Investigating associations between fluvial style and the characteristics and distribution of geomorphic units in non-perennial rivers

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Declaration

I declare that the thesis entitled, "Investigating associations between fluvial style and the characteristics and distribution of geomorphic units in non-perennial rivers" is my own work, that it has not been submitted for any degree or examination in any other university, and that all sources I have used or quoted have been indicated and acknowledged my means of complete references.

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Date: 1 June 2019

Signature:……………………………………………………

Abstract

Although non-perennial rivers are the most dominant river type in arid and semi-arid areas, far outnumbering perennial rivers, recent reviews have shown that the knowledge base supporting non-perennial river research is still in its infancy. This is a cause for concern as non-perennial rivers are increasing in number due to climate and other environmental change, and over-exploitation of catchment water resources. Thus more research is needed to improve decision support in the management of non-perennial systems. This thesis examines key geomorphic units found in non-perennial reaches with contrasting fluvial styles in the Touws and Prins Rivers, semi-arid Little Karoo, Western Cape. The study analyses the different types of bar located within these characterised fluvial styles, as the building blocks of physical habitat suitability and diversity.

Few studies have assessed and investigated the physical characteristics of non-perennial rivers, and this knowledge gap provided the opportunity to examine and explain the associations between fluvial style, and the characteristics and distribution of geomorphic units. In this research, a procedure to observe and measure the characteristics of morphologic features was developed and applied. The approach was based on identifying and describing the morphometric characteristics of channel and floodplain features identified by aerial image analysis and field survey.

Four reaches were surveyed in the study area, including one unconfined single- to dual-thread channel, one single-thread confined channel and two unconfined wandering channels. Analyses of the channel pattern, channel and bar morphology as well as sediment characteristics revealed that forced mid-channel bars associated with leeward deposition behind *Vachellia karroo* trees and woody debris piles were the dominant geomorphic unit across all the study sites. It was further observed that sand and gravel bars were more dominant in the unconfined and wandering channels, and cobble bars were few in all the study sites. Bars in the unconfined and wandering channels were densely and irregularly spaced compared to the bars in the confined channel which were more evenly spaced.

Literature suggested that reaches with the same channel pattern and channel type would display a similar aggregation of bars. However, this was not always observed as the formation of bars was strongly determined by the sediment type and the in-channel / valley floor vegetation which re-route flow, promoting erosion and / or deposition of sediment. Field observations suggest that sediment type and vegetation plays an important role in influencing the distribution of bars in the channel. Furthermore it was discovered that in-channel obstructions are responsible for the formation of forced geomorphic units. These obstructions do not however determine the substrate characteristics of these forced geomorphic units. Through a process of elimination, the valley setting was found to play a greater role in determining the substrate composition of geomorphic units, although local variations in tributary sediment supply may also influence this. It was further found that the morphology of forced geomorphic units was not related to their substrate characteristics.

Keywords: River health; Geomorphic integrity; Physical habitat hierarchy; Physical habitat diversity

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ABREVIATIONS

AI:	Aridity Index
dGPS:	Differential Global Positioning System
GU:	Geomorphic Unit
MAP:	Mean Annual Precipitation
MAR:	Mean Annual Rainfall
MASL:	Meters Above Sea Level
NPR:	Non-Perennial River
PES:	Present Ecological State
UNEP:	United Nations Environment Programme
Veg:	Vegetation
WMA:	Water Management Area
XS:	Cross Section

1. Introduction

1.1 Background

Rivers create unique patterns and can change the face of landscapes over seasonal, decadal, centennial and millennial timescales. The planform pattern of a river is self-organising due to the spatial sorting processes of sediment during flow creating geomorphic units (hereafter GU's), which may interact with flow and sediment transport to enhance pattern development (Kleinhans, 2010). The fluvial style of rivers is defined as the plan view configuration of a river that is influenced by the GU's located in the channel (Brierley and Fryirs, 2005). For example, the percentage of channel length covered by bars and islands is used to determine the degree of braiding (Brierley and Fryirs, 2005). The sorting styles of sediment vary among different types of channel pattern, however, and may be strongly influenced by the floodplain and riparian vegetation (Kleinhans, 2010). These ideas apply to both perennial and non-perennial rivers (hereafter NPR's).

Perennial rivers are those that have continuous surface flow throughout the year, even during times of drought (Rossouw *et al.,* 2005; Skoulikidis *et al*., 2016). Their counterpart, NPR's, flow for a certain time of year and cease to have surface flow in the same year, or may experience periods of no flow that extend beyond a year (Skoulikidis *et al*., 2016). One of the key factors influencing the distribution of NPR's is climate, with most NPR's being located in low latitude and low altitude warm environments with varying degrees of aridity and across a wide range of lithological settings (Tooth, 2013).

NPR's located in drylands are extremely important, as Konnerth (2015) explained that these rivers support both ecosystem and human needs alike. NPR's are the only controllable surface water source in arid and semi-arid environments, and support a range of activities including irrigation, domestic and industrial use (Konnerth, 2015). However, these rivers have become highly modified due to the increasing demands on dryland water resources (Konnerth, 2015).

Skoulikidis *et al*. (2016) used specific flow regimes to classify NPR's and explained that intermittent rivers cease to flow seasonally and last for weeks to months (more than 8 months). Ephemeral rivers only flow in response to precipitation or snowmelt events and last for days to weeks (less than 8 months) (Skoulikidis *et al*., 2016). Episodic rivers only flow for very short periods and last for hours to days, mostly occurring after heavy rainfall events (Skoulikidis *et al*., 2016). The primary distinction between NPR's and perennial rivers lies in their hydrological systems (Seaman *et al*., 2010). The hydrological system of NPR's is spatially and temporally more variable than perennial rivers (Seaman *et al*., 2010). Seaman *et al*. (2016) described NPR's as rivers with a different hydrology compared to perennial rivers, and noted that each NPR is hydrologically distinctive due to the highly variable nature of catchment runoff regimes. NPR's are among the most dynamic, complex and diverse freshwater systems (Skoulikidis *et al*., 2016). They are located in all regions around the world and are by far the most dominant river type in both arid and semi-arid areas (Skoulikidis *et al*., 2016).

The identification of GU's in rivers is challenging, and in fluvial geomorphic literature there is no simple way to classify GU's due to the complex variation among different channels (Wheaton *et al*., 2015). This leads to inconsistencies in describing fluvial landforms (Wheaton *et al*., 2015). The lack of a simple taxonomy makes it challenging to map the GU's in river channels and interpret the work that they do in shaping the river (Wheaton *et al*., 2015). Furthermore, geomorphologists use inconsistent terms to describe GU's that confuse both geomorphologists and non-geomorphologists (Wheaton *et al*., 2015). However, the classification system developed by Brierley and Fryirs (2005) covers a wide range of GU's, is easy to follow, and was designed for dryland environments. This classification system was therefore used to describe GU's in this thesis.

Brierley and Fryirs (2005) explained that mid-channel GU's are accumulations of sediment and are often referred to as bars. Phillips (2011) explained that GU's are specific landforms within a river reach, and may include point bars, forced bars, mid-channel bars, natural levees and riffle-pool sequences that are formed by the erosion of bedrock or by the deposition and erosion of alluvium (Lehotskỳ, 2004). There are many terms that geomorphologists use to describe river landforms, including GU's, channel GU's, habitat units, morphological units and morphostratigraphic units (Wheaton *et al*., 2015). These landforms provide an indication of the development of sediment transport processes as well as channel and floodplain features, which shape river structure and function over time (Brierley and Fryirs, 2005). Likewise, Belletti *et al*. (2017) outlined that GU's are the physical product of flow interacting with factors affecting the reach such as channel and floodplain substrate, slope and vegetation.

Fluvial geomorphologists recognize GU's as the basic structure of the channel and floodplain morphology, formed by the erosion and deposition of alluvium and bedrock (Lehotskỳ, 2004). To summarize, Thomson *et al*. (2001), Brierley and Fryirs (2005) and Phillips (2011) described GU's as being the building blocks of river systems which may be erosional, depositional or transitional.

1.2 Rationale

In South Africa, geomorphologists have played an important role in Environmental Water Allocation since the 1990's, being involved in developing methods which are used to determine the ecological reserve (Seaman *et al*., 2013). However, these methods were designed for perennial rivers and should be adapted for NPR's (Seaman *et al*., 2010; Seaman *et al*., 2013). In order to apply these same methods of study to NPR's, the approach needs to be modified (Seaman *et al*., 2010; Seaman *et al*., 2016).

NPR's provide habitats for a diverse and unique fauna and flora including macroinvertebrates, fish, amphibians, streamside mammals, reptiles and birds (McDonough *et al*., 2011), and function as biogeochemical hotspots that retain, transform and transfer carbon, nutrients and particulate matter (Skoulikidis *et al*., 2016). Isolated pools are one of the most distinguishing characteristics of NPR's and act as an important sanctuary for many of the aquatic plants and animals within the river channel (Seaman *et al*., 2010). Bars create an area for the colonisation of vegetation, which may be protected from floods of a particular magnitude due to the elevation of bars above the channel bed (James and King, 2010). Likewise, cobble bars free of sand create shelter for macroinvertebrates, and vegetated bars and woody debris jams provide cover for various animals (James and King, 2010).

Generally, the diversity of macroinvertebrates in NPR's is lower than their perennial counterparts, although NPR's may support rare species with special adaptations (McDonough *et al*., 2011). The GU's in the floodplain such as cutoff channels may also support habitat for feeding, nesting and resting for a variety of animals (Brierley and Fryirs, 2005). The GU's on the floodplain may also provide habitat for non-aquatic fauna and flora, which influence the ecological functioning of the river (Thomson *et al*., 2001). These units may provide shelter (and shade) from birds of prey and assist in the regulation of nutrient fluxes for riparian plants (Thomson *et al*., 2001). Additionally, NPR's are important water sources and may become hotspots of plant diversity (McDonough *et al*., 2011).

The role of vegetation in NPR's is important as it affects and is affected by the geomorphological processes altering the channel morphology, thus creating a variety of habitats (Curran and Hession, 2013; van Oorschot *et al*., 2016). Depending on its distribution, vegetation may promote either focussed or diffuse flow, while vegetation removal from banklines affects lateral channel dynamics (van Oorschot *et al*., 2016). The distribution of vegetation in the channel influences the settling rate of sediment, creating different river morphologies (van Oorschot *et al*., 2016). In engineered settings, vegetation is traditionally managed or removed from the channel to reduce channel roughness (Curran and Hession, 2013). For example, Curran and Hession (2013) discussed how re-vegetating a braided river caused the channel morphology to change to meandering. It can be seen by Curran and Hession (2013) and van Oorschot *et al*. (2013) that there is a relationship between vegetation, channel roughness, rate of sediment deposition, bar formation and river morphology. Similarly, Gurnell *et al*. (2011) found that vegetation impedes sediment transport, thereby constructing bars, which are then further stabilized by vegetation, which facilitates the development of larger GU's such as islands, which change the channel pattern. Understanding these complex relationships in different fluvial styles would be vital in the prediction of in-channel habitats.

In this thesis the characteristics and distribution of GU's is being studied because this along with the geomorphological processes of a river determines its morphology, influencing the physical framework where the stream biota live (Pulles *et al*., 2007). Not much is known about the water requirement of NPR's from a GU perspective as channel flow resulting from rain or snowmelt can be highly irregular and discontinuous due to the characteristics of in-channel alluvium (Jaeger *et al*., 2017). It is only recently that NPR research has emerged as a multidisciplinary domain that integrates biology, ecology, biogeochemistry, hydrology, geomorphology and river management to advance the perception and understanding of NPR's (Skoulikidis *et al*., 2016). Since relatively little research has been done to understand the relation between morphologic development and flow in NPR's (Heritage *et al*., 2004;

Jaeger *et al*., 2017), an increase in knowledge about the interactions between flow, vegetation, morphodynamics and GU's in NPR's is required to better understand and manage these rivers (van Oorscoht *et al*., 2016).

1.3 Aim

The aim of this project is to evaluate associations between fluvial style and the characteristics and distribution of GU's in NPR systems.

1.4 Objectives

Four objectives were set out to achieve the aim:

1. Define the planform characteristics of non-perennial reaches with contrasting fluvial styles.

2. Identify GU's in the study sites, and characterise their spatial distribution, morphology and substrate characteristics.

3. Classify GU's based on morphology and substrate metrics.

4. Investigate differences in the occurrence and characteristics of GU's with fluvial style.

2. Literature Review

2.1 Non-perennial rivers and geomorphic units

Fluvial geomorphology is the sub discipline of geomorphology focusing on the various landforms associated with river systems as well as the processes that form these landforms, such as the erosion and deposition of sediment due to flowing water (Dollar *et al*., 2006; Rowntree *et al*., 2013). The form and processes that occur within rivers assist in shaping them; rivers are therefore a product of their environment, (Konnerth, 2015). Some of the factors controlling the river morphology are sediment supply, discharge, topography and vegetation (Buffington, 2012). The river channel is the main focus of fluvial geomorphology because it is the most active area where water erodes, transports and deposits sediment (Rowntree *et al*., 2013).

Geomorphological processes in rivers cause channels to constantly change in size and shape creating habitats of varying substrate and structure for vertebrates and invertebrates (Rowntree *et al*., 2013). When studying the health of rivers, fluvial geomorphology assists in investigating the current condition of the river, the effects of future river developments on water and sediment, and in determining the sustainability of future water resource scenarios (Rowntree *et al*., 2013). The study of fluvial geomorphology therefore aims to explain the origin, distribution and occurrence of landforms and morphological features shaped by water (Rossouw *et al*., 2005), otherwise known as GU's.

2.1.1 Sub-groups of non-perennial rivers

Previously, the definition of NPR's has been unclear with different definitions being used (Rossouw, *et al*., 2005). Sheldon and Thoms (2006) defined NPR's as the type of rivers that have extended periods of low flow which is interrupted by infrequent large floods that inundate the floodplain for some time. These rivers also have flow pulse periods that submerge the in-channel GU's more frequently than the floodplain (Sheldon and Thoms, 2006). It is clear that many NPR's are event-driven with episodic extreme changes in the hydrology and physical conditions (Heritage *et al*., 2001; Seaman *et al*., 2016). Rossouw *et al*. (2005) argued that to avoid any confusion with the definitions of NPR's, one definition should be used. Furthermore, Seaman *et al*. (2013) emphasised the importance in determining the degree of perenniality of NPR's because a different approach needs to be taken for each NPR.

NPR's can further be classified into smaller sub-groups that characterise the different types of NPR's found in different environments. Roux *et al*. (2002) classified NPR's into three sub-groups; seasonal, episodic and ephemeral. Later, Rossouw *et al*. (2005) and Skoulikidis *et al*. (2016) classified NPR's into three slightly different sub-groups, semi-permanent, episodic and ephemeral with Skoulikidis *et al*. (2016) adding intermittent rivers to this list. The most abundant, highly distributed and dynamic freshwater ecosystems across the globe are situated in intermittent and ephemeral rivers, and these river types are sometimes grouped together and referred to as temporary streams (McDonough *et al*., 2011).

Table 1 summarises the terminology of some of the sub groups of NPR's defined by different authors. Table 1 clearly shows that since the beginning of the 21st century, there have been many definitions and characteristics for defining the sub-groups of NPR's. For the purpose of this study the term and characteristics used by Rossouw *et al*. (2005) will be followed because these terms were developed in South Africa, and were applied by Seaman *et al*. (2013) in the Mokolo River case study.

2.1.2. Non-perennial rivers located in regions with different climates

Rivers are located in various climatic regions, and those located in hyper-arid, arid, semi-arid, and dry subhumid climates are termed dryland rivers (Tooth, 2013; Konnerth, 2015). Dryland rivers may be allogenic (runoff collection from precipitation in regions with higher humidity) or endogenic (runoff collection from precipitation and groundwater fed from sources located within the arid region) and may be characterised by greater spatial variability in flow with distance downstream than rivers in humid areas (Konnerth, 2015). NPR's are found in different climate regions around the world with varying aridity index (AI) values (Konnerth, 2015). Table 2 shows the range of AI and its associated climate type, developed by the United Nations Environment Programme (UNEP, 1997: Sahin, 2012).

Table 1: Summary of NPR type terminology defined by various authors

River type	Characteristic	Author
Ephemeral	Uncommon and brief flows as rainfall is the only contributor to these rivers, causing the channel to remain dry for most of the year.	Roux *et al*. (2002)
Ephemeral	Do not flow for 26%-75% of the time.	Rossouw *et al*. (2005)
	Flow during and in immediate response to rainfall events.	McDonough *et al*. (2011)
	Characterized by long periods of no flow.	Tooth (2013)
	Flow only in response to precipitation or snowmelt events (days to weeks).	Skoulikidis *et al*. (2016)
Episodic	Do not flow for at least 76% of the time.	Rossouw *et al*. (2005)
	Have seasonal flow in response to elevated groundwater tables, precipitation or snowmelt.	McDonough *et al*. (2011)
	Carry surface water only during very short periods (hours to days), primarily after heavy rainfall events.	Skoulikidis *et al*. (2016)
Intermittent	Have lengthy periods of flow but unpredictable. Some segments of the channel may be inundated with surface flow while other segments experience subsurface flow.	Roux *et al*. (2002)
	Characterized by long periods of no flow.	Tooth (2013)
	Cease to flow seasonally or occasionally (usually for weeks to months).	Skoulikidis *et al*. (2016)
	Cease to flow and may be dry along parts of their length for a variable period annually, or for two or more years in five. Seasonal, or highly variable flow, depending on climatic influences and predictability of rainfall in the area. May experience several cycles of flow, no flow, and drying in a single year.	Rossouw *et al*. (2005)
Seasonal	Have predictable flow during the wet season but remain dry for some months during the year.	Roux *et al*. (2002)
Semiarid	Extreme floods with long periods of low flow. During this time there are lengthy periods of sediment accumulation, interrupted by flood events.	Heritage *et al*. (2004)
Semi-permanent	No flow for 1-25% of the time.	Rossouw *et al*. (2005)

Table 2: Climate types corresponding to AI index defined by UNEP as MAP/PET (Mean annual precipitation/ Potential evapotranspiration (mm)) (Sahin, 2012)

Aridity Index	**Climate Type**
0.05 - 0.2	Arid
0.2 - 0.5	Semi-arid
0.5 - 0.65	Dry sub-humid
0.65 - 0.8	Semi-humid
0.8 - 1	Humid
1 - 2	Very humid

Many NPR's are endogenic with small catchment areas, while a large number of perennial rivers are allogenic with large catchment areas (Konnerth, 2015). The evaporation and infiltration rates along NPR's are high, resulting in large amounts of water loss in the downstream direction, in some cases preventing the discharge of NPR's into oceans (Konnerth, 2015). Jaeger *et al*. (2017) argued that many NPR's do not reach the ocean due to the distance between the upland and floodout zones. In addition to this, the geologic setting such as limited or absent hillslopes between the upland and floodout zones strongly influence the flow of these NPR's (Jaeger *et al*., 2017). More water is lost in NPR's through human practices such as irrigation and livestock farming, adding further stress to the river (Konnerth, 2015). The anthropogenic changes in the channel of NPR's influence the hydrologic and sediment characteristics in the channel (Jaeger *et al*., 2017). These changes are visible in the geomorphology of the channel and floodplain, and in the changes to physical habitat (Jaeger *et al*., 2017).

There are a number of factors controlling the flow regime (consisting of the magnitude, frequency, duration, timing and rate of change in flows) of rivers, with some of the most influential factors being climatic conditions and mechanisms of runoff generation in the catchment (Poff *et al*., 1997; Dettinger and Diaz, 2000; Buffington, 2012; Konnerth, 2015). The occurrence of NPR's is dependent on precipitation and other sources of runoff that is highly variable both spatially and temporally (Jaeger *et al*., 2017). NPR's are found to be located in areas where the vegetation coverage is sparse, unevenly distributed or temporally variable (Jaeger *et al*., 2017). In drier climates, NPR's cover a larger spatial area than perennial rives and in wetter climates perennial rivers cover a larger spatial area than NPR's (Jaeger *et al*., 2017). This is because wetter climates provide sufficient surface runoff that supports perennial rivers rather than NPR's (Jaeger *et al*., 2017).

Dryland areas characteristically have heavy rainfall events which are caused by convective cells, leading to overland flow in a short time period (minutes) (Tooth, 2013; Konnerth, 2015). Jaeger *et al*. (2017) added that in areas with drier climates, convective storms of high intensity cause spatially discontinuous and localized flow. Short overland flow paths occurring after these convective storms may cause flash floods capable of transporting high amounts of coarse grained sediment and may cause scouring and deposition to form GU's (Jaeger *et al*., 2017). This makes deciding over which time scale to assess morphological change difficult as GU's would develop at different rates in different channels (Rowntree *et al*., 2013). Even where precipitation or other sources of runoff are more regular and spatially broader, surface flow may still be highly variable and discontinuous due to the water infiltration losses to unconsolidated alluvium (Konnerth, 2015; Jaeger *et al*., 2017).

2.1.3 Development of morphology due to flow variability

Understanding how river channels adjust due to flooding is important for river management, prediction of future channel adjustment and trends, the identification and mapping of sensitive reaches most likely to undergo major changes and the mapping of morphological change in these reaches (Nardi and Rinaldi, 2014). Once there is an understanding of how channels respond to floods, river management can be improved (Nardi and Rinaldi, 2014). Skoulikidis *et al*. (2016) explained how the lack of understanding NPR's affects how they are perceived, describing how people in arid and semi-arid areas have the least respect towards NPR's because they are often dry or have catastrophic floods, and are therefore viewed more as a danger than as a natural resource to be preserved. Correctly classifying NPR's and the GU's found within them is very important for geomorphic mapping as these maps show the spatial and temporal changes in the channel and assist in improving the understanding of geomorphological processes that control the fluvial style of these rivers (Wheaton *et al*., 2015).

Few studies have investigated how the spatial pattern of channels respond to controlling factors (such as floods) through direct measurement of the amount of morphological change after such events (Nardi and Rinaldi, 2014). Major floods have the potential to widen channels, and understanding this cause and effect process would greatly assist in the prediction of changes in channel pattern, type and morphology (Nardi and Rinaldi, 2014). In many NPR's, the flow variability controls the complex in-channel environment as these rivers characteristically experience long periods of no flow (Sheldon and Thoms, 2006; Tooth, 2013). Contributions to the flow in NPR's are overland flow from local hill slopes, smaller more frequent floods, as well as the infrequent major floods, forming when the rainfall intensity is greater than the surface infiltration rate (Thomas, 1997). Examples of floods affecting the morphology of single thread alluvial, cobble, gravel and bedrock perennial rivers have been described by Fuller (2007) and Hauer and Habersack (2008).

Extreme floods in NPR's are of significance as they condition the channel form and play a major role in the development and destruction of GU's (Tooth, 2000; Heritage *et al*., 2004; Fuller, 2007). Floods that transport a high degree of sediment from the main channel and tributaries play an important role in changing the channel type (Heritage *et al*., 2004). Rowntree *et al*. (2013) supports this, arguing that changes in channel morphology are caused by the cumulative effect of floods that erode and deposit sediment. Tooth (2000) concluded that flash floods are an important factor in NPR's as they greatly affect the channel morphology bringing a sudden change to the geomorphological processes of the channel.

The higher frequency smaller flood events in perennial rivers have a greater effect on the morphological adjustment of river channels compared to the lower frequency major floods (Wolman and Miller, 1960). Furthermore, Fuller (2007) found that large floods in perennial rivers (return interval of 2 per year) adjusted the overall morphology of the channel, while moderate floods (return interval of 14-30 per year) adjusted the features created by the large floods. However, Greenbaum and Bergman (2006) argued that this is not the case in NPR's. Instead, the rare major floods in NPR's have a longer lasting influence on the channel morphology compared to the sporadic small to moderate floods (Greenbaum and Bergman, 2006). There is however still some debate as to whether rare foods of high magnitude are more important for the river system than the more frequent lower magnitude floods (Thompson and Croke 2013).

Seaman *et al*. (2013) explained that channels experiencing changes after an extreme flood would remain unchanged until smaller more frequent floods would reconstruct the channel creating a more equilibrium channel. However, this is untrue in NPR's as no such equilibrium exist in NPR's and is a feature of perennial rivers (Rountree *et al*., 2001). A range of varying flow influences the channel pattern in perennial rivers as Wolman and Miller (1960) explained that moderate, relatively frequent floods are responsible for the size and shape of the channel. However, Tooth (2013) argued that the work done by Wolman and Miller (1960) is not applicable and cannot be transferred and used in NPR's as these rivers do not flow as frequently as their perennial counterparts. The formation and destruction of GU's is highly variable and can be seen after a flood where the most visible change observed is in the planform view, where changes such as channel widening, the erosion of in-channel bars, active channels and floodplain are clearly visible (Nardi and Rinaldi, 2014).

Though floods affect the development of GU's, in some studies it has been observed that the morphology of different channels within the same catchment respond differently to floods of the same magnitude (Nardi and Rinaldi, 2014). This is supported by Fuller (2007) when discussing that different channels in the same catchment experiencing floods with similar magnitudes and frequencies may have different morphological responses in and around the channel. This makes predicting the formation and destruction of GU's difficult (Thompson and Croke, 2013).

Heritage *et al*. (2004) found that floods have different effects on different fluvial styles. Thompson and Croke (2013) explained that depending on the characteristics of the reach, different types of reaches would be dominated by net erosion or net deposition. For example, after a flood event, anastomosing channels with a channel bed composed of bedrock did not have much sediment deposition considering the high amount of sediment transported downstream while anastomosing channels with a cohesive mixed channel bed composed of bedrock, clay, silt and sand had high amounts of sediment loss (Heritage *et al*., 2004). Furthermore, Thompson and Croke (2013) highlighted that the GU's responding to floods should not just be assessed based on net erosion, but should include net deposition as well, as this is part of the geomorphological process and should not be overlooked. Thompson and Croke (2013) found that during a flood, the channel shape influences the formation and location of GU's. It was found that there was a strong correlation between the spatial patterns of erosion, deposition and estimated flood power (Thompson and Croke, 2013; Nardi and Rinaldi, 2014).

Thompson and Croke (2013) analysed a confined bedrock channel and a more sinuous unconfined channel that experienced a number of storms (20 mm to 30 mm of rainfall in one day), saturating the soil, followed by flooding. The confined bedrock channel had coarse alluvium and the unconfined channel had a cleared floodplain, used for grazing (Thompson and Croke, 2013). The flood caused large scale erosion as well as changes to the channel morphology in the confined channel, removing dense riparian vegetation while the unconfined channel experienced large amounts of sediment deposition on the floodplain as well as the lateral expansion of the channel (Thompson and Croke, 2013).

Konnerth (2015) analysed NPR's in several arid regions, and found that generally larger rivers display a channel pattern resembling meandering and braided channels, created by a low gradient. While the smaller rivers displayed a variety of channel patterns which changed quite frequently, and formed due to the spatial and temporal variability of floods (Konnerth, 2015). Smaller and more active channels exist within the macro channel in some rivers, and these channels may undergo seasonal flooding which assists in the distribution of sediment and change in channel morphology (Heritage *et al.*, 2004). Some of the features formed by seasonal flooding include mixed single thread and braided channels, cohesive, noncohesive and bedrock anastomosing channels as well as mixed pool rapids (Heritage *et al.*, 2004).

2.2 Fluvial styles of non-perennial rivers

2.2.1 Definition and description of fluvial styles

River morphology continuously changes in response to channel flow and available sediment transport, which in turn influences the channel pattern (Rowntree *et al.*, 2013). Two important factors in determining the fluvial style are flow strength and sediment characteristics (Figure 1), although there is still some debate around which of these factors has the greater effect (Kleinhans, 2010). Changes in the fluvial style of rivers mostly occur as a result of natural dynamics (Tooth and Nanson, 2004). However, the morphology of the channel is also sensitive to extrinsically driven processes such as climate change, human activity and land use change which alter the pattern of flow and sediment supply (Tooth and Nanson, 2004).

Leopold and Wolman (1957) argued that it is sometimes difficult to categorize the fluvial style only through planform observations, because in reality not all rivers fit perfectly into well-defined categories. However, the channel pattern provides an excellent initial guide in understanding the change in the channel morphology (Brierley and Fryirs, 2005). Rowntree *et al*. (2013) added that although it is possible to identify certain channel types in characteristically distinct geomorphological environments, channels are highly variable in space and time. For example, channels are commonly categorized as braided, meandering and straight when the channel bed is composed of alluvium (Kleinhans and van den Berg, 2011).

Figure 1 provides a summary of measures of the channel planform where it can be seen that single-thread channels may be straight or tortuous (Brierley and Fryirs, 2005). Wandering channels have up to three channel threads, and braided channels have more than three threads (Brierley and Fryirs, 2005). The bars in wandering channels are stabilised and are not inundated as frequently as the dynamic bars in braided channels (Nanson and Knighton, 1996). Braided channels characteristically have high width:depth ratios, many branches, bars and assemblages of smaller channels within the same channel (Kleinhans, 2010; Baar, 2013). Leopold (1957) described braiding as the division of the channel around alluvial deposition, and Huang and Nanson (2007) added that flow is separated by in-channel bars that may become inundated. Braided channels are characterised by higher excess stream power than meandering channels, while anabranching channels tend to occur in low stream power environments with high sediment supply, such as large lowland rivers (Leopold and Wolman, 1957; Huang and Nanson, 2007; Kleinhans, 2010).

Anabranching and anastomosing channels have multiple threads which may be straight or sinuous and although they are found in channels with a variety of gradients, they are commonly found in channels with gentle gradients (Huang and Nanson, 2007; Kleinhans and van den Berg, 2011). Anabranching and anastomosing channels divide and re-join around long, thin ridges or broader islands that are either vegetated or have stable alluvial sediment (Figure 1) (van den Berg, 1995; Tooth and Nanson, 2000; Brierley and Fryirs, 2005; Kleinhans and van den Berg, 2011). These channels may extend in length and become many times longer than the actual width of the channel (van den Berg, 1995). The rate of floodplain and levee aggradation is greater than the rate of channel bed aggradation and may be due to the low stream power often observed which is too weak for significant channel mobility (Kleinhans and van den Berg, 2011).

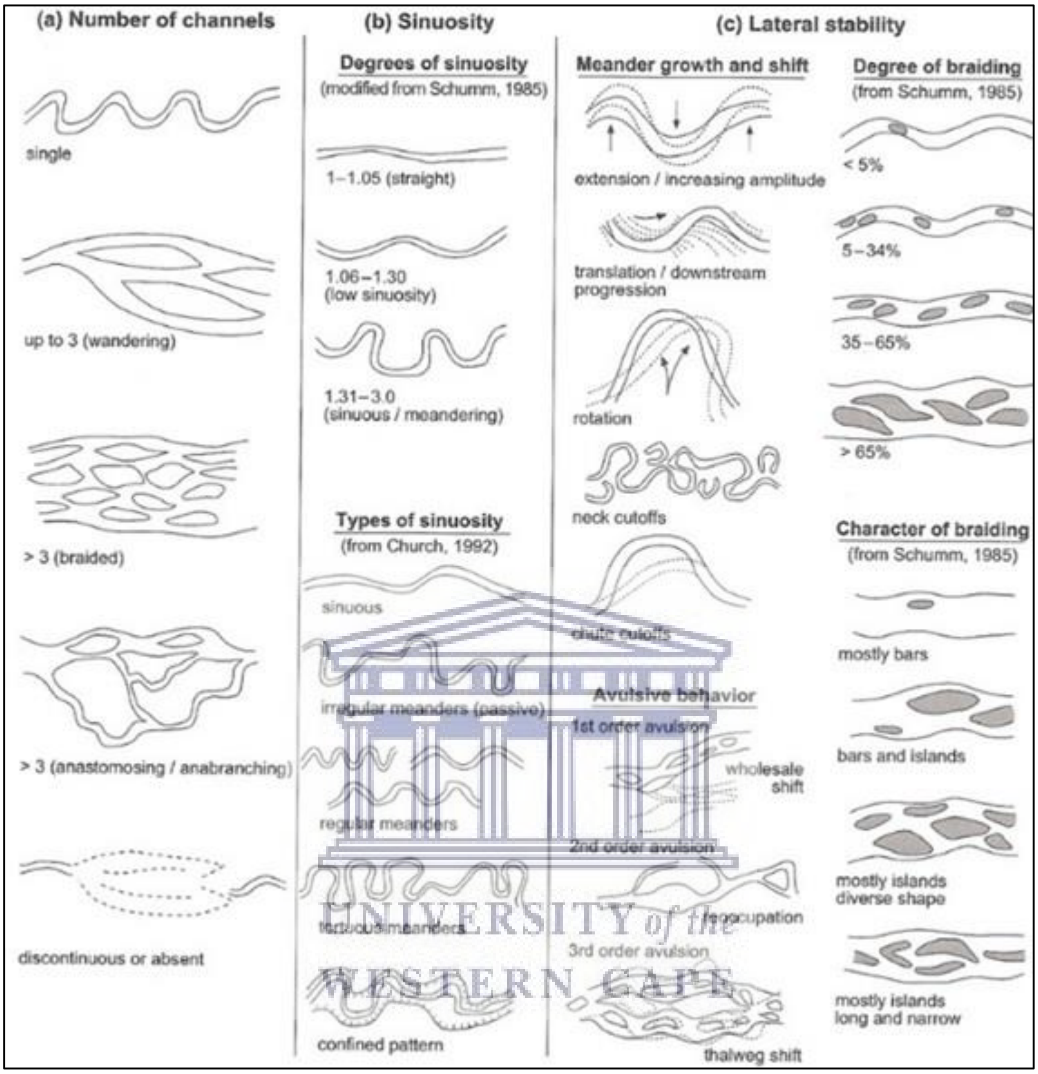


Figure 1: Measures of channel planform (after Brierley and Fryirs, 2005)

When observing anastomosing channels at smaller scales it may resemble either straight, meandering or a braided pattern but when looking at it from a larger scale, it would be seen as anastomosing (Thorne *et al.*, 1993). This shows the importance of thoroughly investigating the study area and not confusing any of the channel patterns as van den Berg (1995) suspected that some of the channels in literature were misclassified due to the transition between two channel types. Although a criteria has been set for rivers to be classified into different fluvial styles, a better representation of natural river systems is a continuous variation of fluvial styles along a continuum defined by energy-resistance relationships rather than a definite stop/start of different fluvial styles (Leopold and Wolman, 1957; Kleinhans, 2010).

2.2.2 Influence of changes in fluvial style on physical habitat

The different habitats found within river channels and the processes that shape them vary spatially and temporally (Rowntree *et al*., 2013). The sorting of sediment and the formation of in-channel and bank attached GU's emerge through the interactions and feedback between flow and sediment size within the channel and this influences the habitat diversity (Lehotskỳ, 2004; Kleinhans, 2010). The physical habitat and its functioning for macroinvertebrates, for example, are created by the channel form and substrate, and therefore any changes experienced in the channel morphology and channel type will affect macroinvertebrate habitat (James and King, 2010).

Gravel, free of fine sediment within the channel provides suitable habitat for macroinvertebrates to spawn, yet the prediction of invertebrate assemblages at varied spatial and temporal scales typically proves to be difficult due to the variable flow of NPR's (Rowntree *et al*., 2013). NPR's have variable sediment characteristics due to the scale and frequency of flow (Puckridge *et al*., 2000). The presence of fine sediment allows percolation to occur, where finer sediment fills the pore space between coarser sediment (Kleinhans, 2010). Pitlick and Wilcock (2013) argued that the infilling of pore space poses a threat to macroinvertebrates that spawn between coarse sediment. For example, Kleinhans (2010) argued that sediment rich water released from dams into rivers in some environments is a problem as the pore filling sediment threatens the spawning of fish and macro invertebrates. Habitats and refugia of macroinvertebrates would be lost if infilling of coarse sediment were to continuously occur (Pitlick and Wilcock, 2013; Rowntree *et al*., 2013).

River health is influenced by a number of inter dependent factors, of which the condition of physical habitat is a critical component (Thomson *et al*., 2001). River classification has become an important method for the implementation of river restoration works and is intended to assist in predicting river behaviour based on its appearance (Lehotskỳ, 2004). Although infilling poses a threat to macroinvertebrates by changing their habitat, this process strengthens the channel banks and encourages vegetation growth (Church, 2006. However, it is noted that with NPR's, vegetation, mammals (wildlife) and terrestrial insects are better suited as indicators of ecological integrity than macroinvertebrates (Seaman *et al*., 2016).

2.3 Geomorphic units

GU's are recognized as the basic physical morphological features of the channel and floodplain formed by the erosion or deposition of sediment (Lehotskỳ, 2004; Kleinhans, 2010). These features may be composed of bedrock and a variety of alluvial forms such as silt, sand, gravel and boulders (Brierley and Fryirs 2005; Wheaton *et al*., 2015). The formation and location of GU's are dependent on the magnitude and duration of flow, previous channel conditions, channel morphology, sediment type, sediment size, fluvial style, channel valley orientation and topography (valley slope and channel confinement) (Bunte and Abt, 2001; Brierley and Fryirs, 2005; Charlton, 2008; Hauer and Habersack, 2008; Buffington, 2012; Rowntree *et al*., 2013; Nardi and Rinaldi, 2014; Wheaton *et al*., 2015). Some GU's are developed by moderate flow and destroyed by extreme flow as Heritage *et al*. (2004) found that floods affect some morphologic features differently than others. Rountree *et al*. (2001) further explained that GU's are stripped by large episodic floods and this may be used as an indicator to explain the changes in the fluvial style of NPR's, especially in mixed bedrock/ alluvial channels.

Bunte and Abt (2001) and Wallerstein *et al*. (2001) further argued that obstructions in the channel may act as loci of sedimentation, thus promoting the development of forced bars. Brierley and Fryirs (2005) agreed saying that some GU's are formed when the divergence of flow around a feature such as a boulder or woody debris create an area of low energy and high bed resistance where deposition is concentrated. Additionally, GU's are formed through the deposition of sediment when the amount of sediment in the channel exceeds the carrying capacity of the river, usually occurring in sand bed channels (Brierley and Fryirs, 2005). Mid-channel bars for example have finer sediment at the tail end of the bar with coarser sediment at the bar head because finer sediment is deposited at the tail end of the bar due to secondary flows, low flow energy and high bed resistance (Bunte and Abt, 2001; Brierley and Fryirs, 2005). Initially the stability of bars is dependent on the bar substrate type, as Rowntree *et al*. (2013) argued that the fine sediment in sand bed channels stabilizes the channel banks and bars, and is also a source of nutrients in the riparian zone.

Although these features may be stable, GU's can change over timescales of a single event to 10 years and this is important for river ecology, providing a physical habitat for aquatic vertebrates and invertebrates (Brierley and Fryirs, 2005; James and King, 2010; Rowntree *et al*., 2013; Gurnell *et al*., 2015). Additionally, the habitat created by the spatial distribution of GU's is influenced by the cumulative effect of floods, channel morphology and available sediment (Brierley and Fryirs, 2005; Pitlick and Wilcock, 2013; Rowntree *et al*., 2013). Thus, reaches with similar characteristics are likely to contain GU's of similar morphology compared to reaches with different characteristics (Thomson *et al*., 2001).

Authors refer to morphological features as GU's or morphologic units and these terms can be used interchangeably. Examples of GU's provided by Brierley and Fryirs (2005) and Phillips (2008) are point bars, scroll bars, natural levees, tail bars, large woody debris jams, alluvial terraces, sand wedges, floodouts, chute cutoffs and pools. Examples of morphological units provided by Rowntree *et al*. (2013) are steps, plane beds, pools, point bars, lateral bars, mid-channel bars, tributary bars, lee bars and islands. There is an overlap in the examples, supporting that these terms (morphological features and GU's) are interchangeable. The most common form of in-channel GU's are bars (Brierley and Fryirs, 2005).

Brierley and Fryirs (2005) argued that sediment accumulations can be related to the size of the channel where they are found. This is supported by Heritage *et al*. (2004), when observing that sediment transported from tributary and the main channel showed a good correlation between channel change and channel type. Kleinhans (2010) further discussed that the type of bars formed in the channel is dependent on the channel width. Rowntree *et al*. (2013) added that GU's change the channel morphology at varying spatial scales, ranging from the structure of the channel bed to the cross section (hereafter XS).

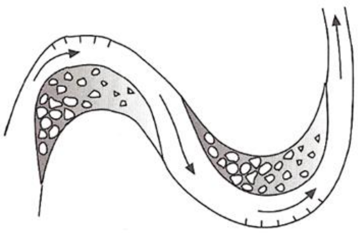
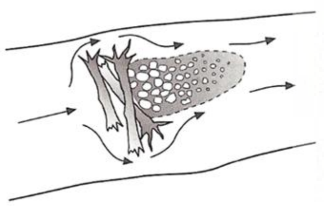
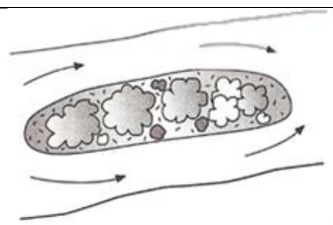
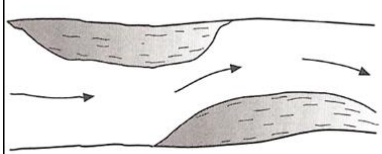
The length and growth of bars can be predicted by the width:depth ratio of the river channel (Kleinhans, 2010). For example, alternate bars grow in channels with a low width:depth ratio and large forced bars may grow so slowly that it acts as an obstruction for the formation of new forced bars (Kleinhans, 2010). Forced bars are present in most rivers because of the curved river banks, when these bars dominate any section of the reach, free bars are less likely to be present (Kleinhans, 2010). Heritage *et al*. (2004) argued that the channel bedrock determines whether alluvium will be deposited or eroded during times of flood and therefore plays a significant role in determining the type of GU's that will form in the active and macrochannel. During a flood, the characteristics of GU's influence the flow hydraulics which in turn influence the spatial distribution of sediment erosion and deposition (Rowntree *et al*., 2013).

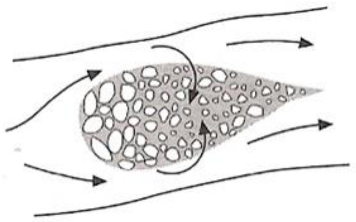
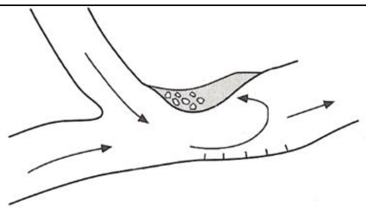
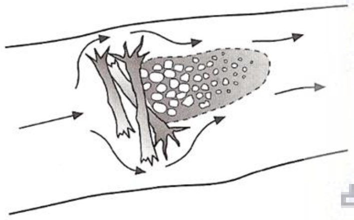
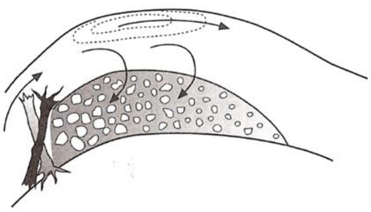
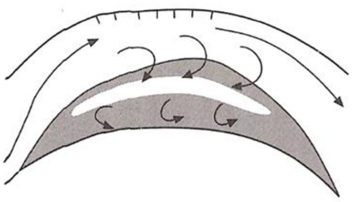
2.3.1 Characteristics of geomorphic units along non-perennial rivers

Understanding a rivers capacity to adjust within its valley setting provides the foundation for assessing how far a river is from its natural condition and is the basis for understanding the changes in the river (Lehotskỳ, 2004). The analysis of river change is required for predicting how rivers will be adjusted in the future (Lehotskỳ, 2004). This provides a geomorphic basis for determining future target conditions required for river rehabilitation or environmental water allocation and creating catchment-framed visions (Lehotskỳ, 2004). Some of the determining factors influencing the development and distribution of in-channel GU's are processes of water flow, sediment movement, slope, substrate and valley configuration (Thomson *et al*., 2001). Brierley and Fryirs (2005) developed a detailed metric system for the characterisation of GU's which include the morphology of these units, with the planform view of GU's providing the initial analysis that determines to which category the observed GU belongs. Table 3 provides a description and location of some bars found within channels described by various authors.

Every GU in the reach is associated with a particular formation process, and these GU's can undergo significant changes over short time periods (Phillips, 2008). It has been suggested by Sheldon and Thoms (2006) that the in-channel geomorphic complexity in NPR's plays an important role in retaining organic matter which is of significance in NPR's. It remains unclear whether the geomorphic changes observed in the channel are representative of the entire channel or only a small extent of the geomorphic response to an event (Thompson and Croke, 2013).

Table 3: Description and location of bars by various authors

Name	Image (Brierley and Fryirs, 2005)	Description and location	Author
Point bar		Dominantly lateral accretion deposits, associated with erosion of the outside (cutbank) of the bend and deposition on the inside. Arcuate shaped bars developed on the convex inside banks of meander bends, generally following the alignment of the bend.	Nanson (1981); Phillips (2008)
		A bar formed on the inside of meander bends in association with pools. Lateral growth into the channel is associated with erosion on the opposite bank and migration of meander loops across the floodplain.	Brierley and Fryirs (2005); Rowntree *et al*. (2013)
		Located on in the inner bank of a meandering river. Narrow single thread rivers and stretches from the thalweg to the channel bank.	Brierley and Fryirs (2005); Kleinhans and van den Berg, (2011)
Lee bar		Accumulation of sediment in the lee of a flow obstruction and located on the lee side of an obstruction.	Heritage *et al*. (2000); Rowntree *et al*. (2013)
Island		Mid-channel bars which become stabilised due to vegetation growth and which are submerged only at high flows that cause overbank flooding.	Rowntree *et al*. (2013)
Lateral bar		An elongate feature located on alternating banks of a relatively straight reach and form during intermittent stages of flood recession.	Brierley and Fryirs (2005)
		Accumulation of sediment attached to the channel, often alternating from one side to the other as to induce a sinuous thalweg channel.	Rowntree *et al*. (2013)
		Located along banks in low-sinuosity reaches or in short relatively straight reaches between meanders.	Phillips (2008)

Longitudinal bar		A form of mid-channel geomorphic unit that is formed as flow divides around a bar structure in the shape of a tear drop. The finer sediment is deposited on the lee side of the bar and the coarser sediment is deposited at the bar head.	Brierley and Fryirs (2005)
		Elongate in the direction of flow, formed in the centre of the channel.	Charlton (2008); Wheaton *et al*. (2015)
Tributary bar		Forms immediately downstream of a tributary junction due to the input of coarse material into a lower angled channel.	Rowntree *et al*. (2013)
Forced mid-channel bar		Associated with sediment trapping behind obstructions and are located in the channel.	Phillips (2008)
		Geomorphic units that are created when an obstruction (bedrock outcrop, boulder, large woody debris or vegetation) in the channel diverges flow around the obstruction.	Brierley and Fryirs (2005).
		Caused by structural elements.	Wheaton *et al*. (2015)
Forced bank attached bar		Bank attached bar form created by a flow obstruction and located on the cannel bank.	Brierley and Fryirs (2005); Phillips (2008)
		Grow from a local obstruction in the channel or a change in curvature of the channel.	Kleinhans (2010)
Scroll bar		Bent ridges visible during low flow (sometimes the extension of point bars).	Kleinhans and van den Berg (2011); Baar (2013)
		Located along the convex bend of meander bends and sometimes on floodplains.	Nanson (1981); Kleinhans and van den Berg (2011)

2.3.2 Distribution of geomorphic units along non-perennial rivers

The development and location of GU's in NPR's vary spatially and temporally and are influenced by the spatial sorting process of the coarse to fine grained sediment found in the river channel and the extended low flow conditions (when sediment builds up) that is disturbed by high magnitude floods (Kleinhans and van den Berg, 2011; Jaeger *et al*., 2017). For example, mid-channel bars are located within or adjacent to the thalweg and are reworked more frequently than those that are attached to the bank, while GU's that are formed by the bedload are reworked as the channel gets flooded causing these bars to shift position (Brierley and Fryirs, 2005). Understanding the distribution of GU's and the patterns associated with them provide insight into their formation and change in the channel network (Kleinhans, 2010).

Within each NPR, the geomorphological processes responsible for the aggradation and degradation of GU's are influenced by the location of a reach within the catchment (Jaeger *et al*., 2017). Jaeger *et al*. (2017) reviewed the work of Schumm (1977) where it was explained that there are three zones within the catchment influencing the channel sediment regime and morphology. These three zones were based on relative elevation and the position of the channel in the catchment. These zones were classified as the: production zone, transfer zone and deposition zone (Jaeger *et al*., 2017). Generally net erosion occurs at the production zone, sediment transport at the transfer zone and net sediment accumulation at the deposition zone (Jaeger *et al*., 2017).

Tooth and Nanson (2011) extended work by Schumm (1977) where it was explained that four geomorphological zones exist within the catchment of NPR's. The upland, piedmont, lowland and floodout (Jaeger *et al*., 2017). However, Jaeger *et al*. (2017) argued that these zones are a broad generalization because they do not consider the full geomorphic diversity driven by climate and the physiographic setting. Jaeger *et al*. (2017) described the channels in the upland zone as single thread steep and small with low width:depth ratios, with poorly sorted sediment ranging in grain size up to boulders. The channels in the piedmont zone generally have a steep to moderate gradient and begin to widen with older alluvium and bedrock found on either side of the channel (Jaeger *et al*., 2017). The channels located in the lowland zone become wider where a higher diversity of GU's are found, some different to those in perennial rivers (Jaeger *et al*., 2017). The channels located in the floodout zone are generally wide and shallow with a low sinuosity (Jaeger *et al*., 2017).

GU's may be located in the channel, attached to the bank or on the floodplain (Brierley and Fryirs, 2005; Phillips, 2011). Identifying the aggregation and location of GU's in a reach helps in understanding the controls that determine the energy distribution in the channel responsible for the positioning of these GU's (Brierley and Fryirs, 2005). The flow patterns in the channel are influenced by the formation of bars in the reach and under given sediment conditions and flow types, GU's are often found in characteristic places in the channel (Brierley and Fryirs, 2005).

2.3.3 Influence of fluvial style on geomorphic units

Brierley and Fryirs (2005) explained that bars are generally classified by their size and shape, and these bars may be single features or a combination of many different types of bars showing multiple depositional stages that have been reworked under different flow conditions. The width:depth ratio of the channel influences the in-channel bar pattern, for as the width:depth ratio increases for the same discharge, its associated flow velocity reduces (Kleinhans and van den Berg, 2011; Rowntree *et al*., 2013). The decrease in flow velocity favours sediment deposition in alluvial channels, as Kleinhans (2010) explained that the amount of energy the channel experiences during flow determines whether or not sediment will be eroded, transported or deposited, and is determined by the fluvial style. For example, sand bed rivers become braided at lower gradients compared to gravel bed rivers because less energy is required to move sand than to move gravel (Kleinhans, 2010).

Tamminga *et al*. (2015) described how the morphology of bars is controlled by the magnitude and duration of flow, channel substrate, vegetation and channel pattern. Jaeger *et al*. (2017) further argued that the development of different bar types in the channel is strongly controlled by the in-channel sediment transfer. Additional factors that are responsible for morphological changes in the downstream direction of NPR's are sediment type, sediment transport and slope (Konnerth, 2015). For example Jaeger *et al*. (2017) discussed that single thread sand bed channels with a low gradient typically have limited bars, while channels with large areas of exposed bedrock have relatively flat surfaces. Jaeger *et al*. (2017) explained that dunes and flow chutes may be found in braided channels with a bed composed of sand and gravel.

The fluvial style is influenced by the bed roughness, as this determines the average flow velocity during flow events (Rowntree *et al*., 2013). The bed roughness is also a key determining factor influencing the flow depth, sediment size and bed structure (Rowntree *et al*., 2013). The sediment type and the ability for it to be transported is another important factor influencing changes in the channel in the downstream direction, dependent on slope and vegetation (Konnerth, 2015). Rivers that have low carrying capacities are known for having multiple channels or wandering tendencies, seen on lower slopes where flow is separated into multiple channel networks (Brierley and Fryirs, 2005).

2.3.4 Influence of vegetation and obstructions on geomorphic units

GU's present in NPR's show the interactions between vegetation and sediment in the channel and assist in explaining the channel pattern and depth dynamics in response to the delivered sediment (Gurnell *et al*., 2015). Kouwen (1969) argued that a continuous increase of in-channel vegetation would increase the channel flow resistance, thus reducing the flow velocity, changing the geomorphological processes. Tooth and Nanson (2000) agreed with Kouwen (1969) when finding that the fluvial processes of NPR's are affected by vegetation and that vegetation plays an important role in the formation of anabranching channels. This is supported by Brierley and Fryirs, (2005) and Pitlick and Wilcock (2013) who argued that vegetated bars are more stable than those that have not been vegetated. Kleinhans (2010) later agreed with Tooth and Nanson (2000) when explaining that channel patterns are dependent on the soil and vegetation characteristics of the floodplain. For example, Kleinhans (2010) argued that strong channel banks promote meandering channels and weaker channel banks promote braided channels (Kleinhans, 2010).

Brierley and Fryirs, (2005) explained that vegetation increases the rate of deposition around bars causing downstream and vertical sediment accumulation, commonly found in anabranching channels. Channel stability is strengthened when bars become vegetated, promoting island formation, which is characteristic of anastomosing channels (Brierley and Fryirs, 2005). Vegetation stabilizes the channel and channel bank by increasing the cohesiveness of the channel sediment, and a change in riparian vegetation will alter the bank stability and affect the channel pattern (Rowntree and Dollar, 1996; Kleinhans, 2010). Vegetation or fine cohesive sediment deposited on migrating bars would slow down the bar movement, stabilize banks, thus reducing bank erosion so that meandering channels may form (Kleinhans, 2010). The movement of bars is further reduced when coarse sediment is deposited on the bars and is only moved when large floods occur (Kleinhans, 2010). The effects of anthropogenic changes to NPR's are mostly visible in the assemblages of riparian vegetation (Jaeger *et al*., 2017).

Previous studies have been done on the effects of woody debris on the channel. These include Graeme and Dunkerley (1993) and Dunkerley (2013) who studied how in-channel vegetation act as obstructions affecting sediment and debris when it is lodged against them. NPR's often have woody debris or vegetation growing in the channel that obstructs the flow causing the formation of forced bars (Dunkerley, 2013). During times of drought the rate of detritus and woody debris in the channel increases and although woody debris can float and much of it is transported by flows in times of flood, some of the in-channel debris gets trapped in an obstruction (Bunte and Abt, 2001; Dunkerley, 2013). Obstructions in the channel such as light woody debris may partially or entirely block the bedload substrate, thus promoting the deposition of coarse sediment upstream of the obstruction and fine sediment at areas where backwater is present (Bunte and Abt, 2001). The effect of woody debris in the active channel is increased when it is lifted out from the bed during flood and flows downstream where it lodges against an obstruction to form a build-up of debris (Dunkerley, 2013). This increases the roughness of the bed and an increase in obstructions when floods occur (Dunkerley, 2013).

Wallerstein *et al*. (2001) identified four types of obstructed flows occurring in NPR's, underflow jam, dam jam, deflector jam and parallel/ bar head jam. Underflow jam was described as a bar forming when water flows underneath a mid-channel debris pile, promoting scouring below the debris and deposition on the lee side of the debris (Wallerstein *et al*., 2001). Dam jam was described as the formation of a bar when water flows against the head of the debris pile, depositing sediment at the head of the obstruction before the flow continues over the obstruction (Wallerstein *et al*., 2001). Deflector jam was described as the deposition of sediment on the lee side of the mid-channel debris pile when the obstruction deflects flow towards the channel bank, creating scouring and pool formation (Wallerstein *et al*., 2001). Parallel/ bar head jam was described as the deposition of sediment between two mid-channel debris piles positioned parallel to the channel banks (Wallerstein *et al*., 2001). However, the absence of obstacles in the channel would result in the absence of any type of jams, thus allowing flow to pass by smoothly and preventing the formation of forced bars caused by woody debris (Dunkerley, 2013).

Riparian vegetation can influence the sediment transport processes in the overbank flow and within the channel (Jaeger *et al*., 2017). Riparian vegetation along with the combined morphology of the channel bed and bank determine the size and shape of the channel (Brierley and Fryirs, 2005). Low amounts of vegetation cover and a strong change in channel slope contributes to facilitating the supply of coarse grained sediment and is particularly evident in narrow canyons or wide braided channels in the piedmont zone (Tooth, 2013). Collins and Bras (2008) stated that a decrease in vegetation during times of drought or because of anthropogenic influences may enhance the sediment transport in the channel. Larsen *et al*. (2004) added that the addition of vegetation can cause obstructions in the main channel and may cause an increase in the aggradation of sediment and influence the channel morphology. This is supported by Shakesby and Doerr (2006) when arguing that the recovery of vegetation may decrease the amount of sediment transported in the channel.

3. Study Area

3.1 Study area description

The study area is located in the Breede-Gouritz Water Management Area (WMA), also known as the primary J catchment (Maherry *et al*., 2013). The size of the Gouritz primary catchment is approximately 45107 km^2 and is made up of 92 quaternary catchments that encompass the Karoo and little Karoo located in the northern and central part of this catchment respectively (Maherry *et al*., 2013). The Prins and Touws River converge in the Touws River catchment (J12) which has an area of 6306 km^2 and form part of the Southern Karoo geomorphic province (Shand, 2004; Partridge *et al*., 2010).

The geomorphological organization hierarchy shows that the higher levels in the hierarchy affect and influence the characteristics (such as erosion) of the lower levels (Partridge *et al*., 2010). Geomorphic provinces are the highest level of organisation in geomorphological hierarchy, defined by a limited range of similar geomorphic features in an area with similar landforms, based on geomorphic history, geological structure, climate, location and altitude (Partridge *et al*., 2010). In 1967 Lester C King characterized 18 geomorphic provinces in South Africa, while 49 years later Partridge *et al.* (2010) used spatial terrain analysis and revised this number to include an additional 16 geomorphic provinces bringing the number of geomorphic provinces in South Africa to 34.

The Southern Karoo geomorphic province is located between the Great Escarpment, Roggeveld Karoo, (Atlantic) Cape Fold Mountains and South Eastern Hinterland on the northern, western, southern and eastern side respectively (Partridge *et al*., 2010). In this geomorphic province, the sedimentary rocks located close to the Cape Fold Mountain Range are more prominently folded where fewer dolerites are observed (Partridge *et al*., 2010). The NPR's in this area have not been deeply incised because Neogene uplift did not greatly affect this province (Partridge *et al*., 2010). The water quality in the Groot catchment is of high salinity, influenced by climate and geology (DWAF, 2004), but the water quality in the upper reaches of the Touws River is good and decreases in quality downstream (Shand, 2004). Figures 2 to 4 were created to provide regional context on the physiographic characteristics that influence river hydrogeomorphology (Gurnelll *et al*., 2015).

3.2 Climate and rainfall in the catchment

The little Karoo is located at an altitude between 71 m and 1692 m above sea level (masl) (Figure 5) and is located between an area that receives summer rainfall in the North and winter rainfall in the South (Partridge *et al*., 2010). The little Karoo has an arid climate (DWAF, 2004; Partridge *et al*., 2010) with the Groot tertiary catchment receiving a mean annual rainfall (MAR) between 375 mm and 457.4 mm between 1924 and 2017 (Mucina and Rutherford, 2006). The Groot tertiary catchment experiences a mean annual runoff of 347 million m^3/annum (DWAF, 2004; Partridge *et al*., 2010). The presence of NPR's is to be expected in the arid climate of the little Karoo with this little runoff compared to the coastal region that experiences an annual runoff of 771 million m^3/annum (DWAF, 2004). The presence of NPR's in this catchment along with the water quality influence the type of land use activities (DWAF, 2004).

3.3 Land use in the catchment

In the year 2000 a 98% accurate estimation of the total local water requirements for the Gouritz WMA amounted to 337 million m^3/annum where around 75.4% was allocated for irrigation (DWAF, 2004). This is of significance because half of the water use in South Africa is allocated for irrigation (DWAF, 2004). The Groot sub catchment receives a runoff of 105 million m^3/annum and the water requirement for this sub catchment amounted to 53 million m^3/annum of which around 92.4% was allocated for irrigation (DWAF, 2004). There are however uncertainties with the total amount of water used for irrigation (DWAF, 2004). Some of the main land use activities in the little Karoo are sheep and ostrich farming, irrigation farming of lucerne, grapes and deciduous fruit (DWAF, 2004).

Some of the anthropogenic impacts on the Touws and Prins Rivers include the clearing of riparian zones, floodplains, overgrazing, and physical disturbances of morphological features (DWA, 2014; Turpie *et al*., 2018). Livestock farming is affected during this clearance of riparian vegetation and allow for the infilling in various areas along the NPR's, thus promoting a better condition as the abundance of karoid vegetation increases (Turpie *et al*., 2018). Anthropogenic activities benefit from in-channel flow as this affects small farm dams, used for irrigation, and a few larger dams, such as the Verkeerdevlei and Gants Dam (DWA, 2014). Groundwater is extensively used for livestock and domestic use (Belcher *et al*., 2007).

The Prins and Touws River supports a variety of anthropogenic activities and have mixed PES values, ranging in the category of B/C or better and C or D (DWA, 2014; Turpie *et al*., 2018).

3.4 Description of study sites

Four study sites with contrasting fluvial styles were established in the Prins and Touws River (Figure 2). The Touws River was classified as an ephemeral river as it does not experience flow for 26% to 75% of the time (Seaman *et al*., 2013; Seaman *et al*. 2016)**.** Both the Touws and Prins Rivers are mixed bedrock alluvial rivers. The four reaches that were surveyed were the Prins Doornboom reach (study site 1), Prinspoort reach (study site 2), Touws Plathuis reach (study site 3) and the Touws Wolwefontein reach (study site 4). These NPR's overlaid the Voorstehoek and Adolphspoort Formation (Bokkeveld group), Rietvlei Formation (Table Mountain Group) and the Wagen Drift Formation (Witteberg Group), (Figure 3). Karoo and Karroid type vegetation was dominant and found in all the reaches. This type of vegetation includes but is not restricted to *Aspalthus hystrix, Vachellia karroo, Tamarix ramosissima, Acmadenia sheilae, Agathosma capensis* and *Phylica paniculata* (Mucina and Rutherford, 2006). Sand, gravel and rocky areas were dominant in the Prins reach while cobble and sand were dominant in the Touws reach, additionally, clay and gravel were observed in some areas of these reaches (Figures 3 and 4). The soils in the Touws River catchment are acidic lithosol soils from the Ordovician sandstones (Mucina and Rutherford, 2006). The soil type (Figure 4) is however only representative of the area outside of the river channel as the valley floor is covered by alluvium, an error due to mapping scale.

The Prins Doornboom reach was classified as an unconfined single thread channel composed of sand, gravel and cobble. Two XS's were surveyed in this reach along a straight part of the reach as it exits a bend. The Prins Doornboom reach is underlain by Rietvlei Formation feldspathic and quartzitic sandstone, siltstone and micaceous shale. The Prinspoort reach was classified as a confined single thread channel with sand deposits between the dominated gravel and cobble bed with some exposed bedrock on the outer bend of the channel. Three XS's were surveyed in this reach, one around a bend and two along the straight part of the reach. The Touws Plathuis reach was classified as an unconfined and wandering channel, dominated by sand and cobbles with gravel in some areas. Two XS's were surveyed in this reach, located in the relatively straight part of the wandering channel. The Touws Wolwefontein reach was classified as a wandering channel with sections of the reach being unconfined. The reach was composed of sand, pebble, cobble and boulders. Five XS's were surveyed around a bend and along the straight part of the reach. The Prinspoort, Touws Plathuis and Touws Wolwefontein reach are underlain by Adolphspoort Formation siltstone, shale and sandstone.

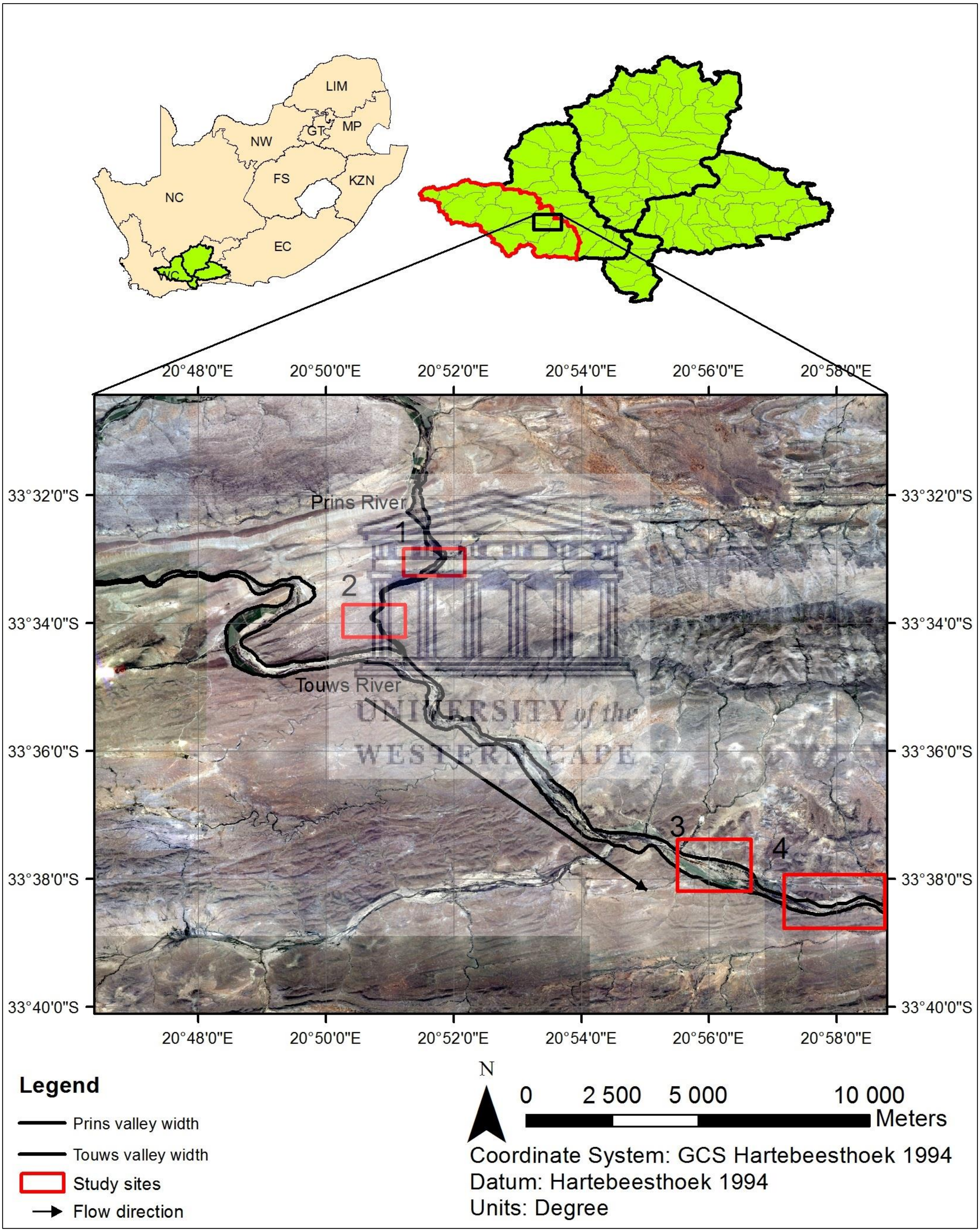


Figure 2: Study area showing the Gouritz WMA and the study sites (Source: Worldview 2)

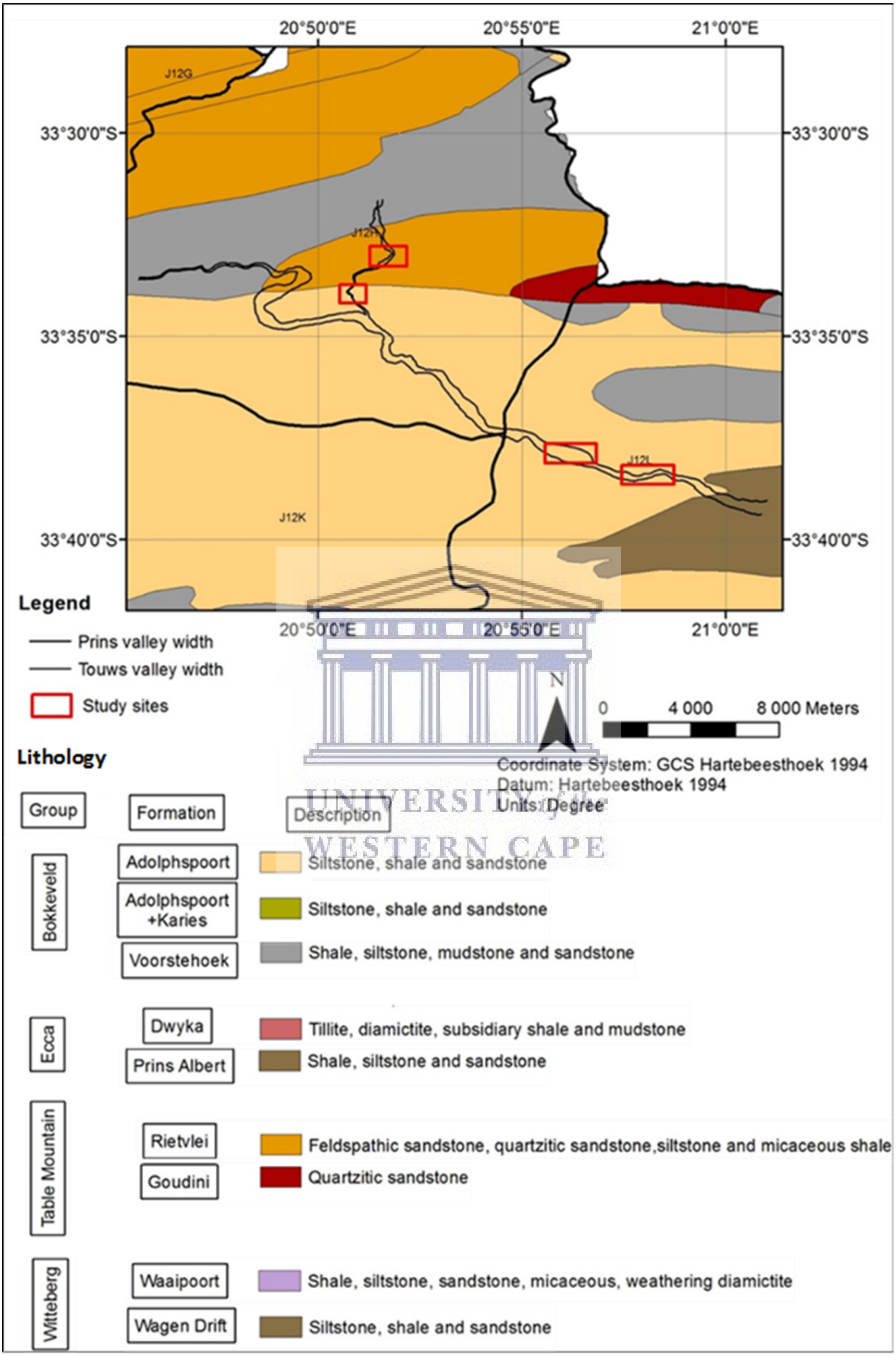


Figure 3: Lithology of study area (Source: Council for Geoscience 2012; 3320 Ladysmith, 1:25000)

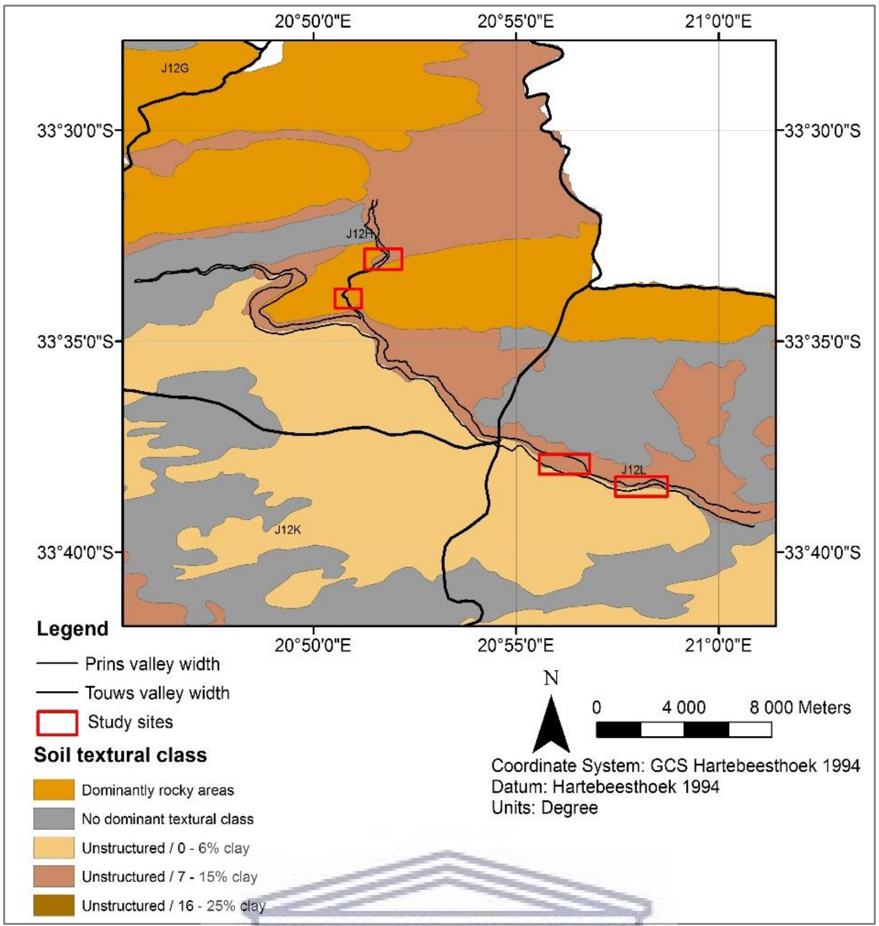


Figure 4: Soil textural class of study area (Source: Council for Geoscience, 2012)

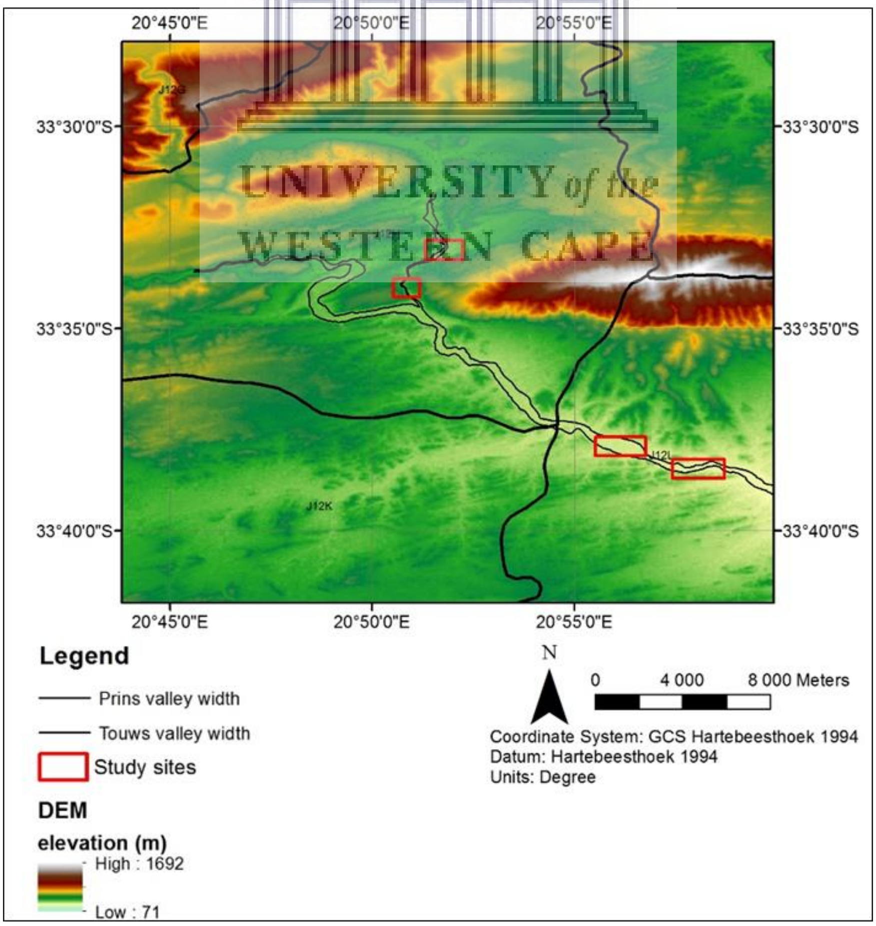


Figure 5: Elevation of study area (Source: van Niekerk, 2016)

4. Methods

4.1 Field data collection

Field visits were carried out when the river bed was dry with only a few pools present at various points across the study sites. Seaman *et al*. (2013) explained that surveying XS's along the channel has importance as the morphology and location of the in-channel GU's can be identified and can later be related to the instream and riparian habitat. Seaman *et al*. (2013) added that conducting field visits when the valley floor is exposed is important because it provides a clear view of the channel morphology and allows sediment samples of bars to be collected.

4.1.1 Morphological survey

The fluvial style of the channel cannot be identified by the planform view alone, as Charlton (2008) argued that this does not show the relation between channels and GU's. It was thus necessary to collect field data. A differential GPS (dGPS) was used to survey the width, cross-sectional morphology and location of in-channel bars across the 4 study sites. The co-ordinates, length, breadth, height and substrate characteristic of each bar intersecting the valley floor XS was surveyed. The XS's were used to map the location and assist in understanding the spatial distribution of in-channel bars while the number of bars observed in each XS and reach was summarised in table form.

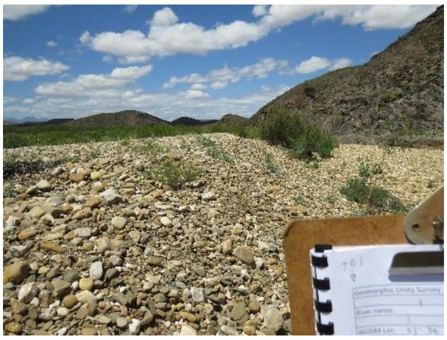
4.1.2 Particle size and sediment collection

The heel-to-toe method described by Bunte and Abt (2001) was followed to conduct pebble counts on gravel and cobble bars, and following the method of Lisle *et al*. (2000), a Wolman's (1957) pebble count was conducted on 100 random gravel sized particles by measuring particle b-axis using callipers. Seaman *et al*. (2013) surveyed the Mokolo River, a NPR where field data was collected during a high and low flow period to observe the channel morphology and obtain sediment samples from the relevant GU's. This method was suitable to use during the low flow condition of the Prins and Touws River. Following the method of Seaman *et al*. (2013), sediment samples were collected from bars with a grain size smaller than 2 mm and brought to the lab for analysis. The calliper and sieving methods were used to obtain D_{50} values of the bars in the Prins and Touws River so that statistical analysis could be performed on the bars in each study site.

4.1.3 Observations of contrasting bar types

Photographs were taken of each surveyed bar and used to identify the different bar types in the different reaches (see Table 4 for an example). The bar type was described using the D_{50}, D_{16} and D_{84} values of the surveyed bars, and the nomenclature of Brierley and Fryirs (2005).

Table 4: Photographs and descriptions of some surveyed bars

Camera facing upstream	Description	Camera facing downstream
	PB10 Moderately well sorted small cobble and moderately sorted coarse sand mixture expansion bar Prins Doornboom reach (See Figure 10 for bar location)	
	PB5 Confined Poorly sorted fine sand bench Prinspoort reach (See Figure 10 for bar location)	
	TWB1 Moderately sorted medium sand longitudinal bar Touws Plathuis reach (See Figure 15 for bar location)	
	TB1 Moderately well sorted small cobble expansion bar Touws Wolwefontein reach (See Figure 17 for bar location)	

4.2 Data Analysis

4.2.1 Channel pattern and long profile

Following the method similar to Seaman *et al*. (2013) and Konnerth (2015), the channel width and length was measured using XS's and spatial analysis. Worldview images of the study sites with a spatial resolution of 0.5 m was visually analysed to identify the channel pattern of the river. With the aid of the river characterisation used by Brierley and Fryirs (2005), the fluvial styles of the study sites were identified and classified (Table 4). Lisle *et al*. (2000) mapped the topography of the channel and the sediment size of the bed material during low flow periods. This method was followed and using a 5 m SuDEM raster file, a long profile of the Prins and Touws River was created, and the underlying lithology of these rivers was plotted along the long profile.

4.2.2 Morphological analysis

The XS width was measured using the dGPS data. A XS similar to Rowntree *et al*. (2013) showing the width of the channel and spatial distribution of the surveyed bars was produced (Figure 6).

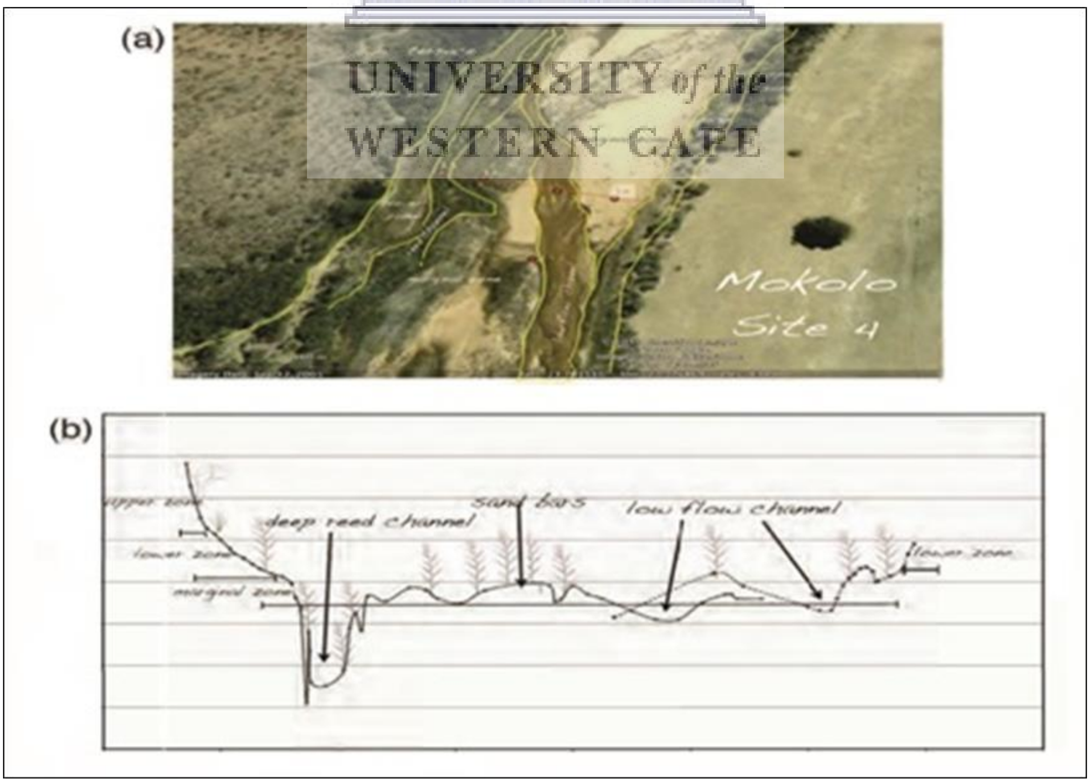


Figure 6: Channel XS of google earth image (after Rowntree *et al*., 2013)

Following the method of Thompson and Croke (2013), the area of bars covering the valley floor in each study site was calculated as follows:

$$\frac{\sum area\ of\ geomorphic\ units\ in\ study\ site}{\sum areaof\ valley\ floor\ swath\ area\ where\ geomorphic\ units\ were\ located}\ X\ 100 \qquad (1)$$

The cross sectional (swath) area of each XS was calculated by measuring the length (m) of the XS (length) and the distance (m) between the furthest upstream and downstream bar (width) that intersected the XS. Formula (1) produced the area of bars per study site relative to the valley width as a percentage.

4.2.3 Particle size analysis

Description of particle size			ϕ = -log$_2$	mm	ψ = log$_2$
Boulder			- 12.0	4096	12.0
	very large		- 11.5	2896	11.5
			- 11.0	2048	11.0
	large		- 10.5	1448	10.5
			- 10.0	1024	10.0
	Medium		- 9.5	724	9.5
			- 9.0	512	9.0
	small		- 8.5	362	8.5
			- 8.0	**256**	**8.0**
Cobble	large		- 7.5	181	7.5
			- 7.0	128	7.0
	Small		- 6.5	90.5	6.5
			- 6.0	**64**	**6.0**
Gravel	very coarse		- 5.5	45.3	5.5
			- 5.0	32	5.0
	coarse		- 4.5	22.6	4.5
		Pebble	- 4.0	16	4.0
	medium		- 3.5	11.3	3.5
			- 3.0	8	3.0
	fine		- 2.5	5.66	2.5
			- 2.0	4	2.0
	very fine	**Granule**	- 1.5	2.83	1.5
			- 1.0	**2**	**1.0**
Sand	very coarse		- 0.5	1.41	0.5
			0	1	0
	coarse		+ 0.5	0.707	- 0.5
			+ 1.0	0.500	- 1.0
	medium		+ 1.5	0.354	- 1.5
			+ 2.0	0.250	- 2.0
	fine		+ 2.5	0.177	- 1.5
			+ 3.0	0.125	- 3.0
	very fine		+ 3.5	0.088	- 3.5
			+ 4.0	**0.063**	- 4.0
Silt					
			+ 8.0	**0.0039**	**- 8.0**
Clay					
			+ 12.0	**0.00024**	**- 12.0**

Figure 7: Wentworth scale showing the size gradation for sediment in the range of sand to boulders (after Bunte and Abt, 2001)

Once the D_{50} of the surveyed bars was calculated, the sediment was classified as sand, gravel or cobble based on the Wentworth scale (Figure 7) (Bunte and Abt, 2001). Two D_{50}

values were calculated for the bars that had a mix of fine and coarse grained sediment, both these D_{50} values were used in naming these bars. The sorting of the sediment was determined using the formula (2) described by Bunte and Abt (2001):

$$\frac{D_{84} - D_{16}}{2} \quad (2)$$

This sorting coefficient ranged between <0.35 (very well sorted) and >4 (extremely poorly sorted) (Bunte and Abt, 2001). The bar classification, D_{50} and sorting coefficient was used to name each bar (Table 4).

4.2.4 Analysis of different bar types

Phillips (2008) assessed the bank attached and in-channel GU's based on their morphology, composition and vegetation which give an indication of the geomorphological processes that created these morphological features. A similar method was followed in classifying the bars in this thesis where the physical characteristics of each bar was surveyed, visually analysed and classified using Brierley and Fryirs (2005). The classification system developed by Brierley and Fryirs (2005) was used to identify GU's in this project as this covered the range of GU's found in the study sites.

4.3 Bar characteristics and morphology

To determine the difference in the occurrence of bars with different fluvial style, different bar types in each XS were numbered. To determine if the diversity of bar form affects the diversity of physical habitat, the diversity of bars per XS and study site was identified. Furthermore, the bars were grouped together based on substrate class where the percentage of bars per substrate class is shown. The D_{50} values of different substrate classes were plotted on box and whisker diagrams showing the range of variability within each substrate class of the bars. Strick *et al*. (2018) used ratios to describe the shape of scroll bars and used the height:width ratios to describe short wide and tall narrow bars. Using a similar method as Strick *et al*. (2018), the physical characteristics of all the bars were described using form ratios.

4.4 Forced bar characteristics and morphology

The forced bars were separated into groups based on substrate metrics and location; those located on the lee side of vegetation (veg) and those located on the lee side of debris piles (debris). The D_{50} values of the forced bars of different substrate classes were plotted on a box and whisker diagram. Bunte and Abt (2001) used statistics to analyse the sediment size distributions in different rivers. A similar method was followed using Spearman's rank correlation (given that the data were not normally distributed) to determine if any correlation exists between substrate characteristics and the morphology of forced bars.

5. Results

5.1 Defining the planform characteristics of the study sites

The planform characteristics of the NPR's in this study are shown in Figure 8. This Figure shows the valley width and accompanying fluvial style found in different reaches of the river. The aerial images in Figure 8 were taken towards the end of 2017 and show the channel pattern and location of the XS's in each study site. Figure 9 shows the longitudinal profile, accompanying lithology, fluvial style and a summary of the distribution of GU's in the study area. In Figures 8 and 9, the vertical line shows where the Prins River joins the Touws River. The average bed gradient for the entire long profile is 0.004.

Generally, the Prins River valley width undergoes a lot of variation as seen in Figure 2 and Figure 8. The valley width in study site 1 is about 140 m wide with the fluvial style being an unconfined single to dual-thread channel. This reach is underlain by Rietvlei Formation sandstone, siltstone and shale with the valley floor being covered by sand, gravel and cobble. This reach had vegetation growing in the channel and an abundance of debris was found in the channel as well. The average bed gradient for study site 1 is 0.007.

Study site 2 was located downstream of study site 1 and the width of the valley margin is a lot narrower than study site 1, being around 47 m - 64 m wide. The fluvial style in this reach was a confined single thread channel. Study site 2 covered a bend in the valley and the thalweg was located at the outer bend against a near vertical rock face. The reach is underlain by Adolphspoort Formation siltstone, shale and sandstone with the valley floor being covered by sand and gravel. There were some cobbles present in this reach, but the bars observed were not composed of cobble material. The presence of vegetation growing in the channel was evident with some debris piles being identified as well. The average bed gradient for study site 2 is 0.009.

The valley width of the river increases significantly where the Prins River joins the Touws River. Study site 3 was located downstream of study site 2, on the Touws River. In study site 3 the shape of the macro channel is relatively uniform and straight. The fluvial style of this reach was a wandering channel. The valley width was much larger than any of the other study sites, being between 740 m and 800 m wide. The reach is underlain by Adolphspoort Formation siltstone, shale and sandstone while the valley floor was covered by sand and gravel. No cobble bars were identified in this reach. Vegetation and debris piles were observed in this reach, but living vegetation (notably *Vachellia karroo* and *Tamarix ramosissima*) was more abundant than debris. The average bed gradient for study site 3 is 0.005.

Study site 4 was located downstream of study site 3 and the valley width was narrower than study site 3, being between 168 m and 266 m. The fluvial style of this reach was a wandering channel with riffle features and cross over points between pools and deeper channel sections located along the thalweg and in parts of the valley where a channel outer bend abuts rock outcrop in the valley margin. The reach is underlain by Adolphspoort Formation siltstone, shale and sandstone with the valley floor being covered by sand, gravel and cobble. There was more cobble and gravel substrate in the upper part of the study site, while further downstream more sand was found in the channel. Vegetation was observed in the entire study site with the presence of debris piles being more abundant after the bend (near XS 12). The average bed gradient for study site 4 is 0.009.

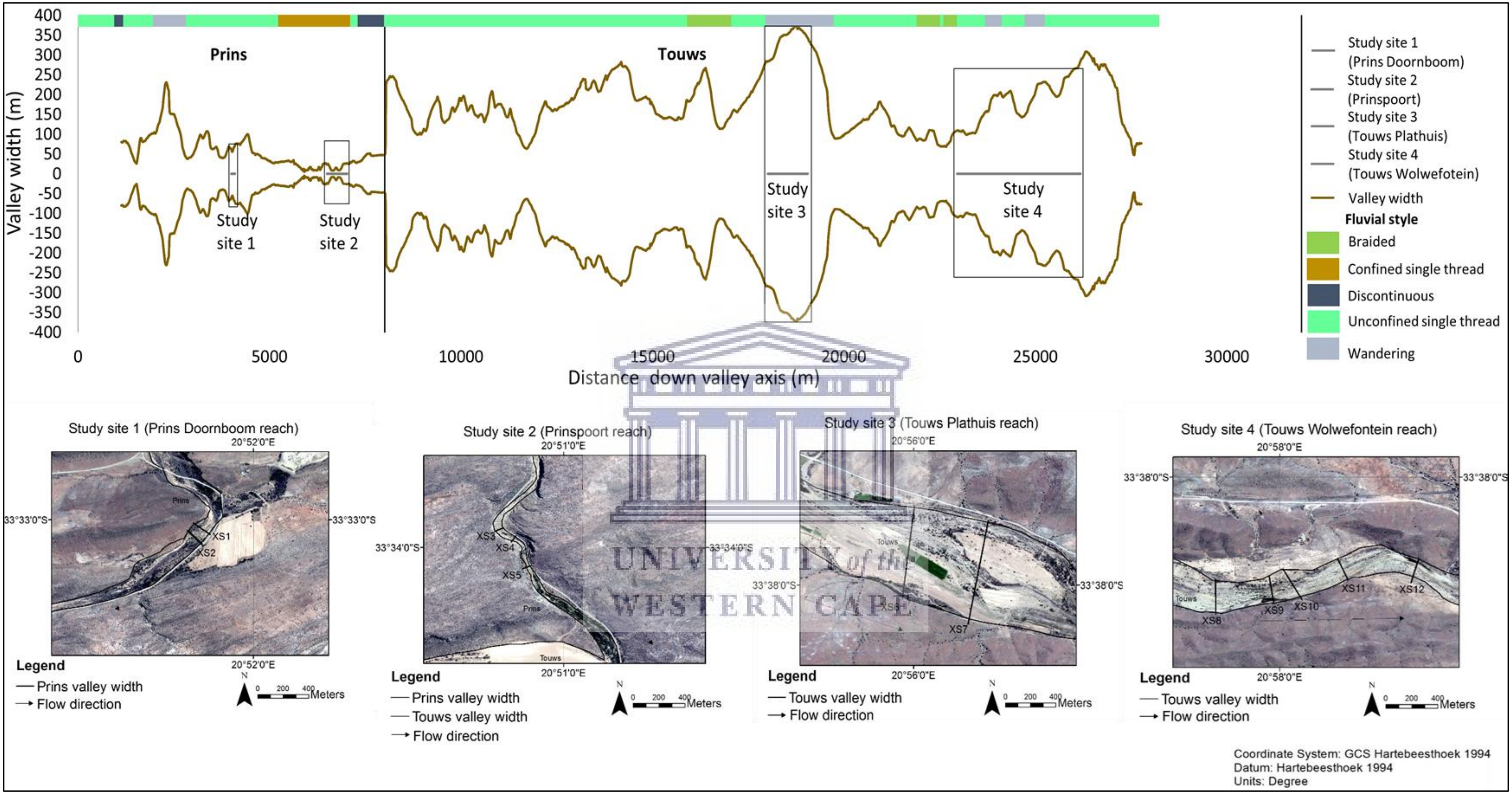


Figure 8: Valley width and fluvial style of the Prins and Touws River with accompanying aerial photographs of the study sites

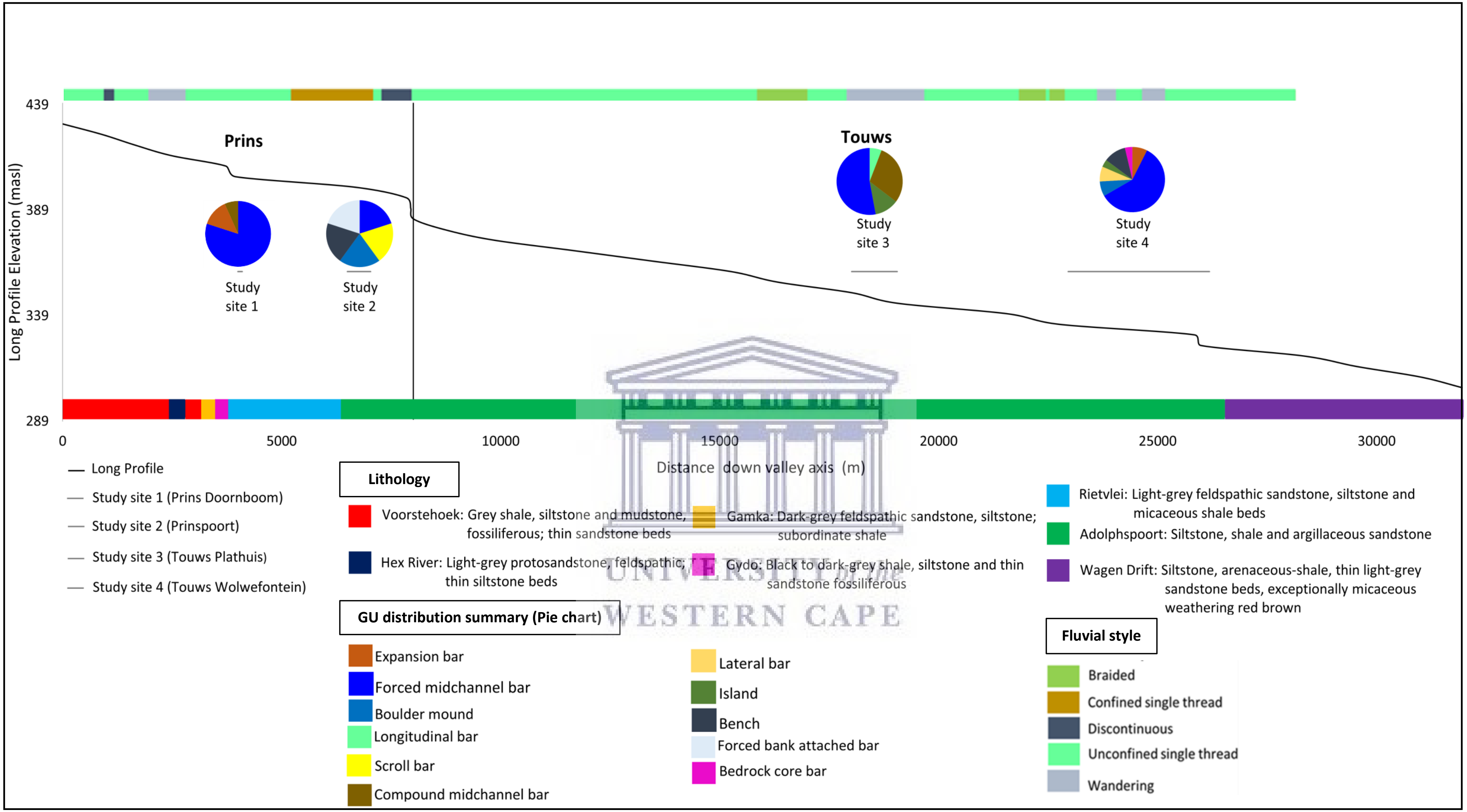


Figure 9: Long profile, lithology, fluvial style and distribution summary of GU's in the Prins and Touws River

5.2 Identifying and characterizing bars in the study sites

Figures 10 to 21 show the XS surface morphology, spatial distribution, height, width and D_{50} of all the surveyed bars across the study sites. Surveyed bars with two D_{50} values represent features composed of a mixture of sand and gravel/cobble material, and the values are displayed with a "/" separator. The channel width can be seen in each XS, and the difference between the confined, unconfined and wandering channels can be observed. Using Brierley and Fryirs (2005) as a reference to identify and classify bars observed in all the study sites, acronyms for the bars were plotted onto Figures 10 to 21 to show the identification and spatial distribution of different bars.

Table 5 provides the description of all the surveyed bars in the study site while Table 6 shows the meaning of the acronyms developed for these bars. In total, twelve XS's were surveyed across all the study sites, with a total 64 bars being identified and surveyed. Eleven contrasting bar types were identified in the study areas (Table 6). Table 7 shows the number of bars identified in each XS and study site for the comparison of habitat complexity in contrasting study sites.

Table 5: Classification of observed GU's based on morphology and substrate composition

Bar codename	Classification (Brierley and Fryirs, 2005; Folk and Ward 1957)	Bar codename	Classification (Brierley and Fryirs, 2005; Folk and Ward 1957)
PB1	Moderately well sorted fine sand forced mid-channel bar	TWB13	Very poorly sorted very fine sand forced mid-channel bar
PB2	Poorly sorted fine sand forced mid-channel bar	TWB14	Moderately sorted small cobble and poorly sorted medium sand mixture forced mid-channel bar
PB3	Moderately sorted fine sand forced mid-channel bar	TWB15	Poorly sorted fine sand forced mid-channel bar
PB4	Moderately sorted coarse sand expansion bar	TWB16	Moderately sorted coarse gravel and poorly sorted medium sand mixture forced mid-channel bar
PB5	Moderately sorted fine sand forced mid-channel bar	TWB17	Poorly sorted very coarse gravel and very poorly sorted medium sand mixture forced mid-channel bar
PB6	Well sorted small cobble forced mid-channel bar	TB1	Moderately well sorted small cobble expansion bar
PB8	Moderately well sorted small cobble forced mid-channel bar	TB2	Moderately well sorted very coarse gravel forced mid-channel bar
PB9	Well sorted very coarse gravel forced mid-channel bar	TB3	Extremely poorly sorted fine sand forced mid-channel bar

PB10	Moderately well sorted small cobble and moderately sorted coarse sand mixture expansion bar	TB4	Moderately well sorted very coarse gravel forced mid-channel bar
PB11	Poorly sorted medium sand forced mid-channel bar	TB5	Moderately well sorted very coarse gravel forced mid-channel bar
PB12	Moderately sorted medium sand forced mid-channel bar	TB6	Well sorted very coarse gravel forced mid-channel bar
PB13	Well sorted small cobble and moderately sorted fine sand mixture forced mid-channel bar	TB7	Moderately well sorted very coarse gravel forced mid-channel bar
PB14	Moderately well sorted very coarse gravel and poorly sorted fine sand mixture compound mid-channel bar	TB8	Moderately sorted very coarse gravel boulder mound
PB15	Very poorly sorted very fine sand forced mid-channel bar	TB9	Moderately sorted very coarse gravel forced mid-channel bar
PB16	Moderately well sorted fine sand forced mid-channel bar	TB10	Moderately sorted medium sand lateral bar
PB1 (confined)	Moderately well sorted very coarse gravel and poorly sorted fine sand mixture forced mid-channel bar	TB11	Poorly sorted medium sand forced mid-channel bar
PB2 (confined)	Moderately well sorted very coarse gravel and poorly sorted very fine gravel mixture scroll bar	TB12	Moderately well sorted very coarse gravel forced mid-channel bar
PB3 (confined)	Poorly sorted medium sand forced bank attached bar	TB13	Very poorly sorted fine sand forced mid-channel bar
PB4 (confined)	Well sorted very coarse gravel boulder mound	TB14	Poorly sorted fine sand island
PB5 (confined)	Poorly sorted fine sand bench	TB15	Very poorly sorted medium sand bench
TWB1	Moderately sorted medium sand longitudinal bar	TB17	Poorly sorted fine sand bench
TWB2	Moderately sorted medium sand compound mid-channel bar	TB18	Extremely poorly sorted very fine sand forced mid-channel bar
TWB3	Moderately sorted medium sand forced mid-channel bar	TB19	Moderately sorted medium sand bedrock core bar
TWB4	Moderately well sorted very coarse gravel and poorly sorted medium sand mixture island	TB20	Moderately well sorted very coarse gravel expansion bar
TWB5	Moderately well sorted very coarse gravel forced mid-channel bar	TB21	Moderately sorted medium sand boulder mound
TWB6	Moderately sorted medium sand compound mid-channel bar	TB22	Moderately sorted very fine gravel lateral bar
TWB7	Moderately sorted very coarse gravel and poorly sorted coarse sand mixture compound mid-channel bar	TB23	Very poorly sorted very fine sand bench
TWB8	Very poorly sorted fine sand compound mid-channel bar	TB24	Moderately sorted coarse sand forced mid-channel bar
TWB9	Moderately sorted vey coarse gravel compound mid-channel bar	TB25	Poorly sorted medium sand forced mid-channel bar

TWB10	Poorly sorted fine sand forced mid-channel bar	TB26	Poorly sorted very coarse gravel forced mid-channel bar
TWB11	Moderately sorted coarse gravel and poorly sorted medium sand mixture island	TB27	Moderately sorted very coarse gravel forced mid-channel bar
TWB12	Very poorly sorted very fine sand forced mid-channel bar	TB28	Moderately sorted coarse gravel forced mid-channel bar

5.2.1 Prins Doornboom reach

Figures 10 and 11 show the surface morphology and spatial distribution of bars found in XS 1 and XS 2. The bars located in XS 1 were distributed in two groups, separated by an area absent of bars. The bars on the left side of the channel were located close to each other, consisting of five forced mid-channel bars and one expansion bar. The remaining three bars on the right side of the channel were clustered, but not as closely-spaced as those in the first group and consisted of two forced mid-channel bars and one expansion bar. The bars in XS 2 were more evenly distributed compared to XS 1. The bars were located in groups of two with a noticeable distance of an area absent of bars between the three groups of bars. Forced mid-channel bars were located in the first and third group and located on the right and left side of the channel respectively. A compound mid-channel bar and forced mid-channel bar were located in the second group and located roughly in the middle of the channel.

5.2.2 Prinspoort reach

The Prinspoort reach was the narrowest reach in the study area. Figures 12 to 14 show the surface morphology and spatial distribution of bars in XS 3 to XS 5. A forced mid-channel bar and scroll bar were identified in XS 3 and were separated by a sudden drop in elevation. A boulder mound and forced bank attached bar were identified in XS 4 and were separated by the active channel. A bench was identified in XS 5 and was located along the right bank of the channel adjacent to a vertical sand wall in the straight channel.

5.2.3 Touws Plathuis reach

The Touws Plathuis reach was the widest reach in the study area. Figures 15 and 16 show the surface morphology and spatial distribution of the bars identified in XS 6 and XS 7. The bars identified in XS 6 were distributed in 3 groups. The first group consisted of one longitudinal bar adjacent to a compound mid-channel bar and a forced mid-channel bar located on the compound mid-channel bar. The second group consisted of a large island with one smaller compound mid-channel and forced mid-channel bar located on top of it.

The third group consisted of two compound mid-channel bars adjacent to one another. One compound mid-channel bar was located on the right side of the channel. The bars identified in XS 7 were distributed into two groups. The first group, located on the left side of the channel, consisted of one forced mid-channel bar and island, relatively close to one another. A smaller forced mid-channel bar was located between the two groups. The second group of bars were located roughly in the middle of the XS with relatively uniform distribution and were all identified as forced mid-channel bars.

5.2.4 Touws Wolwefontein reach

Figures 17 to 21 show the surface morphology and spatial distribution of bars located in XS 8 to XS 12. Nearly all of the bars were located on the right side of the channel in XS 8, with only one forced mid-channel bar located on the left side of the channel. The bars identified on the right side of the channel were one boulder mound, six forced mid-channel bars and one expansion bar, and were all located close to one another. The bars located in XS 9 were distributed into two groups. The first group consisted of one island and forced mid-channel bar located close to one another. The second group consisted of two smaller forced mid-channel bars. One lateral bar was located on the right side of the channel, adjacent to a pool. One group of bars and one individual bar was located in XS 10. The group consisted of one forced mid-channel bar and bench located close to one another. One bench was located on top of the right bank. The bars identified in XS 11 were evenly distributed roughly in the central part of the channel and was not distributed in groups. The bars identified in XS 12 were one bedrock core bar, expansion bar and boulder mound.

Table 6: List of bars identified in all study sites

Acronym	Meaning	Acronym	Meaning
BCB	Bedrock core bar	FMCB	Forced mid-channel bar
B	Bench	I	Island
BM	Boulder mound	LongB	Longitudinal bar
CMCB	Compound mid-channel bar	LatB	Lateral bar
EB	Expansion bar	SB	Scroll bar
FBAB	Forced bank attached bar		

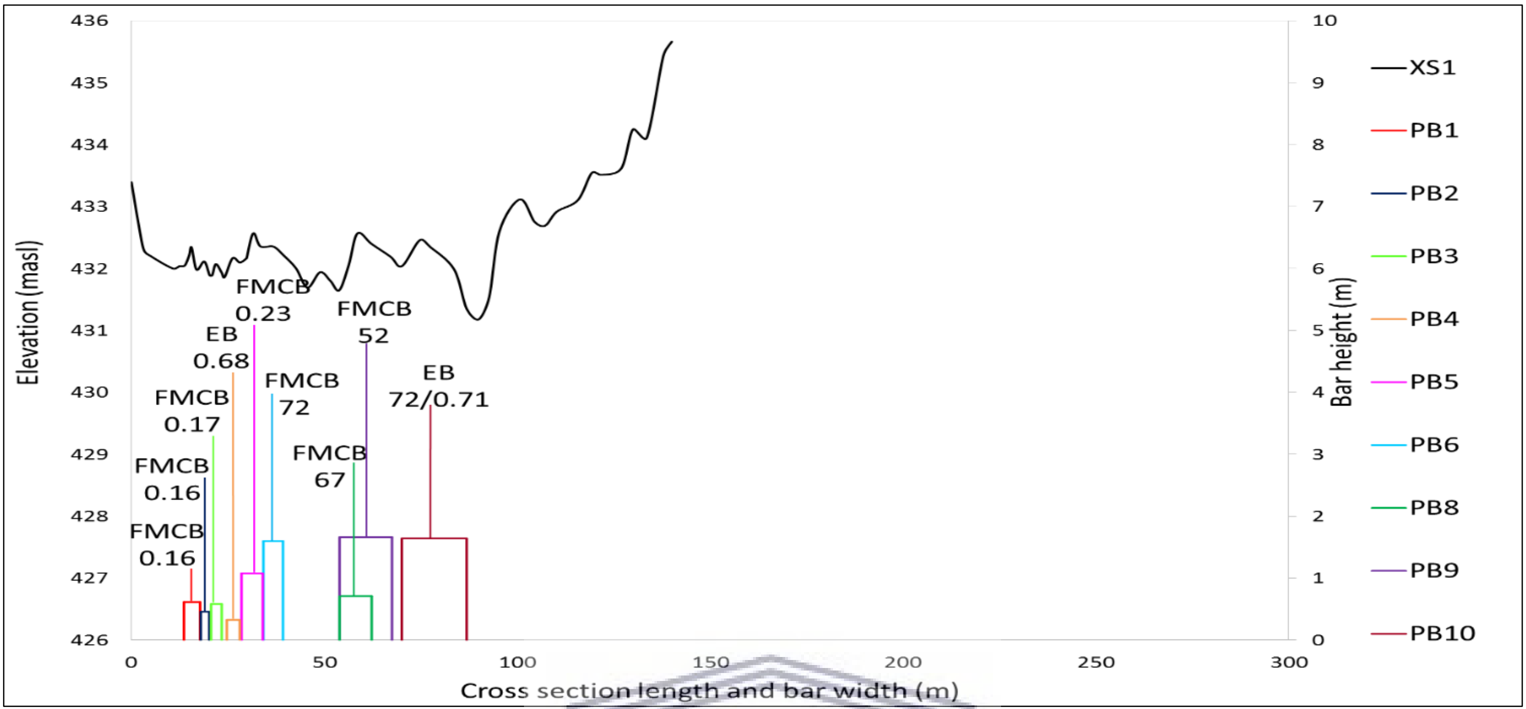


Figure 10: Spatial distribution, height, width and D_{50} of bars identified in XS 1

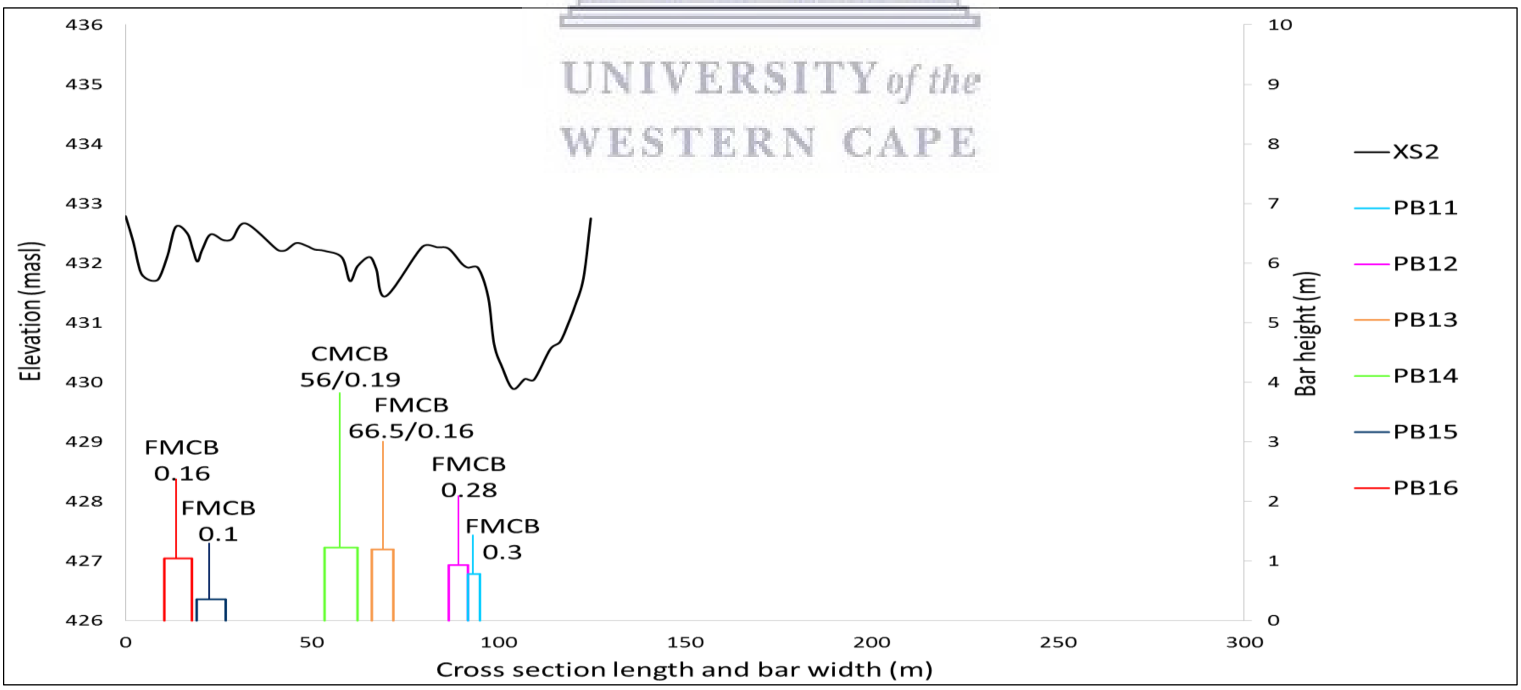


Figure 11: Spatial distribution, height, width and D_{50} of bars identified in XS 2

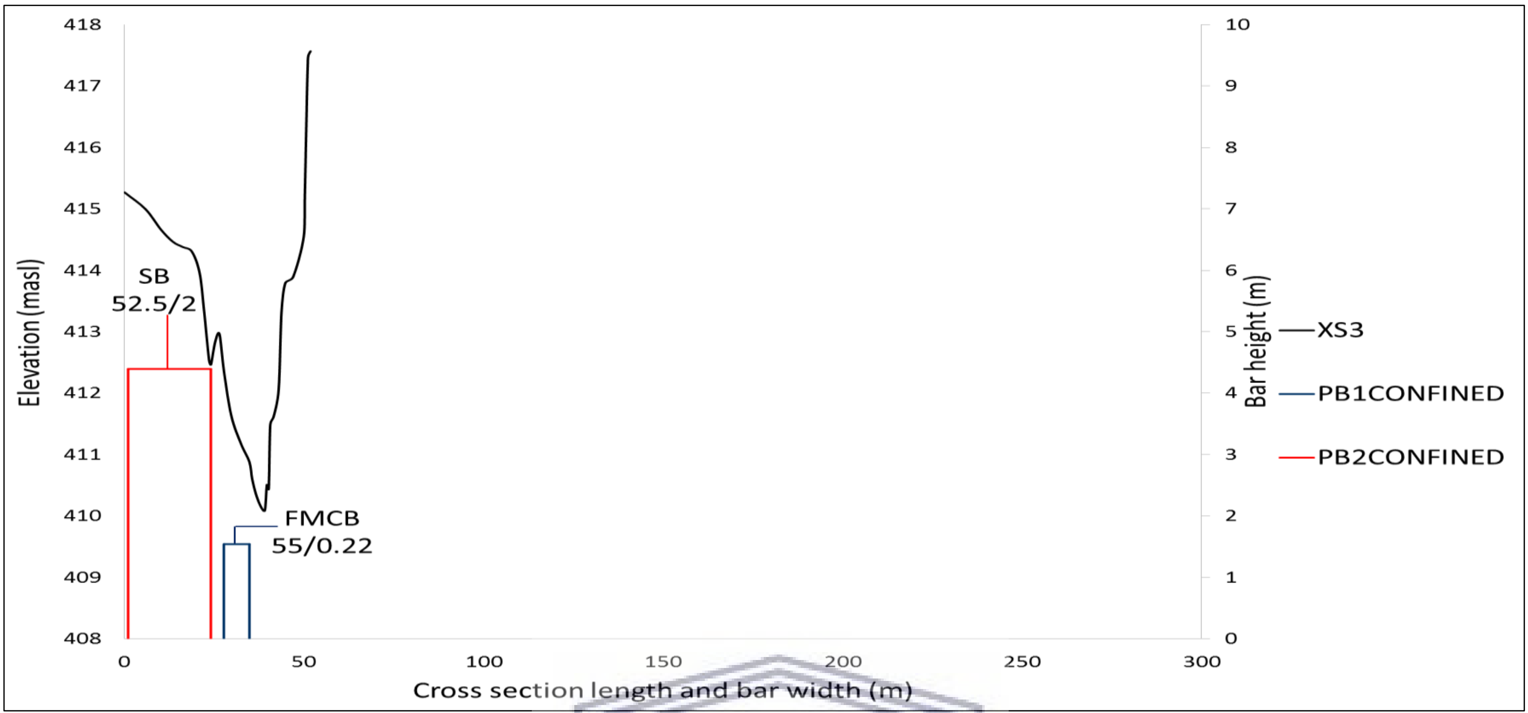


Figure 12: Spatial distribution, height, width and D_{50} of bars identified in XS 3

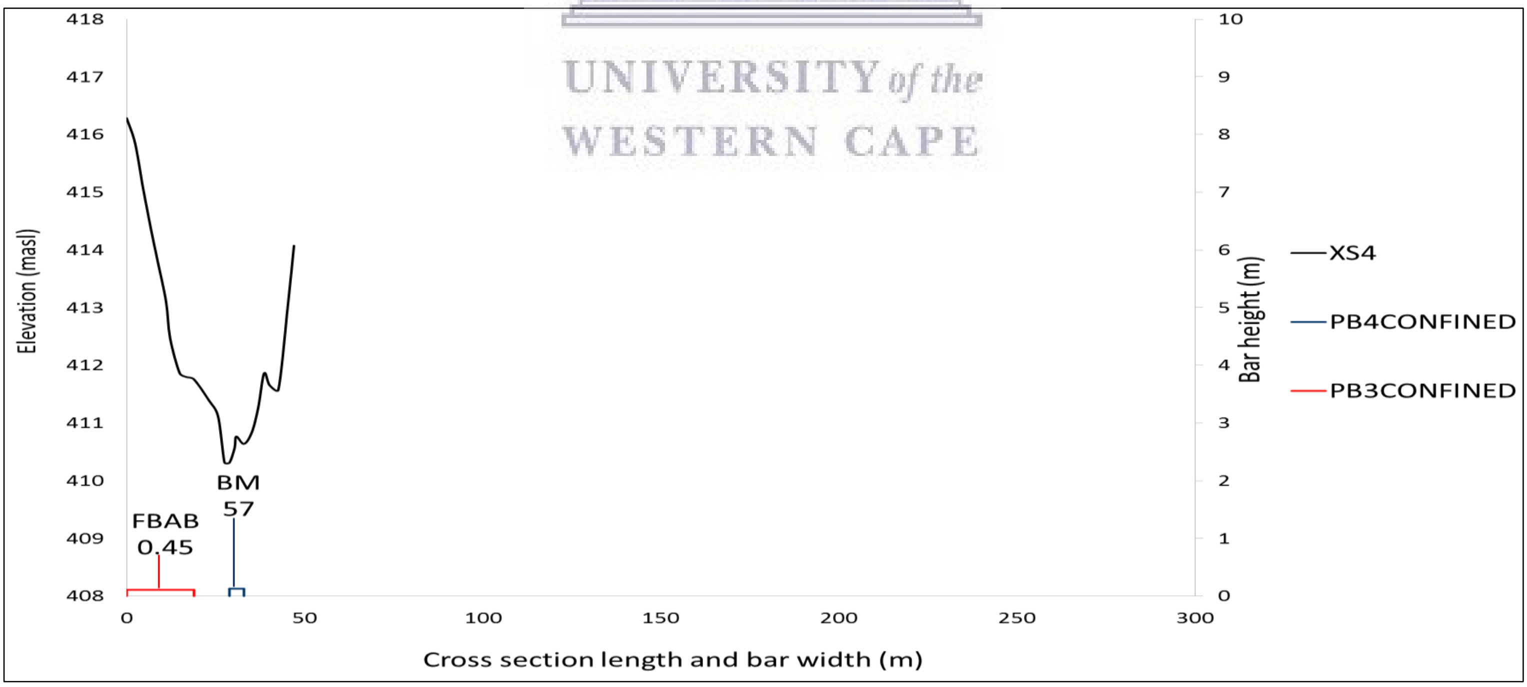


Figure 13: Spatial distribution, height, width and D_{50} of bars identified in XS 4

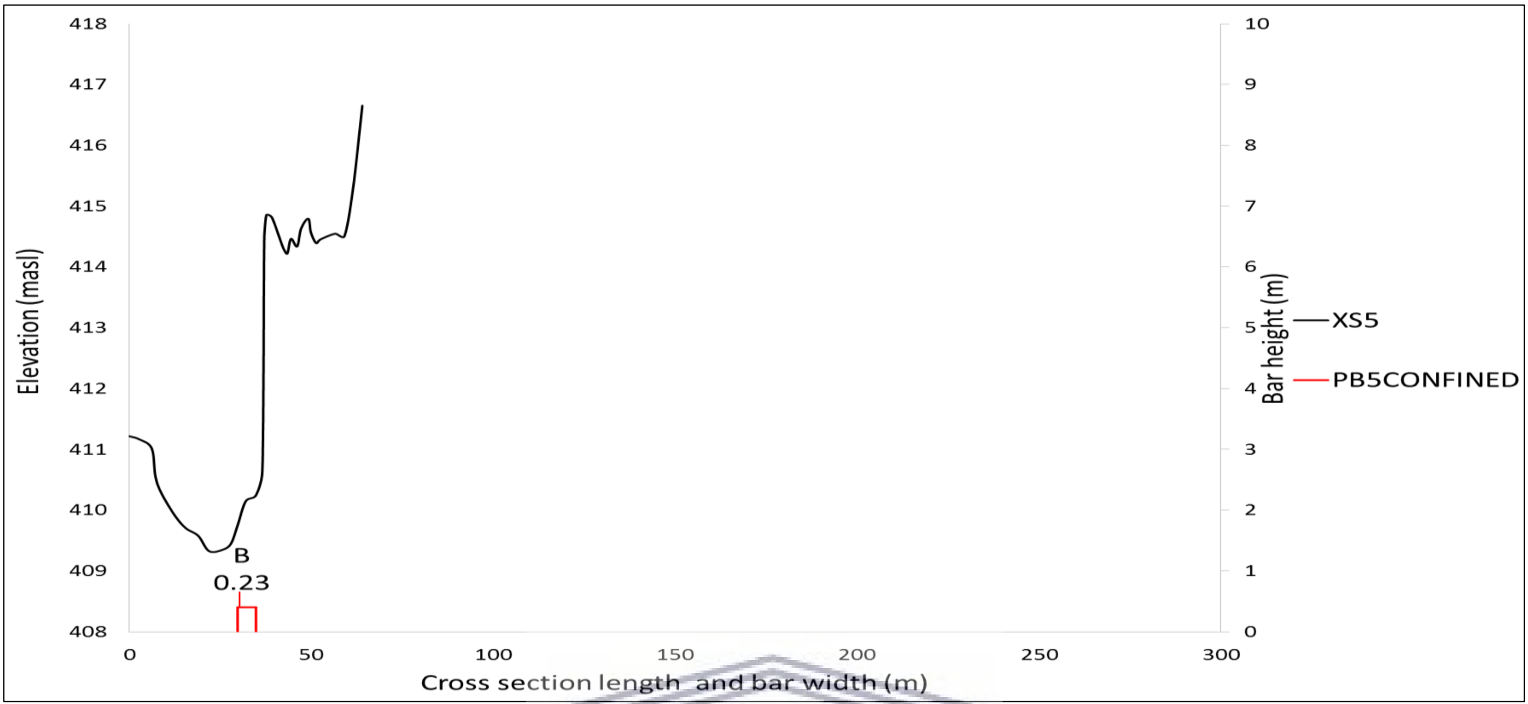


Figure 14: Spatial distribution, height, width and D_{50} of bars identified in XS 5

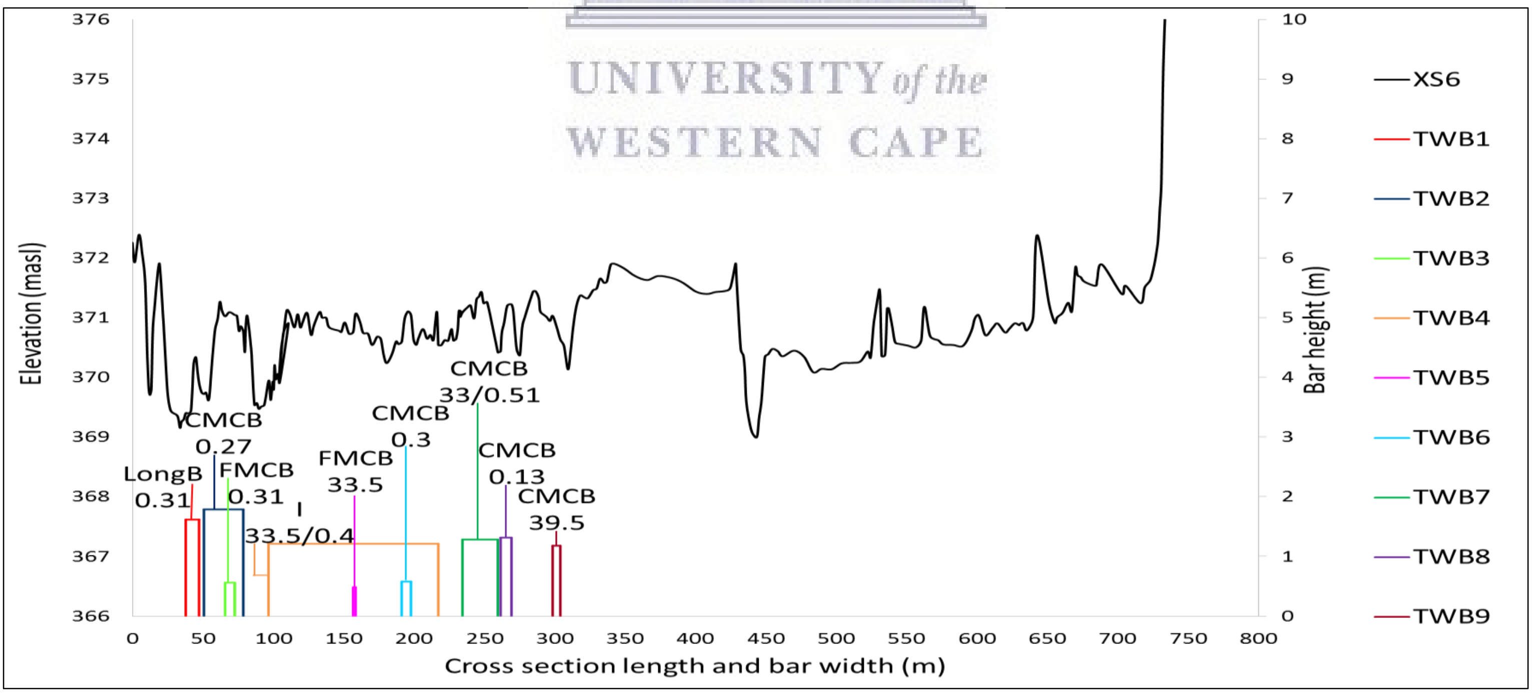


Figure 15: Spatial distribution, height, width and D_{50} of bars identified in XS 6

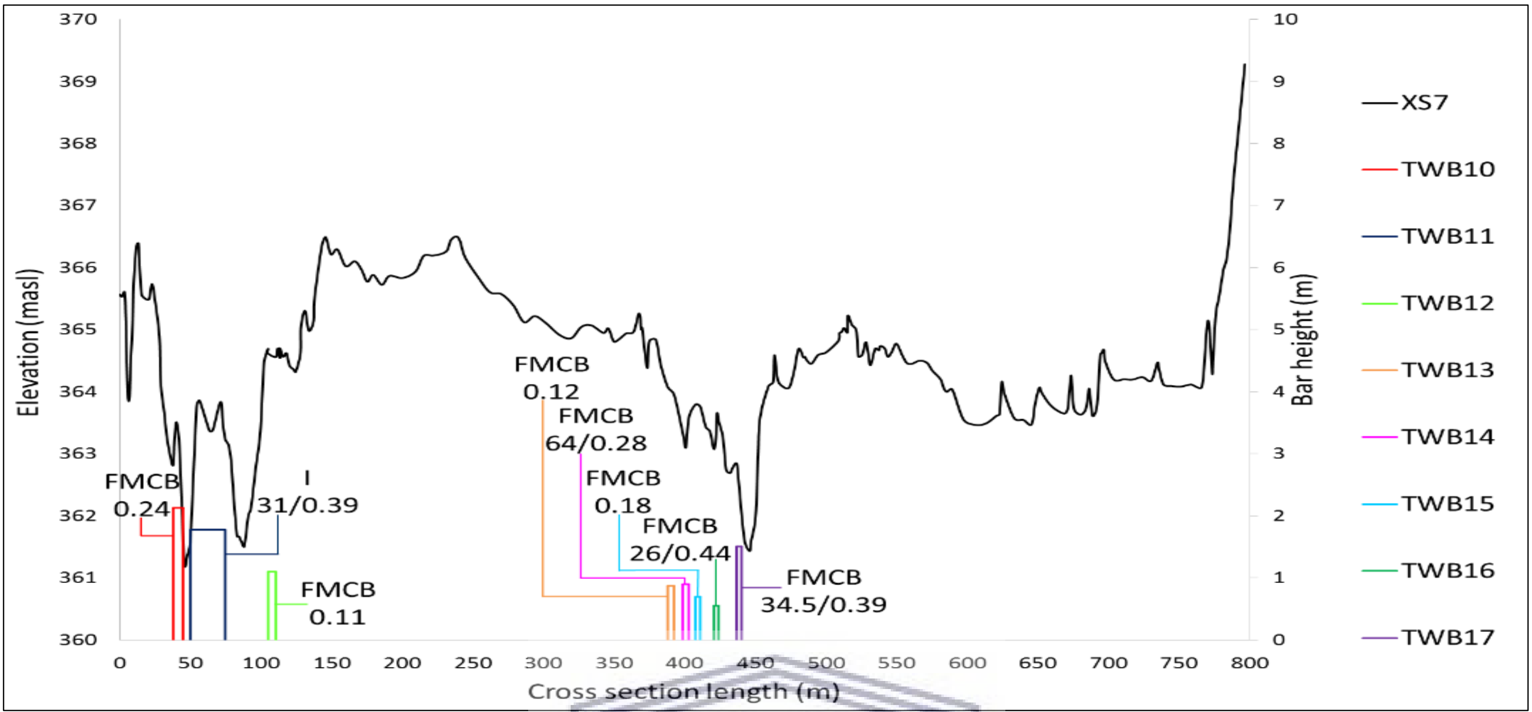


Figure 16: Spatial distribution, height, width and D_{50} of bars identified in XS 7

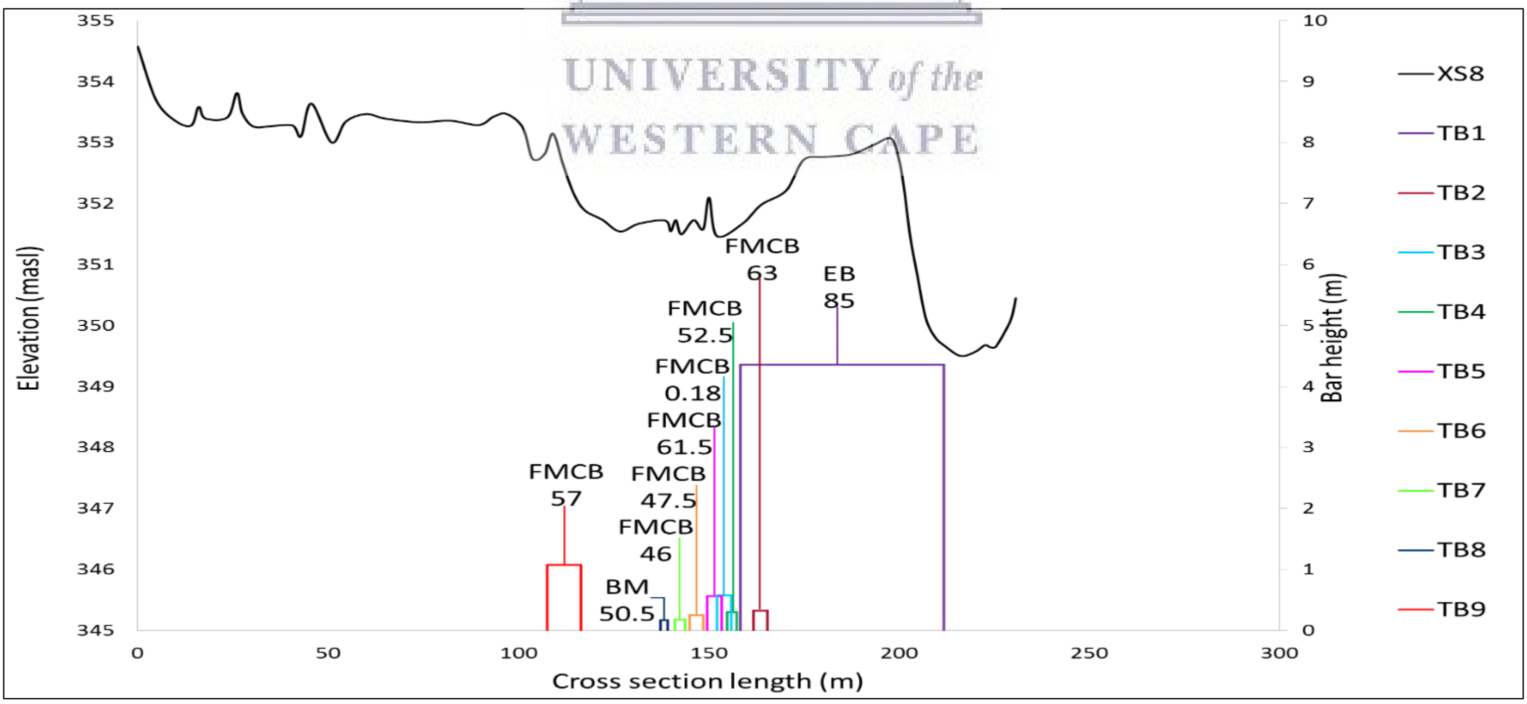


Figure 17: Spatial distribution, height, width and D_{50} of bars identified in XS 8

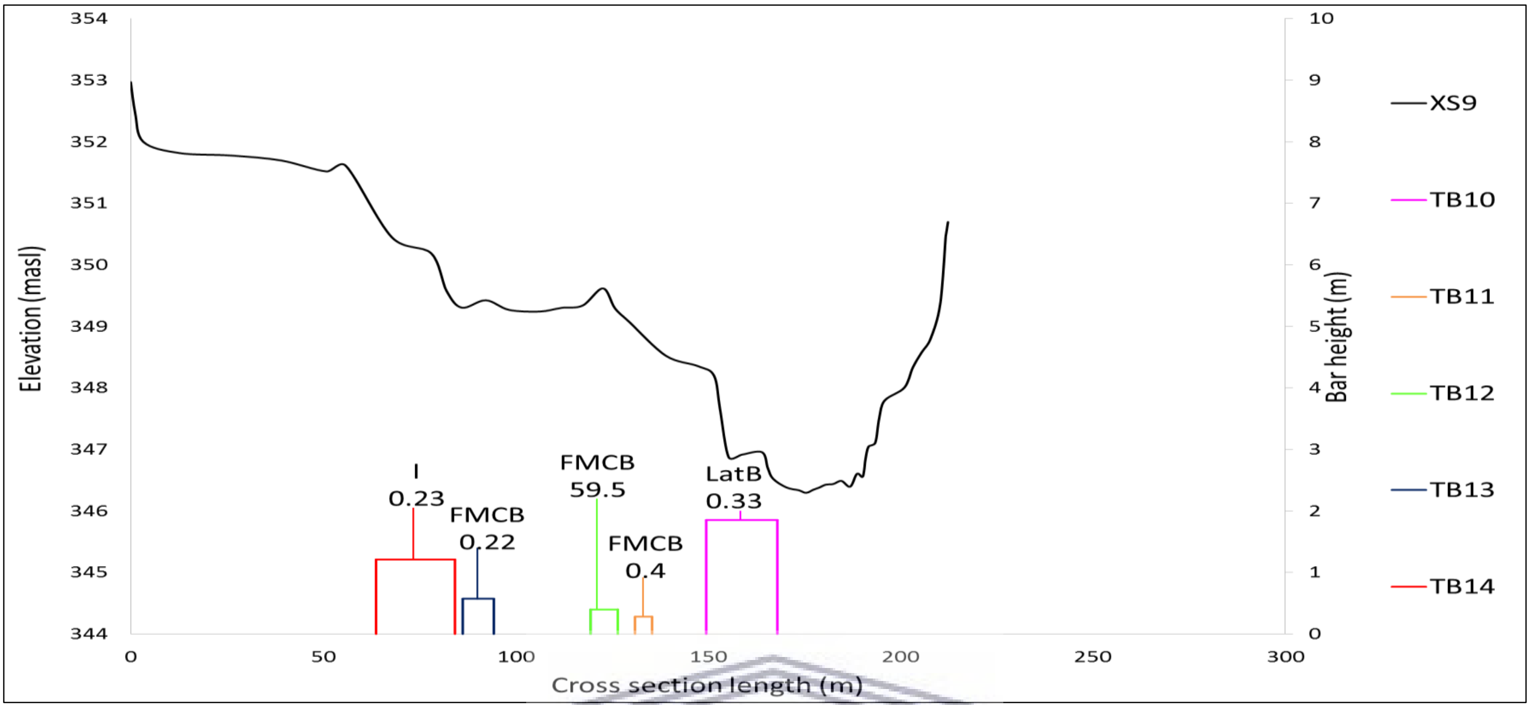


Figure 18: Spatial distribution, height, width and D_{50} of bars identified in XS 9

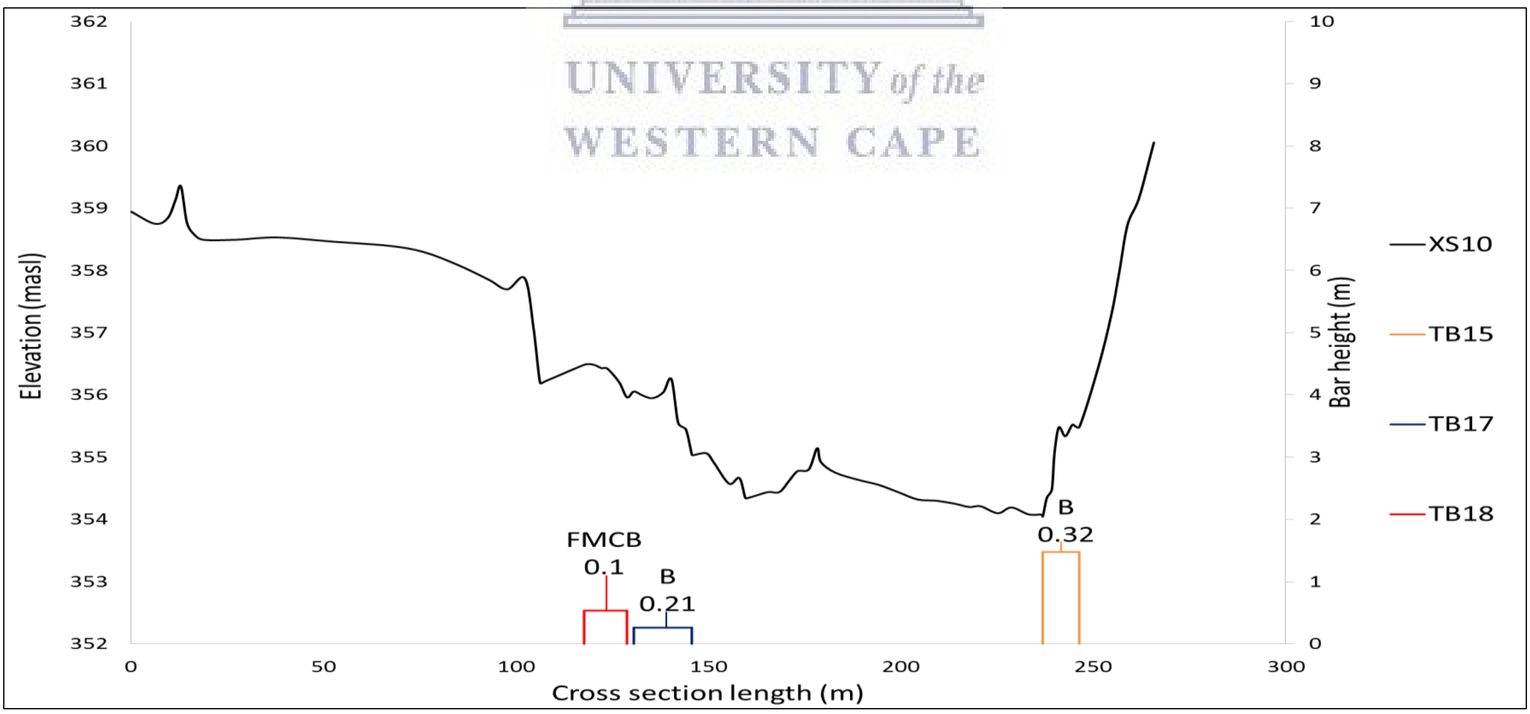


Figure 19: Spatial distribution, height, width and D_{50} of bars identified in XS 10

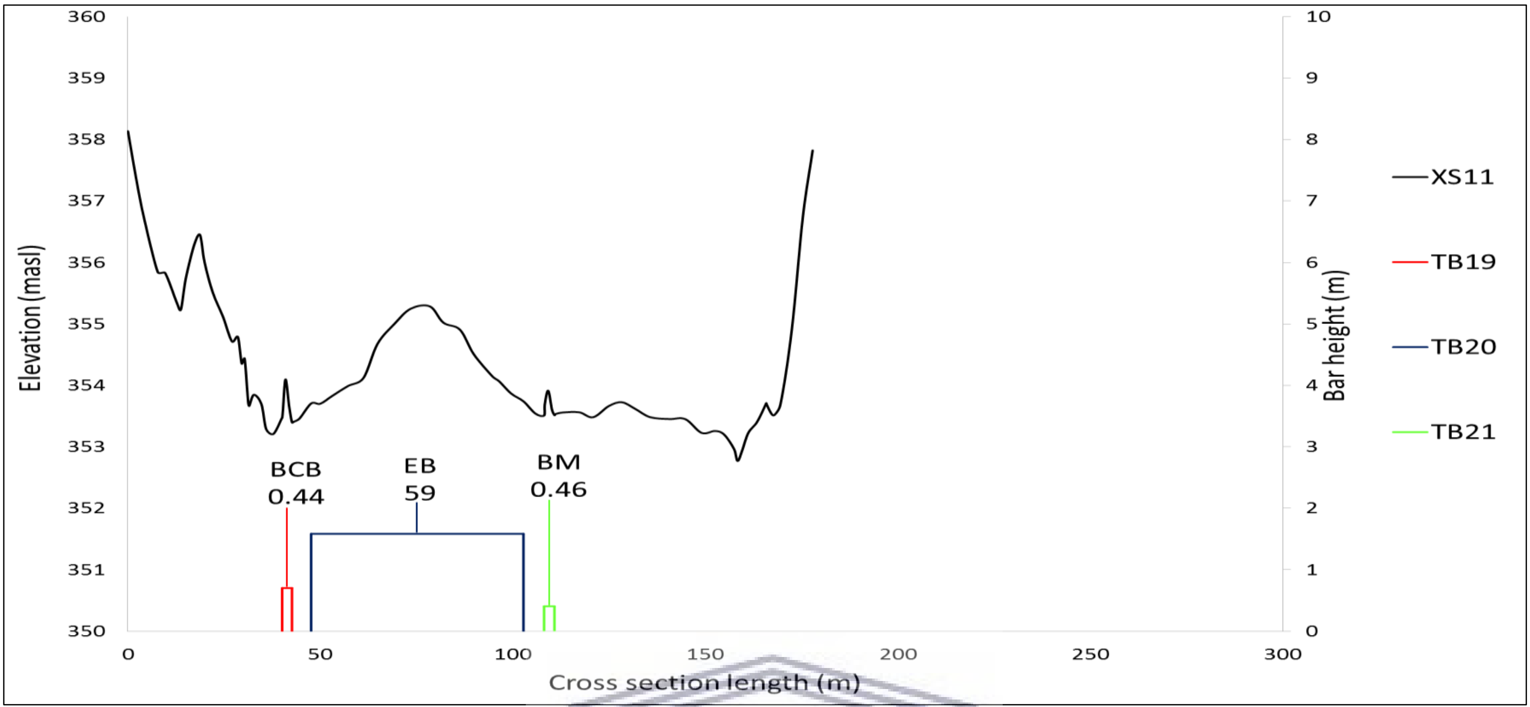


Figure 20: Spatial distribution, height, width and D_{50} of bars identified in XS 11

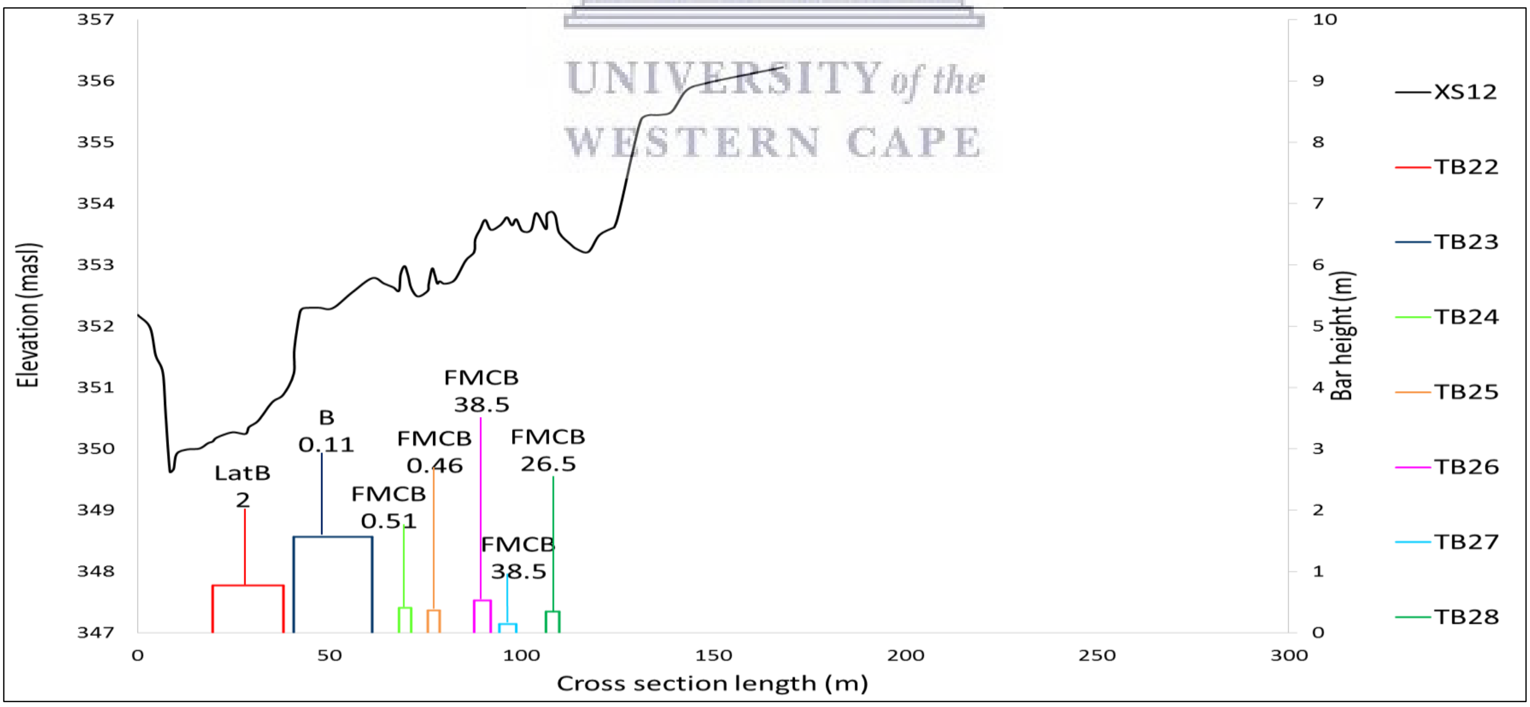


Figure 21: Spatial distribution, height, width and D_{50} of bars identified in XS 12

Table 7: Summary table of observed bars in each XS

Reach	Cross Section	Number of contrasting bar types in XS	Number of bars in XS	Number of contrasting bar types in reach	Number of bars per study site
Prins Doornboom (Study site 1)	**XS 1**	2	9	3	15
	XS 2	2	6		
Prinspoort (Study site 2)	**XS 3**	2	2	5	5
	XS 4	2	2		
	XS 5	1	1		
Touws Plathuis (Study site 3)	**XS 6**	4	9	4	17
	XS 7	2	8		
Touws Wolwefontein (Study site 4)	**XS 8**	3	9	7	27
	XS 9	3	5		
	XS 10	2	3		
	XS 11	3	3		
	XS 12	3	7		

5.3 Investigating differences in the occurrence and characteristics of bars in the study sites

Figure 22 shows the number of each bar type found in the study area, and the number of bars identified in each XS is seen in Figure 23. It is clear that more bars intersect the XS's in the wider channels, increasing the topographic diversity. The overall quantity of bars are greatest in the wandering channel, followed by the straight and confined channel.

The details of the 64 surveyed bars are found in Tables 5 and 7 and shows each bar type and compares the number of bars per XS in the four study sites. The number of contrasting bars identified in the four study sites are as follows: 1 bedrock core bar, 4 benches, 3 boulder mounds, 6 compound mid-channel bars, 4 expansion bars, 1 bank attached forced bar, 38 forced mid-channel bars, 3 islands, 2 lateral bars, 1 longitudinal bar and 1 scroll bar.

Figure 23 shows the number of bars identified in each XS. The highest quantity of bars per XS was identified in the straight and wandering channels while the confined channel had fewer bars. This is related to the size of the channel where it is seen that a higher quantity of bars per XS is located in wider channels (Figures 10 to 21). Figure 24 shows the proportion of the surveyed valley floor area covered by bars. It is clear that the bars in the Prinspoort reach covers the greatest swath area of the valley floor (44% coverage), but has the lowest overall number of bars (Figures 22 and 23). This is the narrowest study site and is occupied by fewer wide bars (Figure 26). The widest reach had the smallest proportion of the valley floor area covered by bars (Touws Plathuis reach with 13% coverage) (Figures 15 and 16). Although most of the bars in this reach were small relative to the valley width there were some bars that were quite large. Although the Touws Wolwefontein reach (14% coverage) and Prins Doornboom reach (16% coverage) were similar in substrate size (Appendix 5), the Touws Wolwefontein reach had seven contrasting bar types while the Prins Doornboom reach only had three (Figure 22).

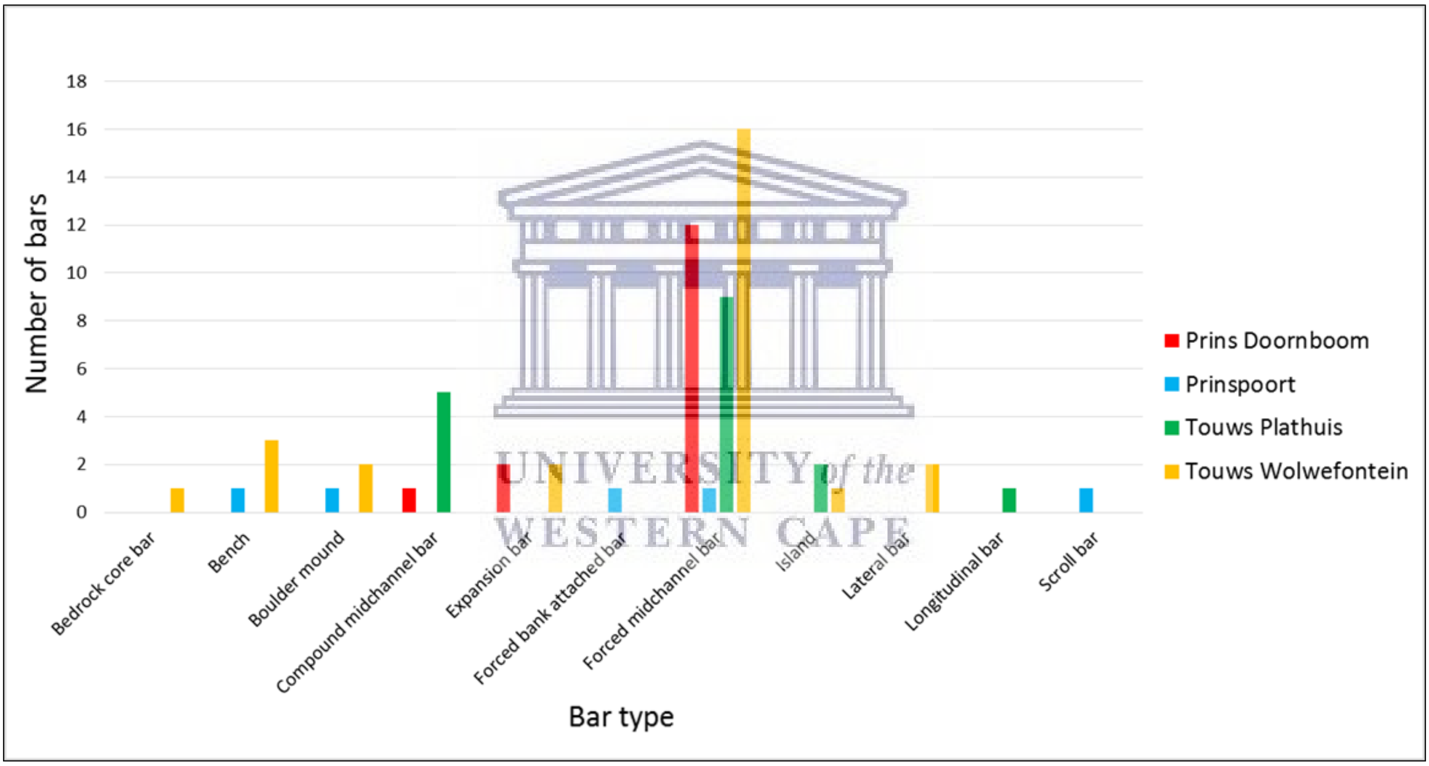


Figure 22: Difference in the occurrence of bars across all reaches

Figure 25 shows the percentage of bars composed of different substrate types across all study sites. The most common substrate compositions of bars were sand, gravel and a mixture of gravel+sand. The Prins Doornboom reach had the highest percentage of sand bars and the Touws Wolwefontein reach had the highest percentage of gravel bars. Cobble bars were found in the Prins Doornboom and Touws Wolwefontein reach, with the highest percentage being located in the Prins Doornboom reach. Bars composed of gravel+sand mixtures were found in all the study sites besides the Touws Wolwefontein reach. Bars composed of cobble+sand mixtures were found in the Prins Doornboom and Touws Plathuis reaches, with the highest percentage being located in the Prins Doornboom reach.

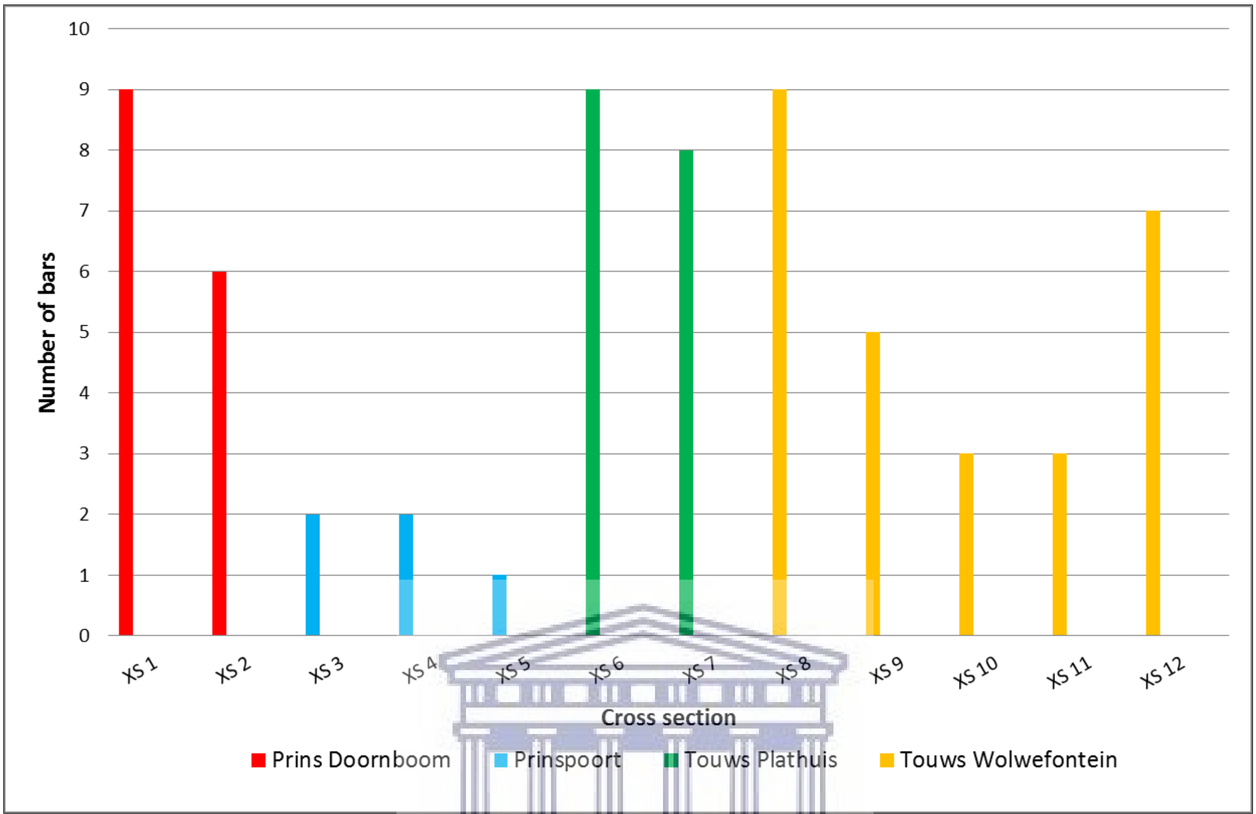


Figure 23: Number of bars per cross section

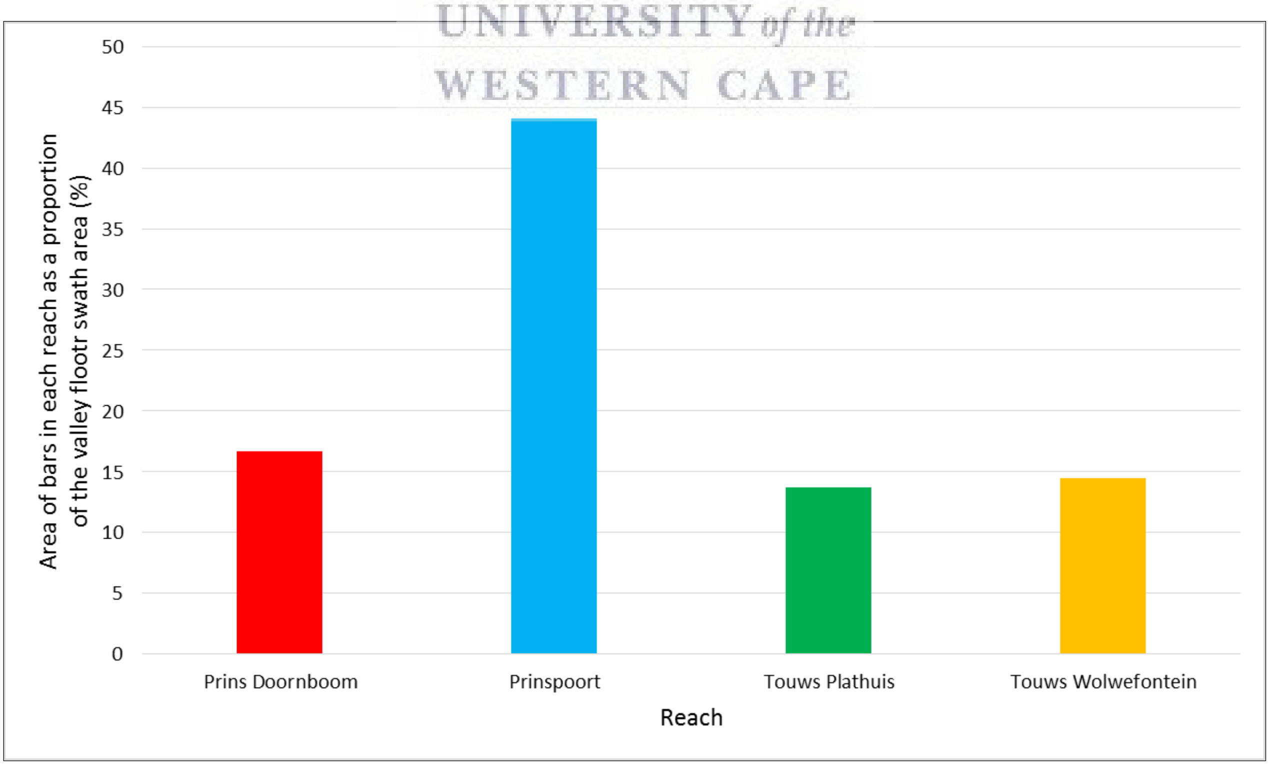


Figure 24: Area of bars in each reach as a proportion of the valley floor swath area

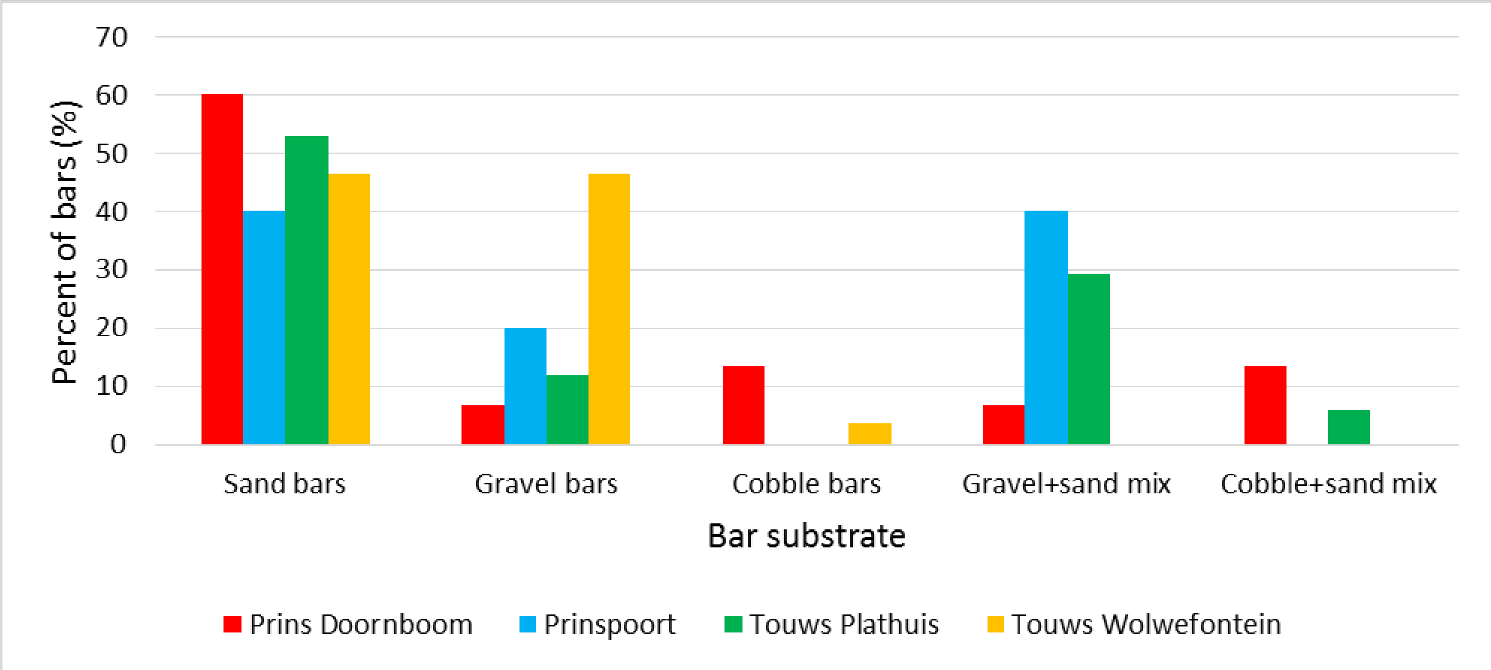


Figure 25: Proportion of bars with varying substrate across all reaches

Figure 26 shows the general shape of the bars surveyed in each study site using various ratios. The solid box represents the bar height:width ratio and provides an indication of the elevation of the bars, large values represent high and narrow bars while low values represent low and wide bars. The vertical line box represents the bar height:length ratio where large values represent high elevation short bars while low values represent low elongated bars. The horizontal line box represents the bar width:length ratio where large values represent narrow short bars while small values represent wide long bars.

The width of all the bars were 2X greater than the bar height with 80% of the bars having a width 4X greater than its height (Appendix 2). The bar width in the Touws Plathuis reach was variable, whereas the width of bars in the Prinspoort reach were more uniform (Figure 26). The bars in the Prins Doornboom reach had the lowest bar heights, with the highest diversity in bar length. Using bar height as a reference, the length of bars in the Touws Wolwefontein reach had the highest uniformity compared to rest of the study sites (Figure 26). Using width as a reference, the highest variability in bar length was found in the Prins Doornboom reach. The reach with the highest bar length uniformity was found in the Prinspoort reach (Figure 26).

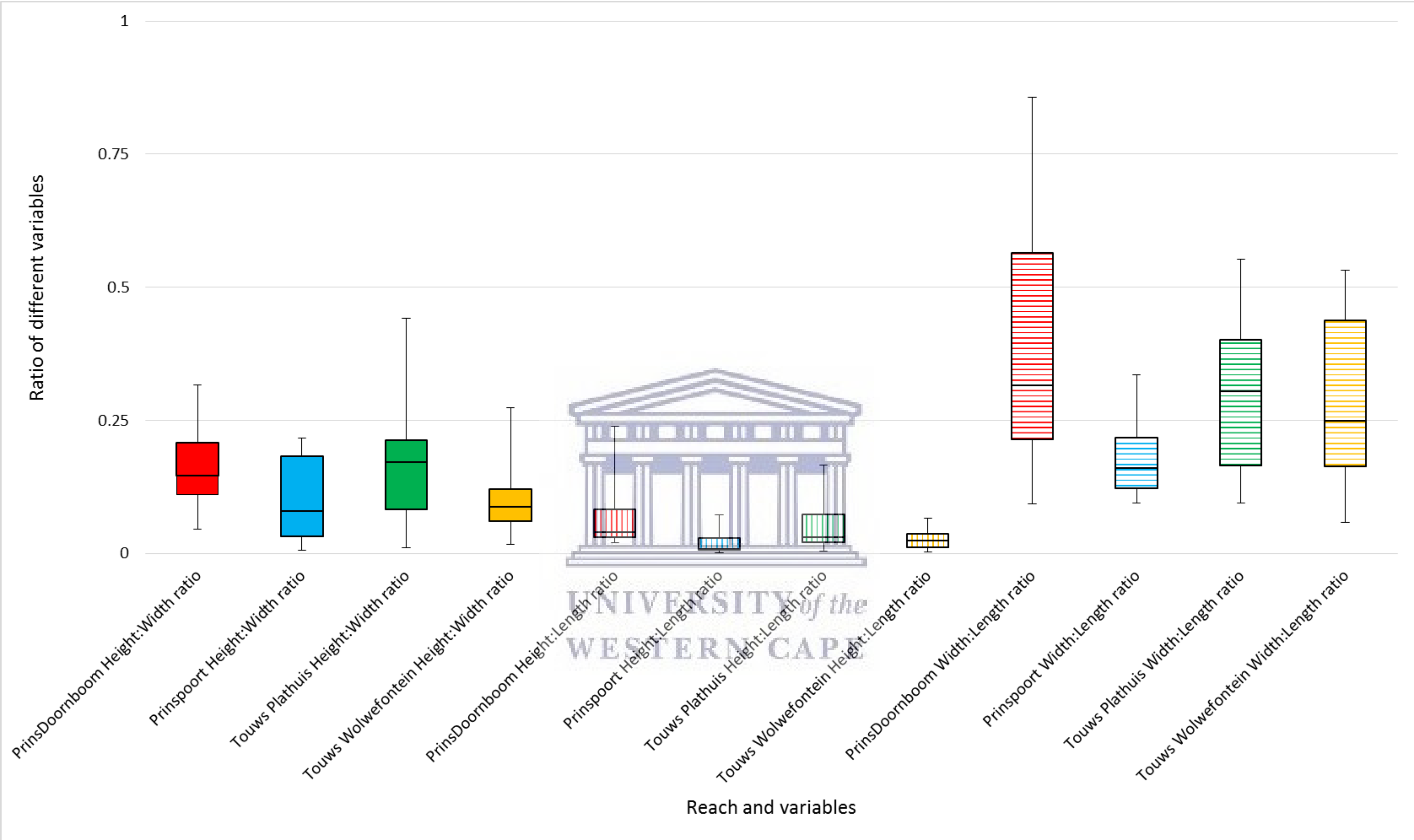


Figure 26: Height:width ratio (solid box), height:length ratio (vertical line box) and width:length ratio (horizontal line box) of the bars located across all reaches

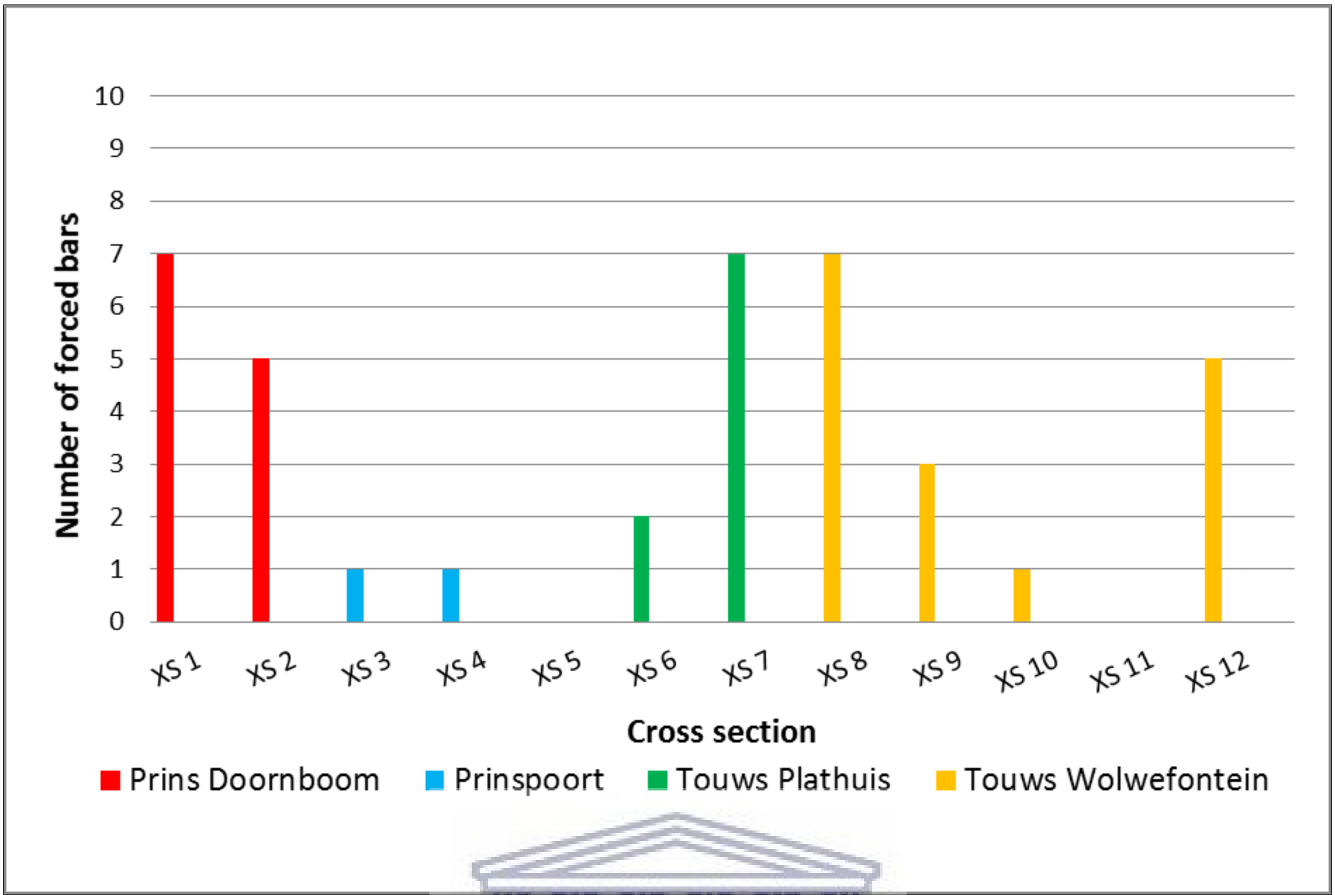


Figure 27: Number of forced bars per cross section

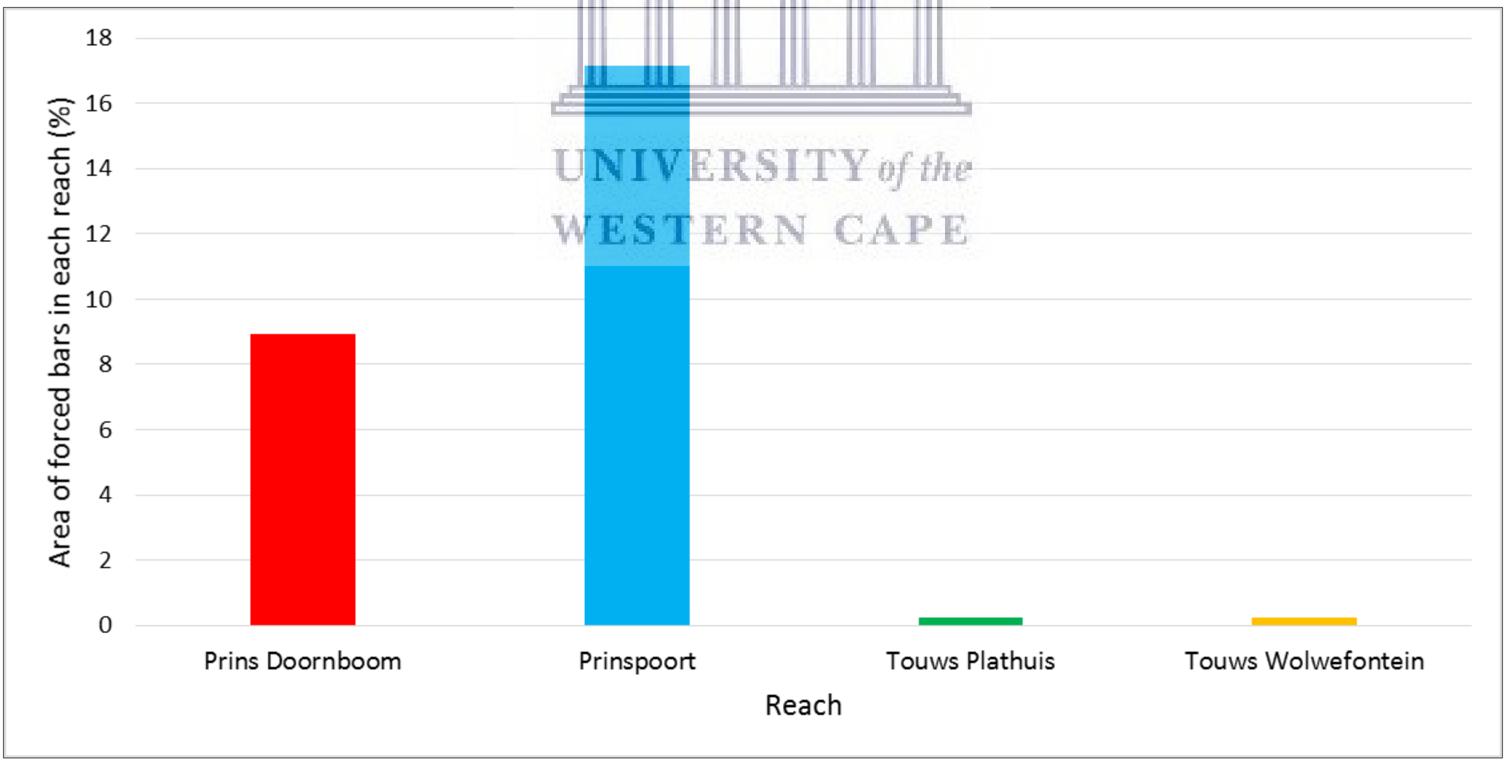


Figure 28: Area of forced bars in each reach as a proportion of the valley floor swath area

Figure 27 shows the number of forced bars per XS. It is clear that a higher quantity of forced bars are found in the wider channels. Although only 2 XS's were surveyed along the straight channel, the results suggest a higher rate of forced bars per XS compared to the confined and wandering channels.

Figure 28 shows the proportion of the valley floor area covered by forced bars for all study sites. Out of the 39 forced bars observed in the study sites, 22 (56%) were located on the lee side of vegetation (*Vachellia karroo*) and 17 (44%) were located on the lee side of debris piles. Similar to Figure 24, the Prinspoort reach had the highest percentage of forced bars covering the valley floor (17%) followed by the Prins Doornboom reach (8.9%) (Figure 28). The reaches with the smallest proportion of the valley floor covered by forced bars were the Touws Plathuis reach (0.24%) and the Touws Wolwefontein reach (0.25%). Although the Touws Wolwefontein reach had the highest quantity of forced bars (Figure 22), the size of these forced bars were relatively small compared to the valley width (Figures 17 to 19 and 21).

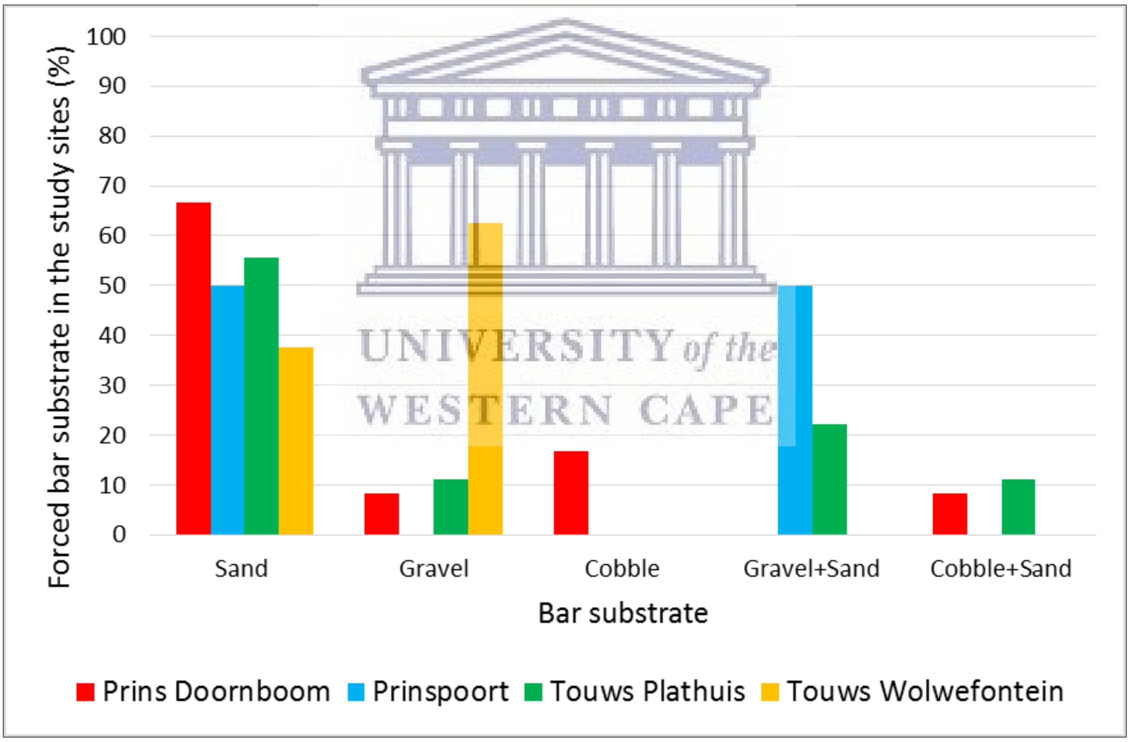


Figure 29: Proportion of forced bars with varying substrate

Figure 29 shows the amount of forced bars with varying substrate in the 4 study sites. It is seen that most of the forced bars were composed of sand, followed by gravel and gravel+sand (Figure 29). Figure 30 shows the percentage of forced bars with different substrate on the lee side of vegetation and woody debris piles across all study sites. The Prins Doornboom reach had the highest percentage of sand bars. In the Prinspoort reach, all the forced sand bars were located on the lee side of vegetation. Forced sand bars located in the Touws Plathuis and Touws Wolwefontein reach were located on the lee side of both vegetation and debris piles.

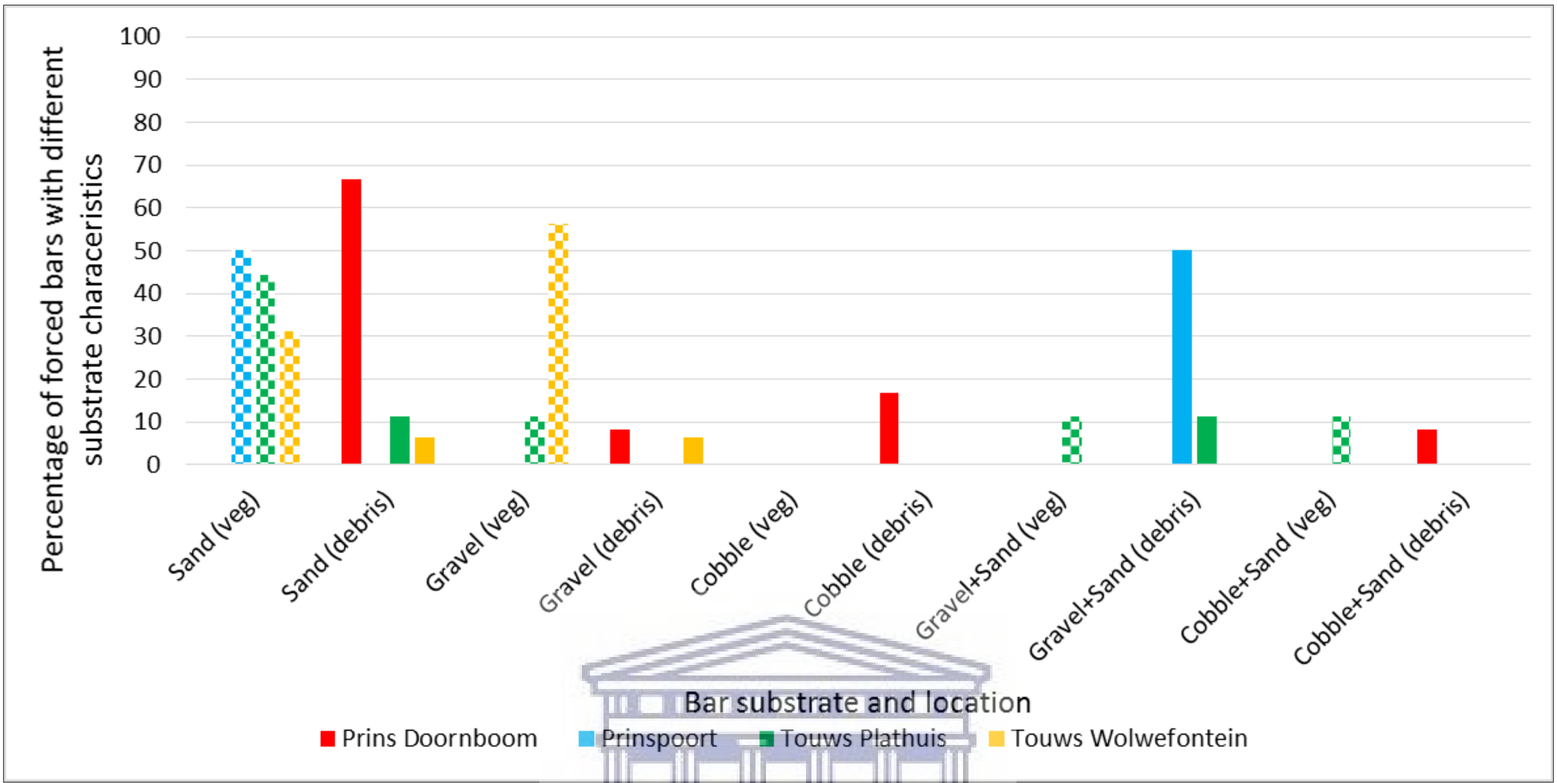


Figure 30: Proportion of forced bars with contrasting substrate characteristics located behind vegetation (checkered bar) and debris piles (solid bar)

Forced gravel bars were identified in three of the four study sites (Prins Doornboom, Prinspoort and Touws Wolwefontein reach). The forced gravel bars in the Touws Wolwefontein reach were located behind vegetation and woody debris, although more forced gravel bars were located behind vegetation. The forced gravel bars located in the Touws Plathuis reach were only located behind vegetation while the forced gravel bars in the Prins Doornboom reach were located behind debris piles. Forced cobble bars were only found in the Prins Doornboom reach.

The forced bars composed of gravel+sand mixtures were located in the Prinspoort and Touws Plathuis reaches. In the Prinspoort reach these bars were only located on the lee side of debris piles while in the Touws Plathuis reach they were located on the lee side of vegetation and debris piles. The highest percentage of bars composed of gravel+sand mixtures were located in the Prinspoort reach, however, it should be noted that only two forced bars were observed in the Prinspoort reach (each bar being 50%).

The forced bars composed of cobble+sand mixtures were found in the Prins Doornboom reach on the lee side of debris piles and in the Touws Plathuis reach on the lee side of vegetation. There was a slightly higher percentage of cobble+sand bars located on the lee side of vegetation in the Touws Plathuis reach than debris piles in the Prins Doornboom reach.

All of the forced bars in the Prins Doornboom reach were located on the lee side of debris piles while most of the forced bars were located behind *Vachellia karroo* in the Touws Plathuis and Wolwefontein reaches. In all of the substrate classes, there were more forced bars located on the lee side of vegetation than debris piles (Figure 30). Figures 31 to 34 show examples of the distribution of forced bars in the Prins Doornboom, Prinspoort, Touws Plathuis and Touws Wolwefontein reaches on the lee side of vegetation and debris piles. Generally, the majority of forced bars in the study area were located behind *Vachellia karroo*, with a smaller quantity of forced bars located behind debris piles of uprooted *Vachellia karroo* that had been transported and deposited downstream by a flood. It can be seen in Figures 31 to 34 that the location of forced bars are dependent on the distribution of vegetation and debris in the channel.

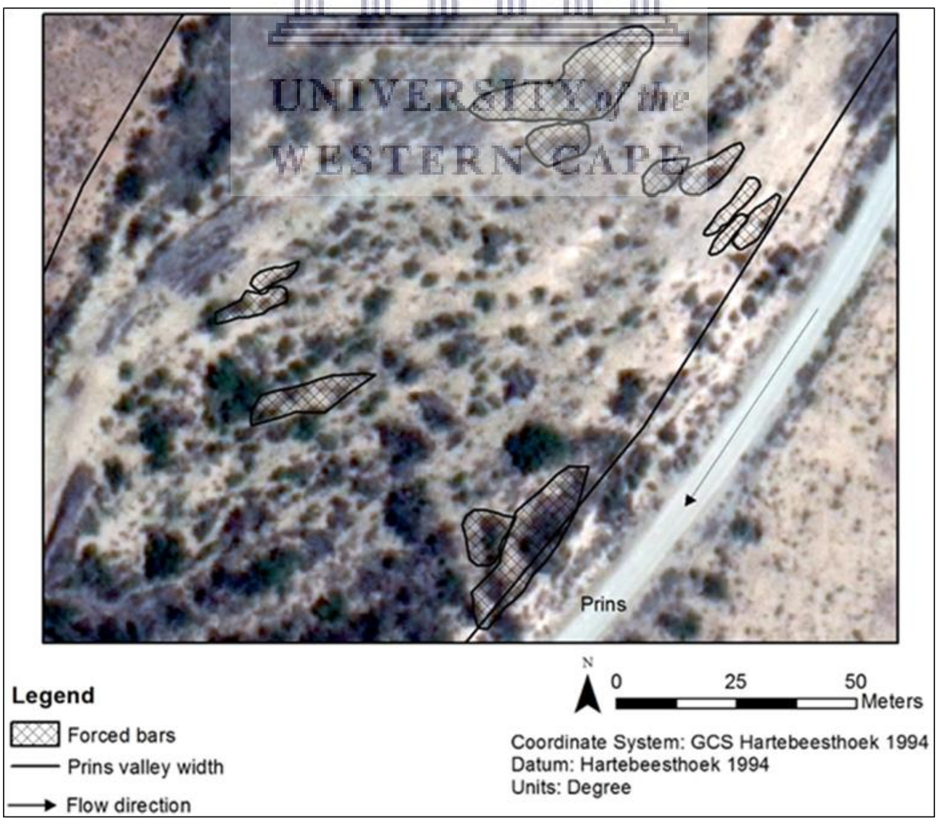


Figure 31: Forced bars located in the Prins Doornboom reach

Figure 32: Forced bars located in the Prinspoort reach

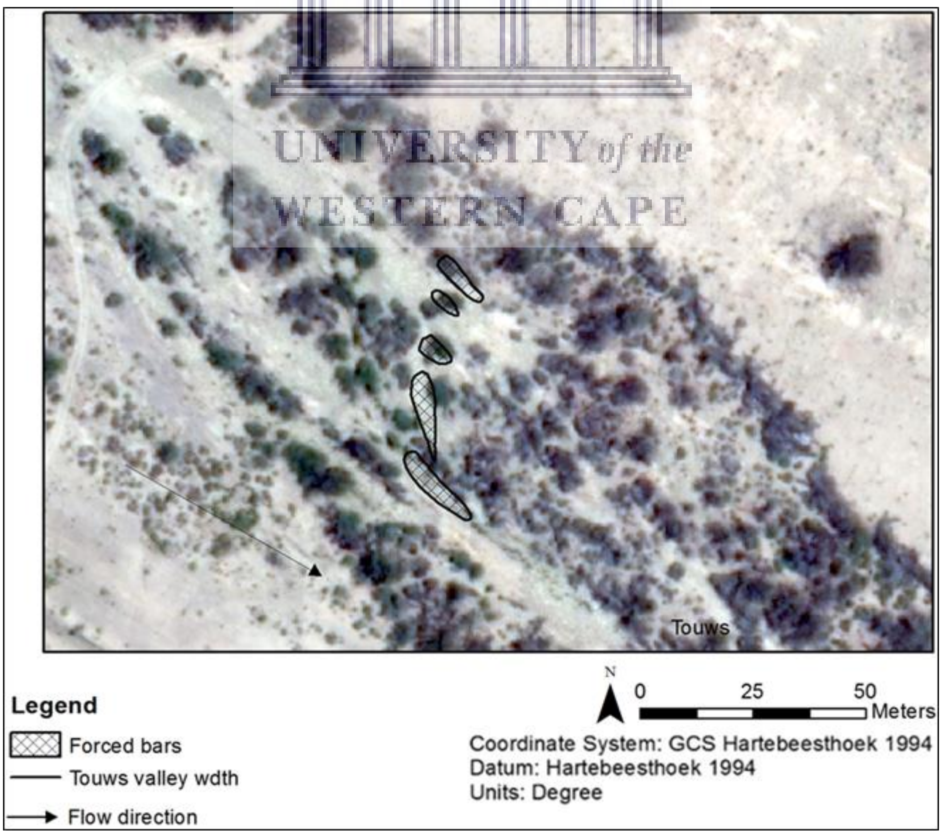


Figure 33: Forced bars located in the Touws Plathuis reach

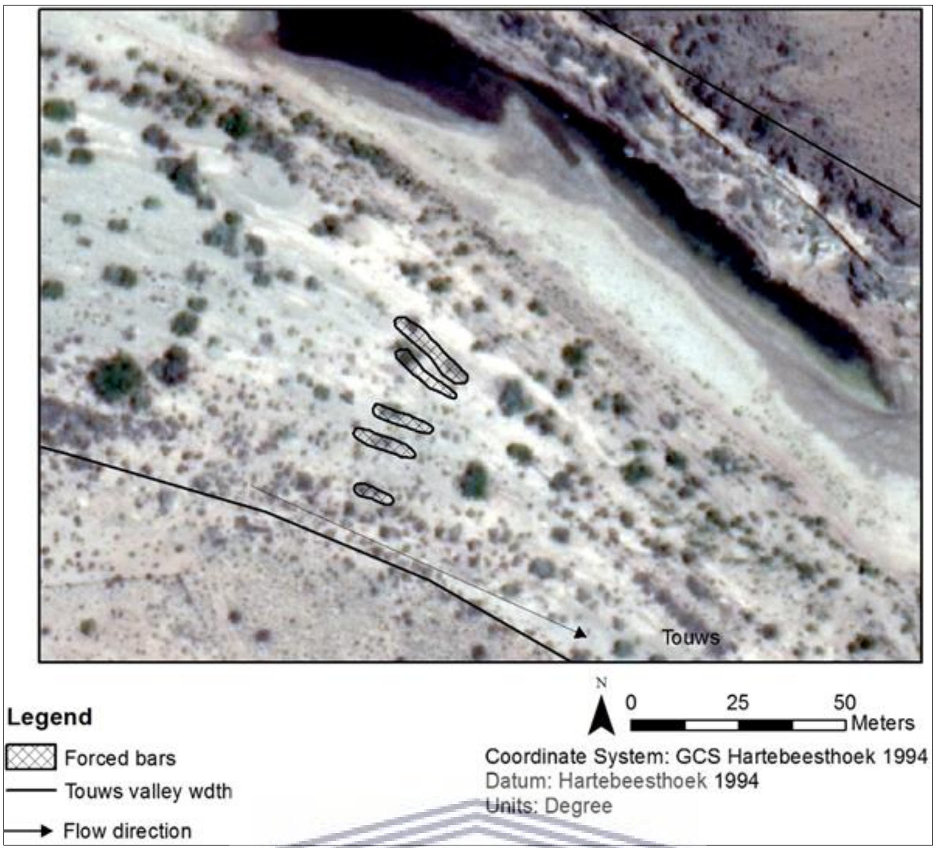


Figure 34: Forced bars located in the Touws Wolwefontein reach

5.3.1 D_{50} and bar morphology

Figure 35 shows the height:width (solid box), height:length (vertical line box) and width:length ratio (vertical line box) of the forced bars in all the study sites. The forced bars in the Touws Plathuis reach had the highest variability in width compared to the rest of the study sites. The width of the forced bars in the Touws Wolwefontein reach were the most uniform.

The widest forced bars relative to bar height was located in the Touws Wolwefontein reach (steepest reach) and the narrowest forced bars relative to bar height was located in the Touws Plathuis reach (most gentle reach) (Table 8). The length of forced bars in the Prins Doornboom reach was large relative to bar height, while the forced bars located in the Touws Wolwefontein reach had a more uniform morphology (Figure 35). Overall, the forced bars in the Touws Wolwefontein reach was the longest relative to the bar height while the Prins Doornboom reach had the shortest forced bars (Figure 35 and Table 8). The longest and shortest forced bars relative to bar width was located in the Prins Doornboom reach (Figure 35). The bars in the Prinspoort reach had the highest uniformity in bar length compared to bar height with the forced bar length being diverse in all the other study sites.

Table 8: Summary table of bar morphology in the study sites

Reach	Valley slope (m/m)	Valley width (m)	Morphology ratios (all bars)			Morphology ratios (forced bars)		
			Height: Width	**Height: Length**	**Width: Length**	**Height: Width**	**Height: Length**	**Width: Length**
Prins Doornboom	0.007	140	0.15	0.04	0.32	0.19	0.05	0.40
Prinspoort	0.009	47- 64	0.08	0.01	0.16	0.11	0.04	0.23
Touws Plathuis	0.005	740- 800	0.17	0.03	0.30	0.21	0.07	0.37
Touws Wolwefontein	0.009	168- 266	0.09	0.02	0.25	0.09	0.03	0.44

Table 9: Spearman's rank correlation between the D_{50} and morphology of forced bars in all study sites

			Height:Width	**Height:Length**	**Width:Length**
Spearman's rho	D_{50} (mm)	Correlation Coefficient	-0.087	-0.084	0.061
		Sig. (2-tailed)	0.575	0.590	0.692
		N	44	44	44

Spearman's rank correlation was used to determine if there was any correlation between the D_{50} and forced bar morphology. This correlation was used because the data was a ratio scale and did not satisfy the parametric assumptions (Field, 2004). The results of the Spearman's correlation (Table 9) show that the relationship between the D_{50} (Appendix 6) and height:width, height:length and width:length ratio (Figure 35) is extremely weak. The results of this Spearman's rank correlation test suggest that other than the substrate size, there are other factors that have a greater influence on the morphology of forced bars in the rivers studied. Appendix 6 shows an overlap between box plots of the same substrate type across different reaches, suggesting that the formation of forced bars are more dependent on an obstruction than on the physical characteristics of the river bed (for example, channel gradient or valley width). Additionally, this overlap suggests that the type of obstruction does not influence the sediment size of bars.

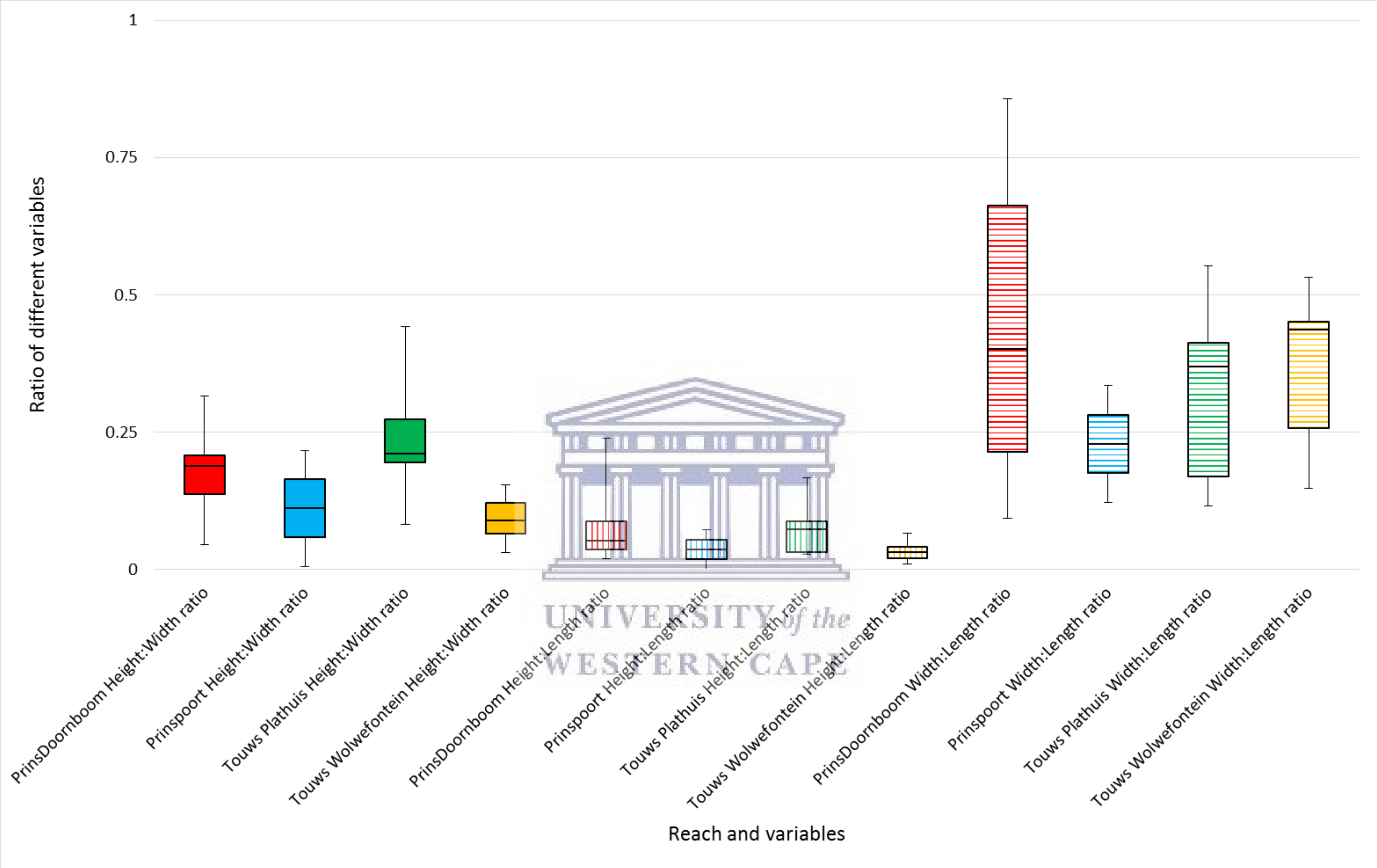


Figure 35: Heigh:width ratio (solid box), height:length ratio (vertical line box) and width:length ratio (horizontal line box) of the forced bars located across all reaches

6. Discussion

6.1 Introduction

Bridge (2003) and Billi *et al*. (2018) determined that the factors controlling the channel patterns of rivers are discharge, slope and sediment grain size. As rivers are the product of many controlling factors, Billi *et al*. (2018) highlighted that the flow energy, particle size, sediment quantity, bed roughness as well as the transport and deposition of sediment (geomorphological processes) influence the fluvial style. Pitlick and Wilcock (2013) summarised this when arguing that the channel pattern, width, depth and slope are influenced by flow of various magnitudes. However, Tooth and Nanson (2004) argue that these energy parameters are only useful when incorporated with the sediments resistance to flow.

Rowntree *et al*. (2013) highlighted the importance of geomorphological processes involved in the formation and destruction of bars, channels and floodplains in NPR's, while Kleinhans and van den Berg (2011) explained how these processes alter a river's planform pattern. The geomorphological processes that occur in alluvial rivers experienced during times of flood influence the channel geometry. This is different for mixed bedrock alluvial rivers as Tooth (2013) argued channel confinement by bedrock or stabilized vegetation makes these rivers more resistant to minor climatic changes. Floods introduce successive change to NPR's by changing the in-channel features through in-channel flow and by introducing sediment of various size and amounts to the river system (Hauer and Habersack, 2008).

The morphological features created by the availability of sediment in the channel influence the channel flow because these morphological features create preferential flow paths (Bridge, 2003). Equilibrium in channel geometry is possible where the sediment transport rate equals the sediment supply rate, and the stability of channel form depends on the balance between sediment, channel gradient and discharge (Church, 2006). This is seen in Figure 36 where Charlton (2008) explained, using a conceptual diagram, that an increase in sediment would favour the aggradation of bars, eventually changing the fluvial style (increased braiding, or floodout development) (Bridge, 2003). Additionally, Figure 36 shows that a decrease in sediment would favour degradation, and would also change the fluvial style (decreased braiding, or channel incision) (Bridge, 2003).

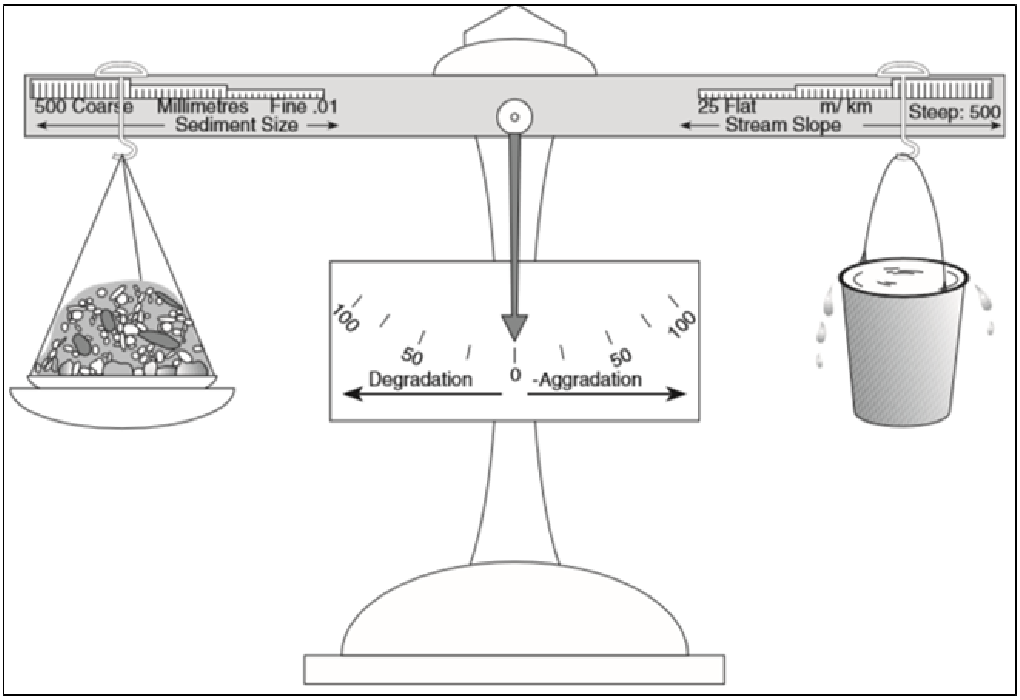


Figure 36: Balance between in-channel flow strength and sediment supply (Charlton, 2008)

6.2 Interpretation of results

6.2.1 Differences in fluvial style

One of the most striking features of the river system studied is the variation in valley width between the four study sites, and associated differences in fluvial style. Kleinhans (2010) and Thompson and Croke (2013) highlighted that the confinement of channels is influenced by vegetation density, channel substrate and geology. The river bed of the Prins Doornboom, Touws Plathuis and Touws Wolwefontein reaches were composed of sand, gravel and vegetation patches, and were wider than the Prinspoort reach. The river bed of the Prinspoort reach was composed of bedrock and sand, and was dominated by gravel and cobble with less vegetation in the channel compared to the other study sites.

The confined channel was located in a gorge with steep rocky sides (Figure 2), supporting that topography influences channel confinement, which further influences the bar morphology (Thomson *et al*., 2001; Buffington *et al*., 2012). This was observed by Thompson and Croke (2013) where flow in a confined channel eroded sediment and bars at a greater rate than in an unconfined channel. Just as in the Prinspoort reach, Thompson and Croke (2013) found coarse sediment in the confined channel. Additionally, the Touws Plathuis and Touws Wolwefontein reaches had larger areas of floodplain with large amounts of alluvial deposition found in the unconfined channel, similar to the study site of Thompson and Croke (2013), suggesting that the geomorphological processes in the studied NPR's may be strongly influenced by geologically-forced variations in valley width.

The average bed gradient of the entire length of the NPR in this study was 0.004. The gradient in the unconfined single to dual-thread channel was 0.007, followed by a steeper gradient of 0.009 in the confined single thread channel, becoming more gentle to 0.005 in the wider wandering channel and then becoming steeper to 0.009 in the narrower wandering channel. The channel gradient affects the amount of energy the channel experiences during discharge (Church, 2006). Konnerth (2010) explained that steep gradients allow a higher flow energy to pass through the channel and transport sediment. Church (2006) argued that discharge determines the scale of the channel and that steeper gradients would facilitate a greater stream power, allowing the channel to mobilize larger types of sediment. Therefore, the morphological features are influenced by the channel gradient, discharge and the type and quantity of sediment available to be reworked (Church, 2006). Brierley and Fryirs (2005) highlighted that channels with lower gradients tend to have lower carrying capacities creating multithread or wandering channels, as is evident in this study.

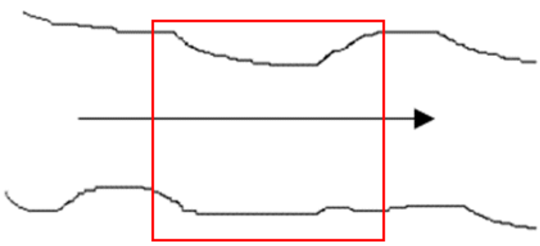
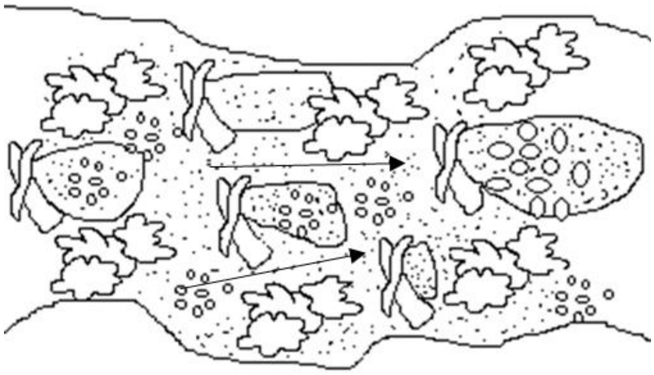
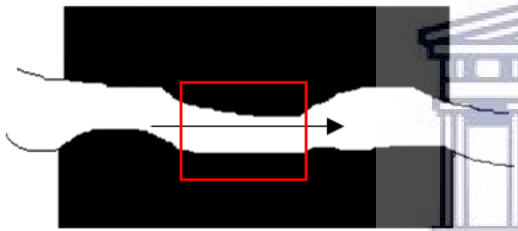
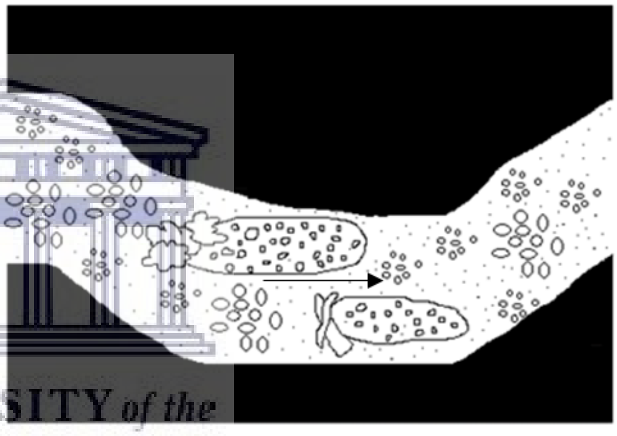
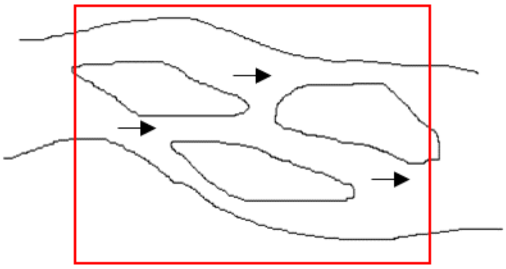
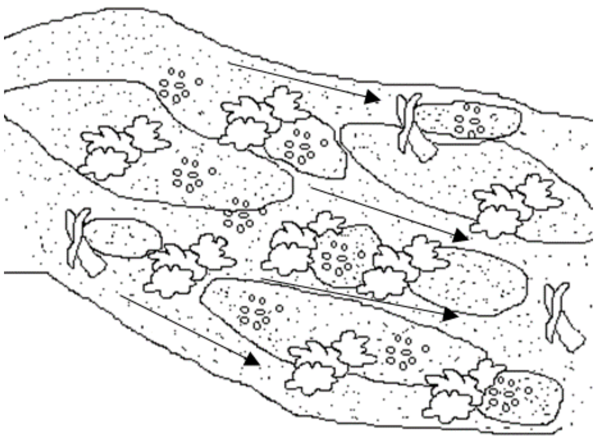
In this study, various bars were observed and classified in the NPR channels (Table 6 and Figure 22). In all of the study sites surveyed, it was found that forced mid-channel bars were the dominant bar type as these bars were located in all of the study sites. Thomson *et al*. (2001) explained how reaches with similar characteristics are likely to contain bars of similar morphology compared to reaches with different characteristics. However, in this study it is evident that the nature of the obstruction, especially the widespread presence of *Vachellia karroo* trees, forces the development of similar morphological features across a range of fluvial styles.

The Prinspoort and Touws Wolwefontein reaches both had an average gradient of 0.009, yet different ranges of sediment size were found amongst these two reaches, suggesting that valley width may be more important than slope in determining sediment transport variation, or that local variations in material supply from tributaries in different settings may be more important than channel transport controls. The Prinspoort reach had coarser sand and gravel bars compared to the Touws Wolwefontein reach (Appendix 5 and 6). Additionally, the average bed gradient of the Touws Plathuis reach was more gentle than the Touws Wolwefontein reach although they were both wandering channels. There were more sand bars and less gravel bars in the Touws Plathuis reach compared to the Touws

Wolwefontein reach (Figure 25). Kleinhans (2010) argued that rivers require energy to move sediment, and since the Prinspoort reach was a confined channel the stream power of floods in this channel is higher than the stream power of floods that are allowed to spread across broad valleys (Figure 37).

Furthermore, van den Berg (1995) argued that single thread channels are associated with a higher stream power and wide channels are associated with a low stream power. Thus during flow, the Prinspoort reach would have more energy due to the valley confinement compared to the Touws Plathuis reach. Therefore the Prinspoort reach would have coarser sediment and less dense vegetation compared to the Touws Plathuis reach. This is supported by Tooth (2013) who argued that a large change in the channel slope, particularly in narrow canyons would facilitate the supply of coarse grained sediment. Although the presence of cobble sized substrate was evident in the Prinspoort reach, no cobble bars were found within this reach (Figure 25 and Appendix 5). This may be due to an insufficient amount of cobble substrate to form bars or because the transport of this substrate is slower and more interrupted than sand and gravel, and is not easily reworked into bars (Kleinhans, 2010). Church (2006) investigated the relationship between sediment transport and the channel form of rivers and found that cobbles are associated with step pools and stable channels, but can undergo destabilisation during debris flow.

Figure 37 is a conceptual model showing how valley setting affects forced bar development. It is seen that flow in the confined channel will be more concentrated than in the unconfined and wandering channels, limiting vegetation colonisation and bar development in this reach. The unconfined and wandering channels have finer sediment located in the channel as well as an increased number of vegetation obstructions, woody debris piles, and bars, due to the broader valleys. The Touws Wolwefontein reach has more gravel and cobble bars than the Touws Plathuis reach due to the channel gradient. However the bars composed of gravel+sand and cobble+sand mixtures are more numerous in the Touws Plathuis reach due to the increased valley width and low gradient of this reach.

Reach	Forced bar substrate and quantity
 Prins Doornboom reach (Single to dual-thread channel)	
 Prinspoort reach (Confined channel)	
 Touws Plathuis reach (Wandering channel)	

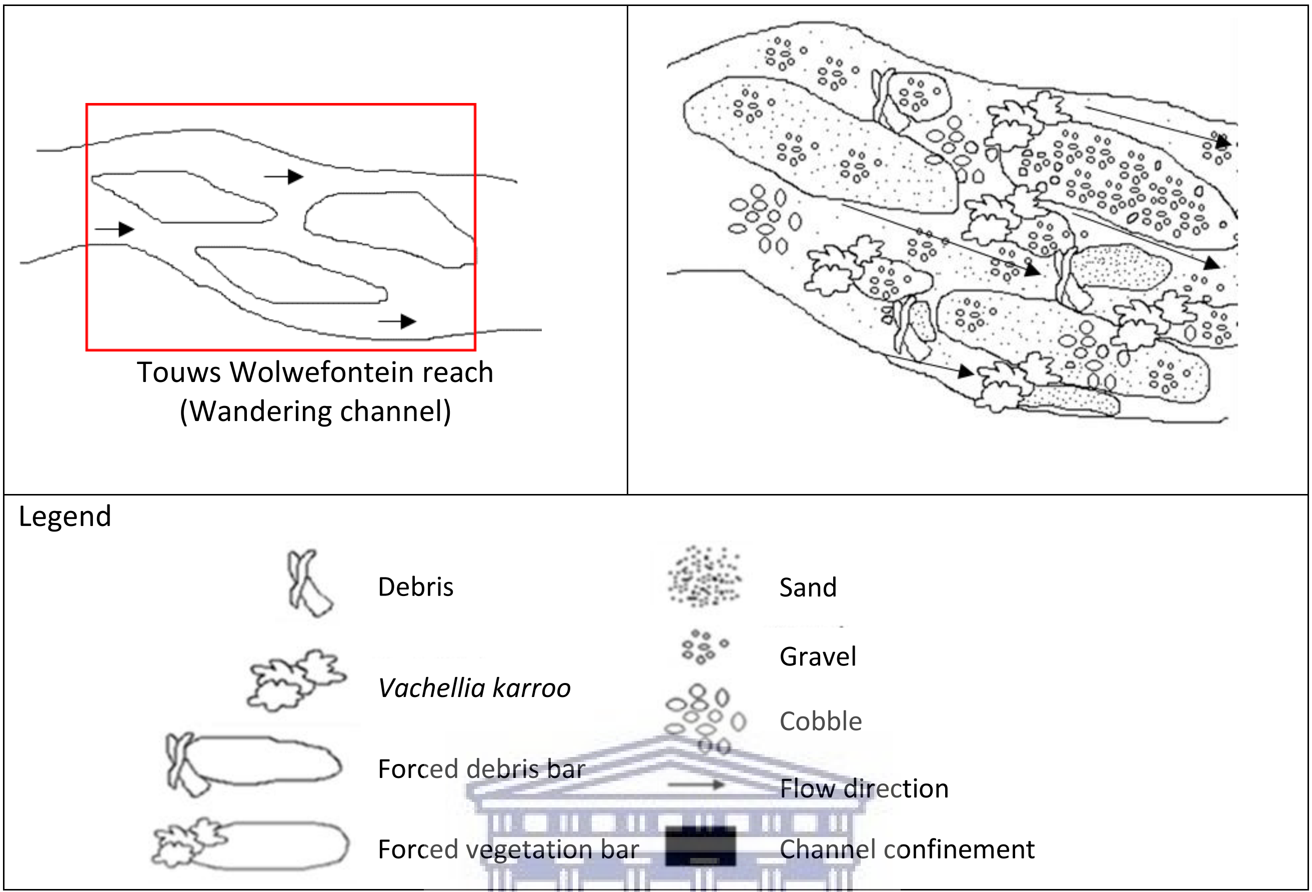


Figure 37: Effect of valley setting on the process of forced bar development

Greenbaum and Bergman (2006) surveyed a NPR in Israel following a major flood. The channel substrate was composed of coarse gravel, cobble and boulders with sand hardly being visible. This suggests that the low frequency high magnitude floods in NPRs have a greater effect on channel and bar morphology than more frequent low magnitude floods, since larger sediment was more abundant in the channel than the finer sediment, although this can also be a function of local variation in supply. The presence of cobble sized substrate in the Prinspoort reach and overall low amount of cobble and coarse gravel bars across all study sites may be due to the finer sediment (gravel and sand) being washed away through floods leaving the cobble sized substrate exposed on the river bed (Plate 1, A1 and A2), while finer sediment covers cobble material elsewhere in the system. The flow energy in the Prinspoort gorge would be higher than in the Touws Wolwefontein reach. This would lead to an increased local supply of cobbles in the Prinspoort reach and an increased supply of sand and gravel but decreased supply of cobbles in the Touws Wolwefontein reach (Plate 1, B1 and B2). There would also be a higher rate of local supply of cobble material within the gorge through mechanical rock weathering processes, and this material would be broken down during transport and be fine within increasing distance downstream of the gorge.

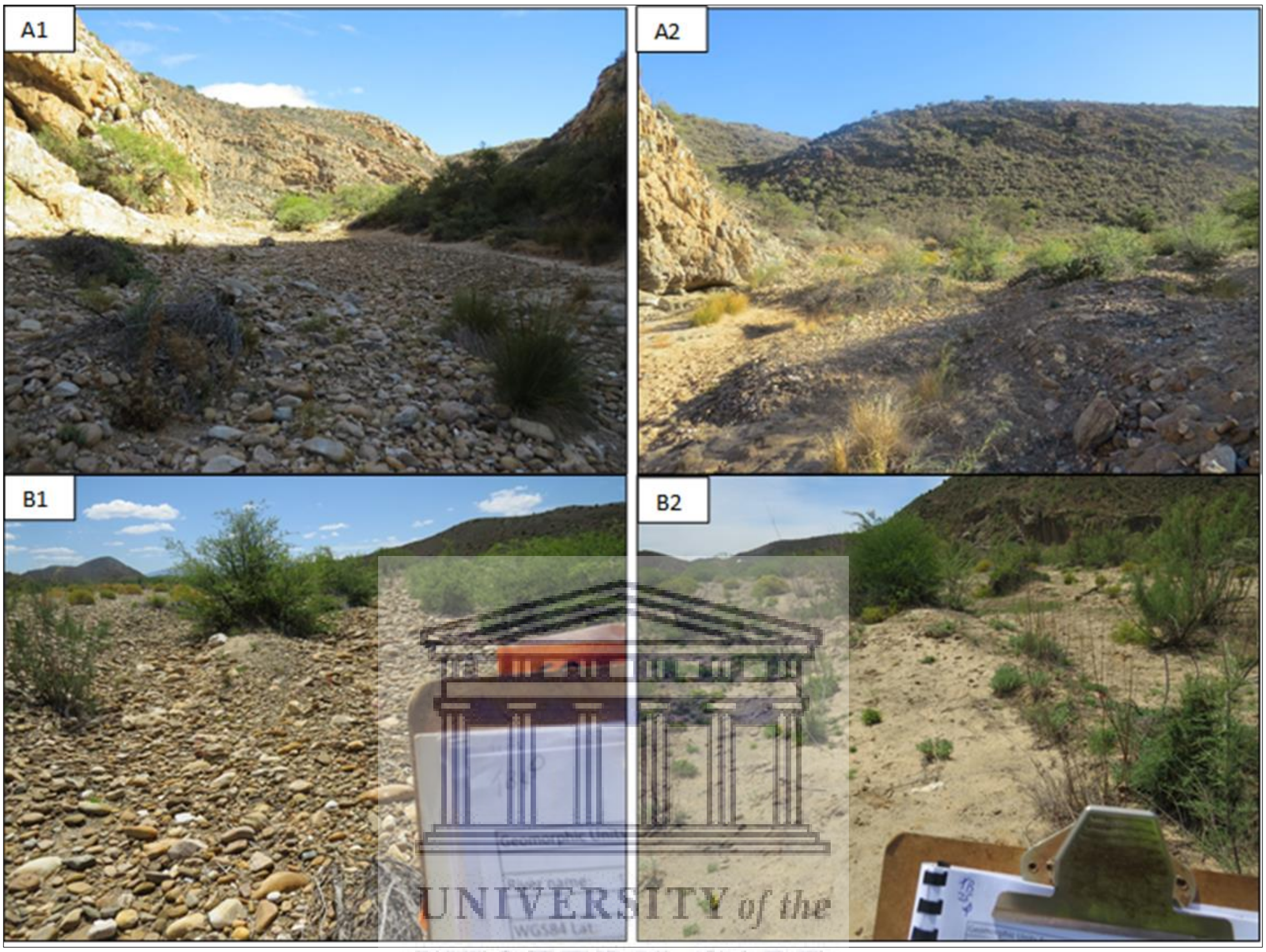


Plate 1: Prinspoort reach (camera facing upstream) (A1 and A2) and Touws Wolwefontein reach (camera facing upstream) (B1 and B2)

6.2.2 Bar variety and substrate

The identification and location of bars on the channel and valley floor/floodplain surface assists in understanding the controls that facilitate the energy distribution responsible for the positioning of these bars (Brierley and Fryirs, 2005). Out of the 11 different bar types found in the study area, the highest and widest bars were located in the Touws Wolwefontein reach and were composed of a combination of coarse and fine-grained sediment (Appendix 5).

Coarse sand to coarse gravel are associated with relatively steep single thread and braided channels and with complex bar development (Church, 2006). This was observed in the Touws Wolwefontein reach, although it has been classified as a wandering channel with unconfined sections. Kleinhans and van den Berg (2011) discussed that narrow single thread channels may contain scroll and point bars, and that generally, bars rarely develop in channels that experience a low discharge. There were no scroll bars observed in the Prins Doornboom reach, and although this reach does not receive much discharge, there were a number of bars present in the reach and may oppose the work of Kleinhans and van den Berg (2011). It is however noted that the work of Kleinhans and van den Berg (2011) cannot be expected in NPR's as their work was based on perennial rivers. Based on literature, unconfined channels characteristically have large floodplains, bank attached bars such as benches as well as mid-channel bars (Milan, 2011; Thompson and Croke, 2013). These characteristics were seen in the Touws Wolwefontein reach as benches, forced mid-channel bars and a large floodplain were observed. Furthermore forced mid-channel bars were the most abundant bar type in the Touws Plathuis and Touws Wolwefontein reaches.

Sand to fine grained gravel are associated with single thread channels with a moderate gradient (Church, 2006). Furthermore, single thread channels are associated with the development of lateral and point bars as well as unstable channels (Church, 2006). This was observed in the Prins Doornboom and Touws Plathuis reaches, although they were classified as wandering and unconfined channels. Coarse to fine grained sand are associated with single thread and meandering channels with a low gradient and the development of point bars, cutoffs and vegetated islands (Church, 2006). The Prinspoort reach had some of these similarities, although there were no point bars present and the gradient was not gentle (compared to the other study sites).

Pitlick and Wilcock (2013) determined the relationship between sediment transport and morphology in regulated rivers by surveying evenly spaced XS's and found that there was a small decrease in median sediment size (D_{50}) with a decrease in channel gradient. This was observed in the study sites (Appendix 5) where an increase in finer sand and gravel bars was observed with a decrease in channel gradient. This relationship was further observed with the forced sand and gravel+sand bars, where coarser forced bar substrate was observed in steeper reaches (Appendix 6).

6.2.3 Bar morphology and substrate

Tooth and Nanson (2000) surveyed a coarse sand and gravel bed NPR in Australia with the gradient ranging between 0.001 and 0.002. Sand and gravel bars as high as 1 m and ridges between 0.5 m and 1.5 m high were located in the channel (Tooth and Nanson, 2000). Similar coarse sand bars were observed in the steepest reaches (Prinspoort and Touws Wolwefontein reach) with the heights of these sand bars ranging between 0.11 m to 0.4 m and 0.26 m to 1.85 m respectively (Figures 12 to 14 and 17 to 21). Furthermore, the heights of coarse gravel bars observed in the Prinspoort and Touws Wolwefontein reaches were similar to Tooth and Nanson (2000). The coarse gravel bars were 0.13 m high and ranged between 0.26 m and 1.85 m high in the Touws Wolwefontein reach (Figures 12 to 14 and 17 to 21).

The bar morphology showed a gradual decrease in size from study site 1 to study site 4 (Figure 26), where the morphology of the bars become shorter in height, narrower in width and longer in length. Interestingly, the highest amount of cobble bars were found in the Prins Doornboom reach (Figure 25) although the gradient of this reach was more gentle than the Prinspoort and Touws Wolwefontein reaches. The coarsest cobble bars were however located in the wandering channel. Although Jaeger *et al*. (2017) argued that limited bars are found in single thread sand bed channels with low gradients, this was not observed in the Prins Doornboom reach and may be due to the effect of vegetation (Figures 10 and 11).

Generally most of the bars in the confined channel were narrow in width, elongated in length and shorter in height compared to the other reaches (Figure 26). The bar morphology in the unconfined channels were generally wider in width, and shorter in length and height compared to the confined channel (Figures 10 to 14 and 26). Furthermore the bar morphology in the unconfined channels was highly variable ranging from narrow and long to wide and short (Figure 26). The bar morphology in the wandering channels generally had a higher variety compared to the other reaches, and there was no dominant type of bar morphology specific to wandering channels (Figure 26).

The sand and gravel bars located in the Prins Doornboom reach were finer than the bars located in the Prinspoort and Touws Wolwefontein reaches. The finest sand and gravel bars were located in the Touws Plathuis reach (the reach with the most gentle gradient). This was expected as the stream power would be lower in channels with lower gradients, therefore the flow energy would not be strong enough to transport larger sediment and only be able to transport the finer grained sediment (Brierley and Fryirs, 2005; Kleinhans, 2010). Church (2006) found that coarse gravel is associated with single thread or wandering channels with a relatively steep gradient and relatively stable channels, this was observed in the Touws Wolwefontein and Prinspoort reach (Appendix 5). Both the Prinspoort and Touws Wolwefontein reaches had the steepest channel gradient, and can be related to the energy-driven sorting processes (Brierley and Fryirs, 2005; Kleinhans, 2010).

Most of the bars in the Prins and Touws River were composed of sand, fewer were composed of gravel and even fewer composed of cobble (Figure 25). The bars composed of gravel+sand and cobble+sand mixtures were few in number but were greater than the cobble bars (Figure 25). The channel bed substrate in the study sites were classified as fine to coarse sand, coarse gravel and very few cobble bars (Figure 25 and Appendix 5). Tooth and Nanson (2000) surveyed a multi-thread channel in Australia and found coarse sand with gravel+fine sediment in the river bed. This is similar to what was found in the Touws Plathuis and Touws Wolwefontein reaches where fine and coarse sand, coarse gravel and fewer cobble bars were found (Figure 25 and Appendix 5).

6.2.4 Influence of channel type on physical habitat

The bar and channel types create physical habitat for vegetation and macroinvertebrates (James and King, 2010). The substrate composition of bars would affect the physical habitat of NPRs. For example, an increased amount of coarser bars would create a physical habitat favourable for macroinvertebrates to spawn and find refugia during periods of active flow (Pitlick and Wilcock, 2013). Based on Appendix 5, the confined and wandering channels would provide favourable habitats for places of refugia and the spawning of macroinvertebrates during periods of flow. Although different fluvial styles have similar bar types, the coarsest sand and gravel bars are found in the confined and wandering channel. Additionally the coarsest cobble bars are located in the Touws Wolwefontein reach.

Seaman *et al*. (2013) discussed the sensitivity of NPR habitat, and described that a state change in the channel bed, for example from gravel to sand bed or cobble to sand bed would have a big impact on ecosystem habitat. The channel bed and width:depth ratio would be changed, altering the channel morphology and dynamics, and may be caused by anthropogenic changes such as dam construction or natural changes such as an increase in the erosion rate of the channel (Seaman *et al*., 2013). Based on the work of Dunkerley (2013), the removal of in-channel vegetation would alter the deposition of debris and sediment type in the Prins and Touws River during flow, thus changing the habitat of macroinvertebrates through processes such as the infilling of pore space.

6.3 Forced bars

The highest percentage of gravel bars were located in the steeper reaches and as the gradient of the study sites decrease, there is a decrease in the percentage of in-channel gravel bars (Figure 25). This is however not the case with sand bars, the reaches with the steepest gradients had the lowest percentage of sand bars and the reaches that were more gentle had higher percentages of sand bars. This may be that the stream power of floods occurring in the steeper reaches would remove the fine grained sediment along with the coarse grained sediment, and depositing the fine grained sediment in the reaches with a more gentle channel gradient (Plate 1). Cobble bars were not located in the Touws Plathuis and Prinspoort reaches, however a mixture of cobble+sand bars were located in the Touws Plathuis reach and cobbles were deposited on the river bed of the Prinspoort reach. This is due to the energy-driven sorting processes (Brierley and Fryirs, 2005; Kleinhans, 2010). Only the Prins Doornboom and Touws Wolwefontein reaches had cobble bars and these reaches were steeper than the Touws Plathuis reach. There were no bars composed of mixed substrate in the Touws Wolwefontein reach which may be related to the high amount of deposition or smaller flow washing away sand from gravel and cobble bars described by Brierley and Fryirs (2005) and Kleinhans (2010). Channel patterns and the river morphology are affected by the sorting of the substrate found within the rivers and at low scales as sediment sorting has a direct effect on bar morphology (Kleinhans, 2010).

6.3.1 Forced bar occurrence

The in-channel vegetation and woody debris piles observed in the channel acted as obstructions, influencing the flow and influencing sediment deposition on the lee side of the obstruction. Bunte and Abt (2001) referred to these in-channel obstructions as large woody debris that alter the transportation dynamics of sediment. Large woody debris redirects in-channel flow, changing the channel morphology and particle size of sediment in the surrounding area of the obstruction (Bunte and Abt, 2001; Wallerstein *et al*., 2001). Furthermore forced bars allow the growth of vegetation in the fine sediment upstream of the obstruction (Plate 2). Based on the classification developed by Wallerstein *et al*. (2001), bar head jams were the most common form of in-channel obstructions for the development of forced bars in the Prins and Touws River (Figure 38 and Table 10).

The majority of the forced bars identified in the study sites were composed of sand and gravel, with fewer forced bars composed of cobble (Figures 29 and 30). This is related to shear stress (varying over smaller spatial scales than stream power) and stream power as it is easier to transport sand and gravel and have it deposited on the lee side of an obstruction during flow compared to cobble (Brierley and Fryirs, 2005; Bunte and Abt, 2001; Kleinhans, 2010; Pitlick and Wilcock, 2013). The forced bars in the Prins Doornboom reach are likely to have formed through the bar head jam process described by Wallerstein *et al*. (2001) (Figure 38 and Table 10).

Plate 2: Vegetation growth in fine sediment upstream of debris piles in the Prins Doornboom (C1) and Prinspoort (C2) reaches

Bunte and Abt (2001) provided a different explanation for the formation of forced bars, explaining that the deposition of debris piles in the channel obstruct flow and facilitate the deposition of coarse sediment on the upstream side of the obstruction. As the sediment deposition increases the gradient upstream of the obstruction decreases and deposition of finer particles begin to accumulate upstream of the obstruction. The lee side of the obstruction begins to receive a decreased amount of sediment from upstream and the fine sediment upstream of the obstruction is eventually removed through winnowing leaving only the coarse sediment behind (Bunte and Abt, 2001; Brierley and Fryirs, 2005). As the debris deteriorates over time, scouring of the upstream coarse sediment starts to occur and deposits the sediment on the lee side of the debris pile (Bunte and Abt, 2001).

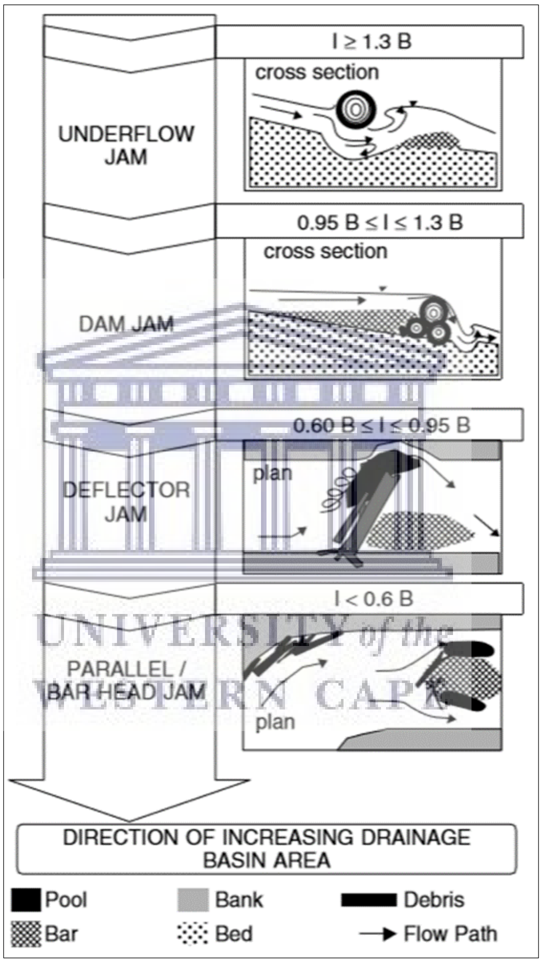


Figure 38: Debris jam classification model (Wallerstein *et al*., 2001)

Table 10: Examples of forced bars in the study sites

Camera facing upstream	Description	Camera facing downstream
	PB1 Moderately well sorted fine sand forced mid-channel bar (Located in the Prins Doornboom reach)	
	PB1 Confined Moderately well sorted very coarse gravel and poorly sorted fine sand mixture forced mid-channel bar (Located in the Prinspoort reach)	
	TWB10 Poorly sorted fine sand forced mid-channel bar (Located in the Touws Plathuis reach)	
	TB26 Poorly sorted very coarse gravel forced mid-channel bar (Located in the Touws Wolwefontein reach)	

Kleinhans (2010) further explained that bars located around bends may have a variation of substrate size ranging from sand to gravel. The variation of substrate size may stretch as far as one channel bank to the other, influencing the morphodynamics and preferred flow pattern (Kleinhans, 2010). The rate of sediment supply is important for the formation of bars, as Lisle *et al*. (2000) explained that high sediment transport rates is either related to sediment supply or a higher shear stress than particle entrainment.

6.3.2 Forced bar prediction

Bars are generally classified by their size and shape (Brierley and Fryirs, 2005). In the Prinspoort reach the dominant GU type was forced bars while the dominant GU's in the confined channel of Thompson and Croke (2013) were benches with an absent floodplain. There were however similarities between the reaches in these two studies as benches were found in the Prinspoort reach and in the confined channel of Thompson and Croke (2013), suggesting that confined channels react similarly to floods, more so when the lithology is similar (sandstone). Thompson and Croke (2013) explained that benches and the floodplain covered 75% of the total area in the unconfined channel. This is different to what was observed in the Prins Doornboom reach where forced bars rather than benches were dominant. Furthermore the bars in the Prins Doornboom reach covered a smaller valley floor area (9%) compared to the unconfined channel of Thompson and Croke (2013) (Figure 28).

In the Prins and Touws River, forced mid-channel bars, expansion bars and compound mid-channel bars were found in the unconfined channel. Scroll bars, forced mid-channel bars, forced bank attached bars, boulder mounds and benches were found in the confined channel. Longitudinal bars, compound mid-channel bars, forced mid-channel bars, islands, boulder mounds, expansion bars, lateral bars, benches and bedrock core bars were found in the wandering channels (Figure 22). This shows that the results observed in this study is similar to what Thompson and Croke (2013) observed when finding that the bar types present in confined and unconfined channels were the same. This observation suggests that the bar type located in NPR's are not dependent on the channel pattern. In this study it was observed that different fluvial styles have similar bar types and therefore specific bar types cannot be predicted just by classifying the channel pattern (Table 5). Field surveys need to be conducted to further determine similarities or differences between bars located within different reaches and to determine if the spatial distribution of GU's can be predicted based on vegetation type and distribution.

6.3.3 Forced bar distribution

Dunkerley (2013) noted that the role of in-channel obstructions in NPR's with alluvial river beds is not as well understood as in perennial rivers. However, studies have been done by Roux *et al*. (2002), Seaman *et al*. (2013), Tooth (2013) and others to narrow this gap. In-channel vegetation is a characteristic of NPR's and may act as obstructions during times of flood thereby facilitating the formation and distribution of forced bars. This is supported by Greenbaum and Bergman (2006) who explained that there were many obstructions in the channel that created forced bars composed of sand after a flood. The NPR's in Israel commonly have armoured riverbeds, (observed in the Prinspoort reach, Plate 1), affecting bed mobility (Greenbaum and Bergman, 2006).

Dunkerley (2013) tried to determine the relationship between woody debris and fluvial style of NPR's and found that almost all woody debris piles were lodged against vegetation, with some lodged against dead debris. One forced bar was located behind vegetation and one behind woody debris in the Prinspoort reach and there were much more forced bars behind vegetation than woody debris in the Touws Plathuis and Touws Wolwefontein reaches (Figure 30). In-channel vegetation in NPR's play an important role as obstructions, allowing the deposition of sediment to occur by increasing the bed roughness (Tooth and Nanson, 2000). Furthermore, Dunkerley (2013) noted that the complete absence of obstructions (for example vegetation or debris piles) in the channel would prevent any of the forced mid-channel bars from forming.

Vegetation located in channels that remain dry for most of the year are well established and directly affect the formation process of bars formed by the deposition of sediment (Tooth and Nanson, 2000). Kleinhans (2010) explained that forced bars are present in most rivers due to the curvature of the river banks. NPR's characteristically have dry riverbeds, riparian vegetation growing down to the base of the river banks, gentle gradients and fine grained sediment in the channel and floodplain (Huang and Nanson, 2007). These characteristics have been observed in the study area.

6.4 Difference in the occurrence and characteristics of bars with fluvial style

6.4.1 Bar variety and substrate

Tooth and Nanson (2000) noted the important effect that vegetation has on the geomorphology and hydrology of a river which in turn influence the formation of forced bars. The removal of vegetation influence the amount of debris located in river channels which affect the channel morphology (Dunkerley, 2013). This was seen in the Touws Plathuis and Touws Wolwefontein reaches where debris piles were lodged in the upstream part of *Vachellia karroo*, further promoting the deposition of sediment on the lee side of the obstruction (Plate 3). This shows that in-channel vegetation influences the channel morphology and affects the geomorphological processes of sediment (Dunkerley, 2013; Seaman *et al*., 2013). Brierley and Fryirs (2005) noted that in-channel bars may be composed of a variety of bedrock and alluvial forms depending on the flow and valley setting. This was evident in the study sites as the bar substrate of the observed bars was similar to what Tooth and Nanson (2000) and Greenbaum and Bergman (2006) observed in NPR's in Australia and Israel.

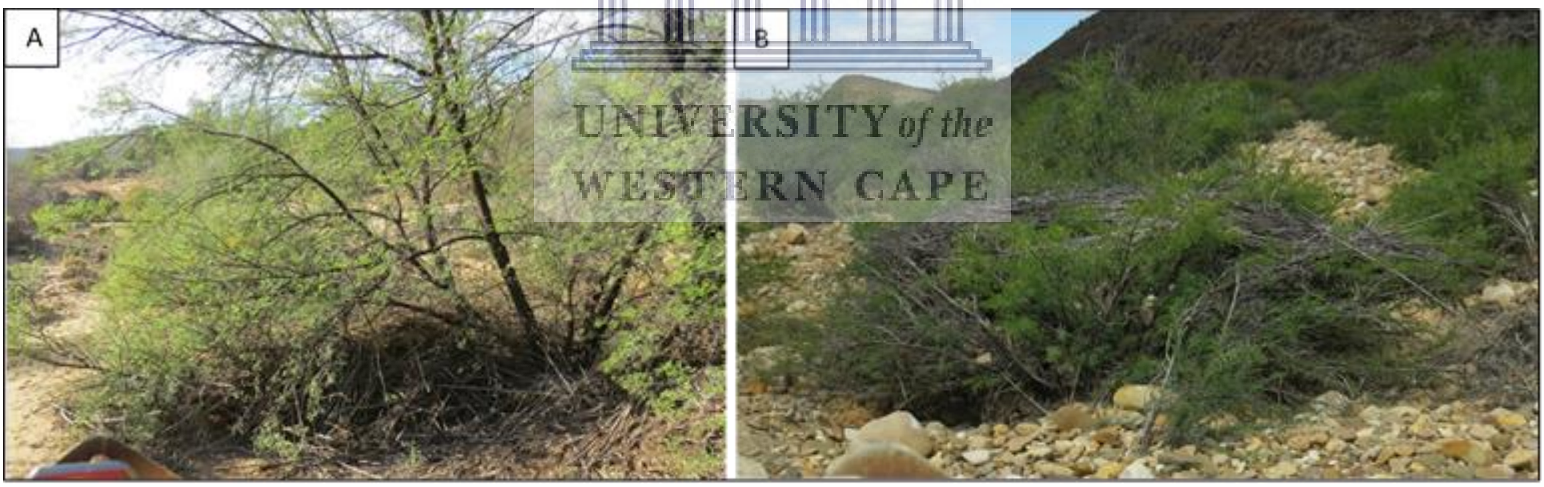


Plate 3: Debris lodged against *Vachellia karroo* in the Touws Plathuis (A) and Touws Wolwefontein (B) reaches

The forced bar substrate in the Prins and Touws River were coarser at the bar head and became finer longitudinally toward the bar tail. Brierley and Fryirs (2005) referred to this and argued that secondary flows cause the finer sediment to move down the bar axis. This is due to a number of reasons, namely, the flow not having enough energy to move the coarser sediment or there is too much bed resistance for the coarser sediment to be moved from the bar head (Brierley and Fryirs, 2005).

It is observed that forced bars of mixed substrate composition were all located behind debris piles in the Prins Doornboom reach. The majority of the forced bars in the Touws Plathuis reach were located behind vegetation. These observations confirm that the obstruction is more important for sediment deposition rather than the type of sediment being deposited. Lehotskỳ (2004), Brierley and Fryirs (2005), Buffington (2012) and Pitlick and Wilcock (2013) verified that one of the variables affecting the morphology of the channel is the quantity and size of available substrate.

7. Conclusion and Recommendations

7.1 Conclusion

In this study 64 bars were surveyed across 4 study sites and 39 (60%) of these bars were identified and classified as forced bars. It was observed that forced bars were the only bar type found in all of the contrasting reaches, suggesting this to be the dominant bar type in the NPR's studied. It was determined that the substrate characteristics of bars are not entirely dependent on the obstruction in the channel. By way of elimination, using Spearman's rank correlation, it was seen that the sediment size did not influence the morphology of bars. Based on these findings it was determined that the valley setting plays a bigger role in determining the formation, sediment size and morphology of bars in NPR's.

Some of the general trends observed in the study area include an increase in the variety of GU's with an increase in channel gradient (study site 4) and channel width (study site 3). Furthermore, it was observed that the study sites with the steepest gradient (study sites 2 and 4) was underlain by the same lithology, Adolphspoort formation (Figure 9). This type of lithology may be a contributor to the comparatively steeper channel gradient. The highest GU diversity was found in the widest reach (study site 3) and shows the importance of valley setting in the development of GU's. This is in line with Pitlick and Wilcock (2013) when mentioning that there would be a larger area for in-channel flow to develop GU's and varying habitats.

The sorting of sediment influences the channel pattern and has a direct effect on bars at small scales (Kleinhans 2010). It was mentioned by Dunkerley (2013) that the complete absence of vegetation in the channel would prevent the formation of mid-channel bars. Vegetation influences the channel morphology and geomorphological processes (Dunkerley, 2013; Seaman *et al*., 2013). The nature of the obstruction is not important in determining the location of forced bars as forced bars occur on the lee side of vegetation and debris piles. Furthermore, the obstruction (veg or debris) does not determine the sediment size of forced bars as there was an overlap in the grain size of forced bars located on the lee side of vegetation and debris piles.

Thompson and Croke (2013) found that the spatial changes in channel morphology influence the formation and deformation of bars and is due to the geomorphological processes of the alluvial channels. This was seen in Figure 23 where the straight channel has a similar number of bars as the wandering channels even though it is narrower than the wandering channels. Furthermore it was discovered that no fluvial style was dominated by only one specific bar type. Although forced bars were the dominant bar type there were various different bar types present in each study site as well.

Further studies on NPR's are necessary to better understand and further contribute to the knowledge about the controlling factors which would aid in better management of NPR's (Tooth and Nanson, 2004). The mapping of past and present bars in NPR's would assist in the reconstruction of past and modern behaviour and in the prediction of future behaviour of these NPR's (Lehotskỳ, 2004; Tooth and Nanson, 2004; Rowntree *et al.*, 2013). These findings can be used by river managers to make better informed decisions on the management of NPR's.

7.2 Limitations and Recommendations

In this thesis, the small study area (1 study site per fluvial style) was a limitation and it is recommended to have 2 or 3 study sites per fluvial style. However, a rapid assessment method would be needed to obtain similar information. This will provide a better understanding of the processes observed in this study. It is recommended to follow the method of Dunkerley (2013) and measure the size of the in-channel obstructions (vegetation and woody debris piles) as it is now known that these features are a characteristic of NPR's and facilitate the formation of forced bars.

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9. Appendices

Appendix 1: Raw data summary table

Name	WGS 1984 LONG	WGS 1984 LAT	River Reach	D16 (mm)	D50 (mm)	D84 (mm)	Feature name (Brierley and Fryirs, 2005)	Analysis type	Sediment type	Bar area (m^2)	Sorting	Classification of the degree of sorting (Folk and Ward 1975)	Bar height (m)	Bar Length (m)	Bar width (m)	Sum of area (m^2) of GU's in reach	Macro channel area (m^2)
PB 1	20.863	-33.551	Prins Doornboom	0.09	0.16	0.22	Forced mid-channel bar	Sieving	Fine sand	45.30	0.63	Moderately well	0.61	6.47	4.19	2384.52	14303
PB 2	20.863	-33.551	Prins Doornboom	0.06	0.16	0.26	Forced mid-channel bar	Sieving	Fine sand	23.89	1.83	Poor	0.46	10.35	2.22		
PB 3	20.863	-33.551	Prins Doornboom	0.08	0.17	0.30	Forced mid-channel bar	Sieving	Fine sand	40.05	0.95	Moderate	0.58	15.50	2.76		
PB 4	20.863	-33.551	Prins Doornboom	0.32	0.68	1.28	Expansion bar	Sieving	Coarse sand	28.79	1.00	Moderate	0.33	10.60	3.35		
PB 5	20.863	-33.551	Prins Doornboom	0.14	0.23	0.44	Forced mid-channel bar	Sieving	Fine sand	66.65	0.83	Moderate	1.08	11.46	5.51		
PB 6	20.863	-33.551	Prins Doornboom	53.52	72.00	93.00	Forced mid-channel bar	Pebble count	Small cobble	46.47	0.38	Well	1.60	6.70	5.05		

PB 8	20.863	-33.551	Prins Doornboom	45.00	67.00	95.32	Forced mid-channel bar	Pebble count	Small cobble	87.51	0.54	Moderately well	0.71	11.80	8.33		
PB 9	20.863	-33.551	Prins Doornboom	36.00	52.00	77.00	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	363.77	0.55	Well	1.66	52.00	13.59		
PB 10	20.863	-33.551	Prins Doornboom	45.84	72.00	98.16	Expansion bar	Pebble count	Small cobble	818.73	0.54	Moderately well	1.64	59.64	16.80		
PB 10	20.863	-33.551	Prins Doornboom	0.35	0.71	1.32	Expansion bar	Sieving	Coarse sand	818.73	0.95	Moderate	1.64	59.64	16.80		
PB 11	20.862	-33.551	Prins Doornboom	0.13	0.30	0.58	Forced mid-channel bar	Sieving	Medium sand	28.06	1.07	Poor	0.78	9.90	3.21		
PB 12	20.862	-33.551	Prins Doornboom	0.15	0.28	0.46	Forced mid-channel bar	Sieving	Medium sand	56.58	0.81	Moderate	0.93	10.76	5.15		
PB 13	20.862	-33.551	Prins Doornboom	48.84	66.50	90.00	Forced mid-channel bar	Pebble count	Small cobble	127.33	0.45	Well	1.20	61.70	5.78		
PB 13	20.862	-33.551	Prins Doornboom	0.07	0.16	0.27	Forced mid-channel bar	Sieving	Fine sand	127.33	0.98	Moderate	1.20	61.70	5.78		
PB 14	20.863	-33.551	Prins Doornboom	37.00	56.00	92.00	Compound mid-channel bar	Pebble count	Very coarse gravel (pebble)	259.67	0.67	Moderately well	1.23	51.00	8.82		

PB 14	20.863	-33.551	Prins Doornboom	0.10	0.19	0.41	Compound mid-channel bar	Sieving	Fine sand	259.67	1.01	Poor	1.23	51.00	8.82		
PB 15	20.863	-33.551	Prins Doornboom	0.04	0.10	0.21	Forced mid-channel bar	Sieving	Very fine sand	86.42	2.71	Very poor	0.36	9.10	7.80		
PB 16	20.863	-33.552	Prins Doornboom	0.07	0.16	0.29	Forced mid-channel bar	Sieving	Fine sand	305.29	0.65	Moderately well	1.05	34.40	7.38		
PB 1 (confined)	20.845	-33.565	Prinspoort	36.00	55.00	75.00	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	74.89	0.53	Moderately well	1.54	21.19	7.11	7162.17	16237
PB 1 (confined)	20.845	-33.565	Prinspoort	0.08	0.22	0.70	Forced mid-channel bar	Sieving	Fine sand	74.89	1.57	Poor	1.54	21.19	7.11		
PB 2 (confined)	20.845	-33.565	Prinspoort	38.84	52.50	78.32	Scroll bar	Pebble count	Very coarse gravel (pebble)	4320.59	0.51	Moderately well	4.39	150.00	24.03		
PB 2 (confined)	20.845	-33.565	Prinspoort	0.13	2.00	2.00	Scroll bar	Sieving	Very fine gravel	4320.59	1.98	Poor	4.39	150.00	24.03		
PB 3 (confined)	20.846	-33.566	Prinspoort	0.17	0.45	0.97	Forced bank attached bar	Sieving	Medium sand	2432.86	1.26	Poor	0.11	154.00	18.91		
PB 4 (confined)	20.846	-33.566	Prinspoort	42.84	57.00	79.12	Boulder mound	Pebble count	Very coarse gravel (pebble)	69.38	0.44	Well	0.13	18.73	4.07		

PB 5 (confined)	20.847	-33.568	Prinspoort	0.09	0.23	0.57	Bench	Sieving	Fine sand	264.44	1.32	Poor	0.40	53.30	5.05		
TWB 1	20.933	-33.628	Touws Plathuis	0.18	0.31	0.49	Longitudinal bar	Sieving	Medium sand	749.93	0.72	Moderate	1.62	100.00	9.43	27082.49	197863
TWB 2	20.933	-33.628	Touws Plathuis	0.15	0.27	0.44	Compound mid-channel bar	Sieving	Medium sand	2021.35	0.78	Moderate	1.79	109.00	27.95		
TWB 3	20.933	-33.628	Touws Plathuis	0.14	0.31	0.48	Forced mid-channel bar	Sieving	Medium sand	85.99	0.89	Moderate	0.56	18.40	6.80		
TWB 4	20.933	-33.629	Touws Plathuis	19.00	33.50	49.32	Island	Pebble count	Very coarse gravel (pebble)	18158.11	0.69	Moderately well	1.21	251.00	120.66		
TWB 4	20.933	-33.629	Touws Plathuis	0.12	0.40	0.81	Island	Sieving	Medium sand	18158.11	1.37	Poor	1.21	251.00	120.66		
TWB 5	20.933	-33.629	Touws Plathuis	19.00	33.50	49.32	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	39.45	0.69	Moderately well	0.48	15.14	1.76		
TWB 6	20.933	-33.629	Touws Plathuis	0.14	0.30	0.48	Compound mid-channel bar	Sieving	Medium sand	72.92	0.89	Moderate	0.58	16.49	6.62		
TWB 7	20.933	-33.630	Touws Plathuis	19.00	33.00	56.00	Compound mid-channel bar	Pebble count	Very coarse gravel (pebble)	3139.53	0.78	Moderate	1.28	145.14	25.19		
TWB 7	20.933	-33.630	Touws Plathuis	0.29	0.51	2.00	Compound mid-channel bar	Sieving	Coarse sand	3139.53	1.40	Poor	1.28	145.14	25.19		

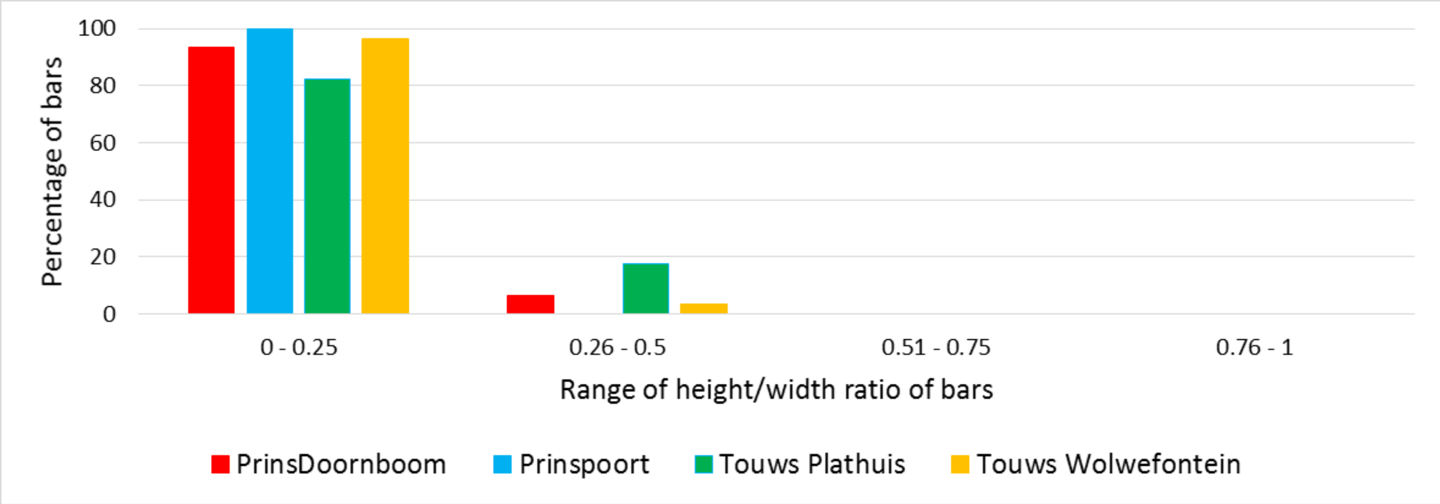
TWB 8	20.933	-33.630	Touws Plathuis	0.06	0.13	0.25	Compound mid-channel bar	Sieving	Fine sand	701.92	2.76	Very poor	1.32	62.65	7.77		
TWB 9	20.933	-33.630	Touws Plathuis	19.00	39.50	73.00	Compound mid-channel bar	Pebble count	Very coarse gravel (pebble)	194.81	0.97	Moderate	1.18	39.26	5.49		
TWB 10	20.939	-33.629	Touws Plathuis	0.10	0.24	0.46	Forced mid-channel bar	Sieving	Fine sand	77.53	1.10	Poor	2.13	12.77	6.98		
TWB 11	20.939	-33.629	Touws Plathuis	19.84	31.00	65.16	Island	Pebble count	Coarse gravel (pebble)	1562.97	0.87	Moderate	1.77	81.00	24.70		
TWB 11	20.939	-33.629	Touws Plathuis	0.18	0.39	0.85	Island	Sieving	Medium sand	1562.97	1.11	Poor	1.77	81.00	24.70		
TWB 12	20.938	-33.630	Touws Plathuis	0.05	0.11	0.22	Forced mid-channel bar	Sieving	Very fine sand	59.36	2.70	Very poor	1.10	13.70	5.34		
TWB 13	20.938	-33.632	Touws Plathuis	0.06	0.12	0.24	Forced mid-channel bar	Sieving	Very fine sand	38.20	2.73	Very poor	0.87	13.10	4.46		
TWB 14	20.938	-33.632	Touws Plathuis	30.84	64.00	114.16	Forced mid-channel bar	Pebble count	Small cobble	16.60	0.94	Moderate	0.90	7.66	4.24		
TWB 14	20.938	-33.632	Touws Plathuis	0.10	0.28	0.71	Forced mid-channel bar	Sieving	Medium sand	16.60	1.42	Poor	0.90	7.66	4.24		

TWB 15	20.938	-33.632	Touws Plathuis	0.07	0.18	0.44	Forced mid-channel bar	Sieving	Fine sand	27.44	1.33	Poor	0.69	7.93	3.27		
TWB 16	20.938	-33.632	Touws Plathuis	16.00	26.00	46.00	Forced mid-channel bar	Pebble count	Coarse gravel (pebble)	64.14	0.76	Moderate	0.55	20.10	3.40		
TWB 16	20.938	-33.632	Touws Plathuis	0.19	0.44	0.86	Forced mid-channel bar	Sieving	Medium sand	64.14	1.09	Poor	0.55	20.10	3.40		
TWB 17	20.938	-33.632	Touws Plathuis	14.84	34.50	83.16	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	72.25	1.24	Poor	1.50	20.67	3.40		
TWB 17	20.938	-33.633	Touws Plathuis	0.12	0.39	2.00	Forced mid-channel bar	Sieving	Medium sand	72.25	2.03	Very poor	1.50	20.67	3.40		
TB 1	20.962	-33.642	Touws Wolwefontein	63.68	85.00	150.00	Expansion bar	Pebble count	Small cobble	20402.86	0.61	Moderately well	4.36	481.00	53.49	51765.05	358304
TB 2	20.962	-33.642	Touws Wolwefontein	40.00	63.00	98.00	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	59.08	0.65	Moderately well	0.33	6.89	3.66		
TB 3	20.962	-33.642	Touws Wolwefontein	0.00	0.18	0.45	Forced mid-channel bar	Sieving	Fine sand	51.98	5.43	Extremely poor	0.58	8.88	3.74		
TB 4	20.962	-33.642	Touws Wolwefontein	33.84	52.50	71.00	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	28.91	0.53	Moderately well	0.30	11.47	2.50		

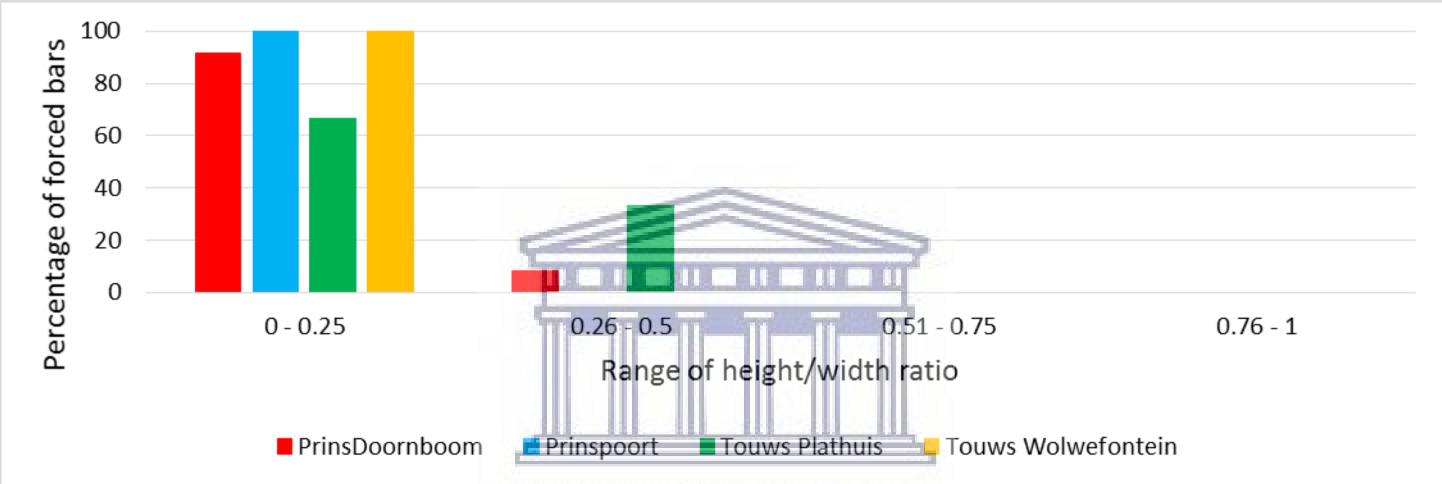
TB 5	20.962	-33.642	Touws Wolwefontein	41.68	61.50	85.16	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	21.79	0.52	Moderately well	0.56	8.50	3.79		
TB 6	20.962	-33.642	Touws Wolwefontein	33.00	47.50	62.16	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	19.25	0.46	Well	0.25	7.90	3.61		
TB 7	20.962	-33.642	Touws Wolwefontein	31.00	46.00	70.64	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	6.34	0.59	Moderately well	0.18	5.20	2.69		
TB 8	20.962	-33.642	Touws Wolwefontein	31.00	50.50	84.16	Boulder mound	Pebble count	Very coarse gravel (pebble)	13.09	0.72	Moderate	0.17	9.70	1.89		
TB 9	20.962	-33.641	Touws Wolwefontein	32.84	57.00	90.32	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	70.00	0.73	Moderate	1.07	18.90	8.88		
TB 10	20.966	-33.641	Touws Wolwefontein	0.15	0.33	0.56	Lateral bar	Sieving	Medium sand	3909.51	0.95	Moderate	1.85	152.00	18.48		
TB 11	20.966	-33.641	Touws Wolwefontein	0.17	0.40	0.78	Forced mid-channel bar	Sieving	Medium sand	72.48	1.10	Poor	0.28	22.72	4.44		
TB 12	20.966	-33.641	Touws Wolwefontein	33.84	59.50	81.48	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	72.57	0.63	Moderately well	0.40	16.15	7.05		
TB 13	20.966	-33.641	Touws Wolwefontein	0.09	0.22	2.00	Forced mid-channel bar	Sieving	Fine sand	111.61	2.24	Very poor	0.57	18.47	8.07		

TB 14	20.966	-33.641	Touws Wolwefontein	0.08	0.23	0.46	Island	Sieving	Fine sand	7092.06	1.26	Poor	1.21	235.00	20.48			
TB 15	20.968	-33.641	Touws Wolwefontein	0.11	0.32	2.00	Bench	Sieving	Medium sand	317.53	2.10	Very poor	1.48	40.00	9.49			
TB 17	20.968	-33.641	Touws Wolwefontein	0.10	0.21	0.44	Bench	Sieving	Fine sand	805.04	1.07	Poor	0.26	71.00	15.08			
TB 18	20.968	-33.641	Touws Wolwefontein	0.03	0.10	0.73	Forced mid-channel bar	Sieving	Very fine sand	106.06	5.58	Extremely poor	0.53	25.12	11.12			
TB 19	20.971	-33.639	Touws Wolwefontein	0.28	0.44	0.80	Bedrock core bar	Sieving	Medium sand	41.97	0.76	Moderate	0.70	17.89	2.56			
TB 20	20.971	-33.639	Touws Wolwefontein	38.00	59.00	94.16	Expansion bar	Pebble count	Very coarse gravel (pebble)	5082.04	0.66	Moderately well	1.58	158.00	55.15			
TB 21	20.971	-33.64	Touws Wolwefontein	0.25	0.46	0.92	Boulder mound	Sieving	Medium sand	25.29	0.93	Moderate	0.41	10.90	2.71			
TB 22	20.976	-33.64	Touws Wolwefontein	0.58	2.00	2.00	Lateral bar	Sieving	Very fine gravel	6177.14	0.90	Moderate	0.77	315.00	18.44			
TB 23	20.976	-33.64	Touws Wolwefontein	0.04	0.11	0.28	Bench	Sieving	Very fine sand	7060.75	2.92	Very poor	1.56	226.00	20.45			
TB 24	20.976	-33.64	Touws Wolwefontein	0.29	0.51	0.87	Forced mid-channel bar	Sieving	Coarse sand	73.07	0.79	Moderate	0.40	21.52	3.18			

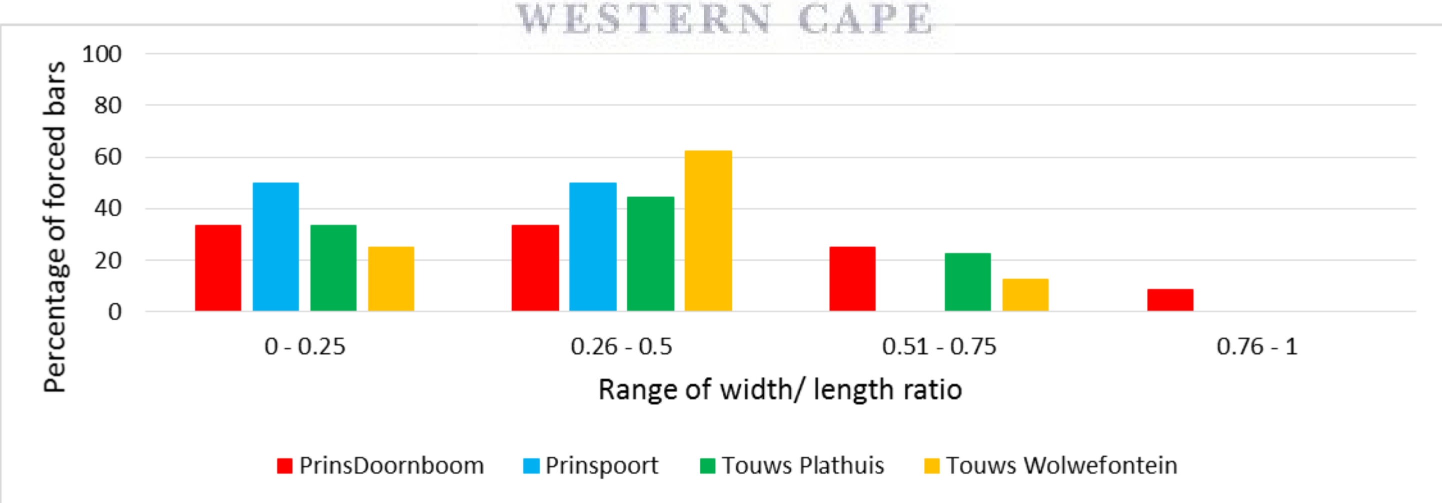
TB 25	20.976	-33.64	Touws Wolwefontein	0.22	0.46	0.97	Forced mid-channel bar	Sieving	Medium sand	40.86	1.08	Poor	0.36	17.20	3.09		
TB 26	20.976	-33.64	Touws Wolwefontein	16.00	38.50	66.00	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	38.44	1.02	Poor	0.52	14.52	4.32		
TB 27	20.976	-33.64	Touws Wolwefontein	20.00	38.50	64.48	Forced mid-channel bar	Pebble count	Very coarse gravel (pebble)	42.31	0.85	Moderate	0.14	14.20	4.39		
TB 28	20.976	-33.64	Touws Wolwefontein	16.00	26.50	50.16	Forced mid-channel bar	Pebble count	Coarse gravel (pebble)	23.02	0.81	Moderate	0.34	9.19	3.47		



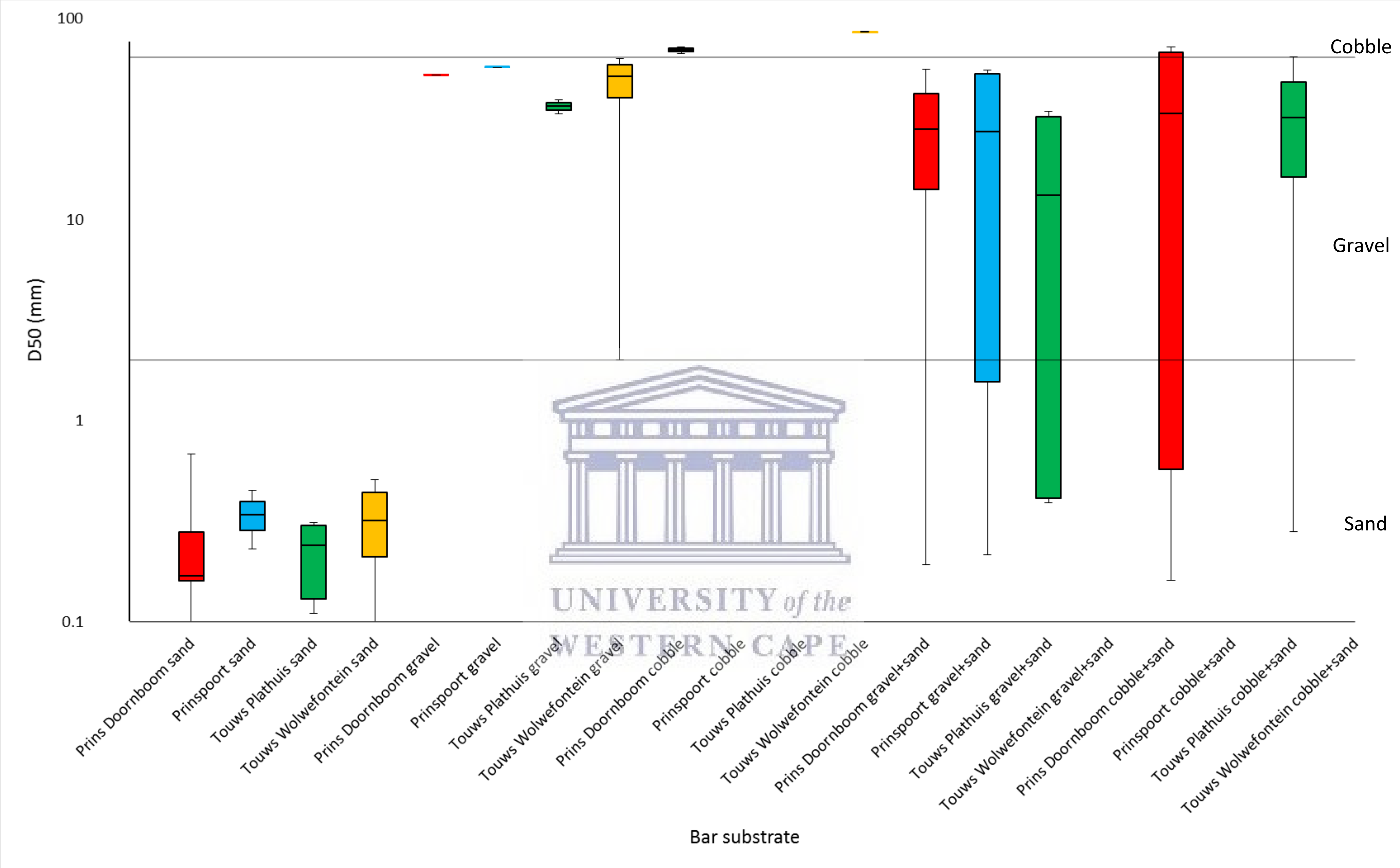
Appendix 2: Proportion of bars in all reaches with height:width ratios in intervals of 0.25



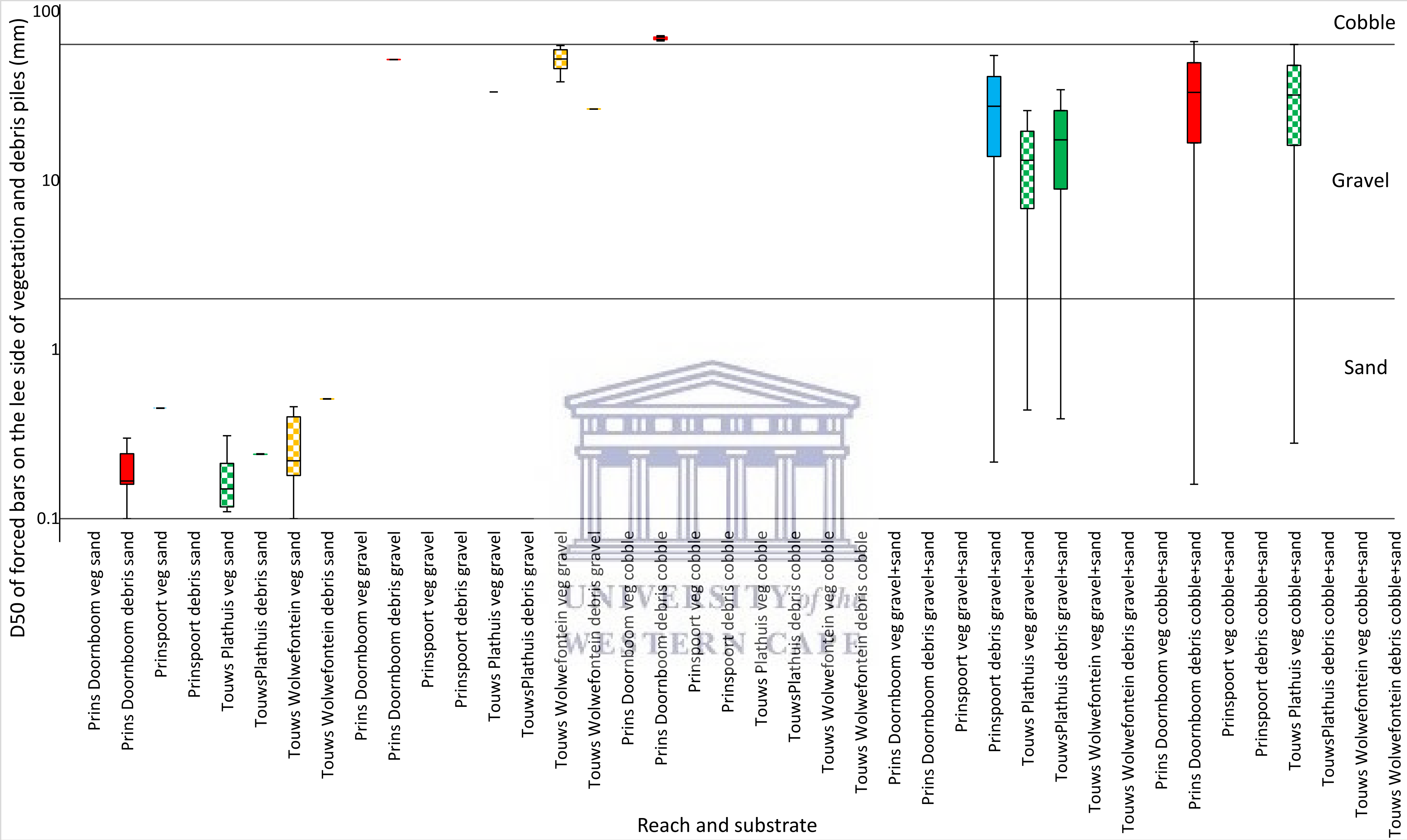
Appendix 3: Proportion of forced bars with height:width ratios in intervals of 0.25



Appendix 4: Proportion of forced bars with width:length ratios in intervals of 0.25



Appendix 5: Box and whisker diagram showing the D_{50} range of all bars across all reaches with varying substrate



Appendix 6: Box and whisker diagram showing the D_{50} range of all forced bars on the lee side of vegetation (checkered box) and debris piles (solid box)