RESPICE PROSPICE

UNIVERSITY of the
WESTERN CAPE

Geomorphic analysis of river character and behaviour in three semi-arid, mountainous catchments in the Eastern Cape, South Africa

Siviwe Pamela Sekese

A thesis submitted in fulfilment of the requirements for the degree of Magister Scientiae in the Department of Earth Sciences, University of the Western Cape

Supervisors:

Dr J Glenday

Dr M.C Grenfell

October 2019

Abstract

The analysis of what controls why rivers are the way they are, and how and why they change is crucial in predicting river dynamics and deriving classification systems that can assist management. A variety of factors control the pattern of fluvial styles in a river system across spatial scales. The geomorphic response of a river to an individual control, such as stream power for example, will vary due to a combination of other contributing factors such as geology and climate. The variation in fluvial style along river longitudinal profiles has been less well described in non-perennial rivers in semi-arid settings than for wetter systems. Therefore, a scientifically informed understanding of the fluvial geomorphology within dryland river systems can aid in improving management and rehabilitation approaches.

This study investigated and characterized the geomorphology of rivers in three semi-arid, mountainous, meso-scale catchments with the aim of understanding the controls on channel properties and the implications for river classification frameworks for South African non-perennial rivers. In the Baviaanskloof, Kouga and Kromme study catchments, rivers flow in valleys where the bedrock material exerts some degree of lateral or vertical confinement. As a result, the variations in their river characteristics were expected to correlate with variations in the valley width. Valleys can be broadly classified as confined or unconfined, with related differences in their vegetation structure, topographic gradient and groundwater-surface water interactions.

In this study, valley specific stream power has been used to predict or explain fluvial styles, sediment distribution and wetland formation processes. These variables change along a river's longitudinal profile with geologic and climatic controls influencing their distribution and pattern. The study employed an automated method for determining valley confinement and specific stream power using the Valley Bottom Extraction Tool. This algorithm mapped the extent and shape of unconfined valley bottoms using readily available spatial data such as a Digital Elevation Model (DEM) and mapped stream channels as input data. Unconfined valleys had large sedimentary fills with a well-developed floodplain whereas confined valleys are set within exposed bedrock or raised terrace material, limiting the formation of floodplains. An advanced terrain analysis method was developed to calculate specific stream power continuously along the heterogeneous valleys of the three sample catchments. Valley metrics were generated for calculating valley specific stream power using a 5 m resolution DEM to determine slope and flow accumulation grid surfaces and a discharge proxy estimated from a rainfall surface and flow accumulation. The method substituted channel width with valley width because bankfull channel width is problematic to measure or estimate for the highly variable flows and the multiple-thread and flood-out styles common in non-perennial rivers.

Results showed that the Kouga catchment had the largest peak in valley specific stream power, attributed to its larger size and confined valley nature, compared to other catchments. Variations in valley specific stream power were strongly driven by variation in slope and valley width in all three catchments. Longitudinal profile analysis showed that the valley specific stream power was more variable in Baviaanskloof, followed by the Kromme then Kouga catchments, which indicated that more numerous fluvial styles would likely be found in the Baviaanskloof compared to the other two catchments.

Channel and planform dynamics data, associated with the variations in valley confinement and valley specific stream power were subsequently collected in the field. A dataset of thirteen variables for 16 sites was derived from the Geographical Information System analyses and field measurements including valley parameters (valley confinement, and valley specific stream power) and channel-reach parameters (elevation, channel width, channel cross-sectional area, channel depth, width to depth ratio, channel roughness, channel slope, median grain size, bed and bank material texture, and fluvial style). Discriminant plots of energy versus resistance (valley specific stream power against sediment properties) provided an integration of the variables which resulted in thirteen fluvial styles with homogenous properties. Six fluvial styles were identified in the Baviaanskloof, three in the Kouga and four in the Kromme main river. This framework can be used to develop new assessment methods designed for non-perennial rivers systems in which considers the valley specific stream power, an empirical indices which encompasses all boundary conditions within valley and river reaches rather than reading landscapes as similar river types.

Declaration

I **Siviwe Pamela Sekese (3346091)** declare that ***Geomorphic analysis of river character and behaviour in three semi-arid, mountainous catchments in the Eastern Cape, 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: Siviwe Pamela Sekese Date: 07 October 2019

Signed...

Acknowledgements

I would like to thank the following people and organisations for their support, without which, this research would not have been feasible:

My supervisor Dr Grenfell. The door to his office was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this thesis to be my own work, but steered me in the right the direction whenever he thought I needed it. Thank you for the insightful comments and encouragement, but also for the hard questions which incited me to widen my research from various perspectives.

My second supervisor, Dr Glenday from SAEON for the continuous support of the MSc study and related research. For her patience, motivation, and immense knowledge. Her guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better supervisor and mentor for MSc study.

The MSc study was funded by the South African based non-governmental organization, Living Lands in conjunction with the Water Research Commission. The "Living Landers" offered support and patience during the time period of the research (and the memorable Indabas and dance floors), I am forever grateful. To Liezl, Ancia, Faith and Julia: Thank you for your support and friendship, we make a great project team! Special thanks to the National Research Foundation for sponsoring my studies and travel costs to academic conferences; I have travelled and learned within my research field because of this opportunity. I was also fortunate to have academic support from the South African Observation Network through fieldwork and logistical assistance and being a conduit to speak about my research. I am also thankful for the landowners and various governmental institutions in the Baviaanskloof, Kouga and Kromme catchment that provided invaluable information and giving permission to conduct studies on their properties, and taking the time to listen and talk about "water" in the catchments. I express my sincere gratitude to the staff at the Earth Science Department, particularly the Institute of Water Studies for facilitating a great atmosphere to complete my research successfully. Particularly Mr Solomons, who went above and beyond in helping me through GIS algorithms and any other machine learning issues.

To my family, for the endless moral support, and encouragement during the course of my study. Thank you for your prayers and believing in me and my abilities as a young, black female researcher. The constant affirmation was motivating. This accomplishment would not have been possible without them

Table of contents

List of Figures

List of tables

List of appendices

List of acronyms

AAR: Average annual Rainfall

AHC: Agglomerative Hierarchical Clustering

AREA: Catchment area

BKK: Baviaanskloof, Kouga and Kromme catchments

DEM: Digital Elevation Model

dGPS: Differential global positioning system

FC: Fluvial Corridor

GIS: Geographical Information System

LiDAR: Light detection and ranging

PCA: Principal Component Analysis

SUDEM: Stellenbosch University Digital Elevation Model

MAF: Mean annual flood

MAP: Mean annual precipitation

MAR: Mean Annual Runoff

MVSA: Multivariate Statistical Analysis

NMBM: Nelson Mandela Bay Metropolitan

TMG: Table mountain group

TRMM: Tropical Rainfall Measuring Mission

UAV: Unmanned aerial vehicle

V-BET: Valley Bottom Extraction Tool

VCA: Valley Confinement Algorithm

VSSP: Valley specific stream power

W/m^{-2}: Watts per meter per second

1. Introduction

1.1. Background: Diversity and complexity of rivers

Rivers are critical components and connectors of the Earth's hydrological, ecological and physical systems (Belletti et al. 2014). For plants and animals; rivers are regarded as refugia and as a food source. For humans, rivers provide a vast amount of support as they are utilized for agricultural, domestic and industrial activities. However, despite the dependency on rivers, human activities have resulted in the degradation of rivers.

The three case-study rivers examined in this study have had varying levels of human impact along their courses and in their catchment areas, but are also responding to significant catchment-scale geomorphic drivers. The Baviaanskloof, Kouga and Kromme (BKK) catchments in the southern Eastern Cape of South Africa are dominated by steep mountains on quartzitic sandstone geology coupled with trunk streams flowing across valley alluvial deposits. Regional climatic conditions are semi-arid and river reaches in many wide valley reaches are non-perennial. The majority of the wide valley bottom area in the three catchments is fertile and used for agricultural purposes. Significant invasive alien plant infestations and agricultural activities in riparian areas and mountain slopes, particularly in the Kromme and Kouga catchments, have resulted in degradation of natural vegetation such as herbaceous wetland vegetation, thicket and fynbos. Flooding, erosion, sedimentation and deteriorating water quality are major issues in the three catchments. While these issues are impacted by land use, they must also be viewed in the context of long-term catchment-scale geomorphic adjustments. The rivers in the three catchments are very diverse in terms of their pattern, shape and evolutionary sequences, and thus, catchment-scale controls have to be considered for rehabilitation and improved river health management to progress.

These differences occur due to the flow and sediment inputs from the wider catchment. River hydrogeomorphic processes and the culmination of river forms are driven by the balance between independent controls, namely geology, climate and human influences, and dependent controls, such as bed and bank resistance to erosion (Bizzi and Lerner, 2015; Hogan and Luzi, 2010). Channel morphology dictates how this energy is partitioned between the river bed and banks (Golden and Springer, 2006).

Stream power can be described as the energy a river requires to move water and sediments (Chang, 1979). Despite the importance of stream power as an integrative, catchment-scale control on river systems, few studies have considered its spatial characteristics along river networks (Knighton, 1999; Song et al. 2014; Lecce and Lecce, 2016). Valley confinement, a product of the resistance of the underlying geology to erosion under the historical flow regimes, also poses boundary conditions on how flow and sediments are distributed across the catchment (Fryirs et al. 2016). These two controls will be investigated in this study in terms of how adequately they can explain the diversity of river styles in a catchment.

The response of smaller units, such as landscape units and reaches, to changes in controls and processes across the catchment is often delayed (Gurnell et al. 2016). This is because the time scales for the effects of different changes (e.g. land cover, berm construction or river straightening) to develop from their initial location across catchments and through channel networks to individual river reaches are not the same (Fashae and Faniran, 2015). These dynamic adjustments are intrinsically linked such that a change to one variable modifies another part in the river (Brierley and Fryirs, 2000; Buffington, 2012; Piégay et al. 2009).

Catchments have long been described in terms of their main geomorphic controlling processes as mentioned above (e.g. Ibisate et al. 2011). In recent years, different studies have reviewed the influence of catchment processes on the channel network, relating reach hydraulic properties to properties of the contributing catchment. These process-form interactions produce geomorphic features at a particular location in landscapes (Brierley and Fryirs, 2014). These varieties of river styles are commonly assessed and investigated at a reach-scale. The current study will employ the hierarchical theory, analysing river networks by looking at the relationship between processes that occur at catchment scale to reach scale in order to understand the character and behaviour of three semi-arid mountainous catchments.

1.2. Rationale and contribution to science

Various studies have incorporated catchment-to-reach assessments but relatively few have been conducted in semi-arid conditions like those experienced in most of South Africa (Addy, 2010; England 2016). Geomorphic processes in semi-arid regions can differ from what has been described in humid areas. In particular, in many semi-arid regions, only large floods which occur rarely, have sufficient energy to move sediments and thereby change the morphology of the river (Parsons and Thoms, 2007). Also, dry river systems have a tendency to decrease in flow volumes longitudinally under their average flow conditions, due to transmission losses, variable discharge, and large bed load (Tooth, 2000). Therefore, as Costigan et al. (2014) mentioned, their downstream hydraulic geometry relationships differ to those in humid regions. This results in different river styles which can be distinctive to semi-arid regions such as South Africa.

Even though the three case-study catchments are located next to one another, differences in geology, climate, and land uses have resulted in a diversity of river patterns in the study area. For management purposes, a catchment-linked geomorphic analysis of river channels in conjunction with hydrological, ecological and social assessments is required. Moreover, there is scope to apply the framework that is being developed through this study in the national-scale river ecosystem classification methods for South Africa, which currently only use the geomorphic provinces (Partridge et al. 2010) as a discriminator of river habitat. Mechanistic descriptors of the controls on fluvial style at catchment-scale will therefore contribute largely to this initiative. The use of GIS, remote sensing and field observations to qualitatively and quantitatively delineate reaches and landscape units using catchment-scale controls provides insight on locations which are appropriate for reach-scale studies, reducing the cost and time of extensive fieldwork.

1.3. Conceptual framework

1.3.1. Hierarchical theory

The theory of hierarchy in systems involves the arrangement of elements at different levels of organization (Montgomery and Buffington, 1997). The element in the higher level, the catchment in this case, has an influence and constrains the character and behaviour of elements in lower levels, such as the channel network or individual river reaches. At the largest scale, catchments integrate all the water in the surface in an area and transport that runoff to a confluence through a network of channels that are situated in valleys of varying confinement (Lord et al. 2009). At the lower levels, channel patterns and processes are normally described in homogenous longitudinal sections termed reaches. In fluvial geomorphology research, studies often answer questions which are relevant over small spatial scales and are often weakly linked to the larger scale processes, such as surface runoff, which occur in the catchment (Schmitt et al. 2014).

Several hierarchical frameworks describing river geomorphology have been applied in South Africa. Rowntree and Wadeson (1999) constructed a hierarchical classification framework for South African rivers. This framework was adapted from the Northern Hemisphere model by Frissell et al. (1986) to be more appropriate to local conditions. The framework is based on a cascading system with six levels, with each level providing input to the lower one. The aim of the framework was to link the river geomorphology with in-stream habitats. The River Style Framework (RSF) has also been applied for the first time in South Africa on the Sabie River (Eze and Knight, 2018). In this study, the authors concluded that the framework was able to identify clear changes in the river geomorphology, describing six fluvial styles and their future trajectories for ecosystem management.

Adopting the principles of river classification from arid Australian rivers, Brierley and Fryirs, (2000) defined the combination of channel pattern, channel and soil attributes and vegetation as the river style. This is informed by higher level factors, from properties of the catchment to those of the local valley reach. The river style is analysed at the reach-scale and comprises of qualitative (vegetation density, number of channels) and quantitative (channel geometry, soil texture, particle size distribution) measurements. Parallel ideas relating to geomorphology research has expanded to investigate the linkages between geomorphology and ecology on river systems. Within these hierarchical levels, ecosystem models are incorporated to show how the river channel and its fluvial styles behave along a longitudinal profile. This is evident by the growth in the number of published work with interdisciplinary journals and some concepts in freshwater ecology. Rivers serve as a physical template for habitats in catchments for either feeding, foraging or breeding. Habitats are defined by location or environment where organisms are most likely to be found and these include biological, physical and chemical characteristics. These physical characteristics particularly relate to geomorphic forms and processes.

Several river ecosystems concepts have been developed parallel to process-based models and classification systems discussed above focusing only on the geomorphology. A summary of these concepts (Table 1.1) are summarized below however, most common inferences are centred around conceptualizing rivers as arrays of large hydrogeomorphic regions created by the catchment geomorphology and hydrology. These regions are given by local changes in the geomorphic and hydraulic conditions which support unique assemblages of species, contributing immensely to river diversity. In particular, Thorp et al. (2006) river ecosystem synthesis merged the ecogeomorphology (ecology and geomorphology) in rivers with a landscape model of hierarchical patch dynamics, however, it does not describe the river as a continuum but as “downstream arrays of large hydrogeomorphic patches”, despite the river ecosystem's being considered in its entirety in earlier hierarchical models. These concepts and models have provided an integrative way of explaining the complexity and variability of rivers through each level of hierarchy. The current study will be solely investigating the geomorphic character and behaviour of fluvial styles in the three catchments, as these provide the physical template for various habitats. The river ecosystem complex will be briefly discussed as an additional and integration tool in understanding the river system and its functions in the ecosystem.

Table 1.1: Summary of available ecogeomorphology classifications (Source: Humphries et al. 2014)

Name of River Ecosystem Concept	**Description**	**Source**
River Continuum Concept	Conceptualize the sources and transport of carbon and energy in river ecosystems	Vannote et al. 1980
Flood pulse concept	Inundation of the floodplain by a flood pulse is the catalyst for material transport and primary production and for movement of that material and energy from the floodplain into the main channel	Junk et al. 1989
Riverine productivity model	material and energy are derived mainly through the local production of phytoplankton, benthic algae, and other aquatic plants and are derived directly from the riparian zone through leaves and particulate and dissolved organic carbon	Thorp and Delong, 1994; Thorp et al. 1998
Riverine ecosystem synthesis	Merging of ecogeomorphology with a landscape model of hierarchical patch dynamics.	Thorp et al. 2006; Thorp et al. 2008
River Wave Concept	describes how river waves interact with their environment	Humphries et al. 2014

The current study will use the river style framework to guide the steps required for analysing the three study catchments. However, the study will refer to the framework as "fluvial style" to encompass every channel pattern (particularly those common in drylands) and fluvial body (wetlands, gullies, terrace etc.) found in the catchments. The current study will also employ the RSF framework to some degree, modifying it to achieve the above-mentioned aims by automating the analyses of the first level of hierarchical (catchment and valleys) controls such as valley confinement and specific stream power. The current research will use this system to guide the different levels of hierarchy, noting the importance of catchment-scale perspective in understanding and managing rivers in South Africa.

The issue in most hierarchical frameworks is the lack of an appropriate framework to guide interdisciplinary paradigms when developing a classification of rivers (Dollar et al. 2007). There is growing recognition that river form and process are due to the interplay between the geomorphology, hydrology and ecology at varying spatial and temporal scales. All of these factors should be reflected in the framework by integrating controls on river form and processes and predicting the response of the river to these changes, and the effects they have on the pattern and functioning of ecosystems and the hydrology in a catchment. Dollar et al. (2007) produced a framework that allows the interdisciplinary study in rivers using a flow chain model that includes the biotic/abiotic agent of change/driver, the substrate on which the driver acts, the controls of the driver of change, and the processes that respond to the change. There are hierarchical flow chain models constructed to evaluate the effects of specific changes in, for example, valley specific stream power (Dollar et al. 2007). This study will apply this concept in reading the landscape of the case-study catchments.

1.3.2. Catchment-scale controls and connectivity

A catchment is defined as a basin shaped area of land which is bounded by natural landscape units such as mountains and hillslopes where surface and subsurface water flows into a network of streams, rivers and wetlands (Beven, 1987). These networks of streams transport sediment and water in the catchment. There is a catchment boundary which is usually a ridge line that separates one hydrological system from another (Brierley and Fryirs, 2014). The development of a catchment channel network is shaped over geologic timeframes which establish boundary condition controls in which rivers operate (Brierley and Fryirs, 2005). These controls (such as valley confinement and specific stream power) dictate the range of channel morphologies within a catchment. Various studies have used this concept in creating river classification systems in understanding the catchment and its constituents (Chang, 1979; Powel, 2009; Ferencevic and Ashmore, 2012; Klösch and Habersack, 2017).

1.3.3. Regional geology and climate

A catchment is subject to geologic and climatic conditions which determine the topography (relief and slope), sediment transport and the discharge. These factors progressively influence the flow and sediment regimes by controlling the input, distribution, and use of energy throughout the catchment.

Climate plays a dominant role in controlling runoff as well as the frequency and magnitude of flood events and bankfull discharge, which drive interactions between the water, sediment and vegetation. Climate also imposes controls on the vegetation cover in a catchment. Rivers are constantly adjusting in response to inter-annual and seasonal variability in climate (Fryirs and Brierley, 2013). The rivers in the study area are located in a semi-arid region where the analysis and classification of river systems are difficult due to the variable flow regimes.

1.3.3.1. Valley confinement

Most rivers flow in valleys where the bedrock material exerts some degree of lateral or vertical control. The differential erosion of hard and soft strata in the valley sidewalls restricts changes in channel and valley width and sediment storage. As a result, river characteristics and behaviour accompany variations in the valley width (Guo-An et al. 2013). Previous authors have reviewed methods for defining valley confinement and it has been quantitatively measured using different metrics for a range of applications in aquatic and riparian ecology and geomorphology (Guo-An et al. 2013; Fryirs et al. 2016).

Fryirs et al. (2016) defined various levels of valley confinement in Australia, New Zealand and the United States by measuring the ratio of the length of channel along either bank lying along a valley margin to the total length of the entire channel. If more than 90% of the river length lies along the valley margin, it is then considered a 'confined valley.' These valley settings are usually bedrock controlled and act as sediment source geomorphic zones (Brierley and Fryirs, 2005). If the valley confinement ratio of the channel is between 50-90% it is considered a 'semi-confined valley' with floodplain pockets. These discontinuous floodplain pockets can migrate laterally and may also be constrained by bedrock. The valley is termed 'laterally unconfined' if less than 10% of the channel margin abuts the valley margin or valley bottom margin. In this valley setting, bedrock is considered to have no influence on the channel planform; banks are usually unstable, constantly reworking themselves at bankfull stage. The current study will use this definition in analysing the outputs from automated valley confinement quantification.

Nagel et al (2014) defined valley confinement as the degree to which geological and topographic features limit the lateral extent of the valley floor and floodplain along a river and created a different method of measuring this using a user defined thresholds. Their method was coded into automated algorithms in a GIS environment called the valley confinement algorithm (VCA). This algorithm was developed based on several previous automated valley confinement mapping algorithms using digital elevation models and streamlines as input data (Benda et al. 2011; Gallant and Dowling, 2003; Hall et al. 2007; Ruefenacht et al. 2005; Strager et al. 2000; Walterman et al. 2006; Williams et al. 2000). However, the VCA is unique because it can include user-defined parameters such as the slope percentage rise (changes in slope) of the terrain moving away from the channel, flood factor (amount of water required to flood the area) and rainfall, therefore can be customized for a wide range of applications (Nagel et al. 2014).

Although the VCA can classify the different valley settings, a major limitation of the toolbox is the flooding method which is constant throughout the valley fill thus does not scale properly throughout large catchments, which would have higher discharges moving downstream. The slope threshold worked very well for the large, unconfined alluvial valley bottoms but failed to delineate any valley floor area for confined, steep slope valleys. Gilbert et al. (2016) created a toolbox which could overcome these short comings, by developing a slope-based approach but operating as a function catchment area (Riverscapes, 2017). This means that the output is scaled based on their location within the catchment. This method calculates confinement along a stream network using stream networks, channel polygons and valley bottom as inputs. The intersection of the valley bottom and the active channel polygon boundaries transfers this information to a river network using a proximity method called near function (Riverscapes, 2017). This is then used to calculate confinement values (0 or 1) along the river length. Zero meaning unconfined, one means confined (Riverscapes, 2017). Areas where these were not defined were coded as partially confined. The current study will make use of this definition as an automated way of estimating valley confinement type.

1.3.3.2. Valley specific stream power

Stream power has great impact on river forms and processes (Knighton 1999). Stream power has been used to estimate sediment transport and explain channel patterns in general. It is a function of discharge, slope and channel/valley width. These variables systematically change along a river’s longitudinal profile as catchment primary controls influence their distribution and pattern.

Different methods for estimating stream power along the longitudinal profile of a river have been developed in response to available data and local conditions. Because of the labour intensiveness of measuring all the input parameters at many sites in the field, models have been developed to estimate some or all of them using other accessible data sources. For example, a study by Knighton (1999) used a model to assess the downstream pattern of stream power in the River Trent Basin. In this study, topographic maps were used to measure channel gradients at 0.5km intervals and an annual discharge relationship was established using stream orders. However, the lack of a suitable profile equation for slope became problematic in the study. More recent studies, such as those modelling stream power for the Bellinger coastal catchment, Wye and Lune rivers, have used digital elevation models (DEMs) and regional catchment area–discharge relationships (Bizzi and Lerner, 2015; Reinfelds et al. 2004). Craddock et al. (2007) developed a terrain analysis method for calculating specific stream power on heterogeneous landscapes in a GIS environment for the Himalayas. The study used a 1km resolution DEM to calculate flow accumulation and weighted this flow accumulation grid with a rainfall surface derived from satellite imagery from the Tropical Rainfall Measuring Mission (TRMM) as a discharge proxy. Then a regime equation, in this case a power law of discharge, was used to calculate an estimate of the channel width based on the estimated discharge grid values along the stream network.

The current study will make use of a similar GIS based approach to calculate an index of stream power spatially along the river networks; however, it will not use a model, such as a power law of discharge, to estimate channel width, but rather use the valley width, as mapped using the VCA algorithm described above. Therefore the resulting index will be referred to as “valley specific stream power” throughout the thesis. This is because when the river is in flood and doing geomorphic work, it is not confined laterally by the channel but rather the valley width (Nagel et al. 2014a). Additionally, several issues are evident in stream power mapping methodologies in the existing literature: (a) regime relations are not good for multiple-thread channel which are common in the study area, and (b) non-perennial rivers are flood-driven and floods commonly fill the valley floor, so dissipation of power is determined by the valley width (or confinement). The geological and geomorphic history, described in section 2.1 and 2.3 in Chapter 2 below, giving rise to alternating confined and unconfined valley settings makes this approach highly applicable in these semi-arid catchments (Nanson and Croke, 1992). The valley specific stream power, together with the valley confinement will be used in selecting sites whereby channel properties can be measured to deduce the river styles and character of the three catchments.

1.3.4. Fluvial corridors and Fluvial Styles

With the recognition that higher level, catchment characteristics significantly control channel morphology and types, analysing the relationship between the catchment, valley and reach is crucial. Changes in the channel morphology are evident in the river corridor, which is the land adjacent to the river and has the ability to accommodate the slope, planform and channel dimensions. The corridor includes the riparian vegetation and the space where the river can re-work sediment deposits and adjust to the changes in boundary conditions (Martínez-Fernández et al. 2017).

Different fluvial corridor characteristics exist for channels over time and in space. For example, upstream in a catchment, fluvial corridors are generally narrower have higher slopes and lower sinuosity which limit the channel's opportunity to re-work itself laterally, whereas downstream there are often lower slopes and broad valleys, so the river may meander and thereby increase the size of the corridor (Venticinque et al. 2016). Various studies have used fluvial corridors in geomorphic assessment and prediction of flood erosion (e.g. Roux et al. 2015; Venticinque et al. 2016).

The reach is used as a reference site for its contributing catchment because many processes and river styles are evident where there is a uniform pattern in the controlling factors over a river length (Figure 1.1). Detailed channel properties studies are usually done at a reach scale where one examines the width, depth, bankfull discharge, and grain size and vegetation composition. These variables influence the channel structure (Brierley and Fryirs, 2005). River planform attributes are assessed by outlining the river in plan view. The number of channels, sinuosity and geomorphic units are a few parameters that can give an indication of channel sensitivity to change in fluvial style (Kuo et al. 2017). These channel attributes are the function of the valley setting and vegetation composition. The bed texture is a function of sediment availability and capacity of the flow to move material, generally under conditions of dominant/bankfull discharge. Changes in any of these attributes can form various types of fluvial styles (Fryirs and Brierley, 2010).

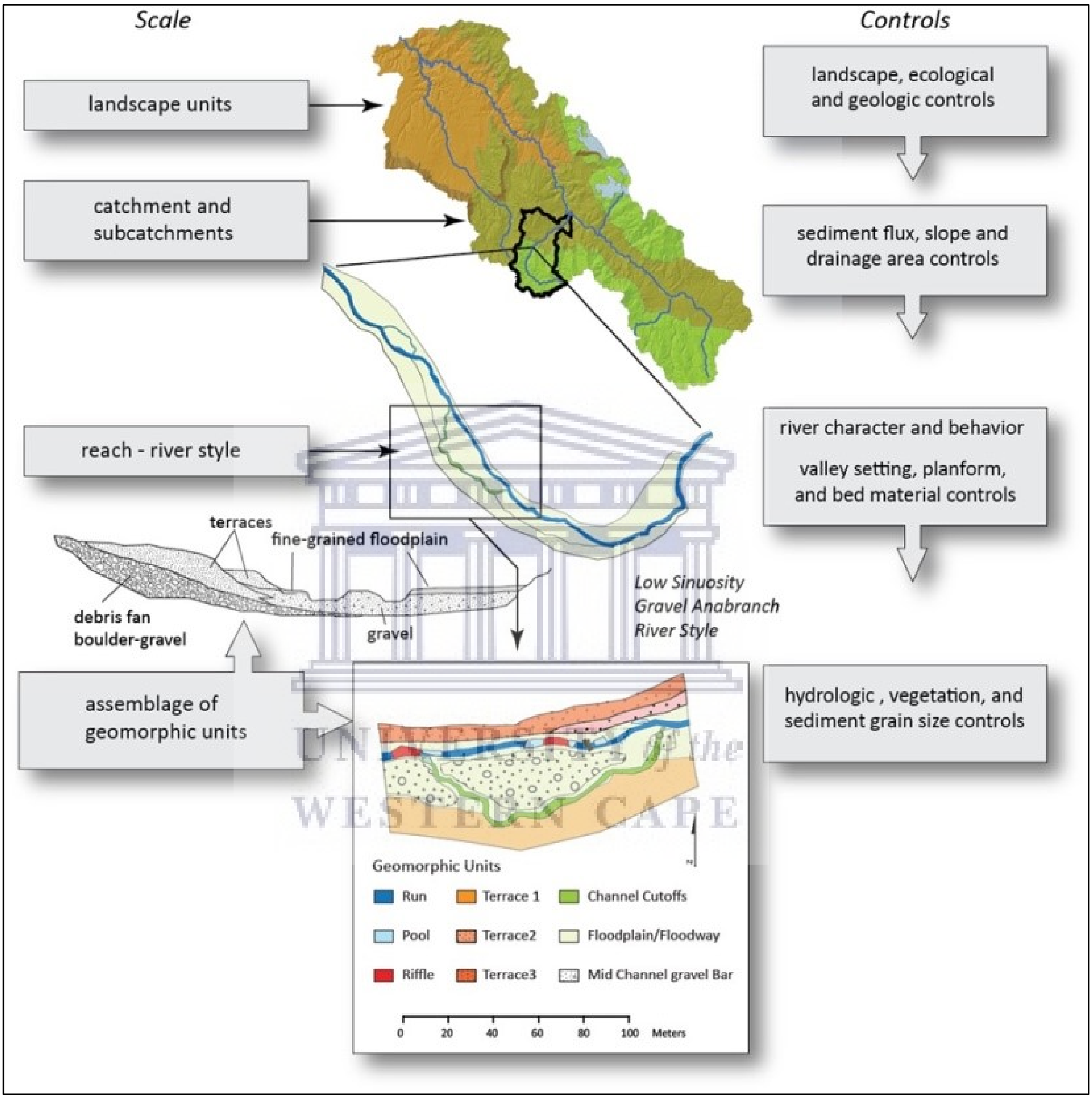


Figure 1.1: The nested hierarchy of fluvial styles (After Brierley and Fryirs, 2005; O'Brien et al. 2017).

1.4. Overall Aim

The aim of the current research is to assess the character and behaviour of non-perennial rivers in three semi-arid, mountainous catchments. This will be achieved by looking for evidence of the influence of different drivers on fluvial styles.

1.5. Objectives of the current study

1.5.1. To determine the downstream variation of two mechanistic controls of fluvial styles: valley setting and valley specific stream power.

1.5.2. To examine the characteristics of selected channel-reaches in terms of morphology, field geo-indicators (channel and soil properties), planform dynamics and their resultant fluvial style.

1.5.3. To explore and design a qualitative classification of fluvial styles for non-perennial rivers based on energy versus resistance.

1.6. Thesis structure

This thesis is composed of six chapters: three of these are synthesis chapters (Chapters 1-2 and 5) and other two are data analysis chapters (Chapters 3-4). Chapter 6 is conclusion. There is some inevitable overlap between the literature review in Chapter 1 and the introductions to the data analysis chapters. Where applicable there is cross-referencing between chapters. The six chapters are briefly described in the section below.

Chapter 1: Introduction – This chapter presents the context and rationale within which the study was undertaken. It gives a general overview of the research topic and reviews the broader literature base to set the scene for the chapters that follow. Key knowledge gaps are also described. The chapter then outlines the research aim, objectives and approach as well as the structure of the thesis.

Chapter 2: Study area and site selection – This chapter introduces the Baviaanskloof, Kromme and Kouga (BKK) catchments. It provides an in-depth view into its biophysical and anthropogenic setting, as well as some of the most important environmental issues in the area. The chapter also gives a synopsis of the selected study sites.

Chapter 3: Catchment-scale controls– This chapter characterizes the spatial distribution of valley specific stream power and valley setting in catchments within semi-arid, mountainous regions with highly diverse geomorphology. A method which is locally appropriate for deriving a spatially continuous index of stream power is developed. The chapter specifically looks at the spatial variation of these controls across each catchment to select sixteen sites for field investigation.

Chapter 4: Channel morphology and planform analysis – This chapter examines the contemporary channel morphology and changes at 16 selected study sites: Topographical survey (channel cross-sections and Manning's roughness); ad-hoc remote sensing (vegetation density); sediment sampling (particle size distribution, sorting and soil texture); visual observation (vegetation type, geomorphic units, water level, etc.). The chapter also uses the data obtained in Chapter 3 and incorporates it with inputs from Chapter 2 on river character and behaviour.

Chapter 5: Synthesis of results– This chapter combines and synthesizes results obtained from Chapter 3 (catchment-scale controls) and Chapter 4 (Channel morphology and planform analysis). The chapter seeks to explain the relationship between valley specific stream power and fluvial styles and the implications on the river ecology with inferences on how successful (or not) the hierarchical classification was for river style and behaviour investigations.

Chapter 6: General conclusions, limitations and recommendations – This concluding chapter summarizes the major findings of the thesis by synthesising the key findings of Chapters 3-5. This chapter specifically highlights the limitations of the current study and recommendations for future research are also presented.

2. Study area description

2.1. Physiographical location

The study area covers the three western Algoa catchments in the Eastern Cape of South Africa: the Baviaanskloof (1234 km^2), Kouga (2659 km^2) and Kromme (1022 km^2) catchments. Together they provide Nelson Mandela Bay Metropolitan (NMBM) and the surrounding Algoa region with over 70% of their existing water supply (Cornelius et al. 2019). The formation of these catchments is the result of geomorphic and geologic processes that occurred over the last 500 million years including major faulting, uplifting and folding, creating the present-day river valleys (Smith-Adao, 2016). The Baviaanskloof catchment is bordered by two parallel mountain ranges which are the Kouga Mountains to the south and the Baviaanskloof Mountains to the north (Figure 2.1). The Kromme and the Kouga catchments are bordered by the Tsitsikama Mountains to the south and Suuranys and Kouga Mountains to the north respectively. The catchments have trellis and parallel drainage patterns in which trunk streams are fed by steep, deeply incised tributaries (Figure 2.1).

The current study will investigate the extent of different valley settings in these catchments as a primary control on channel form and processes. For the Baviaanskloof catchment, the extensive faulting of formations has created short and steep tributaries that drain and erode the mountains forming narrow tributary valleys. Along the main river, differential uplift of fault blocks produced a pattern of alternating valley confinement settings (confined, semi-confined and unconfined) by exposing rock of different ages and hardnesses along the length of the main valley. This has an influence on channel form and processes (Smith-Adao, 2016). A study was done on the Baviaanskloof catchment linking valley morphology to river form and processes however; similar studies have not yet been done on the Kouga and Kromme rivers. As neighbouring catchments they are in the same broad geomorphic and climate region. As a result some similarities in form are expected; however, there are key differences in climate and heterogeneous faulting patterns between then that are expected to create notable differences.

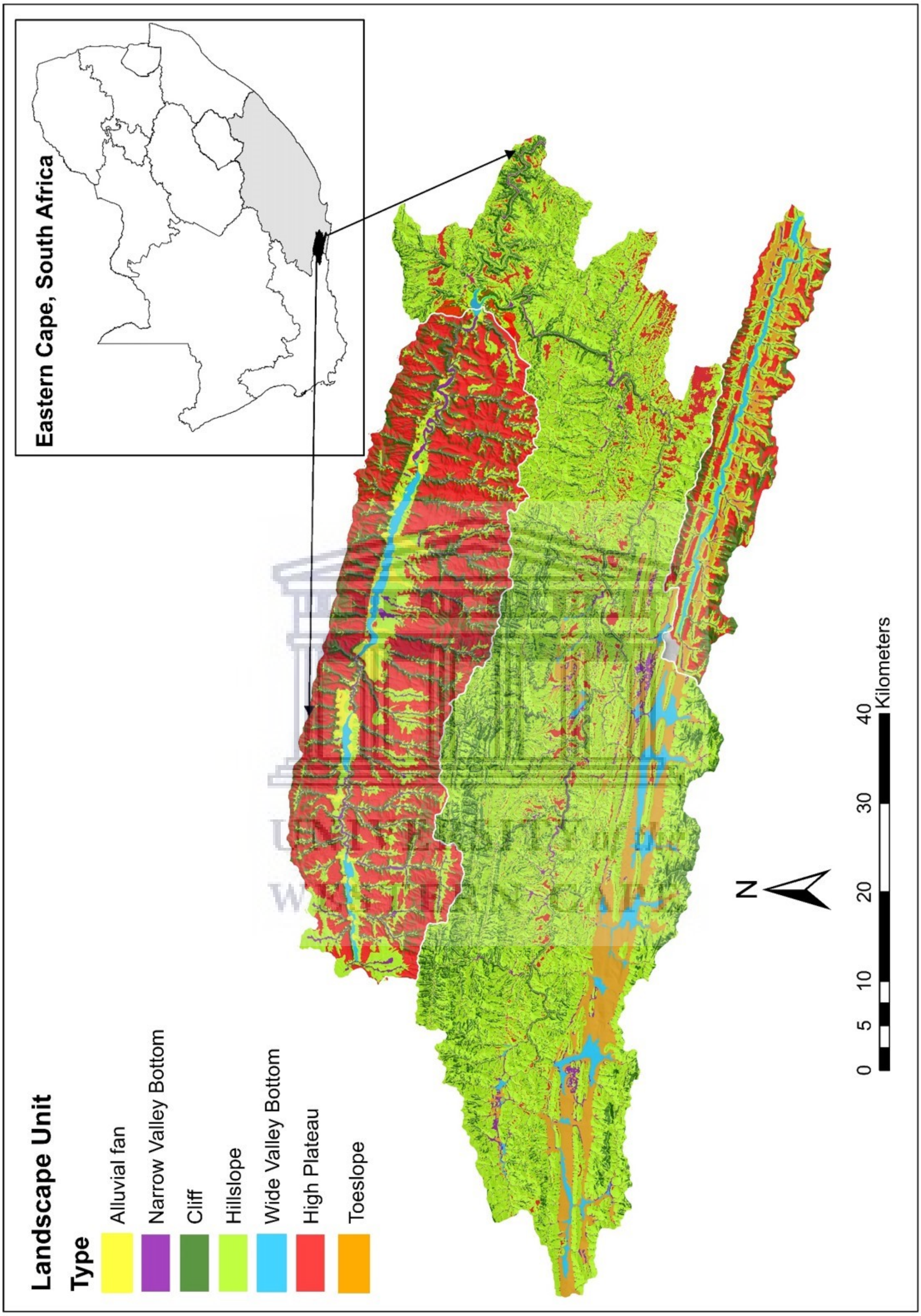


Figure 2.1: Map showing the study area with the different landscape units that exists in the three catchments. Source: SUDEM, HAND, ESRI ArcGIS 10.6.

2.2. Topography and topographic landscape units

All three catchments are dominated by steep mountains with quartzitic sandstone geology and have trunk streams flowing across valley alluvial deposits. Climatic conditions are semi-arid. The widths of the central valley floors fluctuate along the longitudinal profiles and river reaches in the wider valleys are non-perennial.

The topographic composition of the three catchments influences the variation of fluvial style (Figure 2.1). Seven topographic landscape units were delineated in the catchments from a DEM using thresholds of slope and height above nearest drainage (Cornelius et al. 2019). The dominant landscape unit is the toe-slope, covering 32% of the three catchments, followed by the hillslope landscape unit, covering about 29%. The third largest are the high plateaus which cover around 23 % of the catchments, fourth are the cliffs with an area of 10 %. The valley bottom landscape unit (wide and narrow) covers less than 5 % of the combined catchment area of the three.

The majority of the valley bottom areas in the three catchments are fertile and used for agricultural purposes. Significant invasive alien plant infestations and agricultural activities in riparian areas, wetlands and mountain slopes have resulted in degradation of natural vegetation such as thicket and fynbos in the Kromme and Kouga (Chamier et al. 2012). Flooding, erosion, sedimentation and deteriorating water quality are major issues in the three catchments, particularly for farmers. However, flood events are essential in the formation of fluvial styles in dryland river systems (Jaeger et al. 2017).

2.3. Vegetation, Climate and Geology

Long term rainfall analysis from 1959 to 2000 and previous studies show that the mean annual rainfall in the Baviaanskloof is 306 mm per annum, Kouga is 474 mm per annum and the Kromme experiences about 641 mm per annum (Figure 2.4; Lynch, 2003; Rebelo et al. 2006). This, however, can only be regarded as estimation due to the lack of high altitude weather stations to accurately measure topographic effects on rainfall. The Baviaanskloof and Kouga are particularly characterised by an inland valley, hence the resulting climate is drier than the coastal region where the Kromme is situated. The Baviaanskloof and Kromme catchment have a trellis drainage pattern and the Kouga exhibits a dendritic pattern. Most of the narrow valleys sections in the main rivers are perennial however, unconfined valley sites have shown ephemeral river behaviour. The Baviaanskloof is undammed while the Kouga is impounded by the Kouga Dam and the Kromme is impounded by the Churchill and Impofu Dams. There is a lack of long-term stream flow or discharge data for the catchments however mean annual runoff (MAR) in the present ecological and geomorphic state, the Baviaanskloof is estimated around 28 – 31 Mm^3 (Glenday, 2015), the Kouga is estimated at 144 (Hull, 2013) and lastly, the MAR in Kromme is 106 Mm^3 (Middleton and Bailey, 2011; Rebelo, 2012).

The general climate in the study area as a whole is highly variable and the complex topography results in considerable climate differences between the high altitude regions and the valley bottom(Smith-Adao, 2016). The rainfall pattern in the study area is non-seasonal although most of the rainfall occurs during the summer season. It was reported that in the Baviaanskloof catchment, around 194 mm rainfall is expected in the summer and 112 mm in winter(Smith-Adao, 2016). In the Kouga, Mean daily maxima and minima temperatures vary from 29.6°C in summer (February) and 2.4°C in winter (July). Altitude ranges from 0-1758m with relatively gentle to steep slopes on both south and north facing slopes in relation to other parts of the country.

The following regional climate and vegetation description is adapted from (Mucina et al. 2006) which has been subsequently updated over the years. A biome is a region having similar broad-scale environmental factors namely vegetation structure and is exposed to comparable macroclimate (Rutherford and Mucina, 1996). These catchments often have characteristic levels and responses to anthropogenic and natural disturbances such as fires and over-grazing. The vegetation map, was produced by a number of authors, including a detailed vegetation map by Euston-Brown (2006), who have collected secondary data from various national data sources regarding vegetation, climate and geology and with the help of remote sensing data and GIS. Nine biomes exist in South Africa (Nama Karoo, succulent Karoo, Fynbos, Forest, Albany Thicket, Savanna, Grassland, Desert, Indian Ocean Coastal Belt), of which four are present in the Baviaanskloof, Kouga and Kromme (BKK) catchments (Albany Thicket, Fynbos, Forest and Azonal (Figure 2.2; Table 2.1). Each of these biomes has vegetation units where the altitude, geology, climate and flora and fauna taxa are used to describe the regional and local diversity in the natural system in (Figure 2.2).

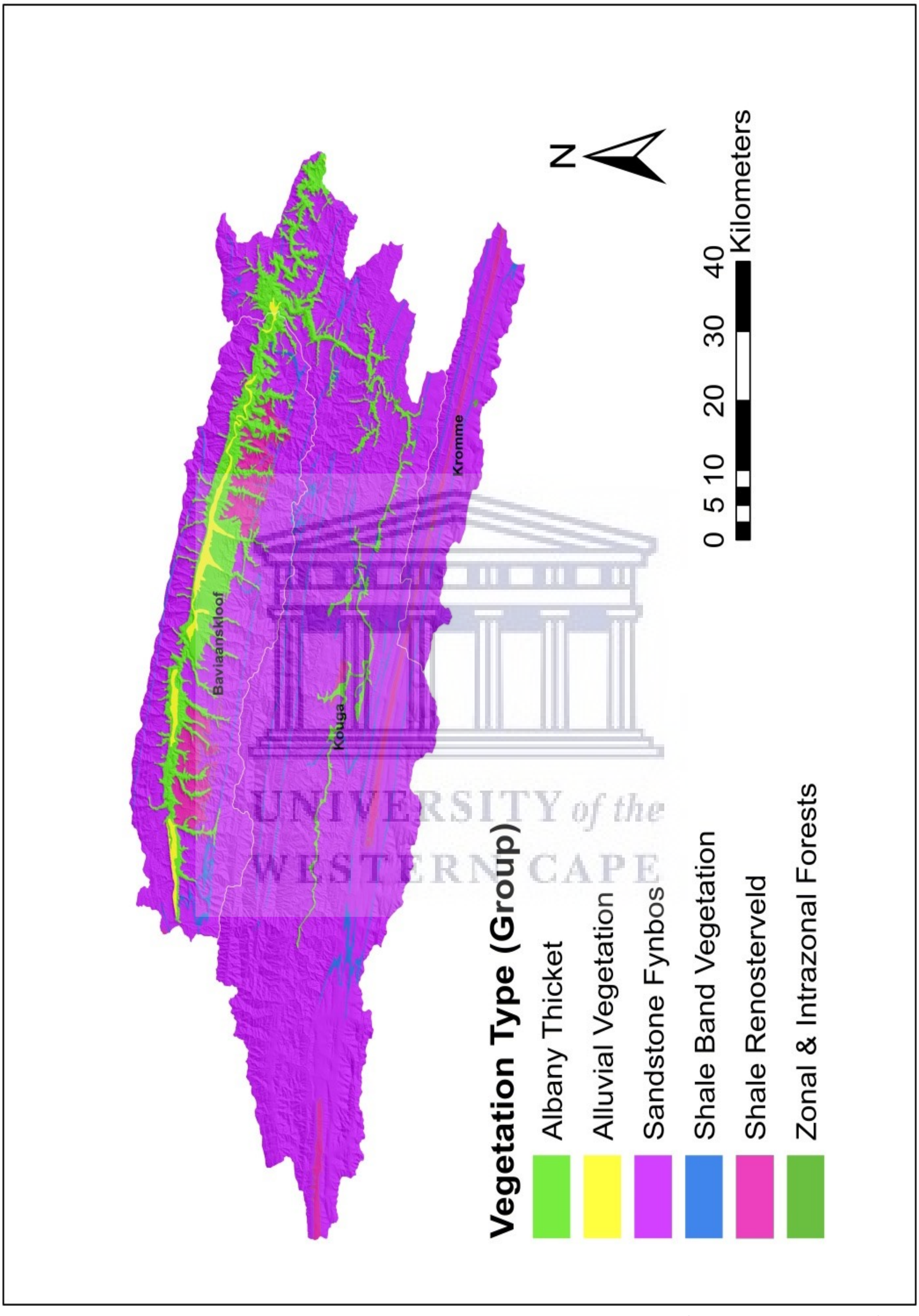


Figure 2.2: The regional vegetation types in the three catchments (Mucina et al. 2006).

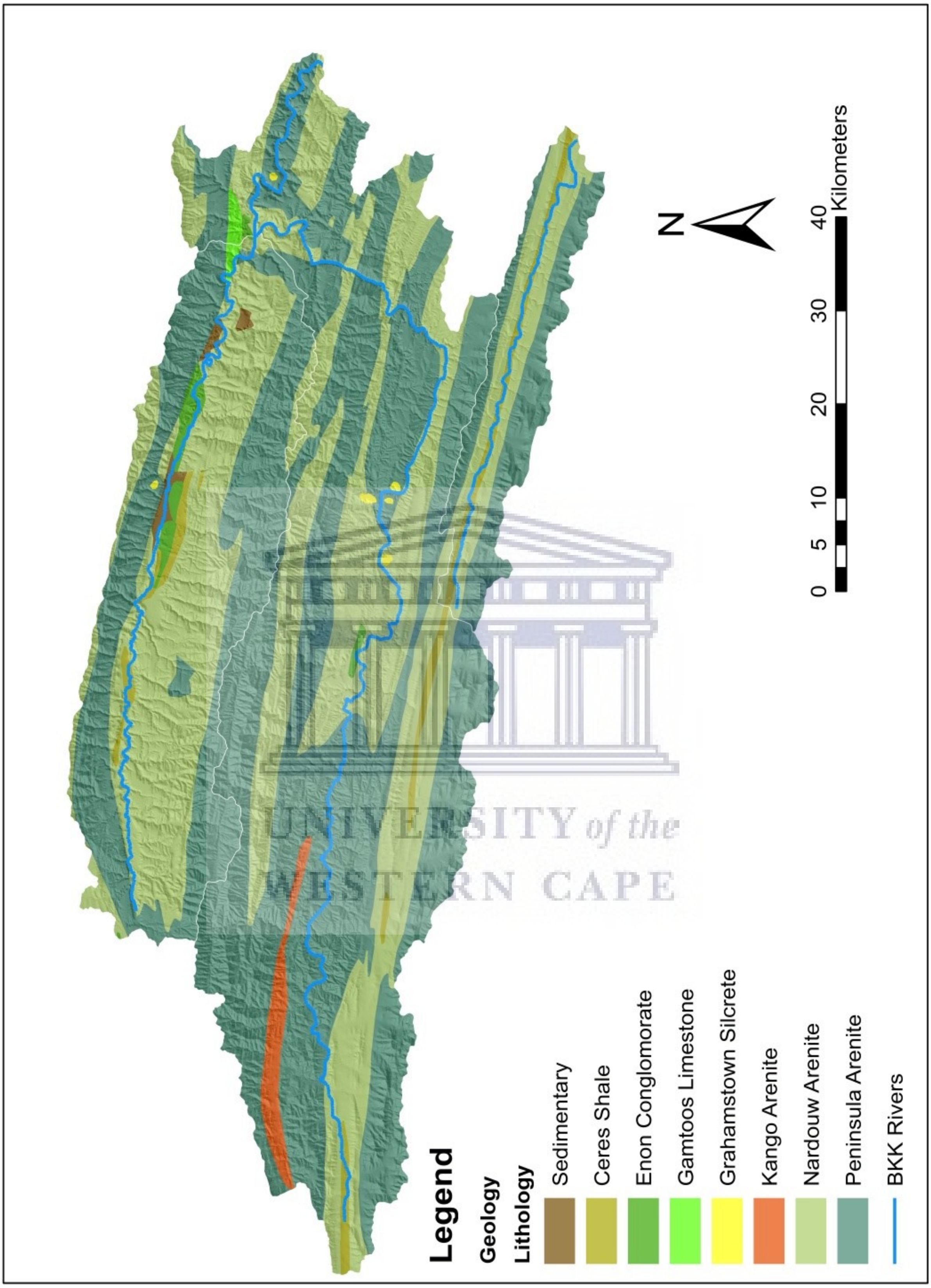


Figure 2.3: Map showing the lithology of the BKK Catchments. These lithology correspond with the vegetation type/biome from Figure 2.2. Source: Council of Geosciences, South Africa.

Table 2.1 summarizes the vegetation units and the estimated areal coverage of each of the units. The largest unit is the Sandstone Fynbos which is in the Fynbos Biome which is dominantly associated with the Peninsula Arenite lithology in these catchments (Figure 2.2 and 2.3). Two other vegetation units in this biome are present in the BKK catchments namely, Shale Renosterveld and Shale band which are predominantly underlain by Kango and Nardouw Arenite (the geologic map is coarse and doesn't show all the subordinate shale layers in the broader formations). Other vegetation units in the three catchments according to size are: Albany thicket and Alluvial vegetation which occurs in the hillslope and valley bottoms and are underlain by a variety of conglomerate, shale, arenite, lime and sedimentary rocks (Figure 2.2 and Figure 2.3).

The dominant vegetation found in the Fynbos unit is mainly proteoid, restiod, ericoid. The medium dense cupressoid-leaved shrubland with resonsterbos and graminoid undergrowth are also present in flat, lower mountain bases of the Baviaanskloof catchment (Rebelo et al. 2006). The valley pattern in these biomes is wide and partly filled with alluvium where the Fynbos grows (Figure 2.2). These vegetation units are also common in high altitude areas.

In the Thicket biome, two vegetation units are present in the BKK catchments namely the Groot and Gamtoos thicket. These units are found on lower slopes and ridges of the Baviaanskloof and in the river valley of the Kromme catchment. The altitude ranges from 0-1100 m with moderate to steep slopes which have dense succulent thicket (Hoare et al. 2006). However, the succulent woody shrubs, have been overgrazed and have led to the subsequent soil loss due to decreased vegetation cover (van Luijk et al. 2013). The main lithology is arenite and shale with shallow, red, clayey soils. There is also a presence of sandstone from the TMG which results in sandy-loamy soils (Hoare et al. 2006).

For the forest biome, the Southern Afrotemporate forest vegetation unit exists along the Tsitsikama Mountains in the Kromme catchment along a narrow, coastal strip (Mucina et al. 1984). This is the smallest vegetation unit in the BKK catchments, covering an area of about 0.4km^2. The forests grow in kloofs with attitudes varying from 10-600m. These forests are also situated and dominantly grow and thrive in regions with high water availability. The geology is dominantly TMG sandstone and shale thereby forming shallow, sandy humic soils (Figure 2.2). Yellowood vegetation is common in these areas (Mucina et al. 1984).

Lastly, the Inland Azonal vegetation biome, the Albany alluvial vegetation is present in the BKK, however, it is only present in the wide floodplains of the Baviaanskloof river where it is surrounded by the thicket and thornveld vegetation such as *Vachellia karroo* (Euston-Brown, 2006*;* Mucina et al. 2006). The geology is mainly from the sedimentary rock of recent alluvial deposits susceptible to erosion (Mucina et al. 2006).

Table 2.1: Summary of area covered by each vegetation unit present in the BKK catchments.

Biome	**% of catchment**	**Vegetation Unit**	**Area (km^2)**
Thicket	10.3 %	Albany Thicket	950.26
Azonal	1.6 %	Alluvial Vegetation	148.42
Fynbos	88.1 %	Sandstone Fynbos	6790.49
		Shale Band Vegetation	128.24
		Shale Renosterveld	1242.36
Forest	0.1 %	Zonal_Intrazonal	3.76

2.3.1. Riparian vegetation

The riparian vegetation in the three BKK catchments is very important from a river ecosystems and agricultural perspective because the riparian vegetation directly affects the channel roughness, and flow pattern and this can be modified spatially or temporally. Riparian vegetation acts as a control on the movement of the river. The narrow-wide valley confinement patterns in the Baviaanskloof and Kromme catchments have resulted in the uneven distribution of sediment deposition following various flood events. The deposition of this fine-grained to medium coarse sediments has allowed the growth of adventitious, fibrous root system vegetation such as palmiet (*Prionium serratum*) in the Kromme catchment floodplain. If left undisturbed, the palmiet results in unchannelled valley bottoms, generally in wider valley reaches (where river has less energy to carve a channel against the strength of palmiet), Pulley et al. (2018) suggested palmiet may have even contributed to widening the valley in the first place. This vegetation has been around thousands of years and forces the water to spread out and sometimes pushes the channel off to one side or the other, eroding along the valley margin. With the constant water logging of these valley fill due to the gentle slope, these wide sections (laterally unconfined) host a variety of wetland species and act as a buffer along the river longitudinal profile. Other vegetation types that grow naturally in the riparian area are from the Lamiaceae family.

The encroachment of invasive alien plants by *Acacia mearnsii* (Black wattle) is a major issue in the Kromme and Kouga catchments, specifically for the riparian areas (Figure 2.4A; Figure 2.4B). The Black wattle is present in the Kouga and Kromme catchments at various sections along the river. Stands vary in age. Older Black wattle can contribute large woody debris inside the channel, further resulting in the modification of the channel roughness.

Figure 2.4: (A) Wide valley section of the upper Kromme and (B) Shows the encroachment of the Black wattle in the riparian area.

3. Catchment-scale controls

3.1. Introduction

The identification of geomorphic controls that determine the channel pattern has been a key focus in fluvial geomorphology. Rivers develop a variety of channel forms, whose attributes differ as a function of position within the fluvial system. These channel forms are a culmination of the wider catchment processes which drive flow, topographic and geometric conditions (Knighton, 1999). The distribution of entrainment, erosion, and deposition processes drive landscape patterns at the catchment scale as well as at finer scales, such as river reaches. The valley setting, stream power, and sediment regime are primary controls of river form (Fryirs et al. 2016). In semi-arid mountainous catchments, high geomorphic and hydrologic variability exist due to highly episodic climatic patterns (Rowntree and Wadeson, 1999). The spatial variability in river channel form reflects the hierarchy of various influences across a range of scales. Where river classification is concerned, the analysis of catchment properties is fundamental in informing the pattern and distribution of fluvial styles that are found in lower hierarchical levels as these are understood to be spatially connected through driving mechanisms and resistive forces (Ferguson, 1981).

Specific stream power is a physical and empirical parameter that describes the energy the river has to move water and sediments. It is a function of slope, discharge and channel width (Chang, 1979). It directly correlates with, and functionally controls, many different aspects of channel morphology and the resultant dynamics. Specific stream power has been used to predict channel pattern, bedload transport, and entrainment and has been used as an indicator of erosion or deposition in stream assessments (Fonstad, 2003; Finnegan et al. 2005; Smith et al. 2009; Kleinhans and van den Berg, 2011; Lecce and Lecce, 2016; Lea and Legleiter, 2016; Kasprak et al. 2017).

However, the calculation of specific stream power requires measured or predicted channel width, which is often difficult to obtain in dryland rivers which commonly have complex and dynamic multiple-threaded and floodout river sections. Many rivers in dryland environments that have a net loss of water to bed infiltration can decline in width with distance downstream and can terminate in a flood-out (Tooth and McCarthy, 2007; Jaeger et al. 2017). This may pose a problem because reaches that are essentially boxed into one pattern class through a fair distance, but in reality have channel dimensions that decline monotonically with distance downstream.

While the issues above are impacted by land use, they must also be viewed in the context of long-term catchment-scale geomorphic adjustments. The rivers in the three catchments are very diverse in terms of their pattern, shape, and thus, catchment-wide controls have to be considered for rehabilitation and improved river health management to progress. Furthermore, while the role of stream power and valley confinement is widely understood, there have been few attempts to integrate these variables into a predictive model of erosion and deposition (Bookhagen and Strecker, 2012). The challenge in creating such models is that sufficient data on discharge, slope and grain size is not readily available at several suitable study sites, let alone covering large regions. Therefore, such analyses generally use a combination of model variables as proxies for field data.

To overcome this problem, the current study proposes to use an alternative method where measured valley width is used instead of channel width in the calculation of specific stream power. This ensures that the relative total flood energy of the river along a long profile is represented in a manner that is independent of the number of channels and fluvial style. This means that the energy predicted, the ability of the river to rework and transport sediments, is a function of the degree of valley confinement, which controls the potential for the river can disperse energy by moving laterally or vertically. Using valley width, an easily measurable parameter, the relative comparison between different parts of the stream will likely more accurately represent fluvial dynamics compared to using assumptions to estimate channel width based on other parameters and algorithms applied at large scales that are better suited for hillslope erosion prediction (Roux et al. 2013). The valley bottom can be limited by geologic and geomorphic structures such as bedrock outcrops, hillslopes, and terraces, thereby influencing the longitudinal stream power series, dictating how energy is concentrated (Nagel et al. 2014; Gilbert et al. 2016).

Some research on the spatial distribution of specific stream power over entire catchments has proposed generalized stream power values and locations of thresholds for changes in channel pattern to occur (Fonstad, 2003; Wolfert, 2001;

Bawa *et al*, 2014; Smith-Adao, 2016; Kasprak et al. 2017). However such generalizations may not be appropriate to apply to different regions or catchments because of the diverse combinations of variables that influence channel form.

Valley morphology (width, size, and shape) is another important primary control (Guo-An et al. 2013; Fryirs et al. 2016; Lisenby and Fryirs, 2017). Where allowed by the valley setting, the flow is dispersed within the river and therefore respond to energy differently across the lateral extent of the valley bottom, affecting erosive forces on river banks, floodplain, terraces and riparian and aquatic habitats (Brierley et al. 2008). For example, confining valley margins are bounded mainly by hard bedrock, thereby forming distinct river forms (particularly in headwater streams) with steep slopes, high flow velocity, and high erosive power, but limited potential to erode laterally relative to the hardness of the rock bounding the lateral extent (Gilbert et al. 2016). Unconfined valleys, in contrast, have low gradient slopes and lower velocity, and lower power with which to erode laterally but their erosive potential can be accelerated due to the erosive alluvium present. In some instances in unconfined valley settings meandering fluvial styles, lateral movement is due to energy excess which allows lateral reworking of sediments.

Thus, viewing valley settings in this manner provides an appropriate foundation to analyze the distribution and spatial transitions in the valley form and processes. In this chapter, the valley setting and confinement indices have been derived to characterize the role of valley setting as a control on channel morphology. In this chapter, two mechanistic controls that is valley setting and valley specific stream power are examined to discern their pattern and variation within and amongst the catchments. This is the first level in the hierarchy of river classification and allows for detailed river channel analysis informed by quantifiable variables.

3.2. Methods

With the recent developments in Geographical Information Systems (GIS), it has become increasingly easy to spatially estimate and analyze specific stream power and map extents of valley bottoms using GIS-based toolboxes and products such as Digital Elevation Models (DEM) and remotely sensed imagery. Extracting geomorphic and fluvial data from a DEM using automated GIS modules provides an alternative method for river typology in order to characterize the physical features and processes in catchments (Table 3.1; Table 3.2; Sermin and Jeff, 2008; Harris et al. 2009; Stott, 2010; Wheaton et al. 2015).

Algorithms and toolkits have aided in the advancement of analysing geomorphic features over large areas using GIS (Table 3.1). These algorithms normally use slope thresholds, flood depth, and drainage area properties to identify the valley bottom in a DEM raster surface. For example, the valley confinement algorithm (VCA) toolbox was created to delineate unconfined valley bottoms for geomorphic and ecological applications in the Rocky Mountains using slope and flood height thresholds (Nagel et al. 2014). However, initial trials revealed this algorithm was not able to delineate narrow, confined valley bottoms, only delineating large alluvial valleys. This was overcome by Roux et al. (2015) in the FluvialCorridor (FC) toolbox and Gilbert et al. (2016) in the Valley Bottom Extraction (V-BET) toolbox, which could map all valley settings. These algorithms do not use single values for slope and flood thresholds across a catchment which evidently does not scale properly in the outputs. The newer algorithms delineate the valley bottoms and valley confinement types as a function of drainage area in conjunction with slope information.

Table 3.1: Review of methods for the automating extraction of valley bottom and setting in a GIS environment. Modified from Gilbert et al. 2016.

Method or tool	**Data requirements and key parameters**	**Reference**
HEC-RAS	River centreline, stream banks, flow paths and cross-sections	Brunner (1995)
Williams et al method	Catchment boundary, drainage network and DEM	Williams et al. (2000)
Multiresolution valley bottom flatness (MRVBF)	DEM	Gallant and Dowling, 2003
Object-based classification	DEM	Straumann and Purves, 2008
FLDPLN	DEM, flow gauge information	Kastens, 2008
River Bathymetry Tool (RBT)	DEM	McKean et al. 2009
HAR	DEM, raster drainage network	Dilts et al. 2010
Height above nearest drainage (HAND)	DEM, raster drainage network	Dilts et al. 2010
Floodplain mapping tool (FMT) and TerEX	DEM, average valley width	Stout and Belmont (2014)
Valley confinement algorithm (VCA)	DEM, NHD+ river line and water bodies, precipitation, catchment boundaries	Nagel et al. 2014
Fluvial Corridor Toolbox	DEM, drainage network polyline	Roux et al. 2015
Valley bottom extraction tool (V-BET)	DEM, stream network	Gilbert et al. 2016

Continuous research has advanced our understanding of the function of specific stream power as a key determinant in fluvial style, flood or erosion power, floodplain formation and as a discriminator in between stable and unstable channels (Brierley et al. 2008; Gartner, 2016; Stacey and Rutherfurd, 2007). Using GIS, the spatial distribution of specific stream power indices representing the flood or erosion power over entire catchments have been estimated across a wide range of climatic and geologic conditions to understand incision rates. Many studies have examined various derivatives of specific stream power (Table 3.2). Most of the indices require a DEM and a streamline network. Estimates of channel width and discharge are commonly derived from regime-based calculations, which are rarely site-specific and are applied as a single value throughout the whole catchment. This current study will make use of spatially variable estimates of valley width for this reason.

Using valley width in stream power estimation, a parameter that can be directly derived from a DEM, the method allows one to fully examine specific stream power variation across entire catchments. This method is a rapid, desktop study approach using GIS-based data such as a DEM, mapped river channels and aerial imagery. This greatly simplifies the task by using digital data sources and automating landscape processes, thereby limiting data collection and point location calculations. Furthermore, higher resolution DEM datasets derived from SRTM, LiDAR and UAV can be used to extract valley and channel geometry where this is lacking.

There is a need, especially in semi-arid mountainous catchments, where there are typically highly variable streamflows, sediment flows, and resultant fluvial styles, for a method for specific stream power estimation that is accessible, reliable and repeatable and uses nationally available data as inputs. This need exists because the information collected at this stage forms the basis for future decisions for a particular channel. An index of specific stream power may be calculated from terrain analysis which is supplemented by a discharge proxy based on the upstream drainage area and rainfall raster surfaces, giving a method that can be used without the need for detailed information on flow and channel properties. Furthermore, there is opportunity for this method to be applied across South Africa to automate river and geomorphic features for national river assessments, such as those that form part of the National Biodiversity Assessments (Driver et al. 2011; Skowno et al. 2018)

Table 3.2: Review of methods to predict specific stream power in a GIS environment.

Method or tool	Data requirements and key parameters	Reference
Stream power index (SPI)	DEM, slope, catchment area	Moore et al. 1991
Jain et al. 2006 method	DEM, catchment area-discharge, stream long profiles	Jain et al. 2006
NetMap	DEM, precipitation, stream flow data	Benda et al. (2007)
Combined automated flood, elevation and stream power (CAFES)	DEM, high-resolution discharge (FEH), digital land use and soil datasets	Barker et al. 2009
SciMap	DEM, Land cover	Durham University - SciMap, 2010
Ferencevic and Ashmore method	DEM	Ferencevic and Ashmore, 2012
Bookhagen and Strecker method	DEM, discharge-weighted topographic methods (TRMM)	Bookhagen and Strecker, 2012
Thomspon and Croke Method	LiDAR, discharge (gauge), channel geometry	Thompson and Croke, 2013

Catchment-level controls discussed above form a basis of river analyses as the highest order factors influencing channel form and processes. For example, sediment supply limited conditions in confined valley settings along the river long profile are typically erosive and become sources of sediment for downstream. These conditions may be variable depending on degree of hillslope-channel coupling (Harvey, 2001). The unconfined valley settings have limited transport limited conditions (Brierley et al. 2008). These transitions form the basis of channel initiation, which can result in diverse alluvial sediment stores such as bars, pools, on the channel bed. In a hierarchical classification of river systems, these catchment controls allow one to select sample sites in which further analyses can be done in order to infer reach and fine-scale processes. As discussed in Chapter two, elements in the higher level, the catchment in this case, constrain on the river character and behaviour of lower levels, such as a channel/river network. The main objective of this chapter is to develop a geospatial model for catchment scale controls namely valley specific stream power (VSSP) and valley confinement in order to predict fluvial styles across three semi-arid, mountainous catchments.

3.2.1. GIS-Based VSSP Workflow

The input parameters for estimating valley specific stream power were calculated for every 100 m section of main river reach using catchment-scale topography and climate data and a series of GIS algorithms (Figure 3.1). A DEM with a 5 m spatial resolution, the Stellenbosch University Digital Elevation Model (SUDEM) (Van Niekerk (2016), was used to derive streamlines, slopes and valley bottom extractions. GIS analyses were carried out using ESRI ArcMap 10.6 with Spatial Analyst, Valley Confinement Algorithm (VCA), Fluvial Corridor (FC) and V-BET extensions (Figure 2). Spatial Analyst in ArcGIS 10.6 was used for the removal of spurious depressions from the land surface using a fill sink command, definition of flow direction (D8 directionality) and accumulation, and definition of a stream network based on a flow accumulation threshold. Depending on the nature of the landscape, this was an iterative process done in order to generate a stream network. The V-BET toolbox was then used to generate the valley bottom extent using the stream line and the DEM as an input. Certain metrics for valley bottom (valley centreline and valley width) were also estimated using the FC extensions.

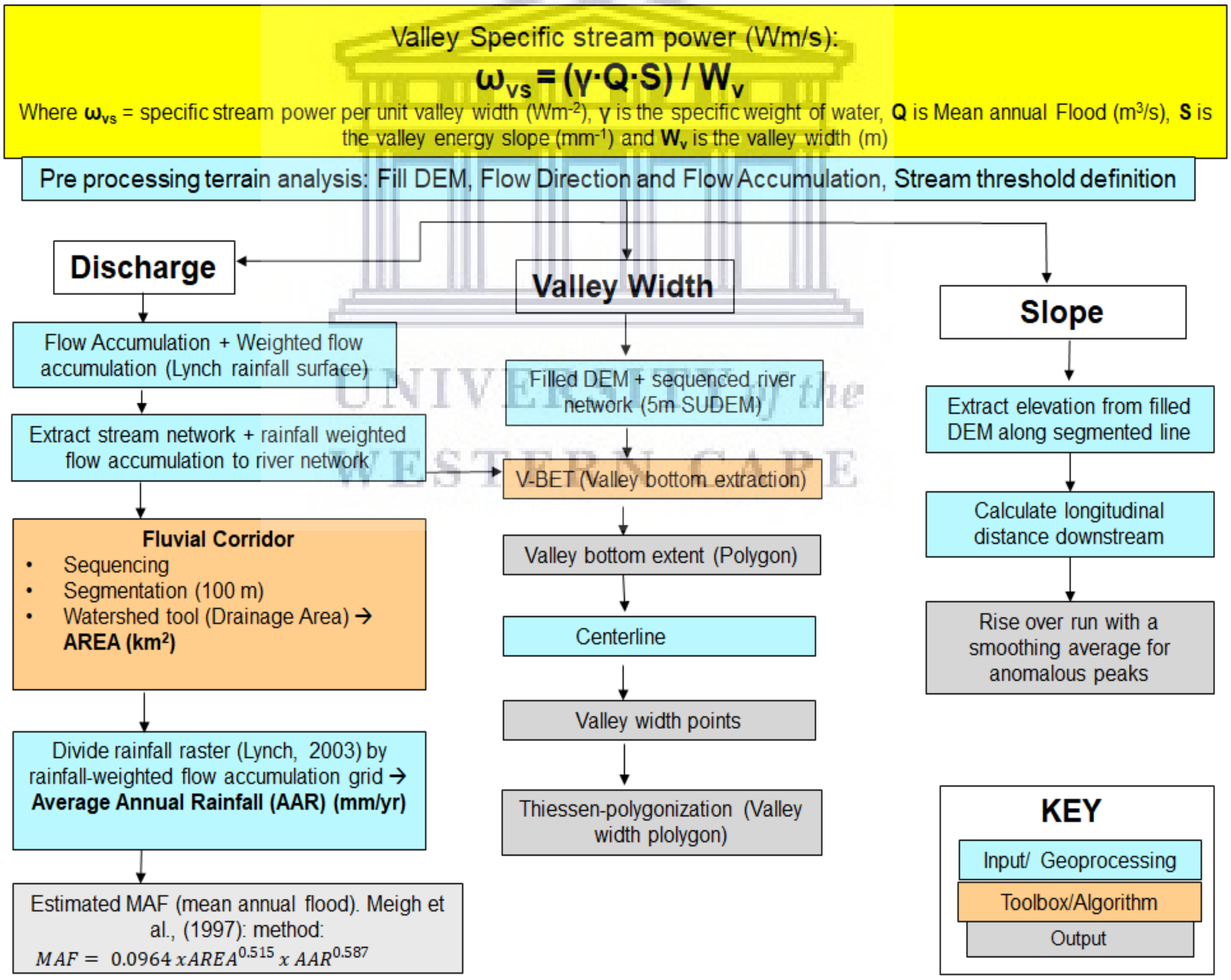


Figure 3.1: Methodological workflow to calculate valley specific stream power in a GIS environment.

3.2.2. . Valley confinement, setting, and topography

A valley centreline was delineated and valley width was calculated using the V-BET valley bottom output polygon (Figure 3.1). Measurements of valley metrics for South African rivers are not available on a national database thus had to be derived using the Fluvial Corridor (FC) (Roux et al. 2015; http://umrevs-isig.fr) algorithm, which characterizes at a network scale and identifies homogeneous reaches. Valley width was estimated using the valley bottom shapefile and centreline. The FC assigns valley width values to evenly spaced points (100 m intervals) along the centreline of the valley polygon. The location of the river channel itself deviates greatly from the valley bottom centreline. Valley width values were therefore assigned to 100 m interval points along the river channel line using the nearest centreline point values. This was done using theissen polygons created from the valley width points on the centreline (Figure 3.1).

In order to classify the level of confinement (confined, partially confined and laterally unconfined) of the valley bottom in different areas, the V-BET valley bottom polygon, the stream network polyline, and a channel polygon (active channel) were used to apply the class definitions of Brierley and Fryirs, (2000). Brierley and Fryirs, (2000) propose a confinement classification based on the proportion of the channel length that is located against the valley margin (See Chapter 1, Section 1.3). This is operationalized within the V-BET toolbox. The tool returns an output shape file that contains a confinement class value (0 is laterally unconfined and 1 is fully confined) calculated for each river segment in the stream network (See Chapter 1, Section 1.3). Places that fell out of these were coded a partially confined valley setting.

Flood regime (Proxy)

In this approach, the method for estimating mean annual flood described in (Meigh et al. 1997) was followed:

$$MAF \;=\; 0.0964\, x AREA^{0.515}\, x\, AAR^{0.587} \qquad (1)$$

Where:

MAF = mean annual flood (m^3/s)

AREA = drainage area (km^2)

AAR = average annual rainfall (mm/yr)

The method requires two inputs: drainage area and average annual rainfall. The river channel lines were segmented into 100m reaches using the FC toolbox. Two steps were then followed to estimate these inputs spatially for these river segments: A) Firstly, the Watershed Tool from the FC toolbox was used to assign drainage areas to each 50m river segment using the flow accumulation grid and a streamline derived from flow accumulation as inputs. The tool extracts the grid cells touching the streamline to produce a point shapefile that is indexed by river reach, i.e. points are an ID number that matches the relevant river reach. However, because of the grid resolution compared to curves in a smooth polyline, not all the extracted points fall on the streamline, and as a result, do not all have a relevant catchment area values. Therefore the maximum value for all points assigned to a numbered river reach was calculated and joined to the segmented streamline using ID numbers. B) To get spatially averaged annual average rainfall as a depth (mm) for the contributing drainage area of each 50 m river segment, a rainfall-weighted flow accumulation grid was created and values were divided by drainage area (non-weighted flow accumulation). The spatial distribution of rainfall in the region was characterized by Lynch, (2003), who used patched daily rainfall time series data (1950 - 2000) and multiple regression to create a surface of mean annual rainfall (Figure 2.4). This surface and the DEM were used to create the rainfall-weighted flow accumulation grid using Spatial Analyst. The relevant rainfall-weighted flow accumulation grid values were extracted for stream segments with the FC toolbox using the same steps as above.

One critical data limitation is that evaporation losses and groundwater flows were not explicitly accounted for in this method, but it was assumed to yield a decent proxy which shows the relative spatial differences in the discharge one would expect between one point within a catchment compared to another and between one catchment and another. It is a simple proxy that quantitatively accounts for spatial differences in the rainfall, across and within the catchments, and in contributing catchment area along the river course, which will have large impacts on discharge at each point.

3.2.3. Valley specific stream power

Specific stream power provides an expression of the available energy for geomorphic work at a given location in the river. The valley specific stream power (VSSP) was calculated for every 50m on the streamline using the valley slope, valley width, and estimated mean annual flood discharge proxy. Valley specific stream power was calculated as:

$$\boldsymbol{\omega_{vs} = (\gamma \cdot Q \cdot S) / W_v} \qquad (2)$$

Where ω_{vs} is the specific stream power per unit valley width (Wm^{-2}), and γ is the specific weight of water (9810 Nm^{-3}), Q is the water discharge proxy estimated from MAF (m^3/s), S is the valley energy slope approximated by the valley slope (m/m) and W_v is the valley width (m).

In ArcGIS 10.6, a simple math statement as described in equation 2 was used to combine the slope, discharge proxy and valley width raster surfaces in the calculation of valley specific stream power.

3.3. Results

3.3.1. Valley characteristics

The V-BET and FC algorithms were able to effectively delineate and classify valley bottoms for all three catchments (Figure 3.2). Summary metrics associated with valley bottoms varied across the three study catchments. The mapped valley bottom in the Baviaanskloof covers approximately 48 km^2, which is 4 % of the total catchment area. In the Kouga, the valley is 20 km^2, which covers 1 % of the total catchment area. In the Kromme it was 17 km^2, covering 5 % of the total catchment area (Table 3.3). The valley bottoms of all three catchments covered similar, very small proportions of the total catchment area. Despite being the largest catchment, the Kouga had the smallest proportional valley bottom area of the three (Figure 3.2).

Table 3.3: Summary table of valley characteristics in the BKK catchment.

Catchment	Catchment area (km^2)	Valley pattern	Valley area (km^2)	Average Slope (m/m)	Average Valley width (m)
Baviaanskloof	1213	Confined	3.27	0.0093	109
		Partially confined	15.32	0.0066	475
		Laterally unconfined	29.43	0.0082	973
		Valley bottom (all)	**48.0**	**0.0241**	**519**
Kouga	2457	Confined	9.56	0.0046	70
		Partially confined	7.36	0.0046	381
		Laterally unconfined	2.96	0.0007	722
		Valley bottom (all)	**19.9**	**0.0033**	**391**
Kromme	358	Confined	0.53	0.0204	137
		Partially confined	7.82	0.0095	274
		Laterally unconfined	8.17	0.0039	393
		Valley bottom (all)	**16.5**	**0.0112**	**280**

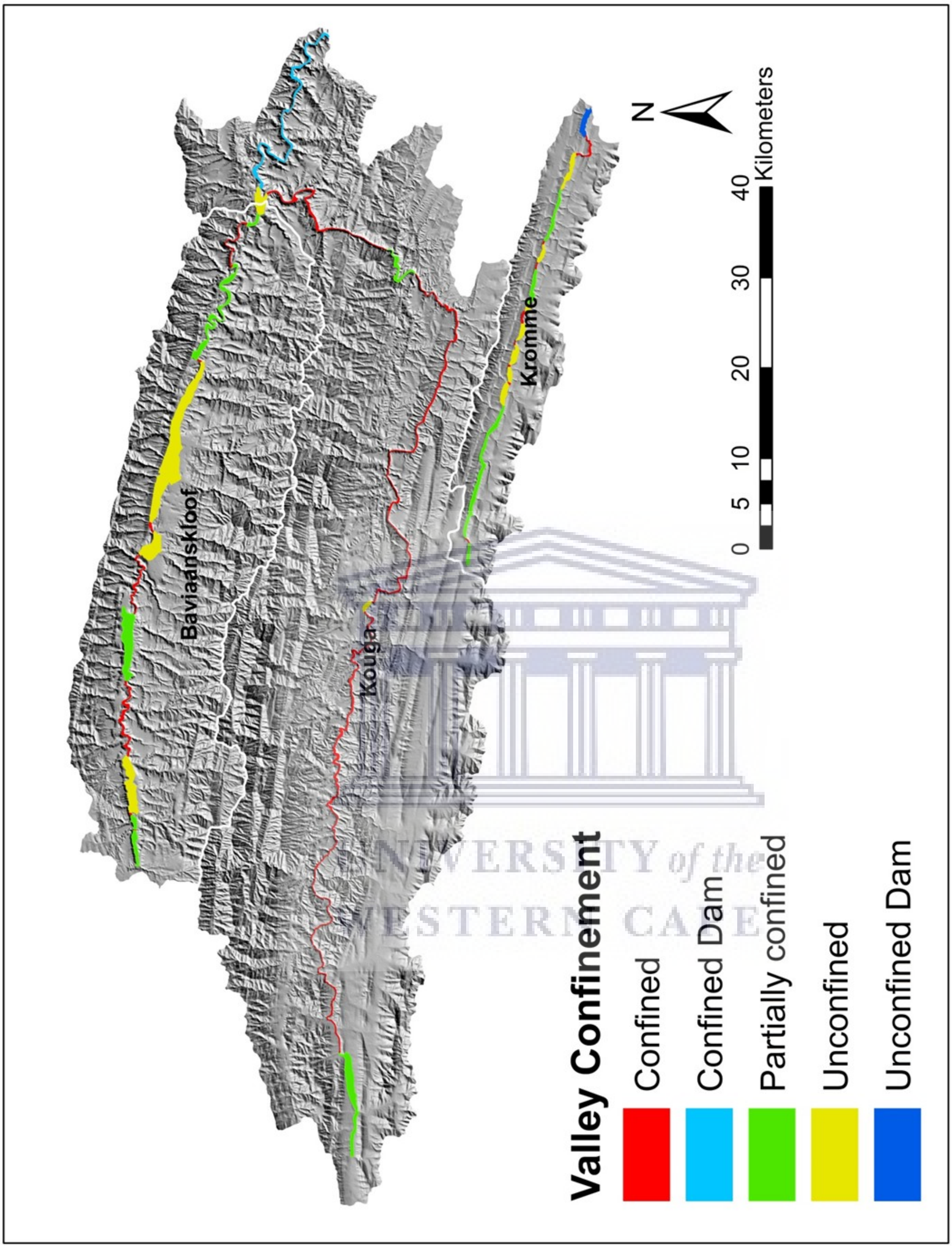


Figure 3.2: V-BET valley confinement output. Red shows the confined valley bottoms, green shows the partially confined valley bottoms and the yellow shows the laterally unconfined valley bottom output. (Source: SUDEM, VBET)

3.3.2. Spatial variation in valley setting and specific stream power

3.3.2.1. Baviaanskloof Catchment

For the Baviaanskloof catchment, 61% of the valley bottom is found to be laterally unconfined (Figure 3.2). These areas are comprised of flat alluvial valley fills along both valley margins with the valley width ranging from 267 to 2578 m (mean, 973 m). The alluvium present in these valley settings has low to gentle slopes from 0.0001 to 0.041 m/m (Figure 3.3; Figure 2.3). Along the valley river long profile, the laterally unconfined valley settings are found between 6-13 km and 44-71km from the start of the valley. This area is where anthropogenic influences are the greatest due to the wide valley morphology being suitable for agriculture. The valley planform is characteristic of a wide valley with laterally-impinging alluvial fans, terraces and old, abandoned channels being the main constraining features in the valley segment. These laterally unconfined valleys have a low VSSP, ranging from 0.001 to 28 Wm^{-2} (Figure 3.3; Figure 3.4).

Partially confined valley settings cover the second largest with about 32% of the overall valley bottom area (Figure 3.2). The pattern of partially confined valleys alternate with confined valley settings along the longitudinal profile. These valleys are between 0-5 km, 25-35 km and at 71-100 km from the start of the valley. Valley width and slope range from 33 to 1651 m and 0.0001 to 0.03 m/m respectively (Figure 3.3). Partially confined in the Baviaanskloof have largely sinuous floodplains which have flow through erodible rock alluvium with pockets of discontinuous floodplains exposing bedrock along the valley margin. The specific stream power in this valley setting ranges from 0.002 to 224 Wm^{-2} (Figure 3.2).

Confined valley settings have an aerial coverage of only 7%, which are mostly located between laterally unconfined and partially confined regions. Valley width ranges from 19.4m to 407m (Table 3.3) while valley slopes in this valley setting ranges from 0.0001 to 0.049 m/m respectively (Figure 3.2; Figure 3.4). The confined valley setting in the Baviaanskloof occur at 3-5 km, 13-49 km, 15-25 km, 35-45 km and 90-98 km from the start of the valley, indicating the high heterogeneity of valley morphology (Figure 3.2). These areas have high specific stream values; similar to the ranges in the partially confined valley settings, however, the confined valley setting tends to generate specific stream powers at the higher end of the spectrum. These range from 0.13 to 2249 Wm^{-2} (Figure 3.2; Table 3.3).

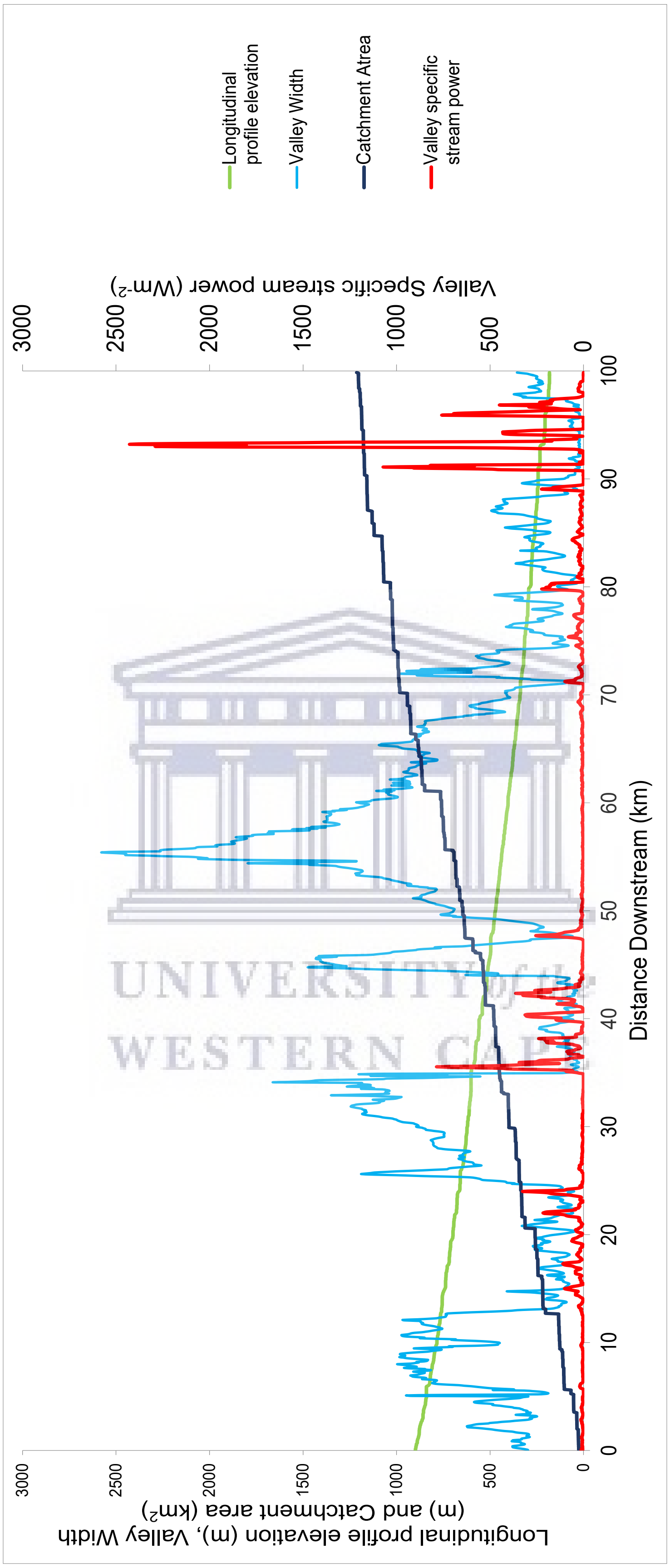


Figure 3.3: Longitudinal variation of valley specific stream power, valley bottom shape (based on valley width) and catchment area in the Baviaanskloof.

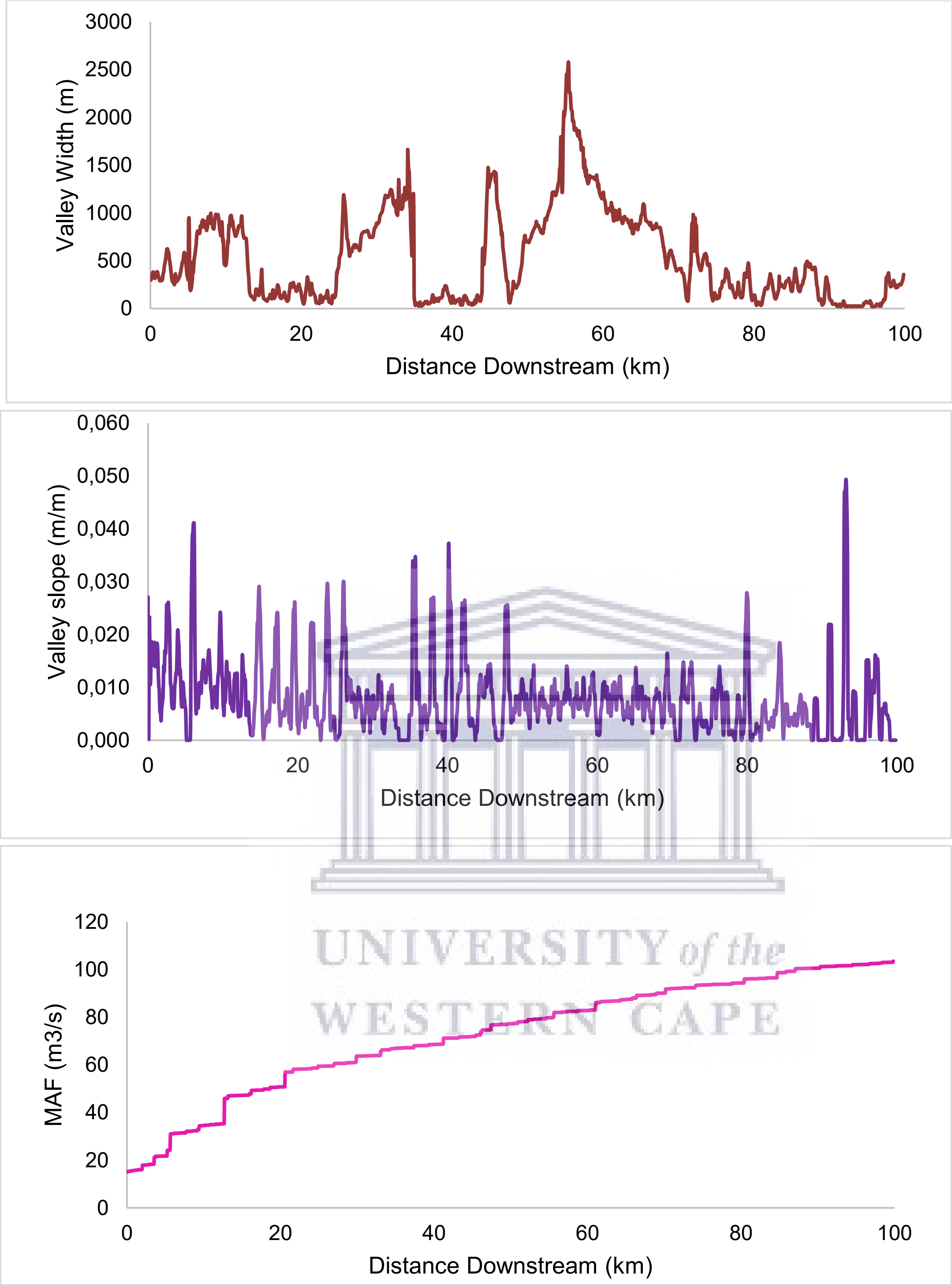


Figure 3.4: Graphing of input data used to calculate VSSP in Baviaanskloof.

3.3.2.2. Kouga Catchment

The Kouga valley also comprises of three valley confinement settings however, laterally unconfined and partially confined valleys cover a small area of the valley with bedrock geology confining the majority of the main Kouga River (Figure 3.2). Laterally unconfined valleys in the Kouga are situated at big confluences, such as where Baviaanskloof and Kouga Rivers meet. These occurred at around 76-78 km and again from 155 to 158 km downstream the long profile with widths in the ranges of 68-2008 m and slopes varying from 0.0001 to 0.0071 m/m (Table 3.3; Figure A-1). The valley specific stream power in this valley setting is low, ranging from 0.000002 to 35 Wm^{-2} (Table 3.3; Figure 3.5).

The partially confined reaches are mostly found along the channels close to tributaries which are connected to the main Kouga River, Along the main river partially confined reaches occur at 13 km from the start of the valley and at 128 -135 km downstream (Figure 3.2). Partially confined valley settings cover around 48% of the main river valley, with valley width varying between 19-907 m (Table 3.3; Figure 3.5). Partially confined valleys are characterized by wide, gentle slope ranging from 0.001 to 0.051 m/m, with a VSSP from 2–1632 Wm^{-2}.

Confined valleys along the Kouga have narrow valley bottoms located in very deep gorges with the valley extent slightly modified by slope processes. Gradients are between 0.001 to 0.062 m/m, with a VSSP from 170 to 5048 Wm^{-2} (Table 3.3; Figure 3.2; Figure 3.5). Although most of the confined valley is straight, some valley bottom segments in this setting have a super-imposed meandering pattern, with hillslopes and smaller tributaries in the upper Kouga catchment being the main local input of coarse sediments in the valley.

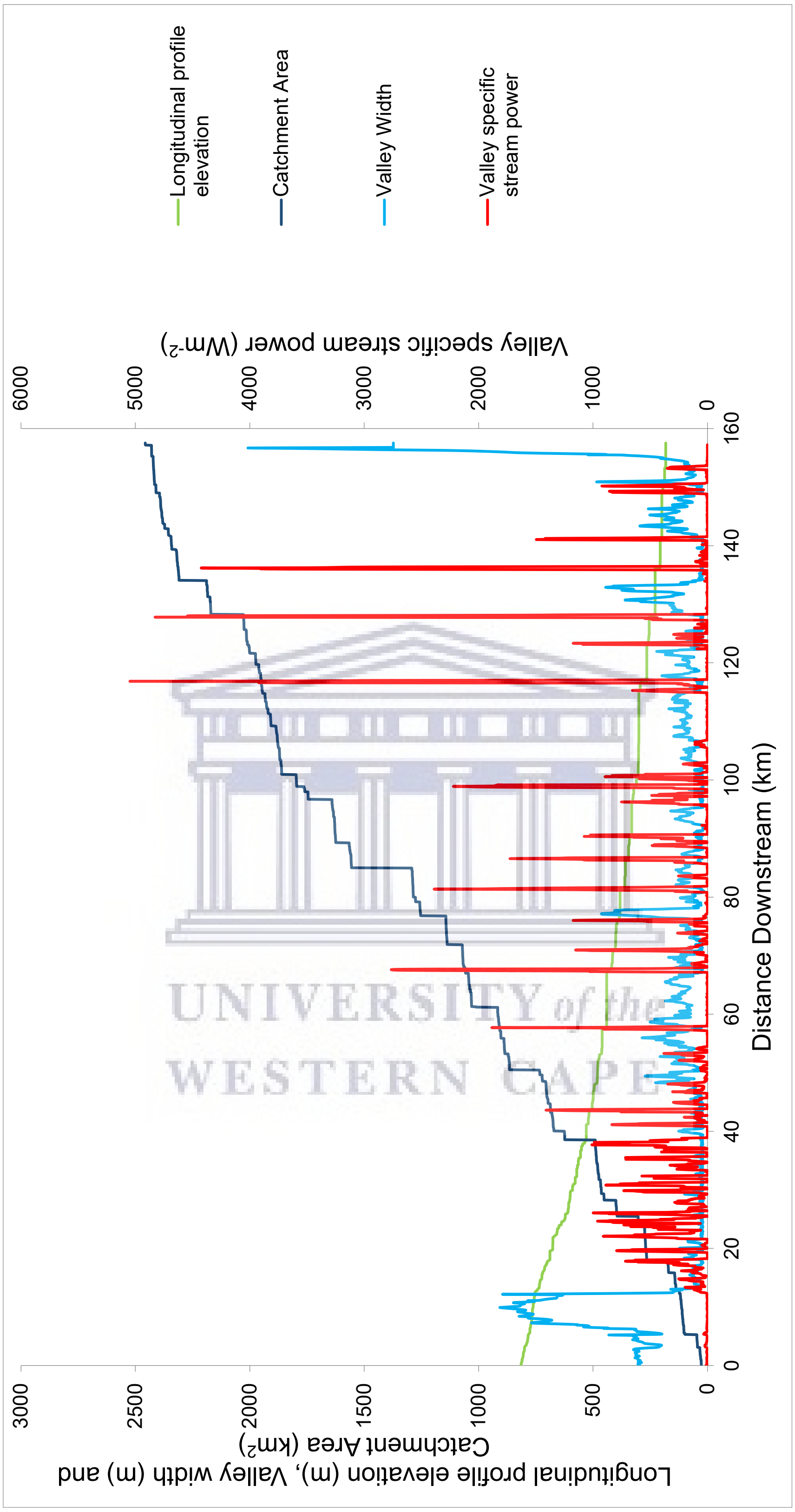


Figure 3.5: Longitudinal variation of valley specific stream power, valley bottom shape (based on valley width) and catchment area in the Kouga.

3.3.2.3. Kromme Catchment

There are multiple different confined sections along the long profile of the Kromme, and these different sections have differing properties and confining features to one another (Figure 3.6). The valley bottom of Kromme catchment is dominantly comprised of laterally unconfined valley settings, with over 49 % of the valley area being classified as unconfined. Valley width ranges from 48 to 689 m whereas the valley slope is between 0.0001 to 0.02 m/m respectively (Table 3.3; Figure B-1). These unconfined valley settings occur at 21-34 km and around 40-54 km from the start of the Kromme valley. A similar pattern of alternating valley confinement to the Baviaanskloof is observed in the Kromme; however, the confined sections between the unconfined are proportionally much smaller in the Kromme. Tributaries in the valley are in confined gorges which are knick points of erosion of the main river. The valley specific stream power ranges from 0.2 -72 Wm^{-2}.

Partially confined regions make up 47% of the Kromme's valley bottom area (Figure 3.2). These regions act as transition zones between the alternating confined and unconfined valleys. This is due to the unchannelled nature of river in the laterally unconfined regions, and this is supported by Pulley et al. (2018) who mentioned that channels can naturally develop at their downstream ends of palmiet basins when the width is pinched off by an alluvial fan and/or the valley narrowing and this has been found to be ecosystem engineers that can colonize across open water bodies, withstand floods, trap sediment, and create the unchannelled condition in a place that previously had a channel. Partially confined valley setting widths vary from 54-497 m and the valley gradient ranges from 0.001– 0.1 m/m (Table 3.3). Along the longitudinal profile, the valley setting is found at the start of the valley to 21 km downstream, and at 35-49 km. This setting is mainly comprised of channel breakdown and resultant flood-outs. This valley setting has a VSSP ranging from 2–185 Wm^{-2} (Figure 3.6).

Lastly, the confined valley settings in the Kromme have the smallest aerial coverage within the valley bottom with only 3 % and having a VSSP between 5 to 307 Wm$^{-2,}$ as seen in Figure 3.6, occurring at an alternating pattern with partially confined valleys at 2 km and around 24-43 km downstream.

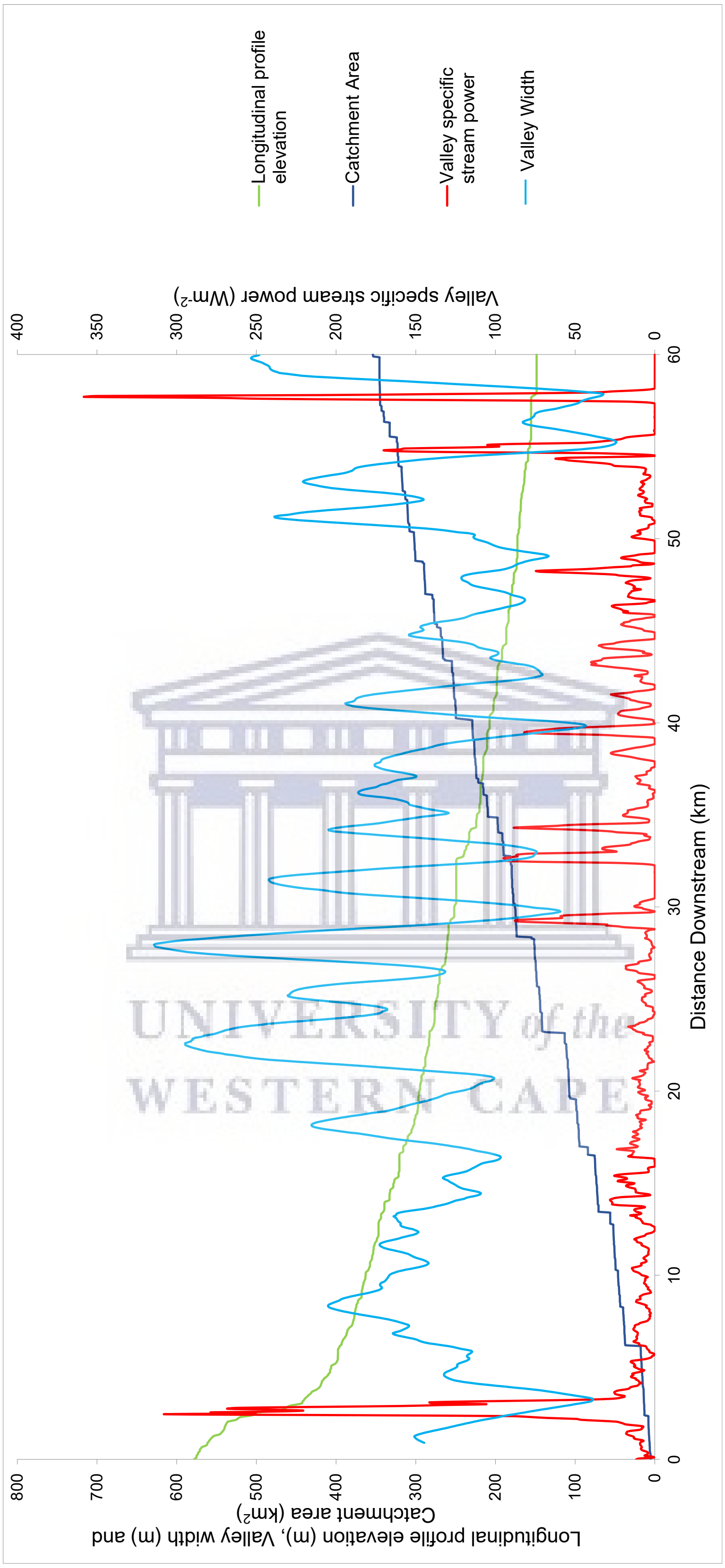


Figure 3.6: Longitudinal variation of valley specific stream power, valley bottom shape (based on valley width) and catchment area in the Kromme.

3.4. Discussion

3.4.1. Comparative analysis amongst and within catchments

Defining valley characteristics by valley confinement (valley width) in South African rivers has been applied at national scale to delineate geomorphic provinces (Partridge et al. 2010). However, within the same province, the valley morphology within catchments differs due to other catchment factors (Dollar et al. 2007; Partridge et al. 2010 ; Ibisate et al. 2011). There is little current research comparing the valley setting and specific stream power on a longitudinal axis in South Africa; however, comparisons with other sites with similar climate and physiography are discussed below.

Analyses revealed multi-peaked specific stream power profiles for the Baviaanskloof, Kouga and Kromme (BKK) catchments. When comparing the three catchments, the Baviaanskloof had a peak in the mid-section and at the end of the valley while the Kouga has multiple peaks and the Kromme valley follows a similar pattern to the Baviaanskloof with an additional peak at the start of the valley (Figure 3.2 and 3.4). This type of non-linear pattern of specific stream power is typical of the south-western South African valleys and rivers draining the escarpment and coastal mountains in South Africa (Rowntree and Wadeson, 1999) and has been observed in the River Trent in England (Knighton, 1999; Phillips and Slattery, 2007). The range and location of specific stream power maxima and minima are similar to previous studies which found maxima values in the confined and partially confined valleys and minima values in laterally unconfined valleys (Table 2; Thompson and Croke, 2013).

The patterns of valley specific stream power are strongly aligned with those of the slope (refer to Figure 3.4, A-1 and B-1), indicating that valley slope is a key driver of VSSP in these catchments. Sensitivity analysis comparing the influence of VSSP with valley slope, width and mean annual flood using a linear trend line also supported this. However, there are some peaks in the VSSP, especially in downstream areas where the width drops but there is no change in slope and this can be attributed to the type of valley fill processes that modify the slope (Schlegel, 2017; Pulley et al. 2018).

The method was able to distinguish different valley settings and the resultant specific stream power patterns across the three catchments. However, specific stream power value thresholds for spatial distribution for large, apparent geomorphic change differ from previous studies such as that by Thompson and Croke (2013) that the. Values for confined valley settings in the Baviaanskloof and Kouga catchments exceed this threshold by more than 70 % while most of the Kromme fell below this threshold, irrespective of the valley setting. Specific stream power derived using GIS in other studies also had higher thresholds, highlighting the difference of distinctive specific stream-power distribution for each catchment and each method of calculating specific stream power as the combination of catchment-scale and local changes in flow and flow accumulation in the river valley (Ferencevic and Ashmore, 2012; Thompson and Croke, 2013). This can also be attributed to the fact that most specific stream power classifications were conducted on sandy/alluvial rivers and the BKK has more mountainous, mixed bedrock-alluvial rivers. Therefore, when these methods are compared, frequent overlaps are observed (Kondolf and Piégay, 2016).

The method used in deriving the discharge regime had an over-estimation of flow in these catchments as estimated by the calculated mean annual flood at the most downstream point in the catchment as compared to approximate flow records into the dams from the Department of Water and Sanitation (DWS).

The high specific stream power areas in unconfined valleys in the Baviaanskloof (approximately around 50 to 80 km downstream) and the Kromme (approximately 12 km downstream) were commonly found before and after large tributary junctions and knickpoints which are areas where the valley was transitioning from confined to laterally unconfined valley settings, causing an abrupt change in valley slope and catchment area (Appendix A; Thompson and Croke, 2013). Areas of declining specific stream power in the three catchments were evident, particularly in the Baviaanskloof (around 20 km and at 80 to 90 km downstream) and the Kouga (at the start of the valley and at every 20 km from 100 km downstream), and appeared to coincide with areas with a small contributing catchment area, even though the valley was confined. Very low specific stream power values (less than 10 Wm^{-2}) were also present in confined regions especially further downstream in the Kouga valley due to low slope values. Tributary confluences in both laterally unconfined and confined valley settings also contributed to the slight decrease of specific stream power due to the valley widening in these areas. These areas were normally 50 to 70 km downstream in both the Baviaanskloof and Kouga valleys.

Confining margins also differed across the catchments. For example, in the confined valleys of the Kouga and Baviaanskloof, the confining margins are hard bedrock cliffs and steep mountain fronts and in the Kromme, the confining margins are softer forms such as early (Pleistocene) terraces, alluvial fans and hillslopes. This coincides with the valley settings found in New South Wales (Fryirs et al. 2016).

The method developed in this study provides a novel terrain analysis framework that can derive valley morphometric data solely from a DEM, producing empirical indices of process that can inform further analyses. This methodological framework for estimating valley confinement and specific stream power can be applied in other catchments with different climate and topography due to the ease of acquisition of nationally available remotely sensed data as input. Further data on the channel network such as the channel geometry, planform and channel bed material are required to fully investigate the causes of geomorphic thresholds that govern the transition from one river form to another (Brierley and Fryirs, 2005).

The GIS-based approach allows for representation of spatial variability at the resolution of the topographic data and long term rainfall data inputs. The VCA, V-BET and FC allowed mapping the extent of valley bottoms across the entire catchment at the fine-scale resolution of the SU-DEM input ($\sim 5\ m\ DEM$) , providing basic mapping information for three large regions for which little information had previously existed. Highly accurate depiction of valley bottoms were however only achievable by manually editing the valley bottom output as expressed by Nagel et al. (2014), Roux et al. (2013) and Gilbert et al. (2016).

In this study, three different valley settings were investigated using three mountainous catchments with different morphologies as a case study. In general, Baviaanskloof had the highest variability in the spatial pattern of the catchment scale controls due to the long valley alternating between confined and laterally unconfined valleys. However, the Kouga had the highest values of specific stream power due to the predominantly confined valley and its size compared to the other two catchments. This results in small valley widths and large gradients dominating the catchment.

Previous studies have shown that specific stream power cannot be solely used as a predictor for geomorphic change and the subsequent fluvial styles (Kleinhans and van den Berg, 2011;Bizzi and Lerner, 2015;Kondolf and Piégay, 2016), The current study incorporated valley setting, which influences deposition and erosion of different valley and river substrates, thereby allowing the potential prediction of different fluvial styles along a long profile (Thompson and Croke, 2013). Field observations of bed and bank material composition would enhance predictive power (e.g. Kleinhans and van den Berg, 2011).

3.4.2. Application of the methodology in other landscapes and limitations of the method

The Lynch (2003) rainfall surface was used instead of hydro-meteorological data from satellites due to the coarser scale of these surfaces for example; the Climate Hazards Group Infrared Precipitation with Station (CHIRPS) is 5km resolution whereas other data inputs are a 5m resolution. Remotely sensed rainfall, however, cover a more recent time period (1980's – present) allowing a more contemporary analysis of catchment controls, especially with recent drought conditions in the region. It is however, important to note that the Lynch dataset provided climate information that represents a longer time period (monthly averages of rainfall for 50 years) thus captures the long-term climatic variability within and across these catchments.

The DEM and the consequent outputs from processing the DEM may not be entirely accurate because it was not able to pick out the channels in the wide, flat floodplain areas where the river cuts through a toelslope or hillslope (common in the Baviaanskloof) thus the flow accumulation lines derived from the DEM did not necessarily match the actual streamline as can be seen on aerial photos or Google Earth Images. To limit such inconsistencies, a manual editing activity of Theissen polygonization and conversions of valley bottoms and valley specific stream power outputs was done (Figure 3.1). The use of Google Earth Pro also provided more speedy editing and iterations of the valley bottom.

A number of fluvial styles are expected to be identified in the next chapters. Depending on the valley confinement type and the transition before and after a particular valley setting, differences in the number of channels and channel geometry is expected, especially when the valley setting is confined and then transitions to a laterally confined valley and this is normally supported by a high valley specific stream power and then changes to a low specific stream power range respectively. This has implications for the type of sediment transported and deposited on various sections of the river. Depending on the energy of the water, the valley specific stream power can modify the channel geometry and roughness in the river. The multi-peaked valley specific stream power pattern also indicates that similar fluvial styles might be observed in the upper catchment and downstream.

The next chapters will therefore assess how well the valley confinement and valley specific stream power index is associated with different fluvial styles based on a set number of channel attributes. Further work is to examine channel morphometrics, particle size and field observation within these valley confinements and specific stream power thresholds.

4. Channel Morphology and planform analysis

4.1. Introduction

Fluvial style refers to the flow and sediment character and behaviour of the river. As previously discussed in the conceptual framework, fluvial styles are controlled by the fluxes between flow (specific stream power), sediment (type and texture) and vegetation structure (stability and density) and combined; these support landscapes which give rise to a wide range of channel patterns. Since the 20th century, research has been increasingly identifying key controlling factors on fluvial styles at the reach scale. Earlier work focused on the way in which channel planform reflects flow energy and sediment supply by zonation of channel types in relation to bed material supply (Wheaton et al. 2015). Nanson and Croke (1992) further classified fluvial styles, particularly multithreaded rivers where they distinguished these rivers based on vegetated or stable alluvial islands and bars which distribute specific stream power at bankfull discharges (Nanson and Croke, 1992). Recent work has mainly focused on the combination of all these factors, including in-channel properties such as local channel slope, which may have the potential to induce marked changes in the pattern of fluvial styles (Guo-An et al. 2013; Brierley and Fryirs, 2014; Marçal et al. 2017).

The different zonation concept is a common way of analysing the downstream pattern of fluvial styles in geomorphology and almost all classification system employ this concept as a way to distinguish and display the overall fluvial styles found in a catchment. It was first introduced in South Africa by Noble and Hermens, (1978) and later modified by Rowntree and Wadeson, (1999) where it provided a spatial framework to delineate water resources units. Zonation allows for the assessment of relationships between the hierarchical levels, and to also distinguish different zones such as mountain streams from river mouth and the expected fluvial styles within them. The current study will employ such a framework in reading the landscape and identifying fluvial styles however, the zonation is based on the valley specific stream power and valley confinement. In South Africa, various fluvial styles have been found to occur in these dryland river systems such as meanders, gorges and floodouts (Tooth, 2000; Tooth and McCarthy, 2007; Eze and Knight, 2018) however, little research has been applied in non-perennial rivers and the current study will expand on this by identifying other fluvial styles, particularly in mountainous channels

In this study, river classification was done for three different catchments by grouping sample areas with similar physical attributes and comparing their channel character and behaviour. Valley morphology, channel-reaches, and geomorphic units have been used in river classification systems that subdivide drainage networks into specific spatial units following nested hierarchies (Frissell et al. 1986; Brierley and Fryirs, 2005; Bisson et al. 2017). A large body of literature exists on different approaches for reach-scale classification, encompassing classifications based on: river geometry and valley landforms (Rosgen, 1994), observed morphology and stream flow patterns (Montgomery and Buffington, 1997), investigating linkages between catchment and hydraulic biotopes (Rowntree and Wadeson, 1999), correlation of downstream sediment storage and landscape connectivity (Brierley and Fryirs, 2005), and dividing reaches based on channel width and remote sensing data (Beechie and Imaki, 2014). Irrespective of the approach, the association of catchment characteristics to channel-reaches is appraised. Within these spatial scales, channel-reach morphology consists of homogenous sequences of river types and channel characteristics and this is used to distinguish one reach from another.

As discussed in the previous chapters, the variation of valley specific stream power, which varies through a catchment, controls, the variation in the channel morphology in a river long profile. With the different valley settings and variable specific stream power, the channel reach morphology is expected to change in a river. For example, channel reaches in confined valley settings are commonly found in headwaters where the gradient is very steep. Thus, despite the small contributing catchment area and hence discharge, the valley specific stream power is high, resulting in the flushing of fine-grained materials, leaving large, coarse-grained materials in the channel bed. This results in certain planforms and dominant geomorphic processes, such as reaches with straight, narrow step-pool channels with low width-depth ratio due to valley margins constricting the channel from moving laterally.

4.2. Methods

4.2.1. Selection of reference sites

Sample study sites were initially selected using GIS by looking at catchment controls responsible for channel morphology (Figure 4.1 and Table 4.1). The sites were selected based on the varying extremities of the catchment properties. The sites were divided firstly according to valley confinement in each catchment namely confined, partially confined and laterally unconfined. Secondly, the study sites were classified into areas of high, moderate and low specific stream power areas (Table 4.1). Transitional areas for these catchment controls were also selected as sample sites for example, areas where the valley transitions from a wide, unconfined setting to a confined valley setting. Final site selection was limited by practical accessibility due to extreme topography, a sparse road and trail network and permissions to cross private properties. Baviaanskloof has nine sites, Kouga has three sites and the Kromme catchment has four sample sites.

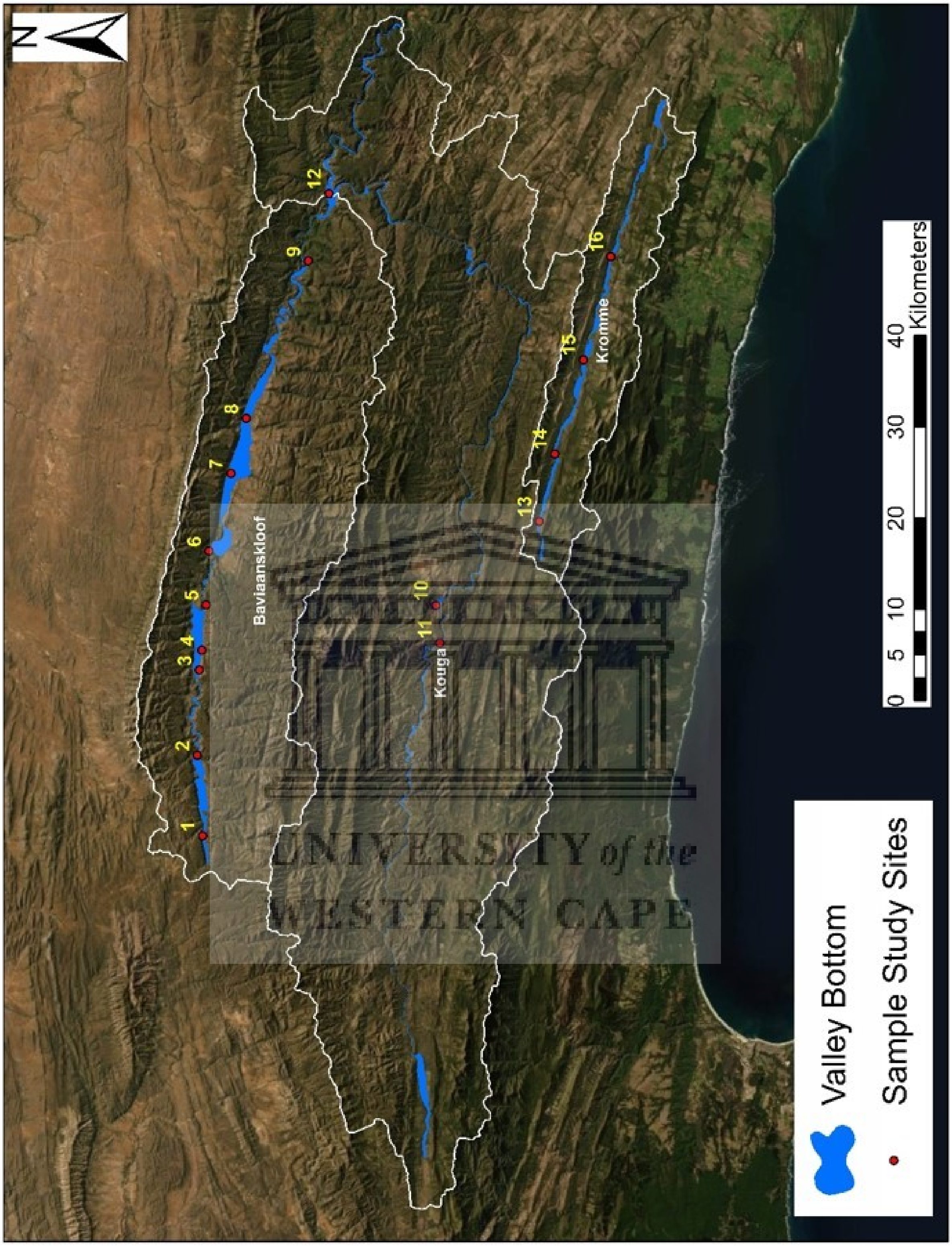


Figure 4.1: Map showing the selected study area sites (reaches) for channel morphology analysis

Table 4.1: List of sites selected in the BKK catchments based on valley confinement and specific stream power. Shows the partially confined valley sites, green denotes the partially confined sites and yellow is laterally unconfined sites. Thresholds for VSSP are also noted.

Catchment	Site name	Site Number	Location		Valley Confinement setting	
			Latitude	Longitude	Type	Valley specific stream power threshold (VSSP)
Baviaanskloof	Nuwekloof	1	-33,521918	23,641372	Partially confined	Low
	Rietrivier	2	-33,519201	23,736360	Partially confined	Low
	Velorenrivier1	3	-33,523908	23,836805	Partially confined	Low
	Velorenrivier2	4	-33,526857	23,860092	Laterally Unconfined	Low
	BoKloof	5	-33,532547	23,913213	Confined	High
	Kamerkloof	6	-33,536778	23,976594	Partially confined	Low
	Joachimskraal	7	-33,560758	24,067406	Laterally unconfined	Low
	Ruse en Vrede	8	-33,577343	24,131816	Laterally unconfined	Low
	Nature Reserve	9	-33,642644	24,315715	Confined	High
Kouga	Braamrivier	10	-33,758897	23,904553	Laterally unconfined	Moderate
	Kritplaas-Brandhoek	11	-33,761686	23,860054	Confined	High
	BVK_KGA_Confluence	12	-33,664800	24,394295	Laterally unconfined	Low
Kromme	Krugers Kraal	13	-33,863283	24,000338	Partially confined	Low
	Kompaniesdrift	14	-33,880557	24,079591	Confined	Low
	Jagerbos	15	-33,911293	24,190140	Laterally unconfined	Low
	Melkhoute Kraal	16	-33,941247	24,311269	Confined	High

4.2.2. Measurement of channel morphological and sedimentary characteristics: Channel reach geomorphic analysis

Field observation at each site included: channel morphology and identification of geomorphic features at each valley setting and specific stream power extremes. Surveying of cross-sections, systematic field observations of vegetation, channel roughness and fluvial style. Soil data such as particle size and soil texture (bed and bank) was collected.

4.2.2.1. Topographic surveying (Channel geometry)

Channel cross-section was surveyed at all sites to examine the channel shape at various types of valley settings. Topographic surveying of channel cross sections was done using a differential Global Positioning System (dGPS), except for a few locations where the satellite signal was weak due to steep rock faces such as in confined valley setting sites. In these cases a theodolite was used.

Areas with anthropogenic interference on rivers such as road crossings, berms and debris dams were avoided as locations for cross-sections to be representative of the natural geomorphic features in the site. Areas where the river was too deep were also avoided.

Three cross sections were surveyed at the majority of the 16 sites. At 5 of the sites only two cross sections were surveyed because of logistical difficulties, depth of pools during the period of May to August 2017 using a dGPS (GeoMax Zenith 20 GPS GNSS Base RTK Rover system). Latitude, longitude and the relative elevation was recorded. The same operator surveyed all cross-sections at a given site to minimize errors. Site 7 and 8 were secondary data obtained from (Powell, 2017) and site 4 was obtained from (Smith-Adao, 2016). The cross-sections were spaced at least 50 m, 100 m and 300 m apart in confined, semi-confined and unconfined sites respectively. Exceptions were made in these intervals to avoid anthropogenic influence such as in sites Kritplaas-Brandhoek and Krugers Kraal. Cross sections were oriented perpendicular to the main channels and covered the whole channel and immediate floodplain. All the flows were contained within one channel to capture the channel shape variability. If the channel was anabranching, then measurements were taken for each branch and summed up.

Channel slope, width, depth and cross-section area, width/depth ratio were calculated using the cross section topography data. Slopes were determined for each site using the difference in elevation measurements between the thalweg of upstream and a downstream point in cross sections. Geomorphic features, identified as described below, were indicated on the cross-valley profile figures.

4.2.2.2. Field observations and image analysis

Channel patterns (straight, meandering or braided) and geomorphic features (terraces, fans etc.) were identified during the surveying using published descriptions however; the identification of features is difficult in semi-arid regions due to rapid changes caused by highly variable climatic conditions (Tooth, 2000; Vyverberg, 2010). In addition, with the aid of Google Earth, aerial imagery, photographic record and detailed field notes, these geomorphic features were noted and analysed at each site using the overall length of the cross-sections at each site as guidance. Surface water height (water level) was not collected during the fieldwork because flow was predominantly well below residual pool volumes due to prevailing drought conditions. Three sites in the Baviaanskloof were data collected as secondary data thus bank and bed images are not available.

Planform types were assigned by looking at (a) valley margin and fill type, (b) channel shape (straight, wandering, meandering or braided and anabranching) and change over time and, (c) vegetation density and change over time, all analysed for 2003 (pre flood year), 2012 (flood year) and 2017 (post flood year). Planform (fluvial) types were named according to the procedural attributes used to name river types in the River Style Framework (Fryirs and Brierley, 2018) for consistency with contemporary river classifications.

4.2.2.3. Channel roughness

Manning's roughness (n) was estimated using the incremental method of Chow (1959). In this approach a base n value is determined based on characteristics of the bed forms and bed sediments which are influenced by flow. The base value is then adjusted by adding additional values which account for channel irregularity (n1); changes in cross-section with distance downstream (n2), obstruction to flow within the channel (n3) and vegetation structure (n4). The additional values are further multiplied by the degree of meandering (m).

4.2.2.4. Sedimentary properties

The aim of sediment sampling is for the semi-quantitative assessment of the particle size distribution of the river channel. Sediment studies offer information about sediment sources, transport history and depositional conditions (Gordon et al. 2004). A variety of methods have been used to sample sediments depending on study aim and site considerations. All methods involve sediment counting or weighing, and determining a number of size fractions (Smith-Adao, 2016). The methods used here minimized bias while being efficient enough to be performed by field assistants.

Channel sediment analysis involved sampling both coarse and fine sediments in the sites to indicate possible relations between energy-resistance of channels, channel geomorphic landforms and vegetation. In areas where the channel had a mixed bed, both coarse and fine sediment were collected. Because the flow conditions initiating their movement were considered to differ, the median grain-size values were calculated separately for each fraction. Field observation of the percent bed cover by coarse fraction were also collected.

- **Coarse sediments**

For coarse sediment characterization at each site, in-situ particle size measurements were done in which 100 particles were measured between the banks of the channel cross-section transects. Sampling began at the downstream end of a run and proceeded upstream while going back and forth across the width of the channel. Particles were selected at 2 m intervals at the front of the collectors' foot. With the use of a gravelometer or a calliper, the B-axis size class was measured (Figure 4.1). The B-axis would prevent a particle from passing through a gravelometer/sieve. The particle size classes were recorded on a modified Wentworth scale (Table 4.2).

Figure 4.2: Image showing the gravelometer template used in the study.

Table 4.2: Showing the different classes measured by a gravelometer in the field. Source: Clapcott et al. (2011).

Particle size class
Small gravel (>2 - 8mm
small-medium gravel (>-16mm)
Med-Large gravel (>16 - 32mm)
Large gravel (>32 - 64mm)
Small cobble (>64 - 128mm)
Large cobble (>128 - 256mm)
Boulders (>256 mm)
Bedrock

- **Fine sediments**

At each site, 50 – 100 grams samples of the fine sediment were collected at the channel bank in a transect using a garden trowel. The samples in each transect were combined into one sample per transect, bagged and stored to be processed in a laboratory.

Clay, silt and sand percentages were calculated using the hydrometer and dry-sieve method (van der Watt, 1966).

The data were entered into Microsoft Excel and averaged and cumulative particle size distribution curves and histograms were developed for each site. The D_{50}, or median, grain sizes of both the coarse and fine fractions for each site were calculated. The variability in grain size was also assessed using the mean and coarsest grain size fractions for each site.

To test valley specific stream power in the prediction of fluvial styles, energy versus resistance graph was plotted using the median grain size of coarse sediments and also using the silt and clay content as supplementary data.

4.3. Results

The following sections describe the results of the data collection for the confined, partially confined, and laterally unconfined valley settings in each catchment. Analysis was done for all 16 sample sites (Table 4.3). Each of the catchments presented distinct river sections downstream structure and geomorphic attributes. Even though the catchments had similar ranges of bed sediment sizes, channel sizes and slopes at the sampled sites, the fluvial landforms differ between them due to the inherent nature and pattern of valley specific stream power. The fluvial styles for all three catchments are shown visually in accompanying Google Earth images and observations of form and structure are described qualitatively. Soil texture results are attached in Appendix C.

[redacted]

Catchment	SN	E (m)	VSSP (Wm^{-2})	VC	CA(m^2)	CW (m)	CD (m)	WDR	MR	S (m/m)	D50_C(m)	D50_F(m)	STCSS (%)
Baviaanskloof	BoKloof	590	456,815	Confined	2,37	10	0,76	13	0,06	0,0070	0,022	0,0006	9,8
Baviaanskloof	Kamerkloof	517	8,935	Confined	23,39	34	1,74	20	0,09	0,0067	0,010	0,0002	29
Baviaanskloof	NatRes	245	136,334	Confined	1,88	9	0.68	13	0,09	0,0030	0,006	0,0005	14,8
	Average	**451**	**201**	-	**9**	**18**	**1,25**	**15**	**0,082**	**0,0056**	**0,013**	**0,0004**	**17,9**
Baviaanskloof	Rus en vrede	443	3,313	Laterally unconfined	67,29	59	2,12	28	0,1	0,0105	0,012	0,0025	8,8
Baviaanskloof	Joachimskraal	394	9,37	Laterally unconfined	39,01	53	1,51	35	0,12	0,0077	0,011	0,0009	9
Baviaanskloof	Verlorenrivier2	628	3,78	Laterally unconfined	9,2	38	1,13	34	0,04	0,0048	0,010	0,0011	16,3
	Average	**488**	**5**	-	**39**	**50**	**1,59**	**32**	**0,086**	**0,0077**	**0,011**	**0,0015**	**11,37**
Baviaanskloof	Rietrivier	760	14,575	Partially confined	18,1	20	0,4	50	0,08	0,0071	0,021	0,0016	8
Baviaanskloof	Verlorenrivier1	655	19,469	Partially confined	27,92	34	1,04	33	0,03	0,0055	0,011	0,0005	14,6
Baviaanskloof	Nuwekloof	874	4,51	Partially confined	6,86	11	0,99	11	0,04	0,0108	0,029	0,0002	6
	Average	**763**	**13**	-	**18**	**22**	**0,81**	**31**	**0,053**	**0,0078**	**0,020**	**0,0008**	**9,53**
Kouga	Kritplaas-Brandhoek	400	93,611	Confined	113,8	56	3,26	17	0,08	0,0104	0,086	0,0003	11
Kouga	Braamrivier	775	27,571	Laterally unconfined	40,02	46	2,26	20	0,09	0,0038	0,012	0,0009	23
Kouga	BVK-KGA Confluence	174	0,19	Laterally unconfined	60,99	112	2,39	47	0,14	0,0126	0,085	0,0005	13
	Average	**475**	**14**		**51**	**79**	**2,33**	**34**	**0,114**	**0,0082**	**0,049**	**0,0007**	**18**
Kromme	Kompanjiesdrift	336	11,667	Confined	119,87	47	4,5	10	0,06	0,0180	0,030	0,0002	7
Kromme	Melkhoute Kraal	209	75	Confined	63,56	36	3,9	9	0,14	0,0003	0,000	0,0002	9
	Average	**273**	**43**	-	**92**	**42**	**4,2**	**10**	**0,102**	**0,0092**	**0,015**	**0,0002**	**8**
Kromme	Jagerbos	254	6,667	Laterally unconfined	54,6	68	1,56	44	0,07	0,0028	0,047	0,0002	6,3
Kromme	Krugers Kraal	403	14	Partially confined	30,27	19	2,81	7	0,12	0,0095	0,030	0,0004	11,8

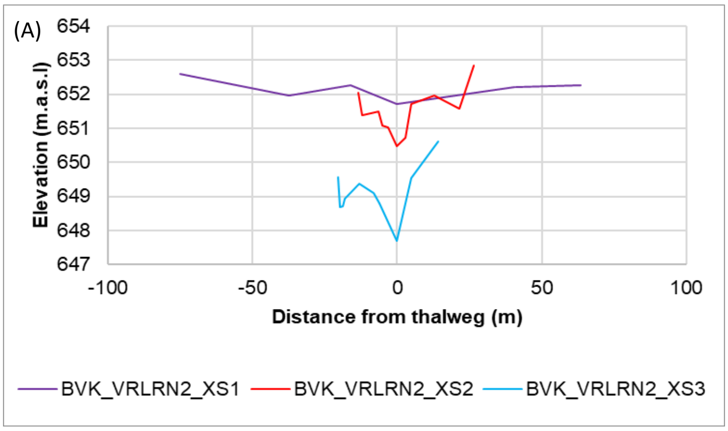
SN = Site Name; E = Elevation; VSSP = Valley specific stream power; VC = Valley confinement type; CA = Cross-sectional area; CW =Channel Width; CD = Channel Depth; MR = Manning's Roughness; WDR = Width to depth ratio; S = Channel bed slope; D50_C = median bed grain size for coarse sediments; D50_F =median bed grain size for fine sediments; STCSS = Soil texture: clay and silt content

4.3.1. Baviaanskloof

4.3.1.1. Laterally Unconfined reaches

Extensive research on channel properties in laterally unconfined valley settings in the Baviaanskloof exists (Powell, 2017; Smith-Adao, 2016). Secondary data shows that these areas have reaches with multiple-threaded channels which meander across the wide valley. Laterally unconfined landforms such as alluvial fans and terraces constrict the reach, decreasing the overall valley width in these areas. Channel width varies from 38 to 60 m in these reaches. At the time of the survey, no surface water was observed however bankfull depth was estimated to be around 1.13 to 2 m with well-developed channel banks, although evidence of bank collapse was observed in Site 4 (Smith-Adao, 2016) and (Figure 4.3). The vegetation density has not changed much over the years. There are patches of highly dense vegetation along the reaches which comprise of reeds, shrubs and grass which have developed after the 2012/13 flood (Figure 4.3C, 4.4C and 4.5C). Although not as extensive compared to urbanized or more intensely farmed areas, anthropogenic influences such as pivot irrigation and farms have also caused abandonment of channels, resulting in narrow, single thread channels in some locations (Powell, 2017) and (Figure 4.3 C). Median grain size for fine sediments varied from 0.9 to 2.5 mm which is moderately to poorly sorted material. Coarse sediments had a median grain size between 10 to 12 mm, which is small to medium gravel. The bank soil texture also showed a high content of silt and clay in these reaches which ranged from 26 to 49 % of the total bank soil samples analysed (Table C-1). Pre flood (2003) and post flood (2017/18) image analysis shows that no extensive changes in the planform except for site 7 and 8 which have been experiencing changes in channel roughness due to the establishment of vegetation after the flood (Figure 4.4; Figure 4.5).

Verlorenrivier2, Site 4



(B) ***Average channel-reach attributes***

Channel width: 38 m

Channel depth: 1.13 m

Cross-sectional area: 9.2 m2

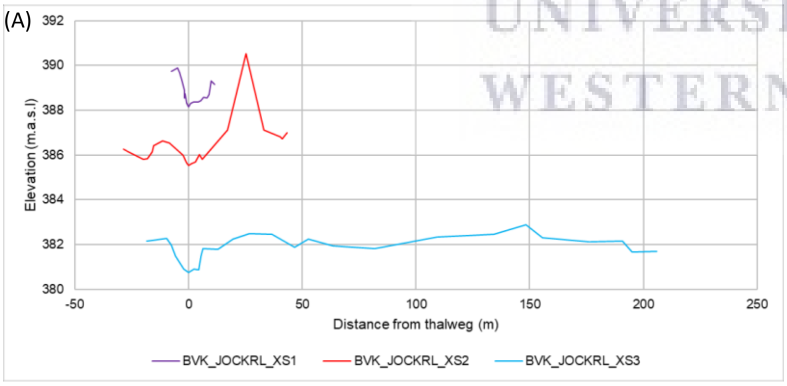
Channel slope: 0.0048 m/m

W/D ratio: 33.90

Channel roughness: 0.038

4.3: Summary of channel attributes, including soil data collected for Site 4. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Planform view of surveyed site. Scale 1 cm = 700m

Joachimskraal, Site 7



(B) ***Average channel-reach attributes***

Channel width: 53 m

Channel depth: 1.51 m

Cross-sectional area: 39.01 m^2

Channel slope: 0.0077 m/m

W/D ratio: 35.52

Channel roughness: 0.103

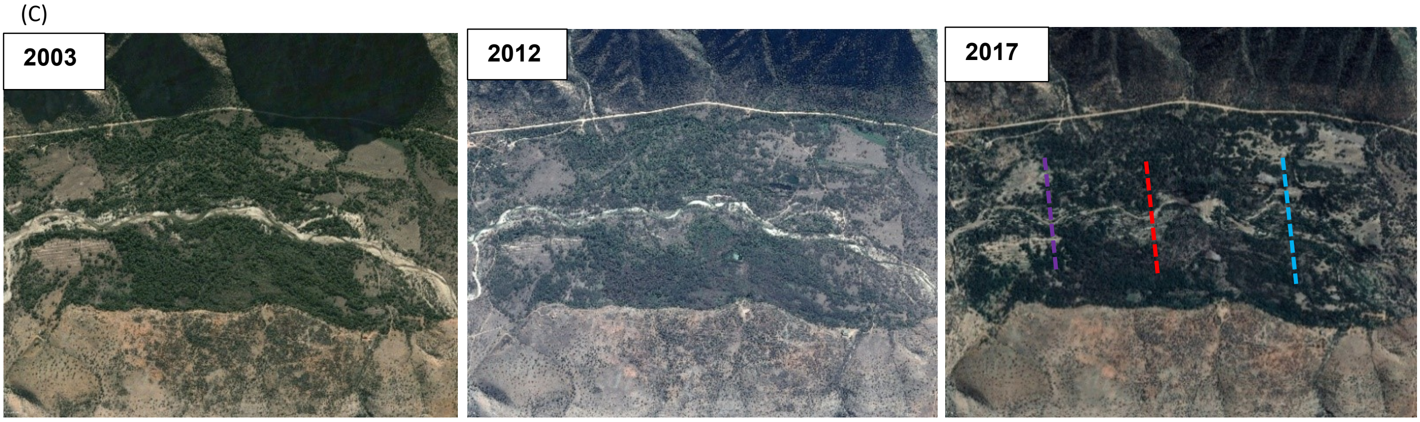
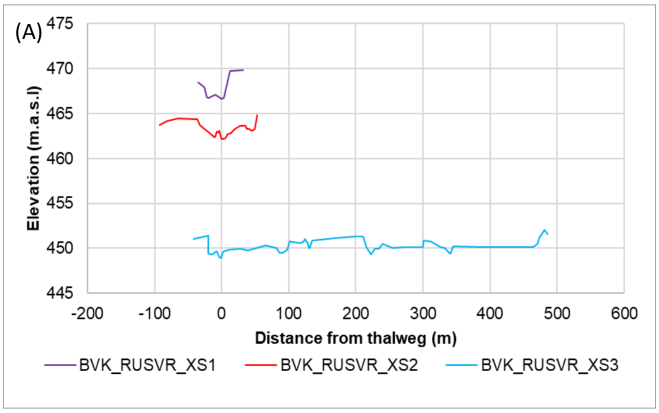


Figure 4.4: Summary of channel attributes, including soil data collected for Site 7. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Planform view of surveyed site. Scale 1 cm = 700m.

Rus n Vrede, Site 8



(B) ***Average channel-reach attributes***

Channel width: 59 m

Channel depth: 2.12 m

Cross-sectional area: 67.29 m^2

Channel slope: 0.0105 m/m

W/D ratio: 27.67

Channel roughness: 0.103

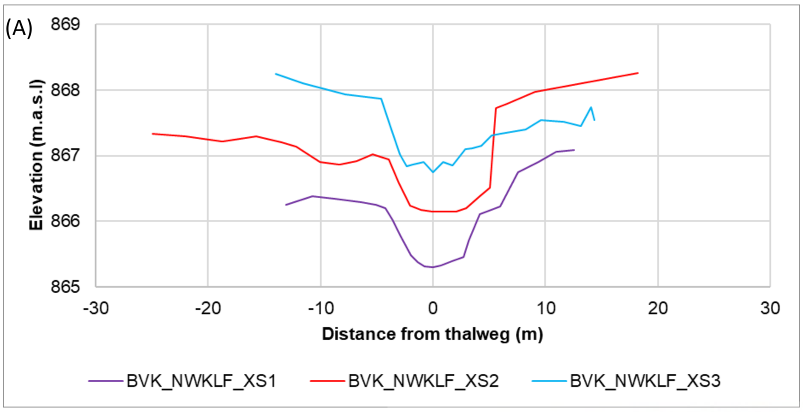
Figure 4.5: Summary of channel attributes, including soil data collected for Site 8. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Planform view of surveyed site. Scale 1 cm = 700m.

4.3.1.2. *Partially confined reaches*

Compared to the confined reaches, the river-channel in this setting is less constrained by the valley margin, thereby constantly adjusting across the valley bottom, with channel width ranging from 10 - 34 m (Figure 4.6B to Figure 4.8B). The fluvial styles of these channels are moderately sinuous and can have numerous inactive channels and small tributaries. The vegetation density in these study reaches is sparse with an average channel roughness 0.05. These areas have well-developed banks although the bank stability may be low, with banks having 6 – 15 % silt and clay content (Table C-1; Figure 4.6B; Figure 4.7B).

Median grain size for fine sediment in the channel varies from 0.2 to 1.5 mm, which is poorly to moderately sorted sand low in fines. The coarse sediments have a median grain size of varying from 11 – 29 mm meaning these reaches are dominated by small to medium coarse gravel sediments in the channel bed. Image analysis of planform dynamics of pre-flood and post flood reveal no major changes in the channel pattern for these reaches (Figure 4.6D; Figure 4,.7D and Figure 4.8D).

Nuwekloof, Site 1



(B) ***Average channel-reach attributes***

Channel width: 11 m

Channel depth: 0.99 m

Cross-sectional area: 6.86 m^2

Channel slope: 0.0108 m/m

W/D ratio: 10.89

Channel roughness: 0.044

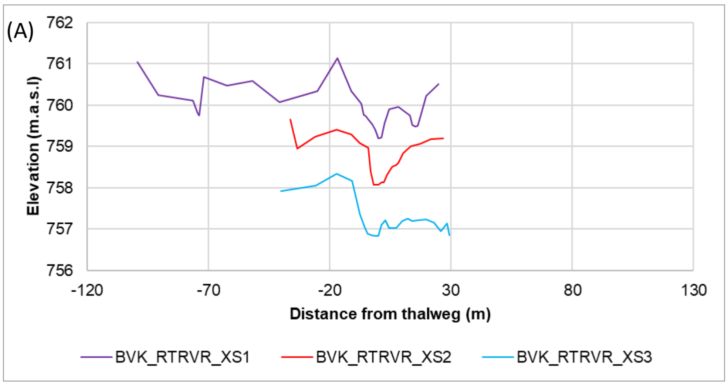
Visually estimated bank cover of course to fine material: 90% sand, 10% rocks

D50: 29 mm ; D84: 89 mm (Coarse)

D50: 0.25 mm; Uniformity Coefficient: 2.6 (Fines)

Figure 4.6: Summary of channel attributes, including soil data collected for Site 1. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Bed and bank view of surveyed channel. (D) Planform view of surveyed site. Scale 1 cm = 700m.

Rietrivier, Site 2



(B) ***Average channel-reach attributes***

Channel width: 20 m

Channel depth: 1.04 m

Cross-sectional area: 18.10 m^2

Channel slope: 0.0071 m/m

W/D ratio: 19.58

Channel roughness: 0.082

Visually estimated bank cover of course to fine material: 15% sand, 85% rocks

D50: 49 mm ; D84: 94 mm (Coarse)

D50: 1.58 mm; Uniformity Coefficient: 11.4 (Fines)

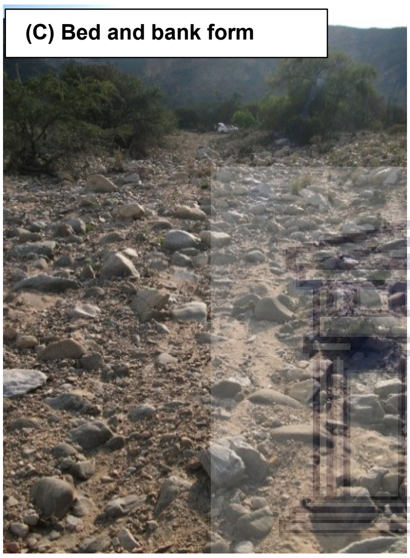
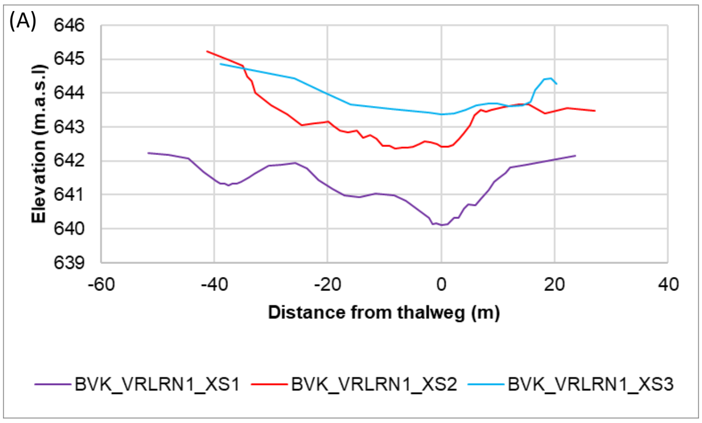


Figure 4.7: Summary of channel attributes, including soil data collected for Site 2. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Bed and bank view of surveyed channel. (D) Planform view of surveyed site. Scale 1 cm = 700m.

Verlorenrivier1, Site 3



(B) ***Average channel-reach attributes***

Channel width: 34 m

Channel depth: 1.04 m

Cross-sectional area: 27.920 m^2

Channel slope: 0.0055 m/m

W/D ratio: 33.12

Channel roughness: 0.032

Visually estimated bank cover of course to fine material: 20% sand, 80% rocks

D50: 53 mm ; D84: 91 mm (Coarse)

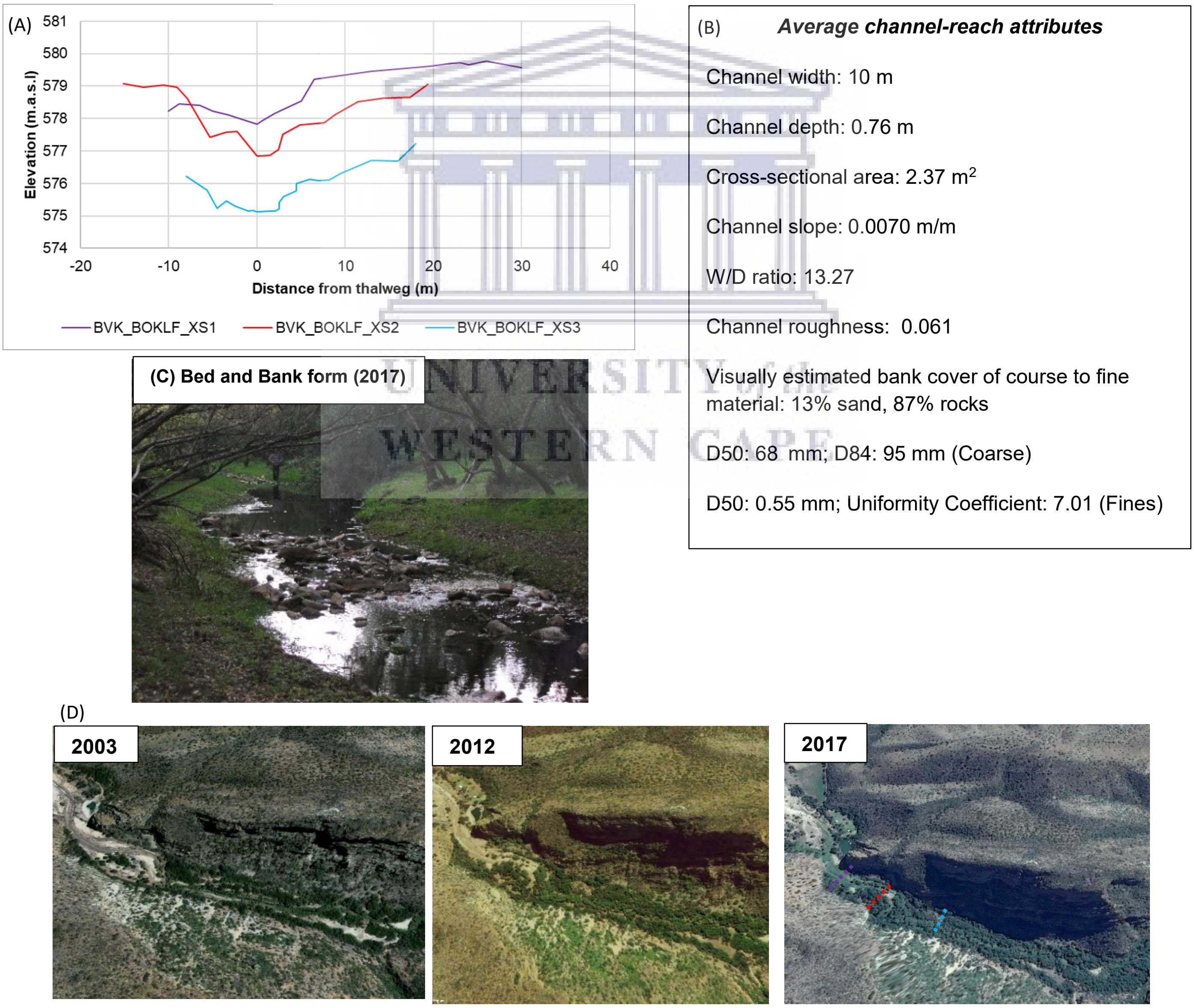
D50: 0.54 mm; Uniformity Coefficient: 5.20 (Fines)

Figure 4.8: Summary of channel attributes, including soil data collected for Site 3. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Bed and bank view of surveyed channel. (D) Planform view of surveyed site. Scale 1 cm = 700m.

4.3.1.3. Confined study reaches

These study reaches are characterized by a single-threaded main channel with slight bends. The river banks are low in height with dense native vegetation such as trees, shrubs, and grass, hence the high channel roughness in these reaches with an average of 0.082 (Figure 4.9B to Figure 4.11B). The channel is narrower than in unconfined areas, with channel width varying from 9 to 34 m. The average bankfull channel depth was 1.04 m) except for the site 6 downstream in the nature reserve. Looking at planform dynamics, the single-threaded nature of the confined reaches have not changed pre and post the flood years which could be related to the nature if the confining layers in these regions being resistant to erosion. The median grain size in the confined reaches ranges from 0.2 to 0.9 mm, a moderately well sorted sand low in fines. The median coarse fragment size in the reaches varies between 6 to 22 mm, with medium to large gravel sizes present on the channel bed. The soil texture reflects the bank stability of the channel and in these reaches, 10 to 20 % is comprised of silt and clay (Table C-1).

Bo Kloof, Site 5



(B) ***Average channel-reach attributes***

Channel width: 10 m

Channel depth: 0.76 m

Cross-sectional area: 2.37 m^2

Channel slope: 0.0070 m/m

W/D ratio: 13.27

Channel roughness: 0.061

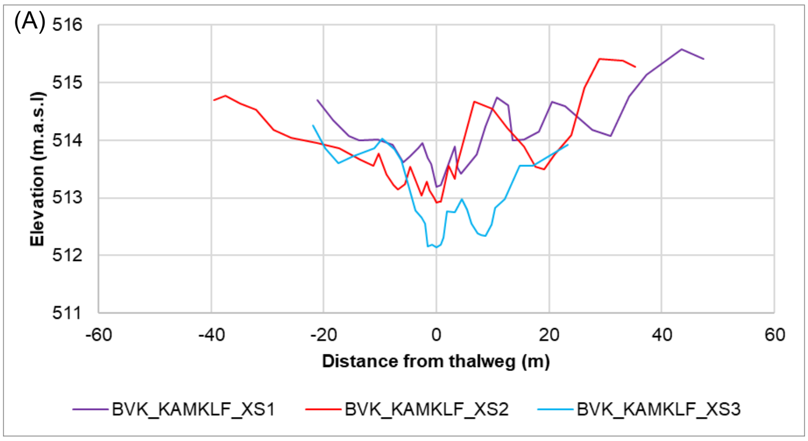
Visually estimated bank cover of course to fine material: 13% sand, 87% rocks

D50: 68 mm; D84: 95 mm (Coarse)

D50: 0.55 mm; Uniformity Coefficient: 7.01 (Fines)

Figure 4.9: Summary of channel attributes, including soil data collected for Site 5. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Bed and bank view of surveyed channel. (D) Planform view of surveyed site. Scale 1 cm = 700m.

Kamerkloof, Site 6



(B) ***Average channel-reach attributes***

Channel width: 34 m

Channel depth: 1.74 m

Cross-sectional area: 23.39 m^2

Channel slope: 0.0067 m/m

W/D ratio: 19.74

Channel roughness: 0.094

Visually estimated bank cover of course to fine material: 70% sand, 30% rocks

D50: 47 mm ; D84: 89 mm (Coarse)

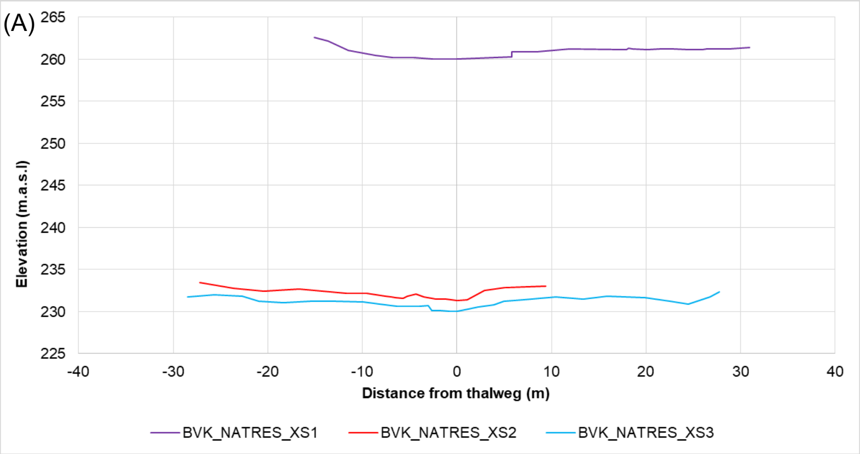
D50: 0.21 mm; Uniformity Coefficient: 5.00 (Fines)


(C) Bed and Bank form

(D)

Figure 4.10: Summary of channel attributes, including soil data collected for Site 6. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Bed and bank view of surveyed channel. (D) Planform view of surveyed site. Scale 1 cm = 700m.

Baviaanskloof Nature Reserve, Site 9



(B) ***Average channel-reach attributes***

Channel width: 9 m

Channel depth: 0.68 m

Cross-sectional area: 1.88 m^2

Channel slope: 0.0030 m/m

W/D ratio: 13.51

Channel roughness: 0.092

Visually estimated bank cover of course to fine material: 50% sand, 50% rocks

D50: 43 mm ; D84: 89 mm (Coarse)

D50: 0.49 mm; Uniformity Coefficient: 5.67 (Fines)

Figure 4.11: Summary of channel attributes, including soil data collected for Site 9. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Bed and bank view of surveyed channel. (D) Planform view of surveyed site. Scale 1 cm = 700m.

4.3.2. Kouga

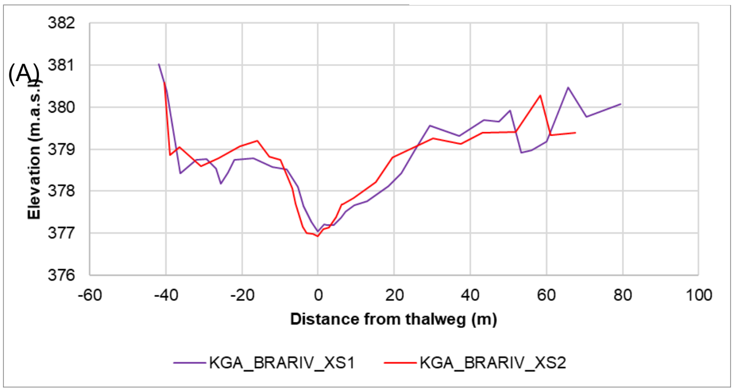
4.3.2.1. Laterally Unconfined reaches

From planform analysis, these reaches have wide channels (56 to 112 m) morphology with multiple-threaded channels that are meandering throughout the valley bottom. The vegetation has a medium density, although primarily occurring by the river bank, giving an estimated channel roughness value of 0.114 (Figure 4.12B). The reaches had an average slope of 0.0082 m/m. Analysis of planform dynamics shows that such reaches are sensitive to channel change. Before the flood, the confined reaches in the Kouga had a single active meandering channel with a lot of sand deposition and vegetation density along the channel banks however, during the flood, multiple rivers and sand bars were formed which has allowed the growth of stable dense vegetation at these the river sections (Figure 4.12D and Figure 4.13D).

Sedimentary data analysis showed that the median grain size of the fine sediments in these laterally unconfined reaches range from 0.4 to 0.85 mm, being poorly sorted sand which is low in fines (Figure 4.12B and Figure 4.13B). For the coarse soil sample analysis, the median grain size was very high, with an average of 85mm which implies that these reaches are dominated by small cobbles. Soil texture analysis also showed that bank stability is low, with 13 - 23 % comprised of silt and clay content.

Braamrivier, Site 10

(A)



(B) ***Average channel-reach attributes***

Channel width: 46 m

Channel depth: 2.26 m

Cross-sectional area: 40.02 m^2

Channel slope: 0.0038 m/m

W/D ratio: 20.35

Channel roughness: 0.092

Visually estimated bank cover of course to fine material: 5% sand, 95% rocks

D50: 36 mm ; D84: 97 mm (Coarse)

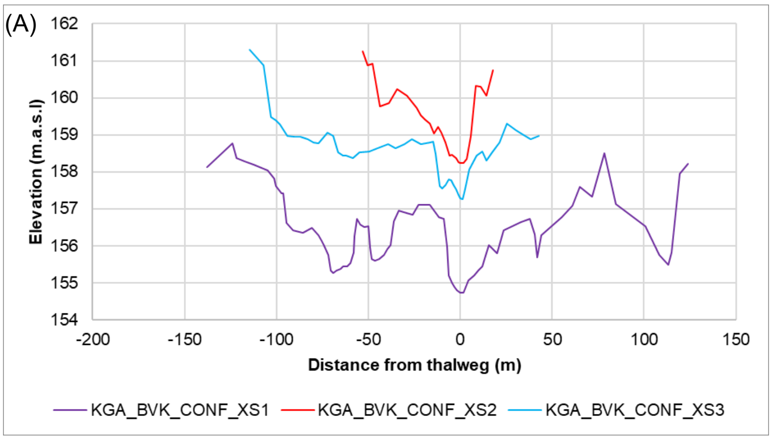
D50: 1.71 mm; Uniformity Coefficient: 4.98 (Fines)

(C) Bed and bank form

(D)

Figure 4.12: Summary of channel attributes, including soil data collected for Site 10. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Bed and bank view of surveyed channel. (D) Planform view of surveyed site. Scale 1 cm = 700m.

Kouga-Baviaanskloof confluence, Site 12



(B) ***Average channel-reach attributes***

Channel width: 112 m

Channel depth: 2.39 m

Cross-sectional area: 60.99 m^2

Channel slope: 0.0126 m/m

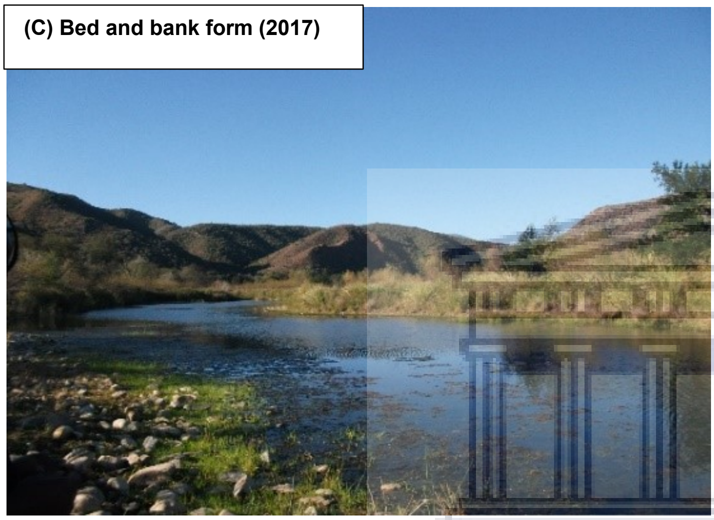
W/D ratio: 46.88

Channel roughness: 0.136

Visually estimated bank cover of course to fine material: 5% sand, 95% rocks

D50: 65 mm ; D84: 99 mm (Coarse)

D50: 1.35 mm; Uniformity Coefficient: 9.19 (Fines)


(C) Bed and bank form (2017)

(D)

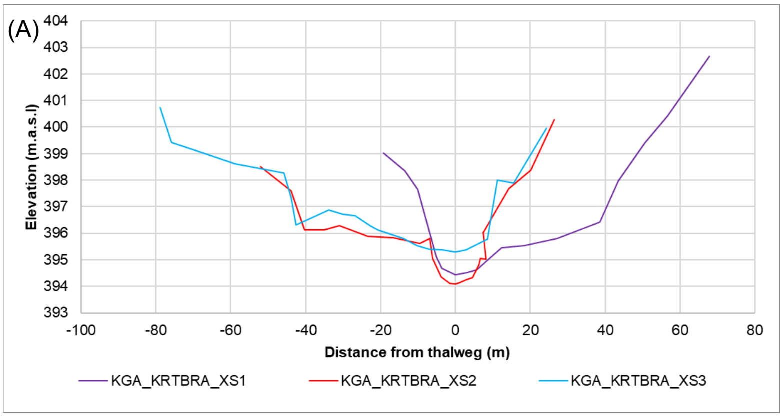
Figure 4.13: Summary of channel attributes, including soil data collected for Site 12. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Bed and bank view of surveyed channel. (D) Planform view of surveyed site. Scale 1 cm = 700m**.**

4.3.2.2. Confined reaches

A survey of the landscape revealed that almost half of the valley bottom area was this type of valley setting, as described in Chapter 3. Looking at the planform dynamics of the confined reaches, the channels in these reaches are characterized by narrow, single-threaded channels located in a gorge, although there are small floodplain pockets in some sections (Site 11). The slope of the confined reach surveyed in the Kouga was 0.0104 mm^{-1}. The straight channel wanders within the bedrock valley margins such that the entire valley floor acts as a channel (Figure 4.14D). There are no alluvial fans which can further constrict the channel.

The vegetation in these reaches is very dense and seemingly occurs where there floodplain pockets are located. Surface water flow was present in all the confined channel reaches at the time of sampling; however, the flow was low due to prevailing drought conditions. For planform dynamics, the reach experienced minor changes in the channel pattern over time in the period assessed, with the removal of vegetation, possibly during the flood, which formed sand depositions where vegetation has since grown back in. The current estimated channel roughness is 0.078. Fine sediments had a median grain size of 0.64 mm, indicating a uniform to medium well sorted material which is low in fines. The silt and clay content account for about 11 % of the soil texture of the bank material (Table C-1). Coarse median grain size was 86mm meaning small cobbles are the dominant bed material.

Kritplaas-Brandhoek, Site 11



(B) ***Average channel-reach attributes***

Channel width: 56 m

Channel depth: 3.26 m

Cross-sectional area: 113.80 m^2

Channel slope: 0.0104 m/m

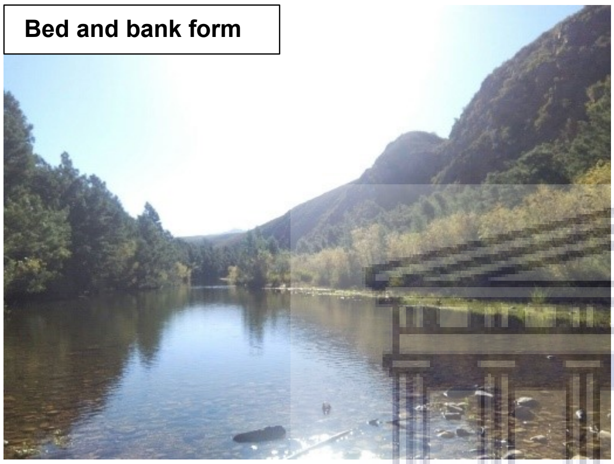
W/D ratio: 17.25

Channel roughness: 0.078

Visually estimated bank cover of course to fine material: 5% sand, 95% rocks

D50: 31 mm ; D84: 96 mm (Coarse)

D50: 0.65 mm; Uniformity Coefficient: 2.09 (Fines)



(D)

Figure 4.14: Summary of channel attributes, including soil data collected for Site 11. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Bed and bank view of surveyed channel. (D) Planform view of surveyed site. Scale 1 cm = 700m.

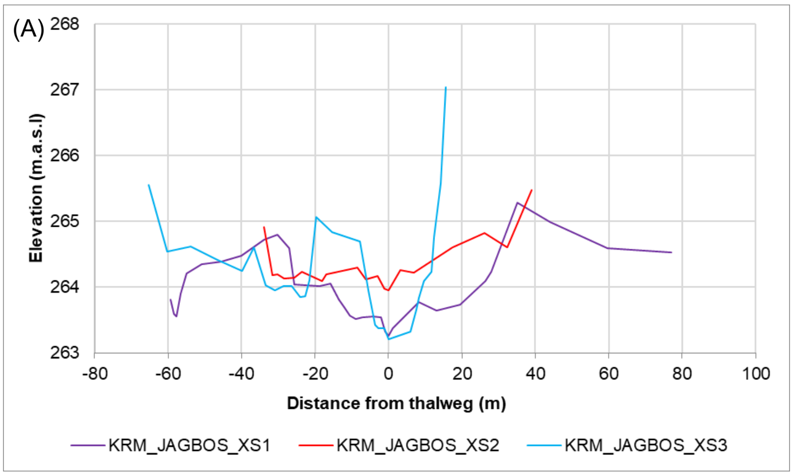
4.3.3. Kromme

4.3.3.1. Laterally unconfined reach

The channel reach morphology in the sampled site with a wide, alluvial valley setting can be characterized by a channel terminating in a flood-out where there is a breakdown of channel flow into low gradient multiple channels. The average channel width at the site was about 68 m with a slope of 0.0028 m/m respectively. From planform dynamics analysis, vegetation was once dense in this flood-out reach (Figure 4.15), covering the whole fluvial style however, the 2012/2013 flood stripped away most of the vegetation, significantly decreasing the channel resistance resulting in a low field estimate of manning's roughness of 0.07. The vegetation is now starting to emerge with a mixture of grass, reeds and shrubs.

Stagnant surface water and pools exist in the reach and the channel banks are poorly developed. Median grain size for fine sediments had an average of 0.2 mm, a poorly to moderately sorted sand materials low in fines, and there was 7 % silt and clay content in the bank material (Table C-1; Figure 4.15) whereas the coarse sediment fraction had an average median grain size of 47 mm, classified as a channel bed dominated by large gravel material.

Jagersbosch, Site 15



(B) ***Average channel-reach attributes***

Channel width: 68 m

Channel depth: 1.56 m

Cross-sectional area: 54.6 m^2

Channel slope: 0.0028 m/m

W/D ratio: 43.59

Channel roughness: 0.070

Visually estimated bank cover of course to fine material: 100 % sand

D50: 47.5 mm ; D84: 87.2 mm (Coarse)

D50:0.40 mm; Uniformity Coefficient: 3.83 (Fines)

(C) Bed and bank form (2017)

(D)

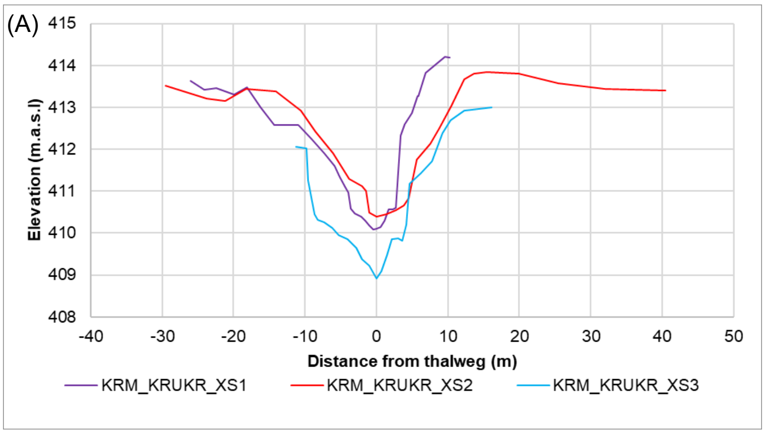
Figure 4.15: Summary of channel attributes, including soil data collected for Site 15. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Bed and bank view of surveyed channel. (D) Planform view of surveyed site. Scale 1 cm = 700m.

4.3.3.2. Partially confined reach

Although partially confined, floodplain and planform influence the channel morphology in the sampled site. The site is located near the headwaters where the channel enters from a confined valley starting in the Tsitsikama Mountains to the south (Figure 4.16). The site has a single-threaded with low-moderate sinuosity channel and old terraces with the average channel width of being around 19 m. The vegetation density is moderate. Average channel depth was more than 2 m (Figure 4.16B).

The reach has been highly modified by anthropogenic activities however; channel planform has remained the same pre and post flood, except for the large loss of vegetation by the river banks. The channel has not fully recovered from this and the images show there is still some sand deposition or bars forming on the channel banks. The median grain size for the site is 0.4 mm, a moderately sorted sand low in fines. , The silt and clay content in the channel banks are very low, with about 12 % of the total content (Table C-1). For the coarse fragments, the average median grain size for the site is 30 mm, which can be indicate that the dominant bed material is medium to large gravel.

Krugers Kraal, Site 13



(B) ***Average channel-reach attributes***

Channel width: 19 m

Channel depth: 2.81 m

Cross-sectional area: 30.27 m^2

Channel slope: 0.0095 m/m

W/D ratio: 6.65

Channel roughness: 0.119

Visually estimated bank cover of course to fine material: 60% sand, 40% rocks

D50: 60.83 mm ; D84: 94.04 mm (Coarse)

D50:1.11 mm; Uniformity Coefficient: 3.74 (Fines)

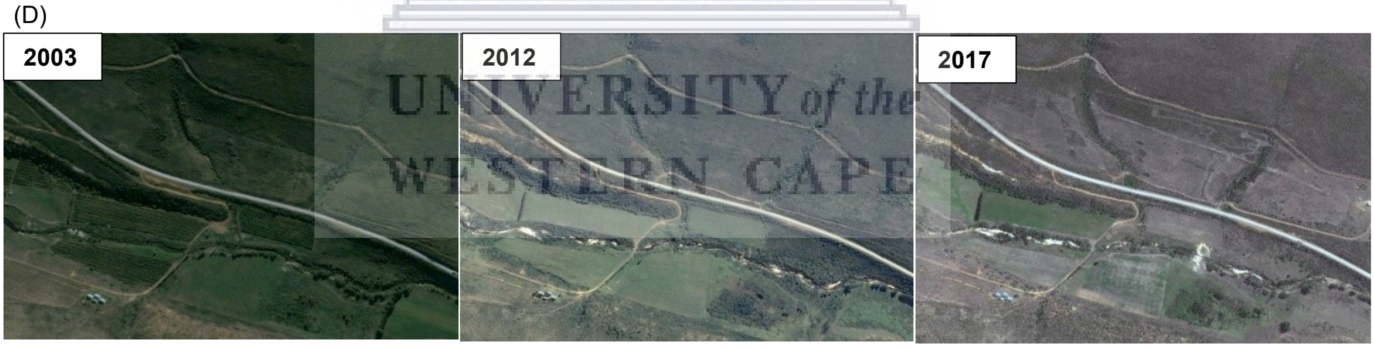


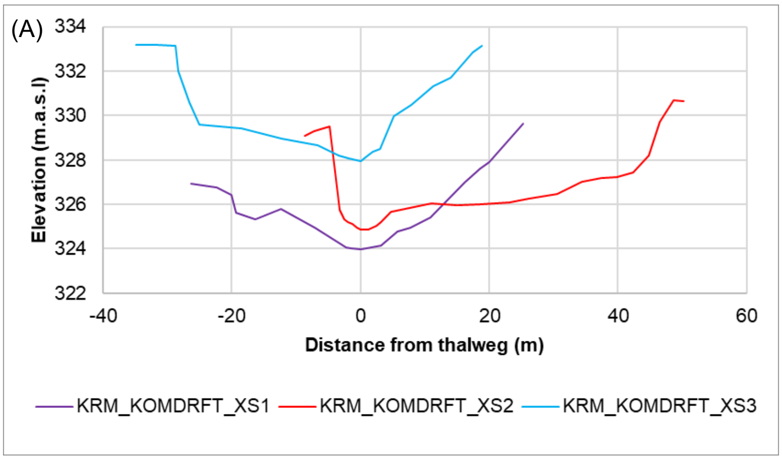
Figure 4.16: Summary of channel attributes, including soil data collected for Site 13. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Bed and bank view of surveyed channel. (D) Planform view of surveyed site. Scale 1 cm = 700m.

4.3.3.3. Confined reaches

The reaches sampled in this valley setting are downstream of broader valleys which then become confined largely by tributary alluvial fans that decrease the available valley floor width. This has resulted in the channel width restricted to ranges between 36 to 46 m and high banks ranging from 4 to 4.5 m. These poorly developed banks are low sloped ones because they keep collapsing. They keep widening, rather than deepening the channel, leading to shorter banks, called down cutting (Figure 4.17B-C; Figure 4.18B-C).

These reaches have an average slope of 0.0092 m/m and unchannelled valley bottom morphology with wetland plants across the whole valley bottom, resulting in a densely vegetated channel morphology type, with an estimated roughness value of 0.102 across the sites. The fine sediments had an average median grain size of 0.2 mm a poorly sorted sand low in fines (8 % silt and clay). For coarse sediments, these reaches were characterized by small to medium material with the median grain size of 15 mm, however, larger soil particles were found on the channel bed from inputs of the tributary.

Kompanjiesdrift, Site 14



(B) ***Average channel-reach attributes***

Channel width: 47 m

Channel depth: 4.50 m

Cross-sectional area: 119.87m^2

Channel slope: 0.0180 m/m

W/D ratio: 10.52

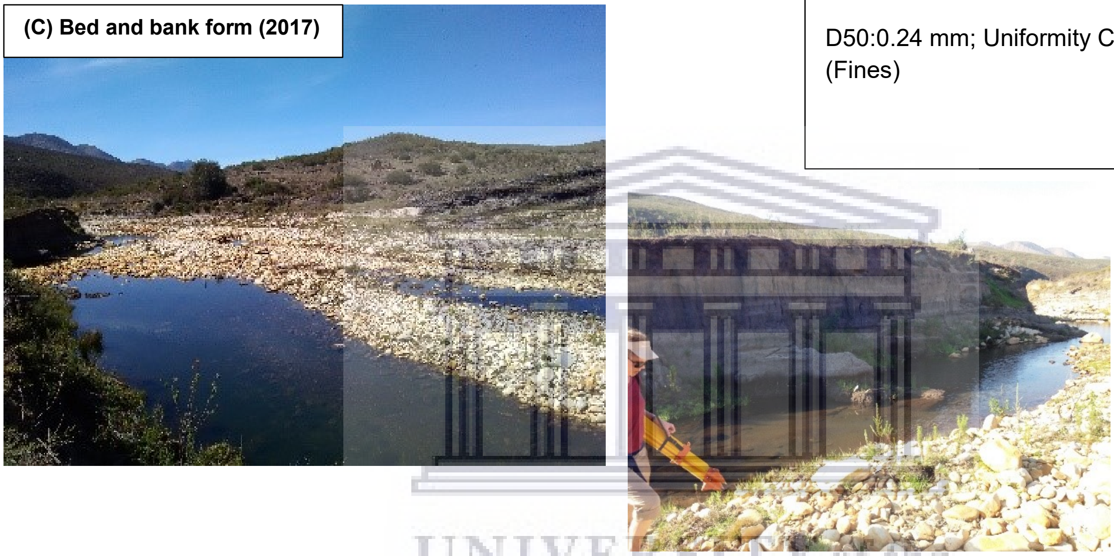
Channel roughness: 0.062

Visually estimated bank cover of course to fine material: 100 sand (peat soil)

D50: N/A ; D84: N/A

D50:0.24 mm; Uniformity Coefficient: 12.10 (Fines)

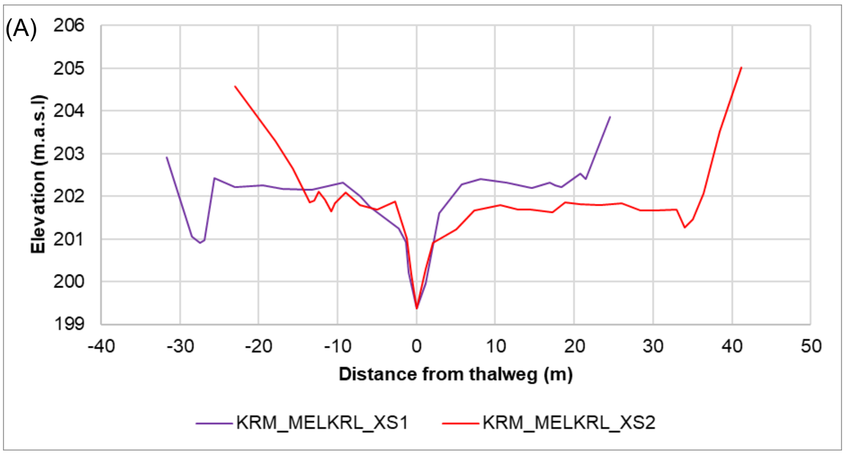
(C) Bed and bank form (2017)



(D)

Figure 4.17: Summary of channel attributes, including soil data collected for Site 14. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Bed and bank view of surveyed channel. (D) Planform view of surveyed site. Scale 1 cm = 700m.

Melkhoute Kraal, Site 16



(B) ***Average channel-reach attributes***

Channel width: 36 m

Channel depth: 3.90 m

Cross-sectional area: 63.56 m^2

Channel slope: 0.0003 m/m

W/D ratio: 9.11

Channel roughness: 0.142

Visually estimated bank cover of course to fine material: 90% rocks, 10% rocks

D50: 30 mm; D84: 90.73 mm (Coarse)

D50:0.43 mm; Uniformity Coefficient: 4.58 mm (Fines)

(C)

Figure 4.18: Summary of channel attributes, including soil data collected for Site 16. Bank and bed texture photos were not taken as it was a thick palmiet wetland. (A) Surveyed channel cross-section data. (B) Averaged channel and reach attributes. (C) Planform view of surveyed site. Scale 1 cm = 700m.

4.3.4. Fluvial Style characterization

Thirteen fluvial styles were observed across the three catchments. The table below shows the full name of the fluvial style and the code (for the purpose of naming and shortening the description (Table 4.4). Further discussions and descriptions of these fluvial styles are provided in Section 4.4. Energy versus resistance graphs was also plotted for the three catchments to explore possible groupings of fluvial styles. The groupings are meant to qualitatively classify fluvial styles by collectively looking at patterns between the energy of the river and median grain size on the channel bed together with the silt and clay content in the channel bank (Figure 4.20A; Figure 4.20B Table 4.5). This classification is exploratory, with evidence based research from literature and the current study (van den Berg, 1995; Kleinhans and van den Berg, 2011; refer Chapter 3; Chapter 4 Section 4.3).

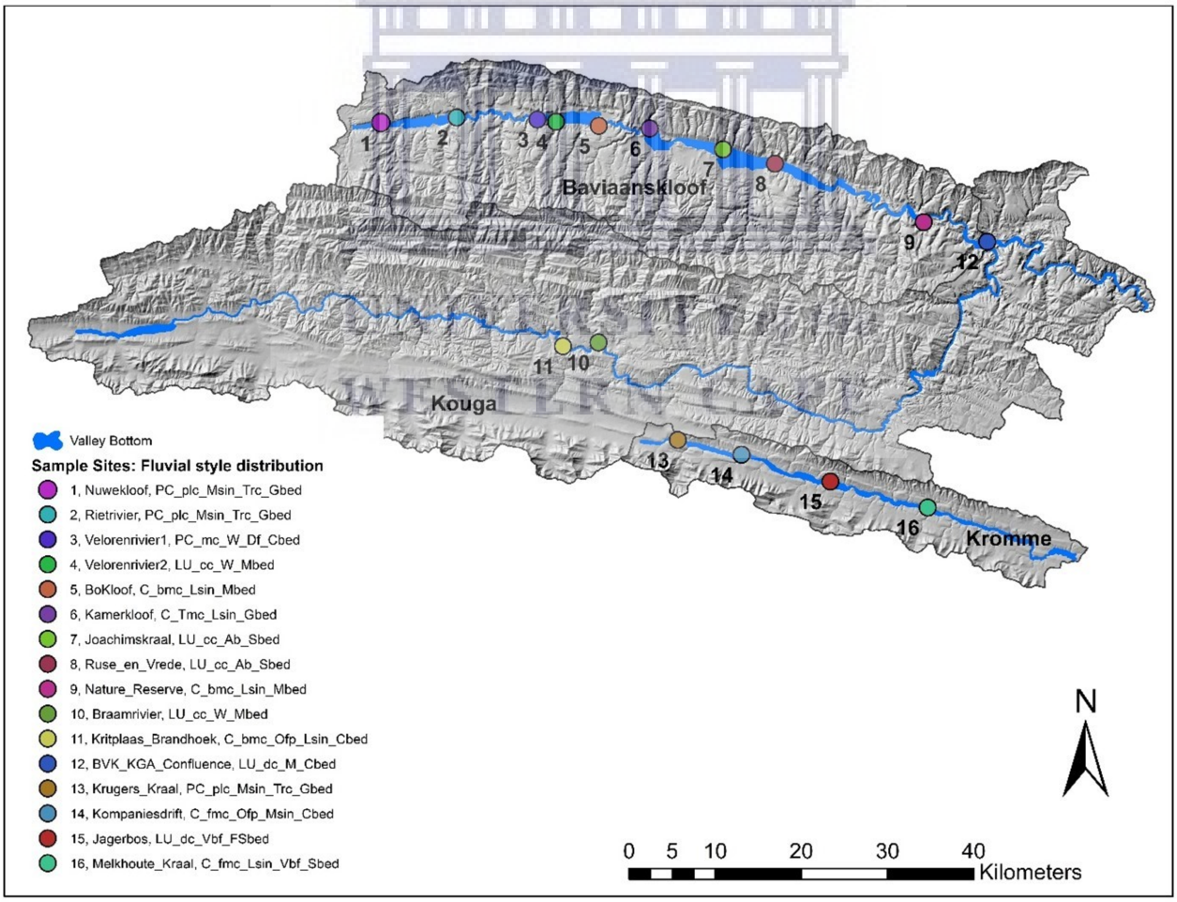


Figure 4.19: Map showing the distribution of fluvial styles in the three catchments. Full description of fluvial code is provided in Table 4.4.

Table 4 .4: Fluvial style classification for each study reach in the three catchments.

Catchment	Site Name (s) of study reach	Fluvial style	Fluvial Style Code
Baviaanskloof	Nuwekloof, Rietrivier	Partially confined, planform controlled, medium sinuosity, terrace constrained, gravel bed	PC_plc_Msin_Trc_Gbed
	Verlorenrivier1	Partially confined, margin controlled, wandering discontinuous floodplain, cobble bed	PC_mc_W_Df_Cbed
	Verlorenrivier2	Laterally unconfined, continuous channel, wandering, mixed bed	LU_cc_W_Mbed
	BoKloof, Nature Reserve	Confined, bedrock margin controlled, low sinuosity mixed bed	C_bmc_Lsin_Mbed
	Kamerkloof	Confined, terrace margin controlled, low sinuosity, gravel bed	C_Tmc_Lsin_Gbed
	Joachimskraal, Rus en Vrede	Laterally unconfined, continuous channel, anabranching, sand bed	LU_cc_Ab_Sbed
Kouga	Braamrivier	Laterally unconfined, continuous channel, wandering, sand bed	LU_cc_W_Mbed
	BVK-KGA confluence	Laterally unconfined, discontinuous channel, meandering, fine sand bed	LU_dc_M_Cbed
	Kritplaas-Brandhoek	Confined, bedrock margin-controlled, low sinuosity, occasional floodplain pocket, cobble bed	C_bmc_Ofp_Lsin_Cbed
Kromme	Krugers Kraal	Partially confined, planform controlled, medium sinuosity, terrace constrained, gravel bed	PC_plc_Msin_Trc_Gbed
	Kompaniesdrift	Confined, fan-margin-controlled, occasional floodplain pocket, medium sinuosity, cobble bed	C_fmc_Ofp_Msin_Cbed
	Melkhoute Kraal	Confined, fan-margin-controlled, low sinuosity, valley bottom fill (wetland), sand bed	C_fmc_Lsin_Vbf_Sbed
	Jagerbos	Laterally unconfined, discontinuous channel, valley fill (floodout), fine grained	LU_dc_Vbf_FSbed

Valley specific stream power was inversely proportional to median bed grain size and proportional to channel bank content (Figure 4.20A; Figure 4.20B). Furthermore, geomorphic units, which are greatly important patches of feeding, foraging and breeding sites in habitats, could be inferred by these groupings. Fluvial style groups plotted with high valley specific stream power and lower median bed grain size were wandering, low sinuosity or anabranching channels, which contradicts the results founded by Kleinhans and van den Berg (2011) which plotted braided channels with scroll bars in these regions. Analysis of channel bank silt and clay content and valley specific stream power showed that channels with high valley specific stream power will also have a high silt and clay content in the channel which indicates fluvial styles grouped here are more cohesive and stable banks but experience a lot of flood power which scours and erode over time.

Five groups were observed from the graph between valley specific stream power and median bed grain size which the fifth were termed as outliers, showing “no grouping “or similarities in the graph (Table 4.5; Figure 4.20A). Four groups were observed from the graph between valley specific stream power and silt and clay content which the fourth were grouped as outliers (Figure 4.21; Figure 4.20B). The tables below summarize the groupings:

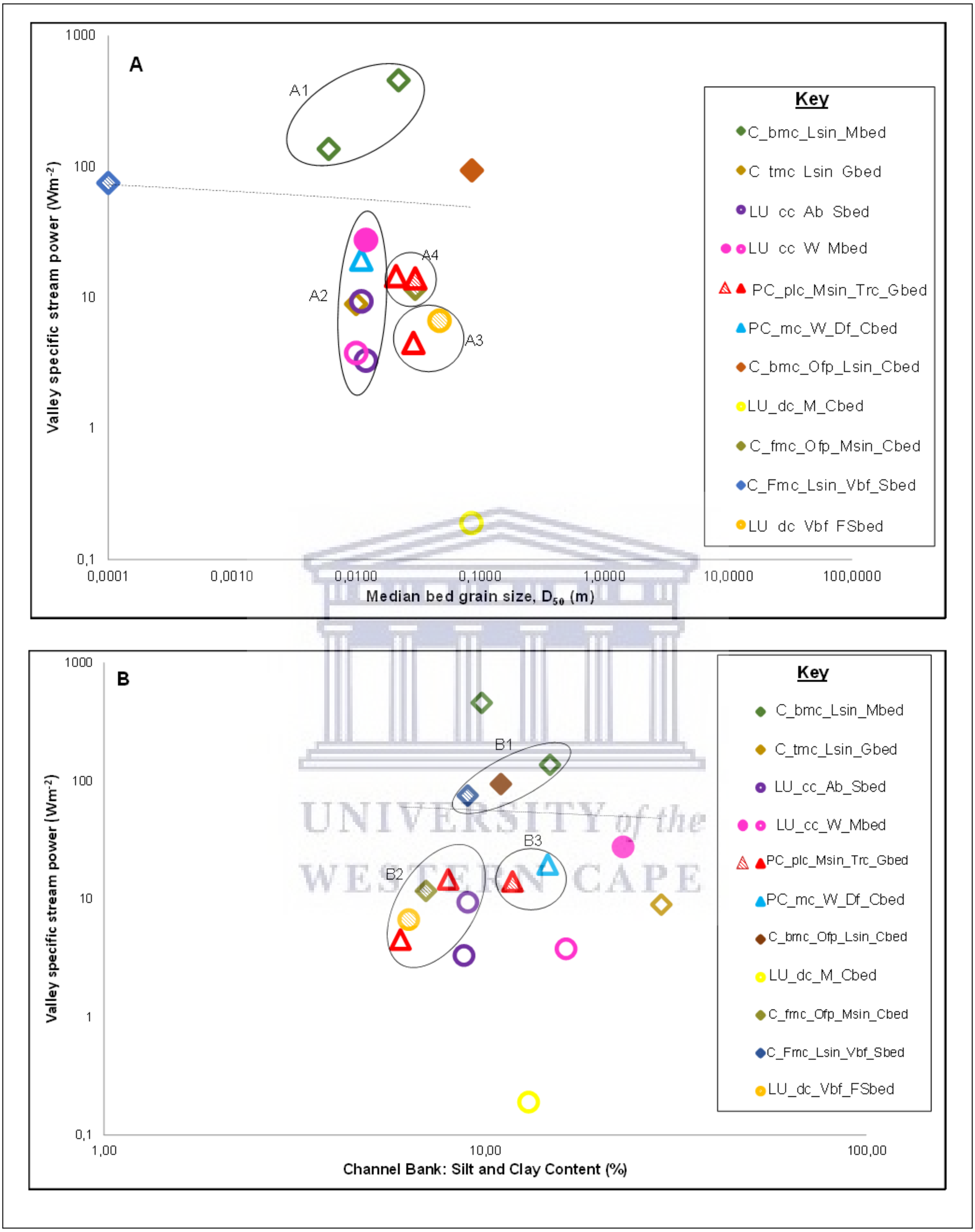


Figure 4.20: Classification of channel pattern of the reaches in relation to energy and bank strength. Data is subdivided by the fluvial styles. Graph A shows the VSSP against the median bed grain size and Graph B shows the VSSP versus channel bank texture. Baviaanskloof fluvial styles are denoted by a hallow shape; Kromme fluvial styles are denoted by the hatch shape and Kouga Sites have a filled shape. Diamond = confined, Triangle = partially confined and Circle = laterally unconfined in all the catchments.

Table 4.5: Summary of groupings by fluvial style from Figure 4.20. Group one is fluvial styles grouped by valley specific stream power and median grain size and group two shows the grouping by valley specific stream power and silt and clay content (bank stability). Colour coding corresponds with site numbers and names in Figure 4.21 and Figure 4.22

Catchment	Site Name	Site Number	Fluvial style	Grouping one	Grouping two
Baviaanskloof	Nuwekloof	1	PC_plc_Msin_Trc_Gbed	**A4: Moderate energy and moderate bed resistance**	**B2: Low energy and low bank resistance**
	Rietrivier	2	PC_plc_Msin_Trc_Gbed	**A3: Lower energy and moderate bed resistance**	**B3: High energy and high bank resistance**
	Verlorenrivier1	3	PC_mc_W_Df_Cbed	**A2: Moderate-low energy and low bed resistance**	**B2: Low energy and low bank resistance**
	Verlorenrivier2	4	LU_cc_W_Mbed	**A2: Moderate-low energy and low bed resistance**	**Outliers**
	BoKloof	5	C_bmc_Lsin_Mbed	**A1: Highest energy and moderate to low bed resistance**	**Outliers**
	Kamerkloof	6	C_Tmc_Lsin_Gbed	**A2: Moderate-low energy and low bed resistance**	**Outliers**
	Joachimskraal	7	LU_cc_Ab_Sbed	**A2: Moderate-low energy and low bed resistance**	**B2: Low energy and low bank resistance**
	Rus en Vrede	8	LU_cc_Ab_Sbed	**A2: Moderate-low energy and low bed resistance**	**Outliers**
	Nature Reserve	9	C_bmc_Lsin_Mbed	**A1: Highest energy and moderate to low bed resistance**	**B1: High energy and moderate bank resistance**
Kouga	Braamrivier	10	LU_cc_W_Mbed	**A2: Moderate-low energy and low bed resistance**	**Outliers**
	Kritplaas-Brandhoek	11	C_bmc_Ofp_Lsin_Cbed	**Outliers**	**B1: High energy and moderate bank resistance**
	BVK-KGA confluence	12	LU_dc_M_Cbed	**Outliers**	**Outliers**

Kromme	Krugers Kraal	13	PC_plc_Msin_Trc_Gbed	**A4: Moderate energy and moderate bed resistance**	**B3: High energy and high bank resistance**
	Kompaniesdrift	14	C_fmc_Ofp_Msin_Cbed	**A4: Moderate energy and moderate bed resistance**	**B2: Low energy and low bank resistance**
	Jagerbos	15	LU_dc_Vbf_FSbed	**A3: Lower energy and moderate bed resistance**	**B2: Low energy and low bank resistance**
	Melkhoute Kraal	16	C_fmc_Lsin_Vbf_Sbed	**Outliers**	**B1: High energy and moderate bank resistance**

Descriptions of the groupings A (Table 4.5; Figure 4.21):

A1: Dominant valley confinement setting is confined. These fluvial styles are grouped together as they show a similar pattern in high valley specific stream (~80 to 500 Wm^{-2}) power and medium to low fine gravel bed median grain size. They are situated in the middle and downstream of the main channel but show similarity in the channel planform in terms of characteristics such as sinuosity, which is very low due the bedrock confining margin which impedes lateral valley movement. The width to depth ratio is moderate which implies that these fluvial styles have a low sensitivity to disturbance and has a good recovery potential. These fluvial styles are also characterised by a low median grain size in coarse and fine material which may be attributed to dense vegetation cover and low VSSP in the immediate upstream region which impede sediment transport (in-stream boundary control on river form and processes).

A2: Valley confinement setting varied with a mixture of laterally unconfined wandering channels in the upper to middle part of the Baviaanskloof and Kouga catchment, another laterally confined but anabranching channel which both have continuous channels and partially confined channels in the upper Baviaanskloof with discontinuous floodplains and confined valley settings with low sinuosity and terraces as margins controls in the middle part of Baviaanskloof again. With these ranges of fluvial styles, it is expected that the channel pattern will vary too, with VSSP being low to medium (up to 10 Wm^{-2}) and a low median grain size. Overall, these fluvial styles are also characterized by a high width to depth ratio which implies that they possess high sensitivity to disturbance and with a low recovery potential if eroded over time. Two of these sites however, experience the total opposite, characterized by sand-dominated, laterally active channels. These fluvial styles have multiple channels with vegetated islands and ponds which might be caused by the fact that in these regions, channel slope does not change much, increasing the number of channels and as a result, low flow efficiency (~1 – 10 Wm^{-2} VSSP). Overall, this fluvial style typically grows wider and shallower therefore the hydraulic stress at the banks increases and accelerates bank erosion and increases sediment supply to the river bed (Figure 4.21).

A3: Valley confinement is ranging (Laterally unconfined and partially confined). These fluvial styles are characterized by discontinuous channels and planform controlled valley margins which have resulted in them being moderately sinuous in the upper Baviaanskloof to meandering channels downstream where there is a Baviaanskloof and Kouga confluence. They have a lower VSSP compared to A1 and A2 (less than 10 $Wm-^{2}$) with a mixed median bed grain size with a lot of fines resulting in various depositional patterns such as bars and islands in these fluvial styles. The width to depth ratio also varies in this grouping where one fluvial style is very low (around 7) and the confluence experiences a higher value which is 45. These have a high width to depth ratio, with a slightly higher median grain size compared to group A1 and A2 (Figure 4.21).

A4: Partially confined, planform controlled fluvial styles in the upper Baviaanskloof and Kromme catchment are grouped in this category with the confined fan margin controlled channel in the lower Kromme catchment. These fluvial styles experience a medium to low VSSP where the medium bed grain size follows the same pattern. Similar to group A3, two of the fluvial styles have a low width to depth ratio, and they’re both situated in the same area within the different catchments. The third one has a high with to depth ratio. These fluvial styles have a similar descriptive pattern of channel planform dynamics as group A3, with a slight difference being apparent as group A4 has a higher VSSP (Figure 4.21).

Outliers: These fluvial styles are grouped as outliers as they do not fall in any distinct grouping. One of the fluvial styles with a major fan margin control from the tributaries which creates these occasional floodplain pockets that create a confining margin to a once partially confined valley setting, is situated in the upper to middle Kromme and

Kouga have a very higher VSSP (above 80Wm-2) and has very little available coarse median bed grain size. This implies either there is higher flood energy before this fluvial style which deposits fines or coarse material or the valley margin has sedimentary geology which erodes and deposits in the river bed. Two of these fluvial styles situated in the middle Kromme experience laterally unconfined discontinuous channels with an apparent valley bottom fill and the other in the middle Kouga with low sinuosity have the same median bed grain size however, have different valley settings and resultant valley specific stream power which implies some other controls (particularly the type of margin control type) have an influence on the distribution of grain size (Figure 4.21).

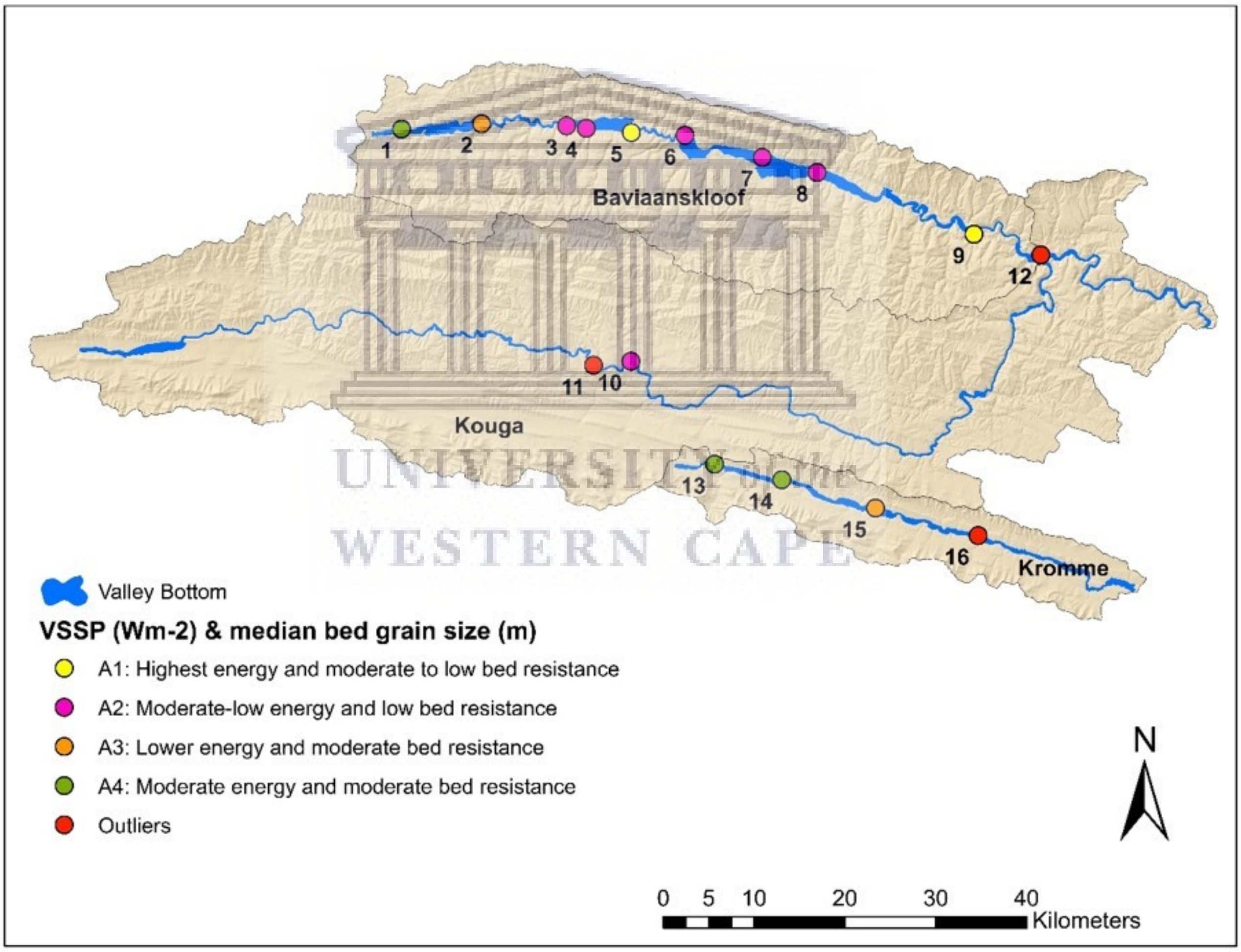


Figure 4.21: Map showing the distribution of the group one fluvial styles' based on the energy (valley specific stream power) and resistance (median bed grain size) found in the three catchments

Descriptions of the groupings A (Table 4.5; Figure 4.22):

B1: These fluvial styles show a similarity in the confinement setting and low to moderate sinuosity in the middle and lower end of the Baviaanskloof and Kromme catchment and in the middle of Kouga. Grouped as all confined valley settings, these fluvial styles all show a similar pattern of high VSSP coupled with a margin control (bedrock or fans). More than (10%) of the channel bank was comprised of silt and clay content, which implies that the channel banks are slightly cohesive and stable thus are less susceptible to erosion than group B2 (Figure 4.22). These fluvial styles have little or no room to move laterally and they are found in mountain streams, most in the upstream parts of the catchments.

B2: These fluvial styles are grouped together because they show a similar pattern of low VSSP and low silt and clay content less than 10 % and are situated in the upper to middle of Baviaanskloof and Kromme catchment. These fluvial styles are mostly laterally unconfined, with the exception of one style being confined however, occasional floodplains and exist where these might cause a decrease in the flood power and weaken the aggregate stability of the channel bank (Figure 4.22).

B3: Both of these styles have a partially confined valley setting however; variety exists where one has a medium sinuosity and the other a wandering channel. These are situated in the upper Baviaanskloof and Kromme catchment. The fluvial styles grouped here show a pattern where it they have a higher VSSP compared to group B, they have a similar silt and clay content compared to group A where it is more than 10 % which creates a greater aggregate of bank stability compared to B1 and B2 although more prone to capping (Figure 4.22).

Outliers: These fluvial styles are grouped because they are outliers, meaning they are not showing a distinct pattern or grouping and these exists in all the catchments, commonly placed in the middle to lower parts of the catchments (Figure 4.22). What is similar in these channels is that they seem to have a very high clay and silt content but a varied pattern of VSSP with confined valley settings having a higher VSSP (more than 1 Wm-2) while the laterally confined valley channels showed to have a lower VSSP, due to their inherently high silt and clay content, these fluvial styles have channel banks which are naturally slow draining and wetter for longer which results in a high risk of structural damage hence a lot of bank collapse was noted in these fluvial style types.

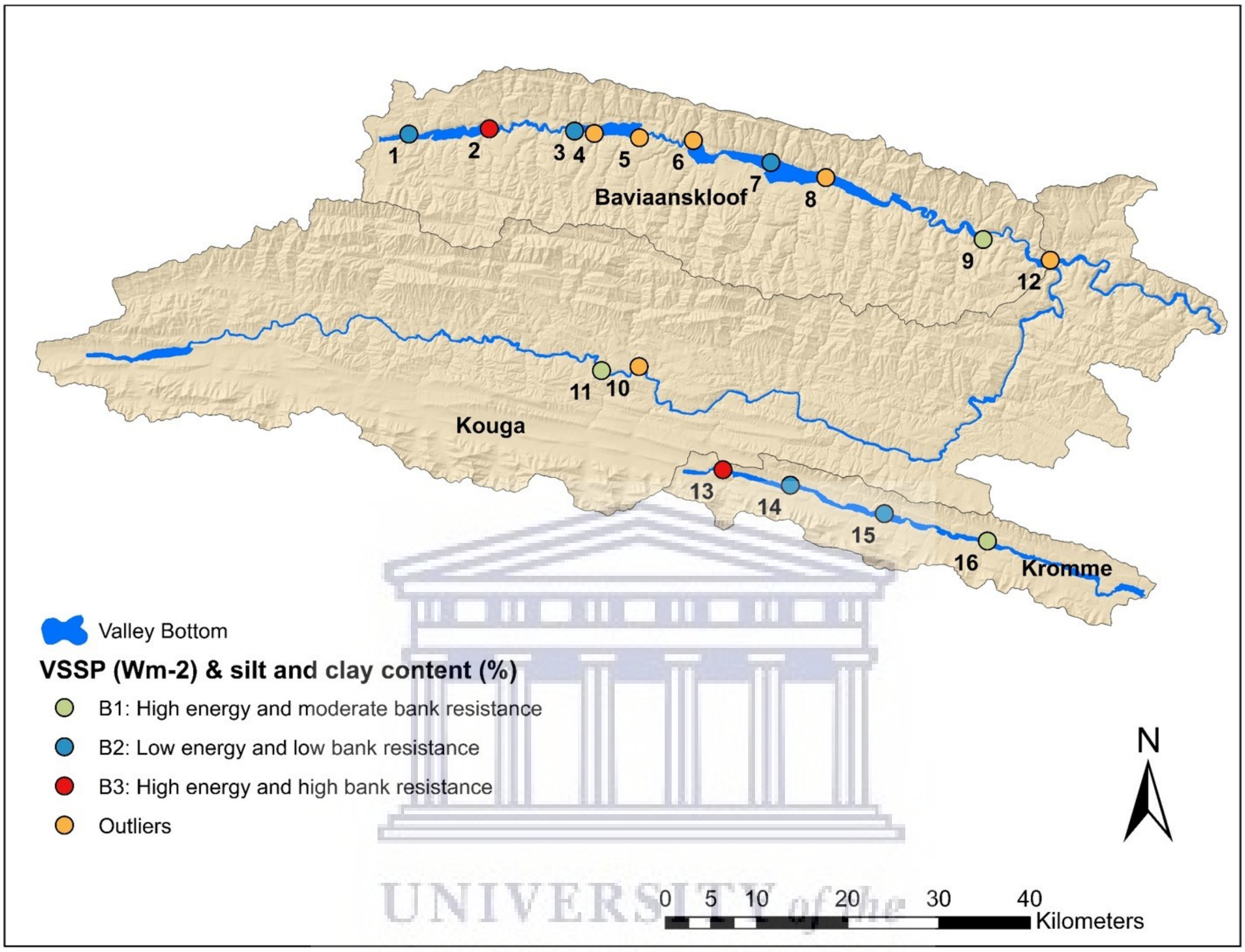


Figure 4.22: Map showing the distribution of the group two fluvial styles' based on the energy (valley specific stream power) and resistance (silt and clay content) found in the three catchments.

Fluvial styles with low valley specific stream power did not have a distinct pattern where there were resultant changes in the median bed grain size. However, all these other fluvial styles were closely grouped together, irrespective of the valley specific stream power and confinement type which indicate that other local variables not included in this analyses, are also important. Both of these sediment variables showed a negative relationship from analysis of trendline, although this was weak and statistically insignificant from the graph (Figure 4.20A; Figure 4.20B).

4.4. Discussion

4.4.1. An analysis of River character and behaviour

A detailed analysis of channel reach morphology was presented in this chapter. The main channel reaches selected in the three semi-arid mountainous catchments show variability within catchments and some similarity amongst the catchments. Field data provided important insights on the changes and the current morphology of these catchments while remotely sensed channel-reach planform analysis provided causes and patterns of changes in the geomorphology of the catchments. For the river behaviour, field assessments of channel reaches were only conducted at low flow stages due to the drought conditions during the field sampling period, however aerial photography allowed for assessment of change or stability in the planform following a major flood event (2012). Previously, a number of studies have tried to characterize fluvial styles on the basis of controlling energy and resistive forces (Frissell et al. 1986). A similar analysis of fluvial styles was adopted to analyse the diversity in the channel morphology at the selected study reaches.

In the Baviaanskloof, six different fluvial styles were identified for the sample sites with low valley specific stream power and in less confined valleys. The **partially confined, planform controlled, medium sinuosity, terrace constrained, gravel bed** fluvial style occurs in the upper part of the catchment (Sites 1 and 2) where the river flows with sufficient accommodation space for a mixture of sediments, particularly coarse sediments. With a moderate sinuosity pattern, this style generally exhibited a single thread channel; however, local widening exists where the channel reach suddenly becomes multi-threaded anabranches. This indicates that two dominant processes occur, namely bank erosion and sediment production in narrower sections and where these local broad zones occur, sediment accumulation is dominant. This phenomenon of two dominant processes are quite common in dryland river systems, particularly in the Middle Fork John Day catchment in Oregon were the same fluvial styles in similar location within the catchment was observed (Brien et al. 2017). These reaches also exhibit undulating topography inset in some areas in abandoned terrace segments where the reaches are strongly planform controlled by the steep cliffs (see Chapter 2; section 2.1). The **partially confined, margin controlled, wandering discontinuous**

floodplain, cobble bed site**,** Site 3, exhibited similar processes and fluvial style as seen in Site 1 and 2, however, the fluvial style is mainly margin controlled meaning the width of the river valley is primarily limited by bedrock. This type is found in both the upper and lower catchment of the Baviaanskloof River where the river is dominantly wandering through the valley walls in a single-thread. With valley specific stream power being also larger compared to Site 1 and 2, Site 3 exhibited a larger variation in bed and bank morphology.

The **laterally unconfined, continuous channel, wandering, sand bed,** similar to **laterally unconfined, continuous channel, anabranching, sand bed** are typically open, wide river sections that have a gentle gradient. This type of landscape allows the floodplain to be filled with-fine grained valley fill which has old terraces which also indicates reworking of sediments over time as observed in New South Wales where regions that had a gentle gradient. Normally, nearer the base levels of large (tributary streams were occupied by these fluvial styles (Fryirs et al. 2016) and in the Baviaanskloof, the reworking of this valley fill revealed hillslope and channel connectivity (Powell, 2017) similar to the pattern of valley and channel attributes observed 30 to 50 km downstream in the Baviaanskloof and Kouga catchments (Refer to section 3.3; 4.3 and Table 4.4). The multiple-thread, continuous channel has a high sinuosity, wandering and anabranching style which may reflect constant channel adjustments. With low specific stream power values, coarse sediment fractions are also present in these channels which are mainly due to the inputs from tributaries hence the multiple channels. Coupled with high a width-to-depth ratio, this implies that the channel reaches experience depositional processes. This type of fluvial style may also promote shallow groundwater tables which can explain why these valleys setting have high vegetation density (and diversity) although reaches with this style in the Baviaanskloof have non-perennial flow.

Confined, bedrock margin controlled, mixed bed are generally straight to slightly sinuous. Found across the catchment area (upper, middle and lower), although covering decreasing lengths, these channel reaches have steep, valley walls comprised of gorges, high plateaus and cliffs which results in a narrow channel type (Table 4.4). Sources of the coarse sediments in these reaches are commonly hillslope deposits, probably through past overland flow. They have high specific stream power which is due to the morphology of the valley which the channel reach is constrained to and this energy is enough to move smaller particles longitudinally to other valley and channel morphology types. **Confined, terrace margin controlled, low sinuosity, gravel bed** is mainly found in the middle sections of the catchment where the channel reaches are confined by terraces, although the bedrock valley margin still influences the degree of the confinement. There is little to no floodplain present with the main source of the bed sediments being probably from vertical accretion or hillslope processes. These areas have dense vegetation which also adds to the channel roughness of the reaches.

In the Kouga, three fluvial styles were found through field and image analysis. The **laterally unconfined, continuous channel, high sinuosity, sand bed** fluvial style is found in the middle section of the Kouga river where a small section is locally wide, due to two large tributaries joining the main river, dominantly a fine sand type of bed form, input from these large tributaries have resulted in a mixture of pebbles, cobbles and boulders being deposited on the floodplain and inside the channel, adding to the channel roughness of the reach (Table 4.4). O'Brien and Wheaton (2015) specifically analysed fluvial styles that were situated before and after large tributaries in the Middle Fork John Day Watershed, Oregon and results showed large tributaries with confluences carrying a mixture of bedload size due to the variation of stream power before depositing in the low energy, laterally unconfined main valley. The local valley specific stream power in this section is relatively low although the tributaries periodically increase the energy. The **laterally unconfined, discontinuous channel, meandering, fine sand bed** style is usually found where the valley is wide, which is not common in this valley setting however, such fluvial styles can be seen at the end of the main Kouga River at the confluence with the Baviaanskloof River. With a low relief, rounded topography, the floodplain is very extensive, allowing for a diversity of vegetation to exist. This multiple-thread, discontinuous channel has a tortuous, meandering planform which is mainly due to the two rivers meeting. The valley setting dictates that these areas should have a low valley specific stream power however, the energy of water from both these rivers may result in a high energy stream at this reach (Lane et al. 2017). The wide valley has large sediment accumulation at specific areas along the meander, which can explain how the channels have become discontinuous at this reach.

Looking at the areal planform view of the main Kouga River, **Confined, bedrock margin-controlled, low sinuosity, occasional floodplain pocket, and cobble bed** fluvial style covers the majority of the Kouga main river, characterized by a narrow channel with occasional floodplain pockets on either side as observed in the delineation of the valley bottom in section 3 and planform analysis in section 4. These mainly occur in tributary confluence zones, where the valley locally widens slightly, and accommodating shallow floodplain pockets. When the channel experiences its high energy flows, this fluvial style is prone to channel adjustments through erosional and depositional processes at these sites.

In the Kromme catchment, **partially confined, fan margin-controlled, low to medium sinuosity, gravel bed** is mainly found where the Kromme valley starts however is also found in the lower parts of the catchment (refer to section 4.3.4). With low to medium sinuosity, the channel reaches possess a moderate valley specific stream power.

Confined, fan-margin-controlled, occasional floodplain pocket, medium sinuosity, cobble bed fluvial style is found in the middle section of the Kromme river. The channel is usually a single-threaded channel which flows between the alluvial fans present where the tributary valleys meet the main channel-reach. These tributary confluences complete a transition from the main river's partly confined fluvial style to this confined style, where the river gains energy and scours the sediments on the surface of the channel-floodplain (Schlegel, 2017). This has resulted in incision being a dominant fluvial process in these channels reach, forming gullies which are periodically filled by deposits from vertical accretion of suspended load. The dominant bed material is cobbles.

The **laterally unconfined, discontinuous channel, valley fill (floodout), fine grained** was found commonly in the middle to low sections of the catchment, At the sampled site, the shallow channel terminated at a floodout where the there is a low-gentle gradient which is probably caused by the upstream incised confined valley transitioning to this wider valley setting, depositing sand sheets at the mouth of this channel. This also explains the high silt-clay content found in this fluvial style. This high content of fines over the years has also resulted from the downstream change in valley slope from low to near uniform gradient and the width increase allowed the fines to deposit and remain in this valley setting. This has created an array of wetland environments forming due to the constant shallow water table.

The **confined, fan margin-controlled, low sinuosity, valley bottom fill (wetland), sand bed** is an unchannelled river type which observed in the lower Kromme. It is similar to Site 6 in the Baviaanskloof where it is a margin-controlled fluvial style however, the planform here is mainly controlled by alluvial fans rather than terraces and sediment regimes differ (refer to section 4.3.1). Sediment rich upstream and alluvial fan inputs are the main source of bed form and material. The fans themselves have surfaces that are fine grained and of low slopes which have accumulated and confined the valley. The vegetation is very dense, as the channel is comprised of wetland vegetation. The valley specific stream power in these channel reaches is moderately high, although the wetland vegetation retains the floods during high flow stages.

4.4.2. Downstream pattern of fluvial styles

In the upper reaches of the Baviaanskloof where the valley is partially confined, a number of fluvial styles are observed. Although similar in valley confinement type, the channel planform differs where the valley starts with a medium sinuosity and then transitions to a wandering fluvial style and this is also evident where the valley specific stream power changes from 5 Wm^{-2} to over 15 Wm^{-2} across the partially confined valley. There are small areas of partial confinement in the middle and lower reaches of the Baviaanskloof however the ones in the upper regions were larger and showed more variation in fluvial styles compared to other areas in the catchment. As you move to the middle reaches, the valley starts to widen, with small areas having gorges and bedrock controlled valley margins. This creates a mixture of bed material however as you analyse the whole valley, these wide valleys have a huge sedimentary fill which has anabranching rivers throughout the valley confinement type, and have a relatively low specific stream power (although higher than partially confined valleys) which could indicate that the number of channels (single versus multiple channels) also has a cumulative effect on the total valley specific stream power in a particular section.

Similar placements of fluvial styles within the various valley settings and specific stream power pattern are evident in the Kromme catchment. The main difference is that the main Kromme valley is comprised of the interlayering of sandstone and shale syncline with Bokkeveld shale running down the centreline more uniformly which creates a landscape of differential erosion where more resistant rock protrudes (even in the bed material) above the weathered rocks of this valley setting. The Baviaanskloof has more uneven faulting and difference between north and south sides of the valley. Kromme is also wetter compared to the other three catchments therefore groundwater table is nearer the surface even in wide valley areas which also promotes the growth of palmiet which is the dominating in-stream boundary control for most of the fluvial styles in the Kromme. This pattern is common in sites where the fluvial styles were in confined valley settings with high valley specific stream power and as a result, the average channel depth in these settings were relatively deep which indicates that valley specific stream power has a large influence in the erosional and depositional pattern in these fluvial styles. Wide valleys in the Kromme were quite different compared to the wide valleys in the Baviaanskloof.

Although both were situated in the middle reaches of the catchments, erosional material (net deposition) from the confined valleys and alluvial fans from tributaries deposit in these valleys, infilling gullies and channels thereby locally increases the longitudinal valley slope. This has resulted in a phenomenon called valley floor planning which has allowed for wetlands in these regions to form, hence most of the fluvial styles in the valley have a lot of sedimentary fill.

In the lower reaches, the pattern of confinement is similar across the catchment, dominantly confined, with all the fluvial styles exhibiting the same type of attributes in terms of valley margin and grain size. It is important to note that fluvial styles found in confined valley settings in the upper and middle reaches had a larger valley specific stream power compared to the lower reaches, which relates to the decreasing slope which ultimately lowers stream power by half.

Fewer inferences can be made about the Kouga catchment and the fluvial styles occurred there because only three fluvial styles were observed in the area. Two fluvial styles were observed in laterally unconfined valleys in the Kouga catchment, the one in the lower reach (site 11 and 12) had a very low valley specific stream power compared to the unconfined valley upstream. Only one other fluvial type was found here, confined by bedrock – this channel type is the most common in the valley (Figure 4.14) – covering half of the valley bottom area, and has similar fluvial styles (and valley specific stream power) as the ones found in the upper reaches of the Baviaanskloof. This catchment is the biggest in the study area but from the analysis of channel attributes and aerial imagery, has not much diversity in fluvial styles which is also attributed by the erosion-resistant Arenite (sandstone) lithology where the valley is situated in, thus valley specific stream power has less influence on the channel pattern here compared to its great influence in moving the bed sediments and pattern as large cobbles and boulders are seen to have been moved by large flood power during flood events.

4.4.3. Other influences on river character and behaviour

The above analysis of river character and behaviour was focused on natural processes and changes in the landscape however, anthropogenic influences and margins (roads, embankments and constructed levees) in the catchment have caused major modification on the rivers (Smith-Adao, 2016; Powell, 2017). Wide valleys present in all the catchments have experienced modifications such as river straightening, which would have locally increased the specific stream power, increasing the rate of channel incision. Agricultural activities have, over the years, changed vegetation and land use cover at the river banks of these channels, changing the channel geometry and roughness of the channel. In confined valley reaches, fewer modifications are present however; as these are flood prone areas and the construction of low water bridges have also modified the channel geometry, slope and bed morphology through the introduction of a large barrier.

Many channel reaches (except for the ones in the Baviaanskloof catchment) experience an infestation of alien invasive species which have had dire consequences for vegetation water use in the catchments (Rebelo et al. 2015). The subsequent removal of this vegetation, even when on the hillslopes rather than in the riparian zones, has caused an increased amount of sedimentation and large woody debris, even in areas that previously did not have such river character (Rebelo et al. 2015). Some of these modifications have affected channel reaches so much that they have become degraded. There may be potential to recover previous fluvial forms through correct management practices; however, this research will not be analysing trajectories for recovery or change.

5. Synthesis

The overarching aim of the research was to develop a hierarchical nested framework for the spatial variation of river styles in three semi-arid, mountainous catchments. The aim was approached in a step-wise manner where, results obtained from each chapter informed either the data collection or the analysis and interpretation of the next. The objective was also to provide an understanding of the river character and behaviour of Baviaanskloof, Kouga and Kromme catchment by looking at drivers of fluvial styles at various spatial scales, and to give insights on developing methods that can aid in explaining the dynamics of dryland river systems.

The use of the hierarchical theory provided a constructive way of understanding the river character and behaviour of the main river system in the BKK catchments and has allowed the current study to dissect the heterogeneity of the river on various spatial scales. A diagram is provided below showing the complete process undertaken to examine the river style and behaviour in the three catchments (Figure 5.1). Ideally this process could be further developed to allow a level of prediction of fluvial style in these kinds of settings.

The process began with delineation of landscape units using a DEM based on thresholds of slope and height above nearest drainage. The dominant unit was hillslopes and toe-slopes on Peninsula formation quartzitic sandstone, which explains the amount of coarse-grained material found in the three catchments and rivers. Sedimentary analysis also confirmed this: large deposits of mixed bed load of coarse material were found in fluvial styles which were confined and partially confined in their valley settings. Brierley and Fryirs (2005) also found that these landscape units, together with this specific valley setting, possess high specific stream powers, thus are termed as source zones for sediments. These however, were found across the longitudinal profile in all three catchments, contrary to studies by Rowntree et al. (1999; 2000) indicating coarse sediments originate from upstream areas. It is evident these river systems are highly variable even within the same geomorphic setting (Thoms, 2006). Plateaus ending in steep cliffs are also common particularly in the Baviaanskloof and Kouga catchments. Where there are confined valleys, there is less connectivity to the hillslope whereas where the valley starts to widen and becomes laterally unconfined, hillslope connection tends to be very large. However, this also depends on the position of that valley setting within the catchment.

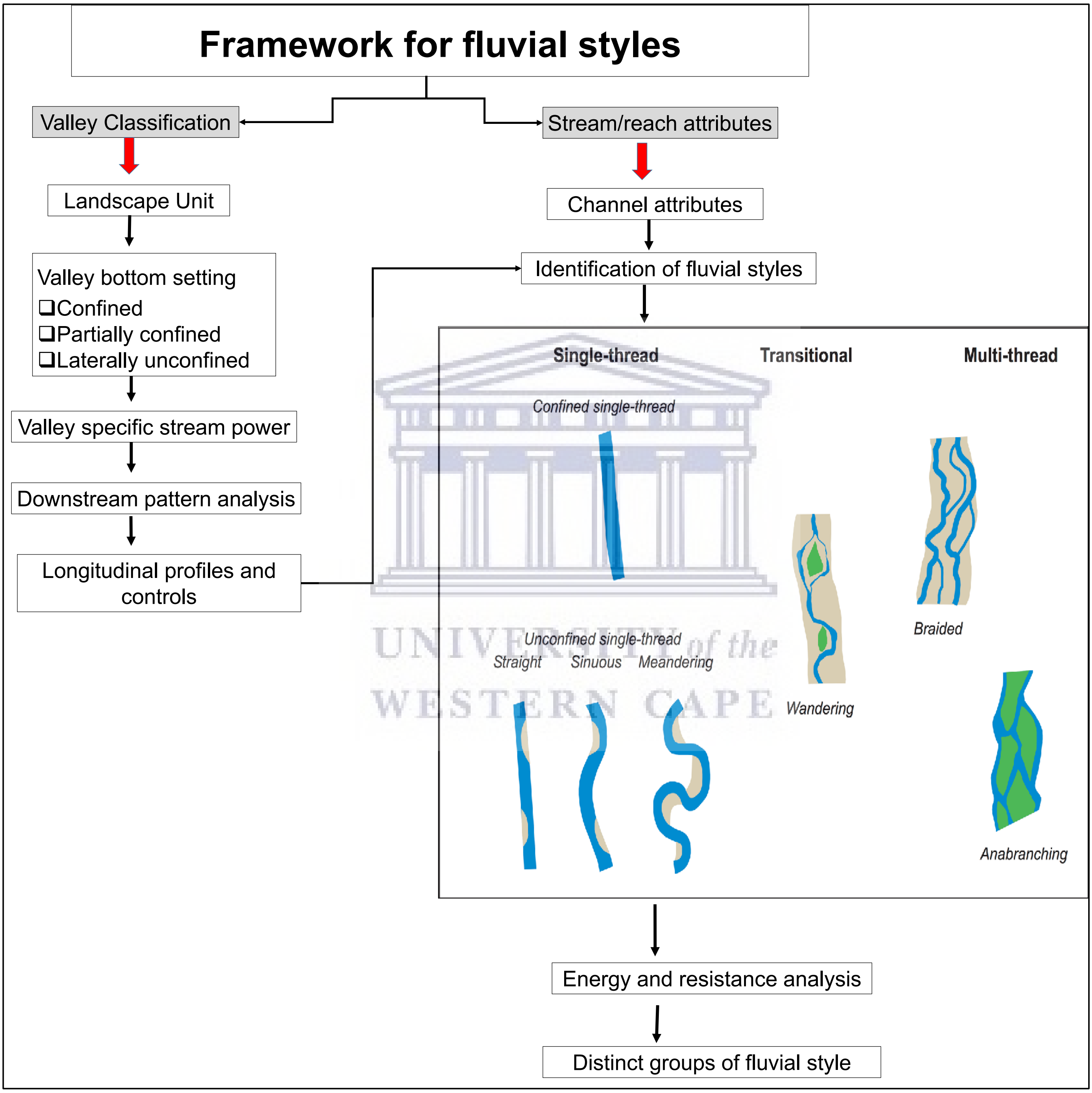


Figure 5.1: Flow diagram with the framework for predicting fluvial styles, river character and behaviour. Specific methodologies used for the framework are discussed in Chapter 3 and 4. Image source: (Belletti et al. 2014)

At the valley hierarchical level, interesting results emerged with distinct patches of valley types across the three catchments. Through the use of automated methods in extracting the valley characteristics (VSSP and confinement), the first objective was accomplished which was, looking at the variation of these characters in a longitudinal profile. As discussed earlier (Chapter 3; Section 3.4.1), the Baviaanskloof experienced the greatest variability in valley properties in both setting and valley specific stream power. Thoms (2006) argues that catchments with high variability support a number of ecosystems. This is true because fluvial styles with anabranching, wandering and straight rivers were situated in this catchment, which support a diversity of habitats. Valley setting was also found to be an indicator of channel adjustment (O'Brien and Wheaton, 2015). The Kouga had the highest average valley specific stream power which coincided with its steep gradient and large tributaries which both increase the stream power. The Kromme showed less variability in setting and energy however, typically with streams gentle in gradient which transition smoothly from a partially confined valley to laterally unconfined. Parts of the main channel in the Kromme switch over time between channelled and unchannelled environments, the channelled phase is important for shaping the valley in a way that it promotes wetland formation. During the fill phase of development, a transition to laterally unconfined valleys (alluvial fan deposits locally modify the valley pattern and slope) occurs with reaches having ample sediment storage with decreasing valley specific stream power. This sediment storage is constantly reworking with cycles of cut and fill processes caused by local changes in gradient and channel width as shown in Figure 3.6; Figure B-1. This forms deposits of fine grain material on the channel bed with gentle gradients, creating natural wetland habitat. This is compatible with the results of Pulley et al. (2018) which used geochronology instead of GIS, to characterize the formation wetlands through gully cut-and-fill cycles in the Kromme valley. Overall, the Kromme and the Baviaanskloof river were found to have the highest capacity for adjustment that is, sensitivity of a channel to natural and human disturbances (Brierley and Fryirs, 2005; Nagel et al. 2014; Wheaton et al. 2015). This is attributed to the area of laterally unconfined valleys; they are most accessible and incur disproportionate pressure from land-use.

In the channel hierarchical level, the fluvial styles in all the catchments tend to form series of patches as you travel downstream along the main river, based on characteristics based on lithology, channel slope, median bed grain size. These provided an in-depth analysis of various channel reaches, behaviour and an understanding of other physiographical controls on river form and processes which was the second objective of this study. Thirteen types of fluvial styles were observed across the BKK catchments, which were also observed in other parts of South Africa (Tooth, 2013; Eze and Knight, 2018) and in Columbia River Basin in America (O'Brien and Wheaton, 2015), Macquarie River in Australia and the Colorado River (Fryirs and Brierley, 2018). This illustrates that similar fluvial styles may be found in different regions which have similar climatic conditions, however, differences in position and function of the fluvial styles within the river systems were observed. These two objectives, completed, allowed for an explorative classification system which can be incorporated to monitoring and reporting frameworks in river management.

***What does this mean for the ecology in these catchments*?** This analysis of the river character and behaviour has provided information on the physical template for habitats. Riverine and riparian ecosystems are sensitive to flow variability, with diverse and distinct habitats (Humphries et al. 2014). For example, high valley specific stream powers (which experience high flows) provide more connectivity of the valley with the channel and the channel with geomorphic units and that can strongly influence ecologies such as aquatic macroinvertebrate communities (Thoms, 2006; Harris et al. 2009). Low VSSP fluvial styles may experience slow moving water, exacerbated by droughts and extreme climatic variability, forming pools and bars which persist and are critical habitats for algae and vegetation. There is opportunity to combine existing river ecosystem concepts in this framework, where the ecology in the river is analyzed together with the fluvial styles. As Thorp et al. (2006), noted "A few of the many examples of patterns in river networks are the alternating distribution of riffles and pools in streams, life history characteristics of species adapted for intermittent streams versus large permanent rivers, changes in functional feeding groups from headwaters to large rivers, and species replacements of microalgae colonizing rocks over time." It is imperative to study the various river ecosystem functions and how their geomorphologies operate on various, similar spatial scales.

6. Limitations and Recommendations

The study introduced some new concepts in analysing the character and behaviour such as automating the estimation of various environmental and geomorphic variables and processes. Particular method limitations were discussed in the various chapters (Chapter 3; Section 3.4). However what is evident in application of the overall framework is that the relatively small number of sample sites may not give sufficient insight across the variability and complexity observed in these catchments. More sampling is needed to be carried out in the main river channels, especially in the mid to lower parts of the catchments where all three catchments experienced the greatest variability in terms of channel attributes and the overall fluvial style characterization. The tributaries which are connected to the main river would also be great sample sites as in regions where the fans were margin controls, valley specific stream power and slope locally increased thus understanding their morphology as well might be valuable. Overall, the main river did provide a cumulative longitudinal pattern of catchment controls which took in to account the contributing area of tributaries.

In chapter 4, it was evident that the distribution and grouping of fluvial styles at channel reach scale had other influences beyond the VSSP, valley confinement, bed and bank material. These are likely to be vegetation type and form which modify the shear stress and roughness of the channels. Channel dimensions such as slope could also influence the distribution of these fluvial styles. More research is thus needed through vegetation analysis (pattern, type, size). Nevertheless, patterns did emerge which were supported by literature.

In addition, to work toward holistic planning for river management and restoration, interdisciplinary studies with fields such as ecology, zoology or chemistry would be needed, which are beyond the scope of this study. This study of the fluvial geomorphology, particularly the fluvial styles in the catchments, provides a basis for understanding the physical position ecosystems function in.

Further studies should focus on the wise-use of big data, incorporating and collecting many datasets pertaining to river character and behaviour, with the aid of machine learning and remote sensing. This can provide additional opportunity to examine the geomorphic condition; historic and current land dynamics to identify rivers in good condition and those who aren’t, to prioritize and assess their trajectories of changes in the future to inform interventions for restoration and management of river systems. As part of on-going research to automate studies in geomorphology, this study has filled a gap in knowledge where derivation of catchment and channel properties is concerned.

References

Addy S. 2009. Hierarchical controls on channel morphology in montane catchments in the Cairngorms, north-east Scotland., University of Aberdeen. **PhD**; 204.

Barker D, Lawler D, Knight DW, Morris DG, N. DH, Stewart EJ. 2009. Longitudinal distributions of river flood power: the combined automated flood, elevation and stream power (CAFES) methodology. Earth Surface Processes and Landforms **34** : 155–161. DOI: 10.1002/esp [online].

Bawa N, Jain V, Shekhar S, Kumar N, Jyani V. 2014. Controls on morphological variability and role of stream power distribution pattern, Yamuna River, western India. Geomorphology **227** : 60–72. DOI: 10.1016/j.geomorph.2014.05.016 [online].

Beechie T, Imaki H. 2014. Predicting natural channel patterns based on landscape and geomorphic controls in the Columbia River basin, USA. Water Resources Research **50** : 39–57. DOI: 10.1002/2013WR013629 [online].

Belletti B, Rinaldi M, Buijse AD, Gurnell AM, Mosselman E. 2014. A review of assessment methods for river hydromorphology. Environmental Earth Sciences **73** : 2079–2100. DOI: 10.1007/s12665-014-3558-1 [online].

Benda D, Michael M, Andras P, Reeves D. 2007. NetMap: a new tool in support of watershed science and resource management. Forest Science **53** : 206–219.

Benda L, Miller D, Barquän J. 2011. Creating a catchment scale perspective for river restoration. Hydrology and Earth System Sciences **15** : 2995–3015. DOI: 10.5194/hess-15-2995-2011[online].

van den Berg JH. 1995. Prediction of alluvial channel pattern of perennial rivers. Geomorphology **12** : 259–279. DOI: 10.1016/0169-555X(95)00014-V[online].

Beven K. 1987. Towards the use of catchment geomorphology in flood frequency predictions. Earth Surface Processes and Landforms **12** : 69-82. DOI: 10.1002/esp.3290120109 [online].

Bisson PA, Montgomery DR, Buffington JM. 2017. Valley Segments, Stream Reaches, and Channel Units. In Methods in Stream Ecology, 3rd Edition. Academic Press; 21–47.

Bizzi S, Lerner DN. 2015. THE USE OF STREAM POWER AS AN INDICATOR OF CHANNEL SENSITIVITY. River Research and Applications **27** : 16–27. DOI: 10.1002/rra.2717 [online].

Bookhagen B, Strecker MR. 2012. Spatiotemporal trends in erosion rates across a pronounced rainfall gradient: Examples from the southern Central Andes. Earth and Planetary Science Letters **327–328** : 97–110. DOI: 10.1016/j.epsl.2012.02.005.

Brierley G, Fryirs K. 2005. Geomorphology and River Management: Application of the River Styles Framework . 2nd ed. Blackwell Publications: Oxford, UK.

Brierley G, Fryirs K. 2014. Reading the Landscape in Field-Based Fluvial Geomorphology. In Developments in Earth Surface Processes , Thornbush MJ, Allen CD, and Fitzpatrick A (eds). Elsevier; 231–257. [online] Available from: http://dx.doi.org/10.1016/B978-0-444-63402-3.00013-3.

Brierley G, Jain V, Brierley G. 2008. Where do floodplains begin ? The role of total stream power and longitudinal profile form on floodplain initiation. Geological Society of American Bulletin **120** : 127–141.

DOI: 10.1130/B26092.1.

Brierley GJ, Fryirs K. 2000. River styles, a geomorphic approach to catchment characterization: Implications for river rehabilitation in Bega catchment, New South Wales, Australia. Environmental Management **25** : 661–679. DOI: 10.1007/s002670010052.

Buffington JM. 2012. Changes in Channel Morphology Over Human Time Scales. In Gravel-Bed Rivers: Processes, Tools, Environments , Church M, Biron PM, and Roy AG (eds). John Wiley & Sons, Ltd; 433–463.

Chamier J, Schachtschneider K, Maitre DC, Ashton PJ, Wilgen BW Van. 2012. Impacts of invasive alien plants on water quality , with particular emphasis on South Africa. Water SA **38** : 345–356. [online] Available from: http://dx.doi.org/10.4314/wsa.v38i2.19 (Accessed September 2017).

Chang H. 1979. Minimum stream power and river channel patterns. Journal of Hydrology **41** : 303–327. DOI: 10.1016/0022-1694(79)90068-4 [online].

Clapcott J, Young R, Harding J, Matthaei C, Quinn J, Death R. 2011. Sediment Assessment Methods: Protocols and guidelines for assessing the effects of deposited fine sediment on in-stream values. Technical Report. Unpublished. Nelson, New Zealand.

Cornelius A, Le Roux L, Glenday J, FT J, Sekese S. 2019. Particpatory Hydrological Modelling for Collective Exploration of Catchment Management in the western Algoa Water Supply Area . Pretoria, South Africa [online] Available from: http://www.wrc.org.za (Accessed 11 May 2019).

Costigan KH, Daniels MD, Perkin JS, Gido KB. 2014. Longitudinal variability in hydraulic geometry and substrate characteristics of a Great Plains sand-bed river. Geomorphology **210** : 48–58. DOI: 10.1016/j.geomorph.2013.12.017.

Craddock WH, Burbank DW, Bookhagen B, Gabet EJ. 2007. Bedrock channel geometry along an orographic rainfall gradient in the upper Marsyandi River valley in central Nepal. Journal of Geophysical Research: Earth Surface **112** : 1–17. DOI: 10.1029/2006JF000589.

Dilts T, Yang J, Weisberg P. 2010. Mapping riparian vegetation with LIDAR data. ArcUser Online, ESRI : 4. [online] Available from: https://www.ersi.com/news/arcuser/0110/mapping-riparian-with-LIDAR-data.html (Accessed 11 October 2017)

Dollar ESJ, James CS, Rogers KH, Thoms MC. 2007. A framework for interdisciplinary understanding of rivers as ecosystems. Geomorphology **89** : 147–162. DOI: 10.1016/j.geomorph.2006.07.022.

Driver A, Sink KJ, Nel JL, Holness S, van Niekerk L, Daniels F, Jonas Z, Majiedt PA, Harris L, Maze K. 2011. National Biodiversity Assessment 2011: An assessment of South Africa's biodiversity and ecosystems. Pretoria.

Durham University - SciMap. 2010. SCIMAP - Diffuse Pollution Risk Mapping: A frameowrk for modelling and mapping diffuse pollution risk across landscapes [online] Available from: http://www.scimap.org.uk/.

Euston-Brown DIW. 2006. Baviaanskloof Mega-Reserve Project: Vegetation mapping contract report on methodology, vegetation classification and short descriptions of habitat units . Project report. Eastern Cape Parks & Tourism Agency: South Africa.

Eze PN, Knight J. 2018. A geomorphological characterisation of river systems in South Africa: A case study of the Sabie River. Physics and Chemistry of the Earth **105** : 196–205. DOI: 10.1016/j.pce.2018.01.001 [online] Available from: https://doi.org/10.1016/j.pce.2018.01.001.

Fashae OA, Faniran A. 2015. Downstream morphologic characteristics of the alluvial section of Lower River Ogun, Nigeria. Journal of Environmental Geography **8** : 1–2. DOI: 10.1515/jengeo-2015-0001 [online].

Ferencevic M, Ashmore P. 2012. Creating and evaluating digital elevation model-based stream-power map as a stream assessment tool. River Research and Applications **28** : 1394-1416. DOI: 10.1002/rra.1523 [online] Available from: http://doi.wiley.com/10.1002/rra.1523 (Accessed 10 March 2017).

Finnegan NJ, Roe G, Montgomery DR, Hallet B. 2005. Controls on the channel width of rivers: Implications for modeling fluvial incision of bedrock. Geology **331** : 229–232. DOI: 10.1130/G21171.1 [online].

Fonstad MA. 2003. Spatial variation in the power of mountain streams in the Sangre de Cristo Mountains, New Mexico. Geomorphology **55** : 75–96. DOI: 10.1016/S0169-555X(03)00133-8 [online].

Frissell CA, Liss WJ, Warren CE, Hurley MD. 1986. A hierarchical framework for stream habitat classification. Environmental management **10** : 199–214.

Fryirs K, Brierley GJ. 2010. Antecedent controls on river character and behaviour in partly confined valley settings: Upper Hunter catchment, NSW, Australia. Geomorphology **117** : 106–120. DOI: 10.1016/j.geomorph.2009.11.015 [online].

Fryirs KA, Brierley GJ. 2013. Geomorphic Analysis of River Systems: An approach to reading the landscape . 1st ed. Fryirs KA and Brierley GJ (eds). Blackwell Publishing Ltd: United Kingdom.

Fryirs KA, Brierley GJ. 2018. What’s in a name? A naming convention for geomorphic river types using the River Styles Framework. Magar V (ed). PLOS ONE **13** : e0201909. DOI: 10.1371/journal.pone.0201909 [online].

Fryirs KA, Wheaton JM, Brierley GJ. 2016. An approach for measuring confinement and assessing the influence of valley setting on river forms and processes. Earth Surface Processes and Landforms **41** : 701–710. DOI: 10.1002/esp.3893.

Gallant JC, Dowling TI. 2003. A multiresolution index of valley bottom flatness for mapping depositional areas. Water Resources Research **39** DOI: 10.1029/2002WR001426 [online]

Gartner J. 2016. Stream Power: Origins, Geomorphic Applications, and GIS Procedures Stream Power: Origins, Geomorphic Applications, and GIS Procedures . Massachusetts [online] Available from: http://scholarworks.umass.edu/water_publications (Accessed 6 March 2017).

Gilbert JT, Macfarlane WW, Wheaton JM. 2016. The Valley Bottom Extraction Tool (V-BET): A GIS tool for delineating valley bottoms across entire drainage networks. Computers and Geosciences **97** : 1–14. DOI: 10.1016/j.cageo.2016.07.014 [online].

Golden LA, Springer GS. 2006. Channel geometry, median grain size, and stream power in small mountain streams. Geomorphology **78** : 64–76. DOI: 10.1016/j.geomorph.2006.01.031 [online].

Guo-An Y, Le L, Zhiwei L, Yanfu L, Heqing H, Brierley G, Blue B, Zhaoyin W, Baozhu P. 2013. Fluvial diversity in relation to valley setting in the source region of the Yangtze and Yellow Rivers. **23** : 817–832. DOI: 10.1007/s11442-013-1046-2 [online].

Gurnell AM et al. 2016. A multi-scale hierarchical framework for developing understanding of river behaviour to support river management. Aquatic Sciences **78** : 1–16. DOI:

10.1007/s00027-015-0424-5 [online].

Hall JE, Holzer DM, Beechie TJ. 2007. Predicting river floodplain and lateral channel migration for salmon habitat conservation. Journal of the American Water Resources Association **43** : 786–797. DOI: 10.1111/j.1752-1688.2007.00063.x.

Harris C, Thoms M, Scown M. 2009. The ecohydrology of stream networks. IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences **328** : 127–136. [online] Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-78951486462&partnerID=40&md5=5b879648084ef07660730e5263d6ba13 (Accessed 16 July 2018).

Harvey A. 2001. Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England. CANTENA **42** : 225–250.

Hoare DB et al. 2006. Albany Thicket Biome. In The vegetation of South Africa, Lesotho and Swaziland , Mucina L and Rutherford MC (eds). Strelitzia: Pretoria; 541–567.

Hogan D, Luzi DS. 2010. Channel geomorphology: Fluvial forms, processes, and forest management effects. 331–371 pp. [online] Available from: http://www.researchgate.net/publication/233777058_Compendium_of_forest_hydrology_and_geomorphology_in_British_Columbia_Volume_1_of_2/file/79e4150b624210d656.pdf#page=370 (Accessed 20 April 2017).

Hull P. 2013. Kouga Dam rehabilitation project: Desktop hydrology assessment. Jeffares & Green: Engineering and Environmental Consulting, Port Elizabeth. Technical Report; 14.

Humphries P, Keckeis H, Finlayson B. 2014. The River Wave Concept : Integrating River Ecosystem Models. BioScience **64** : 870–882. DOI: 10.1093/biosci/biu130.

Ibisate A, Ollero A, Díaz E. 2011. Influence of catchment processes on fluvial morphology and river habitats. Limnetica **29** : 169-182. [online] Available from: http://www.limnetica.com/ Limnetica/Limne30/L30b169_Catchment_processes_fluvial_morphology.pdf (Accessed 20 March 2017).

Jaeger KL, Sutfin NA, Tooth S, Michaelides K, Singer M. 2017. Intermittent Rivers and Ephemeral Streams. In Intermittent Rivers and Ephemeral Streams: Ecology and Management , Datry T, Bonada N, and Boultonn & A (eds). Elsevier Inc.: Washington; 21–49. [online] Available from: http://dx.doi.org/10.1016/B978-0-12-803835-2.00002-4 [online].

Jain V, Preston N, Fryirs K, Brierley G. 2006. Comparative assessment of three approaches for deriving stream power plots along long profiles in the upper Hunter River catchment, New South Wales, Australia. Geomorphology **74** : 297–317.DOI:10.1016/j.geomorph.2005.08.012 [online].

Junk W, Bayley P, Sparks R. 1989. The flood pulse concept in river–floodplain systems. Canadian Journal of Fisheries and Aquatic Sciences Special Publication **106** : 110–127.

Kasprak A, Caster J, Bangen SG, Sankey JB. 2017. Geomorphic Process from Topographic Form: Automating the Interpretation of Repeat Survey Data in River Valleys. Earth Surface Processes and Landforms DOI: 10.1002/esp.4143 [online].

Kastens JH. 2008. Some new developments on two separate topics: Statistical cross validation and floodplain mapping [online] Available from: https://search.proquest.com/docview/193661977?accountid=14166%0Ahttp://xg9ax2jm9j.search.serialssolutions.com?ctx_ver=Z39.88 2004&ctx_enc=info:ofi/enc:UTF 8&rfr_id=info:sid/ProQuest+Dissertations+%26+The

ses+Global&rft_val_fmt=info:ofi/fmt:kev:mtx:disserta. (Accessed 15 November 2015).

Kleinhans MG, van den Berg JH. 2011. River channel and bar patterns explained and predicted by an empirical and a physics-based method. Earth Surface Processes and Landforms **36** : 721–738. DOI: 10.1002/esp.2090.

Knighton ADD. 1999. Downstream variation in stream power. Geomorphology **29** : 293–306. DOI: 10.1016/S0169-555X(99)00015-X [online] Available from: http://www.sciencedirect.com /science/article/pii/S0169555X9900015X (Accessed 12 April 2017).

Kondolf GM, Piégay H. 2016. Tools in Fluvial Geomorphology. 2nd Edition. Kondolf GM and Hervé P (eds). John Wiley & Sons: Chichester, UK ; Hoboken, NJ: 560; ISBN: 978-0-470-684405-4.

Kuo C-WW, Chen C, Chen S, Yang T, Chen CW. 2017. Channel Planform Dynamics Monitoring and Channel Stability Assessment in Two Sediment-Rich Rivers in Taiwan. Water **9** : 84. DOI: 10.3390/w9020084 [online] Available from: http://www.mdpi.com/2073-4441/9/2/84 (Accessed 22 March 2018).

Lane BA, Pasternack GB, Dahlke HE, Sandoval-Solis S. 2017. The role of topographic variability in river channel classification. Progress in Physical Geography **41** : 570–600. DOI: 10.1177/0309133317718133.

Lea DM, Legleiter CJ. 2016. Mapping spatial patterns of stream power and channel change along a gravel-bed river in northern Yellowstone. Geomorphology **252** : 66–79. DOI: 10.1016/j.geomorph.2015.05.033 [online] .

Lecce SA, Lecce SA. 2016. Nonlinear Downstream Changes in Stream Power on Wisconsin 's Blue River Nonlinear Downstream Changes in Stream Power on Wisconsin s Blue River. Annals of the Association of American Geographers **87** :3. Blackwell Publishers: 417-486.

Lisenby PE, Fryirs KA. 2017. Sedimentologically significant tributaries: catchment-scale controls on sediment (dis)connectivity in the Lockyer Valley, SEQ, Australia. Earth Surface Processes and Landforms **42** : 1493–1504. DOI: 10.1002/esp.4130.

Lord M, Germanoski D, Allmendinger N. 2009. Fluvial geomorphology: Monitoring stream systems in response to a changing environment. In Geological Monitoring: Boulder, Colorado, Geological Society of America , Young, R., & Norby L (ed). The Geological Society of America; 66-99. [online] Available from: https://nature.nps.gov/geology/monitoring/ files/geomon-04.pdf (Accessed 26 April 2017).

Lynch SSD. 2003. Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa. WRC Report. Water Research Commission (WRC): Pretoria, South Africa, South Africa.

Marçal M, Brierley G, Lima R. 2017. Using geomorphic understanding of catchment-scale process relationships to support the management of river futures: Macaé Basin, Brazil. Applied Geography **84** : 23–41. DOI: 10.1016/j.apgeog.2017.04.008.

Martínez-Fernández V, González del Tánago M, Maroto J, Gracía de Jálon D. 2017. Fluvial Corridor Changes Over Time in Regulated and Non-Regulated Rivers (Upper Elsa River, NW Spain). River Res. Applic. **33** : 214–223. DOI: doi:10.1002/rra.3032.

McKean J, Nagel D, Tonina D, Bailey P, Wright CW, Bohn C, Nayegandhi A. 2009. Remote sensing of channels and riparian zones with a narrow-beam aquatic-terrestrial LIDAR. Remote Sensing **1** : 1065–1096. DOI: 10.3390/rs1041065.

Meigh JR, Farquharson FAK, Sutcliffe J V. 1997. A worldwide comparison of regional flood estimation methods and climate. Hydrological Sciences Journal **42** : 225–244. DOI: 10.1080/02626669709492022 [online] Available from: http://www.tandfonline.com/doi/abs/10.1080/02626669709492022.

Middleton BJ, Bailey AK. 2011. Water resources of South Africa, 2005 study (WR 2005): report to the Water Research Commission. No. TT 512/11 . Volume 2. Water Research Commission (WRC): Gezina, South Africa.

Montgomery D., Buffington J. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of American Bulletin **109** : 596–611. [online] Available from: https://watershed.ucdavis.edu/education/classes/files/content/page/Montgomery(1997).pdf (Accessed 14 March 2017).

Moore ID, Grayson RB, Ladson a R. 1991. Digital Terrain Modeling : A Review of Hydrological Geomorphological and Biological Applications. Hydrological Processes **5** : 3–30. DOI: DOI: 10.1002/hyp.3360050103.

Mucina L, Rutherford MC, Powrie W, Gerber J, Bezuidenhout H, Sieben EJJ, Cilliers SS, Preez PJ, Manning JC, Hoare B, Boucher C, Rebelo AG, George J, Siebert F. 2006. Inland Azonal Vegetation. In The vegetation of South Africa, Lesotho and Swaziland , Mucina L and Rutherford M (eds). Strelitzia: Pretoria; 618–652.

Mucina L, Geldenhuys CJ, Rutherford MC, Powrie LW, Lötter MC, Maltitz GP Von, Euston-Brown DIW, Wayne S, Dobson L, Mckenzie B. 1984. Afrotemperate, Subtropical and Azonal Forests. In The vegetation of South Africa, Lesotho and Swaziland , Mucina L and Rutherford MC (eds). Strelitzia: Pretora; 586–610.

Mucina L, Rutherford MC, Powrie LW, Mucina L, Rutherford MC. 2006b. Logic of the map: Approaches and procedures. In The vegetation of South Africa, Lesotho and Swaziland , Mucina L and Rutherford MC (eds). Strelitza: Pretoria : 12–29.

Nagel DE, Buffington JM, Parkes SL, Wenger S, Goode JR. 2014. A landscape scale valley confinement algorithm: Delineating unconfined valley bottoms for geomorphic, aquatic, and riparian applications [online] Available from: http://www.treesearch.fs.fed.us/pubs/45825.

Nanson GC, Croke JC. 1992. A genetic classification of floodplains. Geomorphology **4** : 459–486. DOI: 10.1016/0169-555X(92)90039-Q.

Van Niekerk A. 2016. Stellenbosch University Digital Elevation Model (SUDEM): 2016 Edition (v16.xx). Technical report [online] Available from: https://www.researchgate.net/publication/299336022_Stellenbosch_University_Digital_Elevation_Model_SUDEM_2016_Edition_v16xx.

Noble R, Hermens J. 1978. Inland water ecosystems in South Africa - a review of research needs. South African National Scientific Programmes Report No 34. Pretora.

O'Brien G, Wheaton JM. 2015. River Styles Report for the Middle Fork John Day Watershed, Oregon. Ecogeomorphology & Topographic Analysis Lab: Fluvial Habitat Center. Prepared for Eco Logical Research, and Bonneville Power Administration Logan, Utah, Utah State University; 215.

O'Brien GR, Wheaton J, Fryirs K, Mchugh P, Brierley G, Jordan C, Brien GRO, Wheaton J, Fryirs K, Mchugh P. 2017. A geomorphic assessment to inform strategic stream restoration planning in the Middle Fork. Journal of maps **5647** DOI: 10.1080/17445647.2017.1313787.

Parsons M, Thoms MC. 2007. Hierarchical patterns of physical-biological associations in river ecosystems. Geomorphology **89** : 127–146. DOI: 10.1016/j.geomorph.2006.07.016.

Partridge TC, Dollar ES., Moolman J, Dollar LH. 2010. The geomorphic provinces of South Africa, Lesotho and Swaziland: A physiographic subdivision for earth and environmental scientists. Transactions of the Royal Society of South Africa **65** : 1–47. DOI: 10.1080/00359191003652033 [online].

Phillips JD, Slattery MC. 2007. Downstream trends in discharge, slope, and stream power in a lower coastal plain river. Journal of Hydrology **34** : 290-303. DOI: 10.1016/j.jhydrol.2006.10 .018.

Piégay H, Alber A, Slater L, Bourdin L. 2009. Census and typology of braided rivers in the French Alps. Aquatic Sciences **71** : 371–388. DOI: 10.1007/s00027-009-9220-4.

Powel MD. 2009. Dryland Rivers: Processes and Forms. Geomorphology of Desert Environments. 2nd ed. Parsons AJ and Abrahams D (eds). Springer Science: 831. DOI: 10.1007/978-1-4020-5719-9.

Powell R. 2017. Geomorphological connectivity and sensitivity examined in a recently degraded gravel-bed: Implications for floodplain rehabilitation, Rhodes University. **PhD**: 283.

Pulley S, Ellery WN, Lagesse J V., Schlegel PK, McNamara SJ. 2018. Gully erosion as a mechanism for wetland formation: An examination of two contrasting landscapes. Land Degradation and Development **29** : 1756–1767. DOI: 10.1002/ldr.2972.

Rebelo AG, Boucher C, Helme N, Mucina L, Rutherford MC. 2006. Fynbos Biome. In The Vegetation of South Africa, Lesotho and Swaziland , Mucina L and Rutherford MC (eds). Strelitzia: Pretoria; 53–219.

Rebelo AJ, Le Maitre D, Esler KJ, Cowling RM. 2015. Hydrological responses of a valley-bottom wetland to land-use/land-cover change in a South African catchment: making a case for wetland restoration. Restoration Ecology **23** : 829-841. DOI: https://doi.org/10.1111/ rec.12251.

Reinfelds I, Cohen T, Batten P, Brierley G. 2004. Assessment of downstream trends in channel gradient, total and specific stream power: a GIS approach. Geomorphology **60** : 403-416. DOI: 10.1016/j.geomorph.2003.10.003 [online] Available from: http://www.sciencedirect.com/science/article/pii/S0169555X03003556 (Accessed 8 May 2017).

Riverscapes. 2017. Confinement Tool. Riverscapes Consortium [online] Available from: http://confinement.riverscapes.xyz (Accessed 5 March 2018).

Rosgen DL. 1994. A classification of natural rivers: Reply. Catena **22** : 169–199. DOI: 10.1016/0341-8162(94)90001-9.

Roux, C., Alber, A., Piégay H. 2013. Centerline guideline for the FluvialCorridor toolbox, a new ArcGIS toolbox package for exploring multiscale riverscape at a network scale. Sedalp (Sediment Management in Alpin Basins) and CNRS (UMR5600).

Roux C, Alber A, Bertrand M, Vaudor L, Piégay H. 2015. “FluvialCorridor”: A new ArcGIS toolbox package for multiscale riverscape exploration. Geomorphology **242** : 29–37. DOI: 10.1016/j.geomorph.2014.04.018 [online] Available from: http://www.sciencedirect.com/science/article/pii/S0169555X14002219 (Accessed 9 May 2017).

Rowntree KM, Wadeson RA. 1999. A hierarchical geomorphological model for the classification of selected South African rivers . WRC Report No. 497/1/99.

Rowntree KM, Wadeson RA, O’Keeffee JO. 2000. The development of a geomorphological classification system for the longitudinal zonation of South African rivers. South African Geographical Journal **82** : 163–172.

Ruefenacht B, Guay T, Finco M, Brewer K. 2005. Developing an Image-Based Riparian Inventory Using a Multistage Sample : Phase I Report; Department of Agriculture, Forest and Engineering: United States. Prepared for Remote Sensing Applications Centre; 17.

Rutherford MC, Mucina L. 2006. Introduction. In The Vegetation of South Africa, Lesotho and Swaziland , Mucina L and Rutherford MC (eds). Pretoria; 3–11.

Schlegel P. 2017. Spatial Variation in modelled hydrodynamic characteristic associated with valley confinements in the Krom River Wetland: Implications for the initiation of erosional gullies, Rhodes University. MSc; 85.

Schmitt R, Bizzi S, Castelletti A. 2014. Characterizing fluvial systems at basin scale by fuzzy signatures of hydromorphological drivers in data scarce environments. Geomorphology **214** : 69–83. DOI: 10.1016/j.geomorph.2014.02.024 [online].

Skowno AL et al. 2018. National Biodiversity Assessment 2018: The status of South Africa's ecosystems and biodiversity. Synthesis Report. South African National Biodiversity Institute, an entity of the Department of Environment, Forestry and Fisheries, Pretoria; 1-214.

Smith-Adao LB. 2016. Links Between Valley Confinement, Landforms and Vegetation Distribution in a Semi-Arid Valley Floor Environment, Baviaanskloof, South Africa, Rhodes University. **PhD**; 248.

Smith JS, Chandler J, Rose J. 2009. High spatial resolution data acquisition for the geosciences: kite aerial photography. Earth Surface Processes and Landforms **34** : 155–161. DOI: 10.1002/esp [online].

Song S, Schmalz B, Fohrer N. 2014. Simulation and comparison of stream power in - channel and on the floodplain in a German lowland area. Journal of Hydrology & Hydromech : 133–144. DOI: 10.2478/johh-2014-0018.

Stacey M, Rutherfurd I. 2007. Testing specific stream power thresholds of channel stability with GIS. Proceedings of the 5th Australian Stream Management Conference. Australian rivers: making a difference. Charles Sturt University, Thurgoona, New South Wales: 384–389.

Strager J, Yuill C, Wood P. 2000. Landscape-based Riparian Habitat Modeling for Amphibians and Reptiles using ARCINFO GRID and ArcView. USGS sciencebase : 7. [online] Available from: http://proceedings.esri.com/library/userconf/proc00/professional/papers/PAP575/p575.htm (Accessed 26 September 2017).

Straumann RK, Purves RS. 2008. Delineation of valleys and valley floors. Cova TJ (Eds). GIScience 2008, LNCS 5266. Springer-Verlag Berlin Heidelberg; 320 -336.

Thompson C, Croke J. 2013. Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer valley, southeast Queensland, Australia. Geomorphology **197** : 156–169. DOI: 10.1016/j.geomorph.2013.05.006 [online].

Thoms MC. 2006. Variability in riverine ecosystems. River Res. Applic. **121** : 115–121. DOI: 10.1002/rra.900.

Thorp J, Delong M. 1994. The riverine productivity model: An heuristic view of carbon sources and organic processing in large river ecosystems. Oikos **70** : 305–308.

Thorp J, Delong M, Greenwood K, Casper A. 1998. Isotopic analysis of three food web theories in constricted and floodplain regions of a large river. Oecologia **117** : 551–563. DOI: https://doi.org/10.1007/s004420050692.

Thorp J, Thoms M, Delong M. 2008. The Riverine Ecosystem Synthesis: Toward Conceptual Cohesiveness in River Science . 1st ed. Thorp J, Thoms M, and Delong M (eds). Amsterdam Academic Press - Aquatic ecology series.

Thorp JH, Thoms MC, Delong MD. 2006. The riverine ecosystem synthesis: Biocomplexity in river networks across space and time. River Research and Applications **22** : 123–147. DOI: 10.1002/rra.901.

Tooth S. 2000. Process, form and change in dry land rivers: a review of recent research. Journal of Earth Sciences **51** : 67–107.

Tooth S. 2013. Dryland fluvial environments: assessing distinctiveness and diversity from a global perspective. In Treatise on Geomorphology , Shroder F (Editor in C and Wohl E (Volume E (eds). Elsevier Inc.: San Diego, CA; 612–644.

Tooth S, McCarthy TS. 2007. Wetlands in drylands: Geomorphological and sedimentological characteristics, with emphasis on examples from southern Africa. Progress in Physical Geography **31** : 3–41. DOI: 10.1177/0309133307073879.

Vannote R, Minshall G, Cummins K, Sedell J, Cushing C. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences **37** : 130–137. DOI: https://doi.org/10.1139/f80-017.

van den Berg JH. 1995. Prediction of alluvial channel pattern of perennial rivers. Geomorphology **12** : 259–279. DOI: 10.1016/0169-555X (95) 00014-V .

van Luijk G, Cowling RM, Riksen MJPM, Glenday J. 2013. Hydrological implications of desertification: Degradation of South African semi-arid subtropical thicket. Journal of Arid Environments **91** : 14–21. DOI: 10.1016/J.JARIDENV.2012.10.022 [online] Available from: https://www.sciencedirect.com/science/article/abs/pii/S0140196312002996 (Accessed 30 September 2019).

van der Watt H. 1966. Improved tables and simplified procedure for soil particle size analysis by the hydrometer method. South African Journal of Agricutural Sciences **9** : 911–916.

Venticinque E, Forsberg B, Barthem R, Petry P, Hess L, Mercado A, Cañas C, Montoya M, Durigan C, Goulding M. 2016. An explicit GIS-based river basin framework for aquatic ecosystem conservation in the Amazon. Earth System Science Data **8** : 651–661. DOI: 10.5194/essd-8-651-2016.

Vyverberg K. 2010. A Review of Stream Processes and Forms. Technical Report; California Department of Fish and Game. California; 36.

Walterman M, Fisk H, Lachowski H, Maus P, Stephens R, Breeden C, Rightmyer D. 2006. Mapping Valley Bottoms for Resource Management; Technical Report. Watershed Management. Prepared for United States Department of Agriculture; 4.

Wheaton JM, Brierley G, Bangen S, Brien GRO. 2015. Geomorphic Mapping and Taxonomy of Fluvial Landforms. Geomorphology **248** : 273–295. DOI: 10.1016/j.geomorph.2015.07.010 [online] .

Williams WA, Jensen ME, Winne CJ, Redmond RL. 2000. AN AUTOMATED TECHNIQUE FOR DELINEATING AND. Environmental Monitoring and Assessment **64**. Kluwer Academic Publishers; Netherlands: 105–114.

Wolfert H.P. 2001. Geomorphological Change and River Rehabilitation. Faculty of geosciences. Utrecht University. **PhD**; 199.

Appendix A

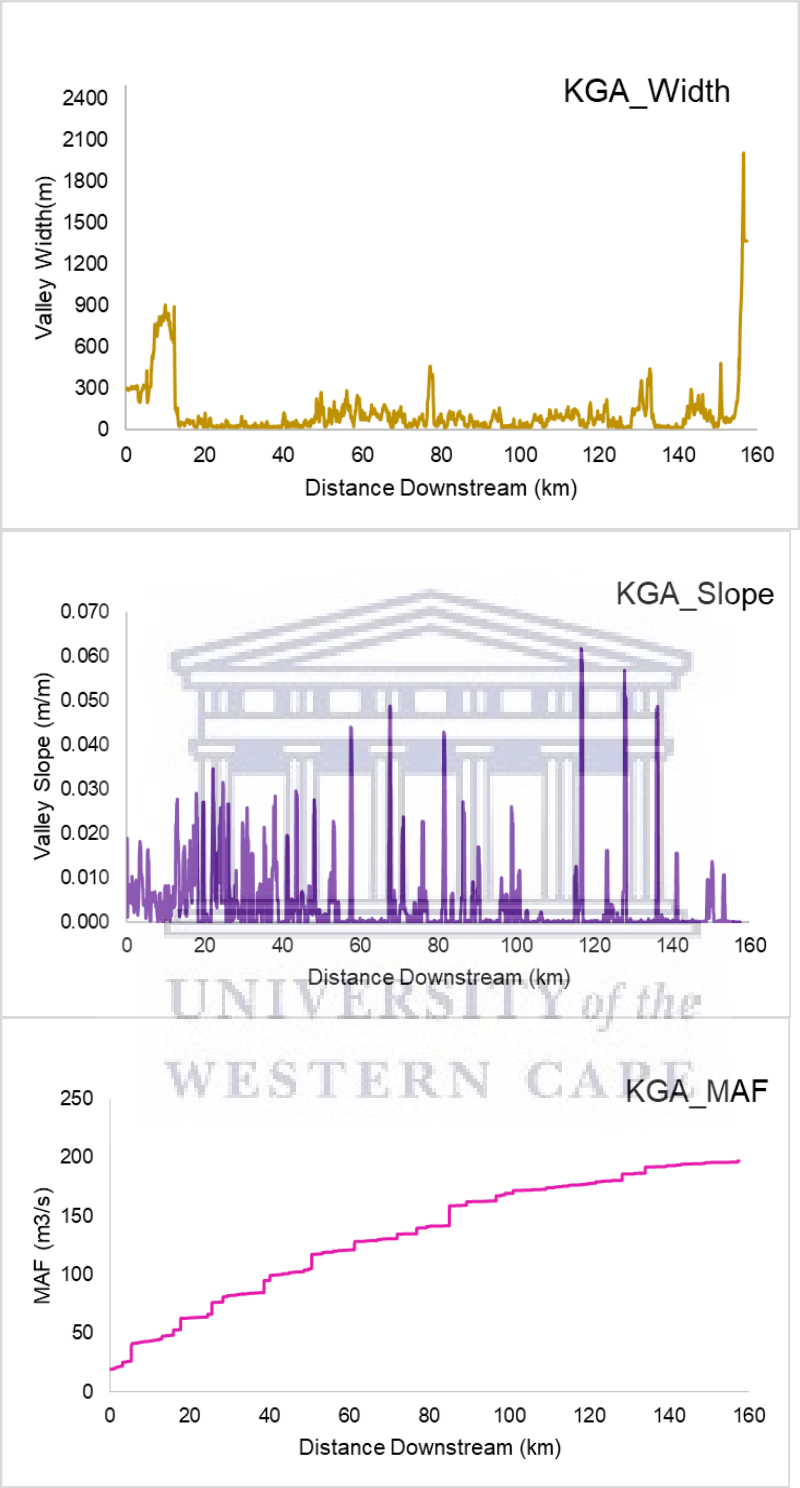


Figure A-1: Graphing of input data used to calculate VSSP in Kouga

Appendix B

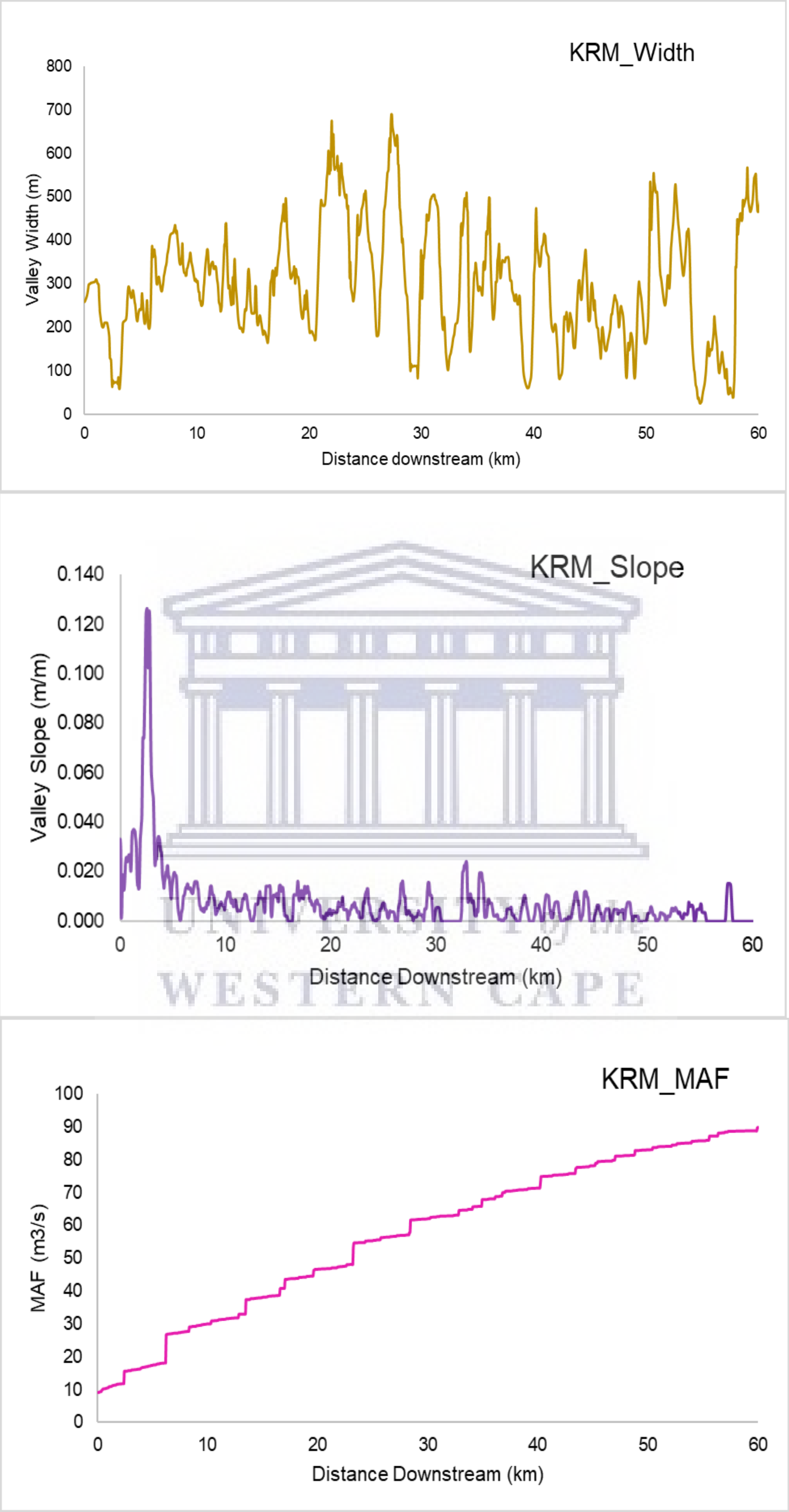


Figure B-1: Graphing of input data used to calculate VSSP in Kromme

Appendix C

Table C-1: Percent of Sand, silt and clay analyzed from Elsenburg Laboratory

Klant / Client: LivingLands

Lab Verwysing / Lab Reference: PS-2018.01.028
Kliënt verwysing / Client Reference: S P Sekese

Lab No	Monsterverwysing / Sample Reference	Tekstuur / Texture	Sand	Slik / Silt	Klei / Clay	Total Silt and Clay	Site Name
			(%)	(%)	(%)	%	
N/A	BVK_Rus_Vre_BT	Sand	92	2	6	**8**	Rus en vrede
PS/18/00323	BVK_BOKLF_BT	Sand	91	4	5	**9**	BoKloof
PS/18/00328	BVK_KMKLF_BT	Sandy Loam	71	24	5	**29**	Kamerkloof
PS/18/00331	BVK-KGA_Conf_BT	Loamy Sand	87	6	7	**13**	BVK-KGA Confluence
PS/18/00332	BVK_NATRES1_BT	Loamy Sand	85	10	5	**15**	NatRes
N/A	BVK_Joac_BT	Sand	91	4	5	**9**	Joachimskraal
PS/18/00338	BVK_RIERIV_BT	Sand	92	4	4	**8**	Rietrivier
PS/18/00342	BVK_VELREN1	Loamy Sand	85	6	9	**15**	Verlorenrivier1
PS/18/00343	BVK_NUWKLF_BT	Sand	94	2	4	**6**	Nuwekloof
PS/18/00344	BVK_VELREN2_BT	Loamy Sand	84	8	8	**16**	Verlorenrivier2
PS/18/00349	KGA_Krit_Bra_BT	Sand	89	6	5	**11**	Kritplaas-Brandhoek
PS/18/00351	KGA_MelkHKraa_BT	Sand	91	4	5	**9**	Melkhoute Kraal
PS/18/00352	KGA_Braa_BT	Sandy Loam	77	16	7	**23**	Braamrivier
PS/18/00357	KRM_Kom_BT	Sand	93	2	5	**7**	Kompanjiesdrift
PS/18/00359	KRM_KruKra_BT	Sand	89	6	5	**11**	Krugers Kraal
PS/18/00360	KRM_Jag_BT	Sand	94	2	4	**6**	Jagerbos