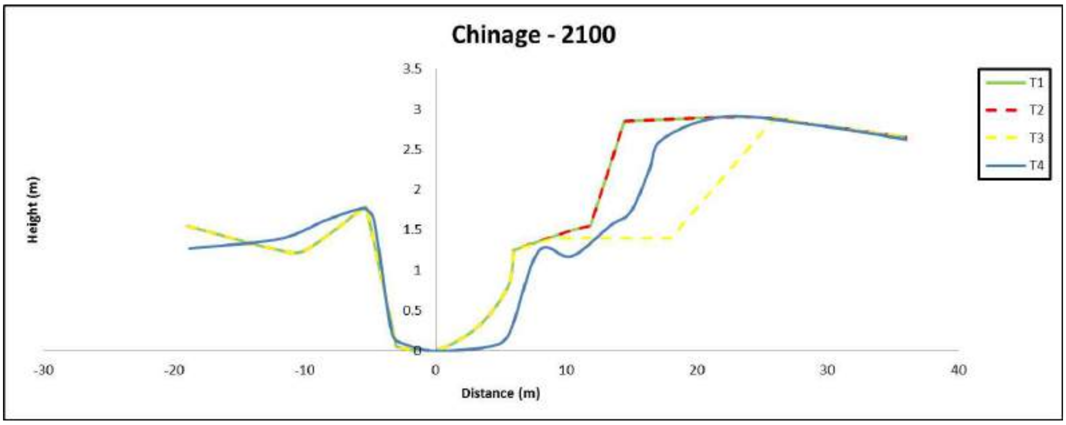
Appx. Figure 16: Chainage 1200 in T1, T2, T3 and T4.



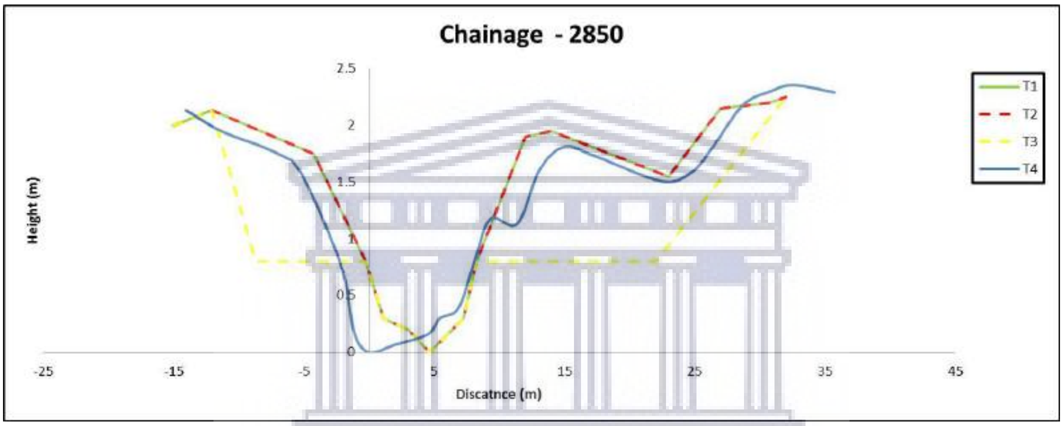
Appx. Figure 17: Chainage 1450 in T1, T2, T3 and T4.



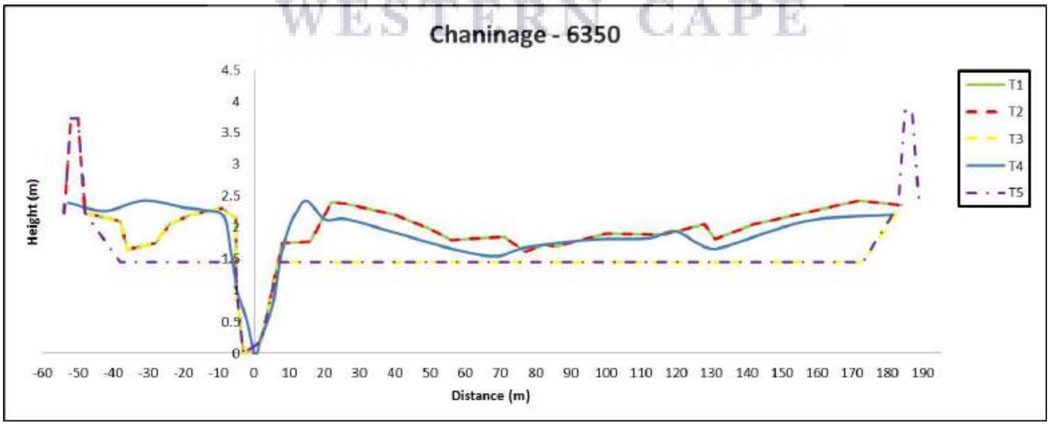
Appx. Figure 18: Chainage 1850 in T1, T2, T3 and T4.



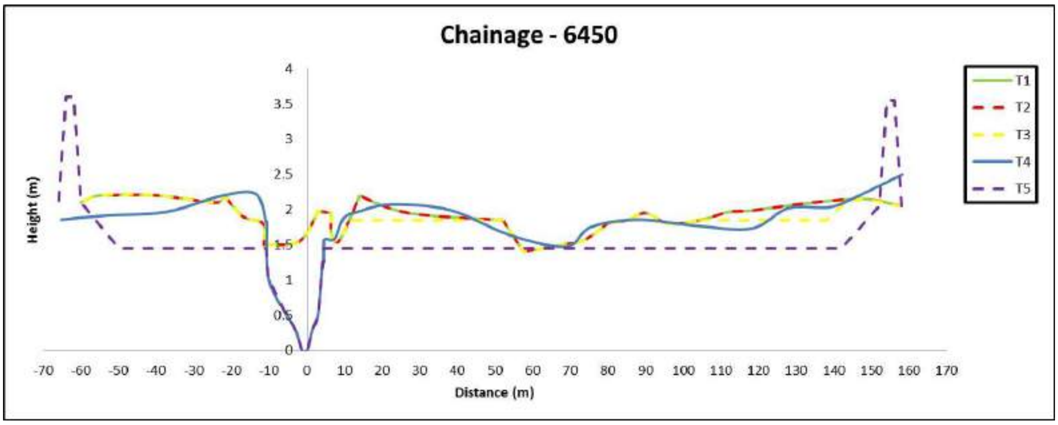
Appx. Figure 19: Chainage 2100 in T1, T2, T3 and T4.



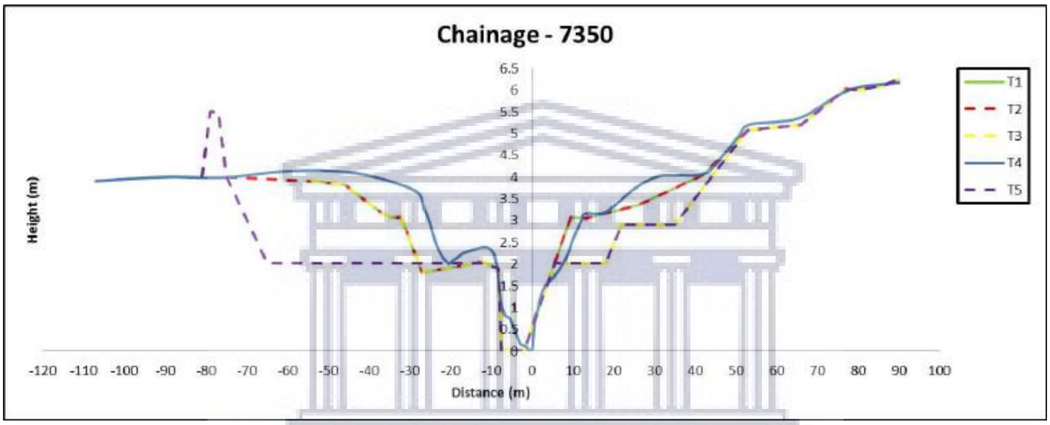
Appx. Figure 20: Chainage 2850 in T1, T2, T3 and T4.



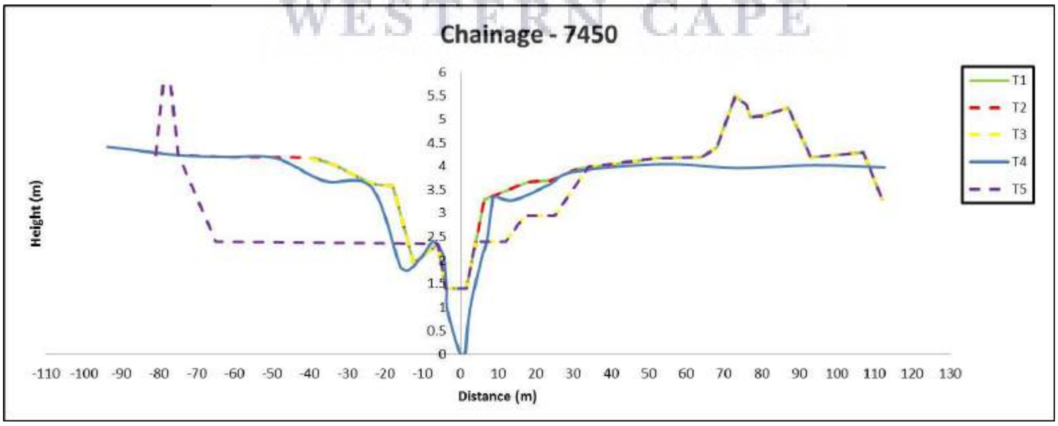
Appx. Figure 21: Chainage 6350 in T1, T2, T3, T4 and T5.



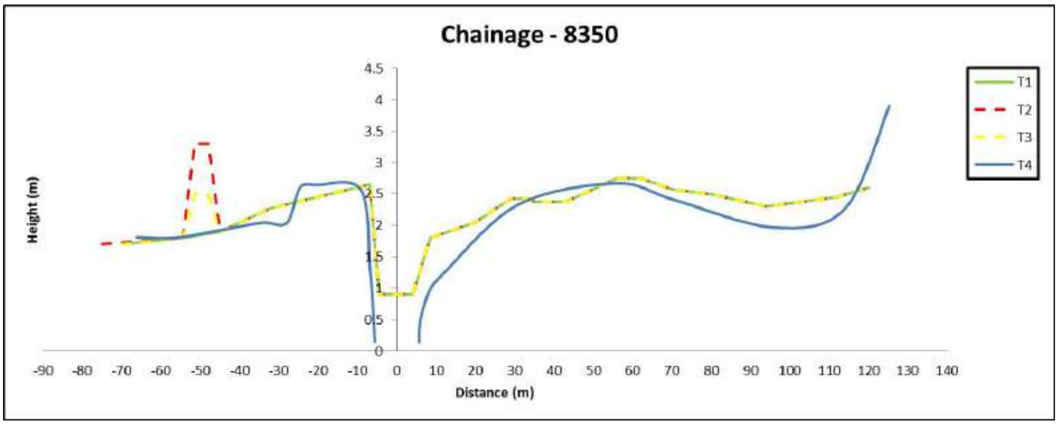
Appx. Figure 22: Chainage 6450 in T1, T2, T3, T4 and T5.



Appx. Figure 23: Chainage 7350 in T1, T2, T3, T4 and T5.



Appx. Figure 24: Chainage 7450 in T1, T2, T3, T4 and T5.



Appx. Figure 25: Chainage 8350 in T1, T2, T3, T4 and T5.

APPENDIX E. ECOLOGICAL ASSESSMENT

Appx. Table 14: Available historic ecological data for period 1997 and 2020.

Date	Description	Reference
1988	Lourens River management plan. Vegetation community structure	Lourens River Conservation Society 1988.
1997	Physical channel characteristics: Cross-sections were set up, where the following data was collected: Biotope proportions, Discharge Channel width and depth measurements, Mean range and depth velocity, Percentage of dominant biotopes Location of water's Edge, Substrate composition Using modified Wentworth scale , Water Quality. Temperature, pH, Conductivity and Total Dissolved solids (TDS), Dissolved oxygen (DO), Total suspended solids (TSS) Riparian and Instream vegetation Using the Braun Blanquet Method Categorized by Habitat type and Growth form Freshwater fish Community composition Distribution Habitat requirements Aquatic macro-invertebrates and assessment of invertebrate habitat Using SASS 4 sampling protocol Collection and identification of crabs Algae composition Condition assessment Index of habitat Integrity (IHI),	Tharme *et al.* 1997
2000	Physical channel characteristics:t6tt Channel and Water width measurement's Macro-features (islands, bars, bank, etc.) Engineering structures (Gabions and berms) Condition assessment Index of habitat Integrity (IHI), Vegetation community structure	Brown *et al.* 2000
2003	Condition assessment Index of habitat Integrity (IHI), Geomorphological Index (GI), Aquatic macro-invertebrates and assessment of invertebrate habitat Using SASS 5 sampling protocol Assessment of Invertebrate habitat	RHP 2003

Date	Description	Reference
	Condition assessment Riparian vegetation Index (VRI), Aquatic macro-invertebrates, Fish Assembly Integrity Index (FAII),	
2005	Physical channel characteristics: Percentage embeddedness of substrate Average Stream Width Average deep water depth Estimated stream velocity Water Clarity Canopy cover Percentage substrate size composition Water Quality. Temperature, pH, Conductivity and Total Dissolved solids (TDS), Dissolved oxygen (DO), Total suspended solids (TSS) Aquatic macro-invertebrates and assessment of invertebrate habitat Using SASS 5 sampling protocol Assessment of Invertebrate habitat	Ollis 2005
2006/07	Aquatic macro-invertebrates and assessment of invertebrate habitat Using SASS 5 sampling protocol	Haskings 2006/2007
2011	Aquatic macro-invertebrate. • Using South African Scoring System (SASS 5). Crabs. • Number of individuals caught per hour, expressed as Catch Per Unit Effort (CPUE). Assessment of invertebrate habitat. • Using the Integrated Habitat Assessment System (IHAS)	Southern Waters 2011.

Appx. Table 15: SASS 5 Scoring sheet

SASS Version 5 Score Sheet

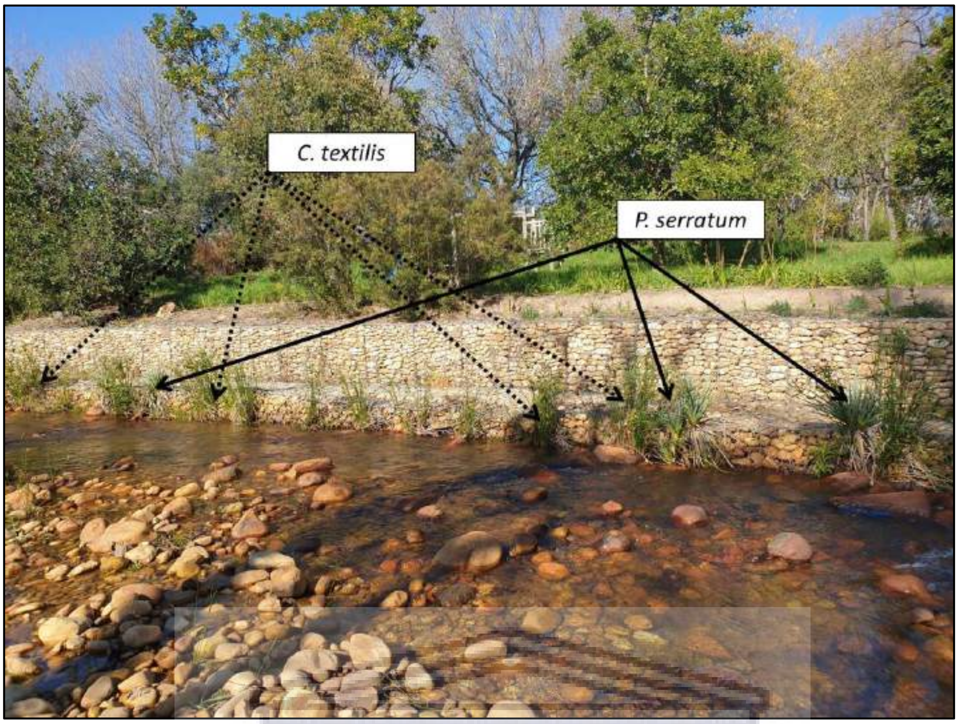
Version date: Feb 2005

Date:	/ /		(dd.ddddd)	**Biotopes Sampled**	**Rating (1 - 5)**	**Time (min)**
RHP Site Code:	-	**Grid reference (dd mm ss.s) Lat:**	**S**	**Stones In Current (SIC)**		
Collector/Sampler:		**Long:**	**E**	**Stones Out Of Current (SOOC)**		
River:		**Datum (WGS84/Cape):**		**Bedrock**		
Level 1 Ecoregion:		**Altitude (m):**	m	**Aquatic Veg**		
Quaternary Catchment:		**Zonation:**		**MargVeg In Current**		
	Temp (°C):	**Cond (mS/m)**		**MargVeg Out Of Current**		
Site Description:	**pH:**	**Clarity (cm):**		**Gravel**		
	DO (mg/L):	**Turbidity:**		**Sand**		
	Flow:	**Colour:**		**Mud**		
	Riparian Disturbance:			**Hand picking/Visual observation**		
	Instream Disturbance:					

Taxon		S	Veg	GSM	TOT	Taxon		S	Veg	GSM	TOT	Taxon		S	Veg	GSM	TOT
PORIFERA (Sponges)	5					**HEMIPTERA (Bugs)**						**DIPTERA (Flies)**					
COELENTERATA (Cnidaria)	1					Belostomatidae* (Giant water bugs)	3					Athericidae	10				
TURBELLARIA (Flatworms)	3					Corixidae* (Water boatmen)	3					Blephariceridae (Mountain midges)	15				
ANNELIDA						Gerridae* (Pond skaters/Water striders)	5					Ceratopogonidae (Biting midges)	5				
Oligochaeta (Earthworms)	1					Hydrometridae* (Water measurers)	6					Chironomidae (Midges)	2				
Hirudinea (Leeches)	3					Naucoridae* (Creeping water bugs)	7					Culicidae* (Mosquitoes)	1				
CRUSTACEA						Nepidae* (Water scorpions)	3					Dixidae* (Dixid midge)	10				
Amphipoda	13					Notonectidae* (Backswimmers)	3					Empididae (Dance flies)	6				
Potamonautidae* (Crabs)	3					Pleidae* (Pygmy backswimmers)	4					Ephydridae (Shore flies)	3				
Atyidae (Shrimps)	8					Veliidae/M...veliidae* (Ripple bugs)	5					Muscidae (House flies, Stable flies)	1				
Palaemonidae (Prawns)	10					**MEGALOPTERA (Fishflies, Dobsonflies & Alderflies)**						Psychodidae (Moth flies)	1				
HYDRACARINA (Water mites)	8					Corydalidae (Fishflies & Dobsonflies)	8					Simuliidae (Blackflies)	5				
PLECOPTERA (Stoneflies)						Sialidae (Alderflies)	6					Syrphidae* (Rat tailed maggots)	1				
Notonemouridae	14					**TRICHOPTERA (Caddisflies)**						Tabanidae (Horse flies)	5				
Perlidae	12					Dipseudopsidae	10					Tipulidae (Crane flies)	5				
EPHEMEROPTERA (Mayflies)						Ecnomidae	8					**GASTROPODA (Snails)**					
Baetidae 1sp	4					Hydropsychidae 1 sp	4					Ancylidae (Limpets)	6				
Baetidae 2 sp	6					Hydropsychidae 2 sp	6					Bulininae*	3				
Baetidae > 2 sp	12					Hydropsychidae > 2 sp	12					Hydrobiidae*	3				
Caenidae (Squaregills/Cainfles)	6					Philopotamidae	10					Lymnaeidae* (Pond snails)	3				
Ephemeridae	15					Polycentropodidae	12					Physidae* (Pouch snails)	3				
Heptageniidae (Flatheaded mayflies)	13					Psychomyiidae/Xiphocentronidae	8					Planorbinae* (Orb snails)	3				
Leptophlebiidae (Prongills)	9					**Cased caddis:**						Thiaridae* (=Melanidae)	3				
Oligoneuridae (Brushlegged mayflies)	15					Barbarochthonidae SWC	13					Viviparidae* ST	5				
Polymitarcyidae (Pale Burrowers)	10					Calamoceratidae ST	11					**PELECYPODA (Bivalves)**					
Prosopistomatidae (Water specs)	15					Glossosomatidae SWC	11					Corbiculidae	5				
Teloganodidae SWC	12					Hydroptilidae	6					Sphaeriidae (Pills clams)	3				
Tricorythidae (Stout Crawlers)	9					Hydrosalpingidae SWC	15					Unionidae (Perly mussels)	6				
ODONATA (Dragonflies & Damselflies)						Lepidostomatidae	10					**SASS Score**					
Calopterygidae ST,T	10					Leptoceridae	6					**No. of Taxa**					
Chlorocyphidae	10					Petrothrincidae SWC	11					**ASPT**					
Synlestidae (Chlorolestidae)(Sylphs)	8					Pisuliidae	10					**Other biota:**					
Coenagrionidae (Sprites and blues)	4					Sericostomatidae SWC	13										
Lestidae (Emerald Damselflies)	8					**COLEOPTERA (Beetles)**											
Platycnemidae (Brook Damselflies)	10					Dytiscidae/Noteridae* (Diving beetles)	5										
Protoneuridae	8					Elmidae/Dryopidae* (Riffle beetles)	8										
Aeshnidae (Hawkers & Emperors)	8					Gyrinidae* (Whirligig beetles)	5										
Corduliidae (Cruisers)	8					Haliplidae* (Crawling water beetles)	5										
Gomphidae (Clubtails)	6					Scirtidae (=Helodidae Marsh beetles)	12										
Libellulidae (Darters)	4					Hydraenidae* (Minute moss beetles)	8					**Comments/Observations:**					
LEPIDOPTERA (Aquatic Caterpillars/Moths)						Hydrophilidae* (Water scavenger beetles)	5										
Crambidae (=Pyralidae)	12					Limnichidae	10										
						Psephenidae (Water Pennies)	10										

Procedure: Kick SIC & bedrock for 2 mins, max. 5 mins. Kick SOOC & bedrock for 1 min. Sweep marginal vegetation (IC & OOC) for 2m total and aquatic veg 1m2. Stir & sweep gravel, sand, mud for 1 min total. * = airbreathers
Hand picking & visual observation for 1 min - record in biotope where found (by circling estimated abundance on score sheet). Score for 15 mins/biotope but stop if no new taxa seen after 5 mins.
Estimate abundances: 1 = 1, A = 2-10, B = 10-100, C = 100-1000, D = >1000 S = Stone, rock & solid objects; Veg = All vegetation; GSM = Gravel, sand, mud SWC = South Western Cape, T = Tropical, ST = Sub-tropical
Rate each biotope sampled: 1=very poor (i.e. limited diversity), 5=highly suitable (i.e. wide diversity)

APPENDIX F. PHOTOGRAPHS



Appx. Figure 26: Left bank of the river with gabion mattresses, showing C. textilis and P. serratum on the channel edge. Photograph taken by Dirk Campher (2020).

Appx. Figure 27: Left bank of the river downstream of Meadow Lane, showing *O. moniliferum. Photograph taken by Dirk Campher (2020)*.

Appx. Figure 28: Homeless resident living under Andries Pretorius Bridge on the left bank.