Hydrogeomorphic controls on the longitudinal distribution and dynamics of reed beds in non-perennial river systems, Western Cape, South Africa.

Nomanesi Makhonco

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

Supervisors:

Dr. MC Grenfell

Dr. SE Grenfell

January 2020

Declaration

I **Nomanesi Makhonco**, student number **3346000** declare that the thesis entitled "***Hydrogeomorphic controls on the longitudinal distribution and dynamics of reed beds in non-perennial river systems, Western Cape, South Africa.***" is my own work, that it has not been submitted before for any degree examination in any other university and that all the sources I have used or quoted have been indicated and acknowledged by means of complete references.

Signed this day 28 of January 2019

Signature:

Abstract

Non-Perennial Rivers are often considered systems of low ecological and economic value due to prolonged periods of no flow. Despite the importance of non-perennial rivers in dryland environments in providing habitat to fauna and flora, non-perennial rivers remain some of the least studied freshwater ecosystems in the world. Reed beds are among the vegetation types found along these river systems. The aim of this research is to advance understanding of hydrogeomorphic controls on spatial variation in reed bed location, aerial extent, and sediment characteristics, with a view to providing insight that can be applied in the determination of environmental water requirements for non-perennial rivers. The study was conducted in four study reaches with contrasting fluvial styles in the Touws and Prins River systems.

WorldView-2 imagery of the study site taken at the time of field survey in 2017 was used to map the recent distribution of reed beds along the Touws and Prins River systems. This was examined together with 2013 aerial and 2014 SPOT 6 imagery. All three imagery sets were then examined in order to identify changes in reed bed distribution before and after the 2014 flood event (Q_{peak} ~ 785 m^3/s). Field dGPS valley morphological surveys, and measurements of substrate and stem characteristics were collected in four reaches along the two rivers, to quantify Cheźy -based vegetation-related hydraulic roughness variation. This was done in order to establish sediment composition and the influence of vegetation-related hydraulic roughness variation on sediment composition.

The field work and image analysis showed that reeds located in upper reaches, where the reaches are dominated by resistant rock layers, exposed bedrock with little to no sediment. Most of the reeds found in these reaches grow along channel corridors on small heaps of sediment . These reed patches undergo slight changes in reed bed area. The reed bed patches remain persistent through dry and wet periods. However, a reduction in area during periods of no flow with increase in patchiness can be observed. Following a flood event an increase in reed bed area with a decrease in patchiness occurs. Reaches located downstream dominated by less resistant rock layers with wider valleys and multi-threaded channels. The reed beds here are distributed across the channel in masses of mainly fine sediment. These reaches have very large patches of reeds which increase in area after a flood. However, the reed bed area decreases dramatically during periods of no flow, resulting in an increase in reed patches.

The following conceptual model is proposed to explain changes in reed bed distribution before and after a flood event for the Prins and Touws River systems: Large floods arrive at a time when reed bed area is low after a dry period and grazing pressure which limit aboveground production. The rhizome network, however, are still intact buried by sediment. These subsurface rhizome network extend beyond the pre-flood reed bed area and respond to the flood very quickly by sprouting stems, so that soon after a large flood there is a large reed bed area again. Over time, without more floods, reed bed area shrinks again due to grazing and low flows which only inundate the channel or near-channel environment, so that reeds further away are reduced and cannot recover (although the rhizomes remain intact) until the next big flood event. Since these rhizome network need a substrate to grow in, reeds are favoured in reaches that have wider valley floors, where fine sediment accumulates. As such, the physical geomorphological setting controls the spatial distribution and patchiness of reed beds. A seasonal or aseasonal episodic flooding favours the re-establishment of reeds. The sediment and water supply provided by the flood promotes the growth and persistence of reed beds along non-perennial rivers, which has implications for environmental water allocation strategies.

Keywords: reed stem characteristics; hydraulic roughness; geomorphology-vegetation interactions; rhizome network; geomorphological zones.

Acknowledgements

I would like to give all the glory to my Lord and saviour Jesus Christ for everything, in times when I was frustrated, I always knew where to run to, ndiyabulela Bawo for the provision.

I would firstly like to express my sincere gratitude to my supervisors; Dr M. Grenfell and Dr S. Grenfell, y'all are couple goals, when I grow up I wanna be like yous. To Dr M. Grenfell you don't say much Doc but you do much, thank you for tirelessly helping in every way in the making of this thesis. I cannot thank you enough for the tremendous guidance and support you have given throughout this research. Your efficiency is to be applauded. It is my prayer that you never grow tired of doing such good work. May God bless you! To Dr S. Grenfell thank you for being you, for always being a mother to me whenever I needed you. Thank you for your guidance and insightful inputs.

To my team mates Keaton and Curtis, oh man, it was wonderful working with you guys. I have had the best time of my life laughing at your silly jokes. You both have such humble gentle spirits. Thank you for always helping me and being a gentleman to the rose (me) among the thorns (you guys). I truly appreciate you guys, thank you for all those deep conversations we had.

I would like to thank the whole team of the non-perennial rivers project, both for funding and support.

Thank you to all my family and everyone who cheered me on. I would like to thank my church pastor and congregants, thank you bazalwane for your prayers.

Lastly but not least I would like to take this time and thank my handsome husband Mthunzi Yaze, thank you sthandwa sam for your prayers, love, support... and for literally helping me on this thesis. I love you!

To my sister:

I would like to dedicate this thesis to my sister Babalwa Mandilakhe Makhonco Mbali who has always made sure that I am well taken care of in every way. Thank you mntaka Mama, may God bless you in accordance to His will for your life. You are a blessing indeed to me. I cannot thank God enough for you. Thank you for allowing God to use you.

Abbreviations

DWA:	Department of Water Affairs
DWAF:	Department of Water Affairs and Forestry
Gouritz WMA:	Gouritz Water Management Area
MAP:	Mean Annual Precipitation
MAPE:	Mean Annual Potential Evaporation
MAT:	Mean Annual Temperature
N-PRs:	Non-perennial River Systems
PES:	Present Ecological State
SA:	South Africa
MFL	Maximum Flood Level
AHG	Average Ground Height occupied by Reeds
ASH	Average Stem Height +AHG

Table of contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1 Background to research

There has been a growing interest in the role of interactions between vegetation and geomorphology in shaping fluvial environments, from evolutionary to modern-process timescales. However, much of this work has mainly been done in perennial systems (e.g. Corenblit *et al*., 2016; Gibling and Davies, 2012; Gran *et al*., 2015; Surian *et al*., 2015). These interactions have also been to some degree highlighted in dryland rivers (e.g. Grenfell *et al*., 2014; Kotschy *et al* 2008; Tooth and McCarthy, 2007; Tooth *et al*., 2014; Tooth, 2018). One of the key ways in which vegetation and geomorphology interact is through the interplay between channel competence and capacity (Corenblit *et al*., 2016). This interplay can be exemplified by reed bed wetland environments. For example, when a dense stand of reeds is established within a channel, roughness and sediment trapping efficiency are greatly increased, and this can result in flow diversion, and channel abandonment and infilling (Tooth *et al*., 2014).

Many non-perennial rivers alternate between reaches of open channel form and reaches with either broad-spanning or confined in-channel reed beds (Tooth and McCarthy, 2007), often found concentrated in floodouts (Tooth and McCarthy, 2007). Floodouts are unchanneled alluvial surfaces where channelized flow and bedload transport terminate (Tooth, 2000). Floodouts serve as seed banks for the establishment of reeds (Tooth *et al*., 2014). Often the establishment of a stand reeds within a channel initiate and maintain floodout development (Tooth *et al*., 2014). Floodout characterise many non-perennial rivers. Although reeds play an important role in floodplain wetland dynamics (Tooth, 2000), the hydrogeomorphic controls on the distribution and dynamics of reed beds in different physiographic settings are poorly understood. This hampers the ability to manage these habitats and the many ecosystem services that they provide.

Phragmites australis (*P. australis*) is an example of a reed that can be found occupying floodplain wetland environments. *Phragmites australis* is found in a variety of environments ranging from aquatic and semi-aquatic. The reed has often been termed an “ecosystem engineer” (Jones *et al*., 1994). In South Africa, *P. australis* plays a significant role in areas where rainfall is highly variable and pasture often difficult, these reeds offer a source of relatively dependable grazing. *P. australis* also provides several vital ecosystem services (Kotze *et al*., 2009), such as water quality improvement; habitats and food supply for a number of animals. The extensive rhizomes and deep root networks that *P. australis* possess enables it to efficiently trap sediment and provide cohesion for surface sediments thus allowing for bank stabilization. This reed is also important for flood attenuation during large flood events (Frankenberg, 1997; Haslam, 1972; Köbbing *et al*., 2013; Kotze *et al*., 2009; Mal and Narine, 2004). The reed *P. australis* also has several human uses these include hatching, medical uses; craft work and paper produce (Gibbs *et al*., 1990). However, due to the reed's vigorous rapid growth, several methods have been suggested to try and manage its growth (e.g. Baldwin *et al*., 2010; Engloner, 2009; Meyerson *et al*., 2009). Thus the studies that have been done on *P. australis* fall mainly into two broad categories: water quality and anthropogenic flow disturbances (e.g. Adam and Bate, 1999; Burdick *et al*., 2001; Chambers *et al*., 1998; Meyerson *et al*., 2009; Phillip and Field, 2005; Robertson and James 2007) in perennial systems. The few studies done in non-perennial rivers have mainly examined the functional traits of reed beds (e.g. James *et al*., 2001).

Non-perennial river systems (N-PRs) are characterised by rare but extreme flood events that reset the geomorphological template (Heritage *et al*., 2004). This increase in flow variability acts against reed expansion, both by removing reeds during high flows and by reducing regeneration during low flows (Kotschy *et al*., 2000). As such extreme flow variability in N-PRs creates conditions that seem challenging for plant growth. However, these reeds are still able to cope with this flow variability. Kotschy and Rogers (2008) found that the reeds (*Phragmites mauritianus)* traps sediments including fine clay particles in rhizomes resulting in reed bed persistence. The continual accumulation of sediments caused by the plants also results in further vegetation establishment and bar formations and consequently change in the channel morphology (Corenblit *et al*., 2016)

The central hypothesis of this study is that, the persistence of reed beds, in particular the common reed *P. australis* in N-PRs is largely controlled by sediment accumulation within the reed beds. Fine particles such as silt and clay enhance the persistence of reed patches by complexing with organic matter. Through this, moisture and nutrients are retained, and the cohesion of the sediment is improved. This therefore enhances the resistance of reeds to being removed by floods (Edmaier *et al*., 2014; Kotschy *et al*., 2008). The build-up of this sediment also affects channel morphology and the spatial distribution of reeds, as reeds lacking fine sediment are easily removed (Kotschy *et al*., 2008). The following aim and objectives have been identified:

1.2 Aim and objectives:

Aim:

To understand hydrogeomorphic controls on reed bed persistence in non-perennial River systems.

Objectives:

1. To characterize the valley physiographic setting, distribution, substrate characteristics and hydraulic roughness characteristics of reed beds in selected reaches with contrasting fluvial styles.

2. To document changes in the distribution of reed beds in the study reaches over time as a measure of reed bed persistence, paying particular attention a large flood event.

3. To investigate relationships between valley physiography, substrate characteristics, and hydraulic roughness and persistence in the study reaches.

4. To develop a conceptual model of the hydrogeomorphic controls on reed bed persistence in non-perennial river systems.

1.3. Structure of thesis

Chapter 1 highlights the importance of understanding interactions between vegetation and geomorphology in non-perennial rivers. Attention is given to the importance of reed beds. The aim and objectives are then identified within the same chapter. In Chapter 2, a background into non-perennial rivers is given. An in-depth review of studies on interaction between vegetation and geomorphology in both drylands and humid temperate regions is done, research gaps pertaining to dryland rivers are identified. Chapter 3 describes the equipment and methods that were used to collect and analyse the data. Chapter 4 presents the results and short description of the results. Lastly, the general discussion, conclusions and recommendations of the study are described in Chapter 5.

Chapter 2: Literature review

2.1 Introduction

The previous chapter offered an overview on the importance of reed beds in Non-Perennial River Systems (N-PRs). This chapter offers a review of literature that deals with both international and national literature on dryland rivers, mainly focussing on geomorphology-vegetation interactions and the field of biogeomorphology, which looks holistically at these interactions. All of this is viewed through the lens of dryland rivers and how these interactions differ from those that occur in perennial rivers. Please note that the term dryland river is used interchangeably with non-perennial river.

Rivers are an important resource of water for both humans and the ecological environment. Rivers consist of natural flows which are the flows that rivers naturally have without disturbance by human activities such as dams (Poff *et al*., 1997). Natural flows consist of low, medium and high flow regimes (Poff *et al*., 1997). The natural flow regime of a river is governed by five components; magnitude, frequency, duration, timing, and rate of change and is often intrinsically variable (Poff *et al*., 1997). This variability is critical to ecosystem function and native biodiversity. Non-perennial river systems are highly variable and are characterised by flow cessation and drying which can be caused by several processes such as transmission loss, evapotranspiration, downward shifts in groundwater tables, hillslope runoff recession, and freeze-up (Larned *et al*., 2010). The lack of flow in the rivers often results in hydrological disconnections which in turn cause aquatic habitat patches. These disconnections however cease when flooding occurs (Larned *et al*., 2010). It is this flow variability that distinguishes N-PRs and the geomorphology-vegetation interactions that take place in these systems.

2.2 Non-perennial rivers

River systems can be broadly classified into two types; perennial rivers which flow throughout the year and non-perennial rivers, which are rivers that do not flow all year round (Rossouw *et al*., 2005; Skoulikidis *et al*., 2017). N-PRs remain poorly understood because a large amount of research has been focused on perennial rivers. Globally, non-perennial rivers constitute more than 50% of the total river network (Datry *et al*., 2014) and constitute 70% of South African rivers (Rossouw *et al*., 2005). Previous studies have suggested that the number of N-PRs would increase as a result of the conversion of perennial rivers to N-PRs due to climate change, land use alteration and water abstraction (Larned e*t al*., 2010).

Despite the difference in flow between perennial and non-perennial rivers, methods from temperate humid regions which are designed for perennial systems are still being used to assess all dryland rivers (Seaman *et al*., 2010). This becomes a problem as most dryland rivers do not function as those found in temperate humid regions. N-PRs can be classified according to the most common perceptions as semi-permanent, ephemeral and episodic (Skoulikidis *et al*., 2017). Semi-permanent rivers have no flow for 1%-25% of the time; ephemeral rivers have no flow for 26-75% of the time and episodic rivers usually have no flow at least 76% of the time (Rossouw *et al*., 2005).

In South Africa, N-PRs have a variety of fluvial styles, e.g. braided, single-thread straight, meandering, anabranching/anastomosing and distributary Rivers, and floodouts (Figure 2.2). (Jaeger *et al*., 2017). The geomorphological features of these rivers are spatially discontinuous due to the flow variability in these rivers (e.g. Grenfell *et al*., 2014)). There are four distinct geomorphological zones in N-PRs; upland, piedmont, lowland and floodout (Tooth and Nanson, 2011). Several N-PRs fail to reach coastline and may terminate inland topographic basins on alluvial plains. When this occurs a floodout zone is established (Jaeger *et al*., 2017). Therefore, flow variability has a strong control in producing floodouts as the sediment to discharge ratio increases (Grenfell *et al*., 2014). In floodouts zones flow and sediment characteristics are to a large degree determined by the distance from upland and piedmont sources. Channel sediments are coarse if the distance is small, the opposite is true for large distances (Tooth, 2000).

Floodouts host a considerable number of wetlands in dryland rivers (Tooth *et al*., 2002). Most wetlands in drylands are maintained by river inflows that combine with other factors such as faulting, rock outcrops, swelling soils, and ponding by tributary or aeolian sediments which all serve to inhibit drainage (Tooth and McCarthy, 2007). These factors coupled with variations in sediment supply, vegetation communities, and levels of animal activity, promote a diverse range of wetlands that span a continuum along dryland rivers (Tooth and McCarthy, 2007). Many of these factors have to some degree been studied along these systems. The vegetation communities along these rivers which influence several processes are spatially vast and the dynamics of these vegetation communities in these floodplain wetlands are also important. Reed beds which grow along the corridors of dryland rivers may offer some insight into the dynamics offered by vegetation in floodplain wetlands (Tooth *et al*., 2014).

2.3 The common reed (*Phragmites australis*)

The genus *Phragmites* contains three species, two of which are indigenous to southern Africa; *Phragmites mauritianus* and *Phragmites australis* (James *et al*., 2001). *P. australis* (Cav.) Trin. ex. Steud. (Common reed) is a perennial grass with stems that can reach a height of 4m, the stems vary in diameter from 4 to 10 mm (Haslam, 2009; Meyerson *et al*., 2009). *P. australis* is often found in sandy, clay, loam, brack/saline environments (Gibbs *et al*., 1990). The rhizomes of *P. australis* are perennial and have both horizontal and vertical components. The horizontal rhizomes are responsible for extending the size of the clone, while the vertical rhizome give rise to annual upright stems (Gibbs *et al*., 1990). Roots also develop from these rhizomes and other submerged parts of shoots (Mal and Narine, 2004). The rhizomes can extend 2 m deep down to reach deep water, and they often form dense mats (dense impenetrable monocultures) on the earth's surface and disable other plants from becoming established (Mal and Narine, 2004), the dead stems have also been noted to decompose slowly and increase the risk of fires in wetlands (Chambers *et al*., 1998; Mal and Narine 2004).

P. australis establishes new stands by both seed and rhizome dispersal, while existing stands expand mainly through clonal growth (Mal and Narine, 2004; Meyerson *et al*., 2009). *P. australis* can tolerate high salinity (up to 30 ppt) mainly due to its root and rhizome system that is in fresh or only brackish water (Adam and Bate, 1999). *Phragmites* in high salinity areas tend to be shorter. The reed can survive long periods of inundation (Adams and Bate, 1999). These are some of the adaptions which make *P. australis* an efficient coloniser and a nuisance in many countries (e.g. Ailstork, 2001; Meyerson *et al*., 2009). *P. australis* can produce a huge number of seeds, however, germination rates are variable and low, as such, establishment and expansion mainly occurs through clonal growth from rhizome fragments. The rhizome segments containing axillary buds are often carried away by water after a flood and re-establish elsewhere. Colony expansion occurs primarily by rhizomes in wet organic soils and stolons in sandy soils (Ailstock *et al*., 2001). The seeds normally germinate and establish in spring/ early summer (Rea, 1996), both the seeds and rhizomes can be carried by water and establish in a new location. This, therefore, makes hydrochory an important factor in *P. australis* dispersal in river systems. Rhizomes have several functions including being responsible for the spread of the roots system and production of aerial stems (Haslam 1972). Due to its efficiency to adapt to various environments as a result of its functional traits, *P. australis* has been hailed as an ecosystems engineer (Rea, 1996).

Phragmites australis provides a number of ecosystem services which include regulating and supporting benefits: flood attenuation (the spreading out and slowing down of floodwaters); sediment trapping (the trapping and retention of sediment carried by runoff waters); Erosion control (controlling of erosion, principally through the protection provided by vegetation); toxicant removal (removal by the wetland of toxicants (e.g. metals, biocides and salts) carried by runoff waters. The ecosystems services also include provisioning benefits such as the provision of natural resources i.e. livestock grazing and craft plants (Kotze *et al*., 2009). the reed provides shelter for many bird species and other animals. It also provides a food source to a large number of insects and is associated with many fungi (Gibbs *et al*., 1990).

2.4 Vegetation distribution as a consequence of flow regime

In perennial river systems vegetation tends to be distributed in a sequence of zones from the water's edge to the outer riparian area. These vegetation zones are broadly divided into the wet bank and the dry bank. The banks in all have four zones [marginal, lower dynamic, lower, and upper] that each have distinguished vegetation which has adapted to the disturbance gradients that exists in each area (Reinecke *et al*., 2015). The marginal zone for example, is composed of obligate-wetland species i.e. reeds, these species were noted to share fluvial disturbance traits such as reproducing both sexually and vegetatively, having a flexible habit and an adventitious root system (Reinecke *et al*., 2015). The marginal zone composed of obligate species is inundated for more than half the year by floods smaller than the 1:2 flood (Reinecke *et al*., 2015). The development of this species distribution in perennial rivers is highly affected by the natural flow regime of a river (Nilsson and Svedmark, 2002; Poff *et al*., 1997).

Although vegetation is generally sparse in semi-arid environments, many dryland rivers do support dense stands of riparian vegetation (Powell, 2009; Tooth, 2000). The distribution and abundance of vegetation is usually largely controlled by the availability of water, with many species only found within or close to river channels (Tooth and Nanson 2000). *Phragmites* are found to occur in a patchy distribution along dryland rivers (Kotschy and Rogers, 2008). These reed beds can also form discrete, longitudinally discontinuous patches along the river (James *et al*., 2001). Flooding is a major driver of reed patch dynamics in semi-arid rivers (Kotschy and Rogers, 2008). Erskine *et al*. (2009) found that different riparian species have different tolerances and growth responses to flood disturbances. The hydraulic stability, associated with the magnitude and frequency of flood flows can tell whether a river channel is dominated by macrophytes, bryophytes or periphyton (Biggs, 1996). Aquatic macrophyte for example are highly sensitive to hydrological changes and mirror spatial gradients in unit stream power and substrate calibre, as well as climate (Gurnell *et al*., 2010). This association with hydrological and sedimentary conditions helped to explain assemblages of aquatic macrophyte species, which in turn have been shown to correspond to variations in slope, channel width and depth, substrate calibre, flow types and rock type (Holmes *et al*., 1998).

Cheng *et al*. (2007) investigated the relationship between floods and dispersal and sprouting of seeds of Salicaceae species (*S. alba*; *P. canescens*; *P. jrtyschensis*, *P. laurifolia*, and *P. nigra*), and found that the ripening and dispersal periods of Salicaceae species seeds overlap largely with flood occurrence periods, and the sprouting and natural regeneration of seeds depend greatly on flood events and that floods supply soil water and increase groundwater level of riparian land through flood irrigation and horizontal infiltration to maintain the normal growth of the riparian forests. Floods therefore have great influence on the formation, succession, and distribution of riparian vegetation especially in arid and semi-arid areas.

Oliveira *et al*. (2015) had similar findings when looking at a variety of grass species in the Pantanal wetlands in Brazil and noted that greater species richness existed in flood prone zones and that flooding plays a crucial role in seasonal vegetation dynamics. Surian *et al*. (2015) also found that in a braided channel the erosion of riparian vegetation is not always controlled by the magnitude of flow but by the flood frequency. Recent work by Zhang *et al*. (2018) also showed that during flooding the biomass and photosynthesis of offspring shoots, rhizome length, and the number of buds, rhizomes and offspring shoots of *Phragmites australis* are significantly greater than those in the drought period.

Many drylands rivers are characterised by high gradients because they flow down steep pediments. As such the magnitudes of infrequent flood events in dryland rivers are often much greater than those found in rivers draining humid-temperate catchments of similar size (Costa, 1987).Thus vegetation establishment in semi-arid rivers is often hindered by the increased changes in the geomorphological template, as the high flows rework unconsolidated sediment and reduce the substrate stability required for vegetation establishment (Rountree *et al*., 2000). As such, floods have been found to reduce vegetation persistence by damaging stems and rhizomes through burial by sediment and physical damage by the flow near the patch edge where rhizomes are shallow and stems are short (Kotschy and Rogers, 2008). *Phragmites* seedlings have also been noted to rarely grow under inundated areas and that colonisation occurs through vegetative clonal expansion during inundation (Baldwin *et al*., 2010; Weisner *et al*., 1993). During drought years lower flows allow the sediment to stabilise and vegetation to establish (Rountree *et al*., 2000). Once colonisation has occurred in order to minimize the damaging effect of floods, essentially two strategies are adopted by aquatic plants to avoid uprooting; avoidance (e.g. minimization of drag and frontal area through bending in the direction of flow) and tolerance (maximisation of the resistance to breakage by strengthening tissues) (Puijalon *et al*., 2011), the former is often the dominant mechanism in *P. australis*.

2.5 Plants as ecosystem engineers

There has been an extensive literature that has solemnly focused on the role of vegetation in influencing river hydrology and geomorphology in humid temperate regions with a few in dryland regions. These studies have been placed under the umbrella of biogeomorphology. Biogeomorphology is a multidisciplinary field of work that looks holistically at the interactions and feedbacks between organisms and the physical earth (Coombes, 2016). These organisms can either be plants or animals. Various authors such as Corenblit *et al*. (2009) and Gurnell *et al*. (2012) have offered reviews in this field of work, specifically looking at the effects of plants on the physical landscape. And others have looked at a combination of plants and animals as ecosystem engineers (e.g. Harvey *et al*., 2014). This therefore offers a basis into how geomorphology-vegetation interactions might also play out in dryland rivers.

According to Jones *et al*. (1994, p 374), "*Ecosystem engineers are organisms that directly or indirectly modulate the availability of resources (other than themselves) to other species, by causing physical state changes in biotic and abiotic materials. In so doing they modify, maintain and/ or create habitats*". Gurnell *et al*. (2012) used the term "ecosystem engineers" to describe certain riparian and aquatic plants which trap and stabilize sediments, organic matter and the propagules of other plant species. By trapping and stabilizing these sediments the plants modify the local sedimentary and morphological environment, leading to the development of landforms and associated habitats. This facilitating the rapid establishment of other plants that can in turn reinforce the development of landforms.

Reed beds in semi-arid regions have also been described as ecosystems engineers (e.g. Kotschy and Rogers, 2008; Rea, 1996). This term was used mainly because reed beds stabilise alluvial bars and control the geomorphic change in semi-arid rivers characterised by extreme flood and drought events. Corenblit *et al*. (2016) found that landforms colonised and stabilised by vegetation, resulted in increased sediment trapping. These findings are similar to those of Surian *et al*. (2015) who noted that erosion of marginal vegetation which supplies wood to the channel increased in-channel vegetation establishment. Gran *et al*. (2015) concluded that vegetation in braided rivers has an important effect on channel dynamics as it traps sediments, closing off weaker braids and resulting in the emergence of one or two dominant channels. These authors had similar views to those of Gurnell *et al*. (2012) who looked at both riparian and aquatic plants and found that the effect of vegetation on channel dynamics depends both on the energy of the system and the strength of the vegetation.

Hydraulic roughness of vegetation can be defined as the effect vegetation has on flow which leads to sediment deposition (Baptist *et al*., 2007). Riparian and aquatic vegetation increase flow resistance and decrease flow velocity and the shear stress available for erosion (Thornes, 1990). Hydraulic resistance/ roughness is dependent on properties of vegetation, such as areal density, flexibility, patchiness, age, seasonality, and foliage (Albayrak *et al*., 2012; Busari and Li, 2016) Hydraulic resistance due to patchy vegetation leads to sediment deposition upstream of the vegetation (van Dijk *et al*., 2013). The Manning, Chézy and Darcy–Weisbach equations have been widely used in order to investigate the hydraulic roughness caused by vegetation (James *et al*., 2001).

Tooth and Nanson (2000) found that small in-channel shrubs (teatree) in association with alluvial sedimentation highly influenced the formation and maintenance of anabranching in an ephemeral river, firstly by forming ridges which grow in size and interact with other ridges (Figure 2.1). As the ridges lengthen further, they coalesce with downstream ridges to form narrow, elongate, stable features that subdivide the channel-train into anabranches. Parker (1976) also noted that dryland sediments are not generally rich in cohesive silts and clays and unless riparian vegetation is sufficient to stabilise the channel banks and discourage the formation of new channels, channel widening will promote the development of a braided channel pattern through the instability of sediment transport in wide channels. Vegetation in semi-arid environments thus plays an important role in narrowing channels after they have been widened by major flood events (Powell, 2009).

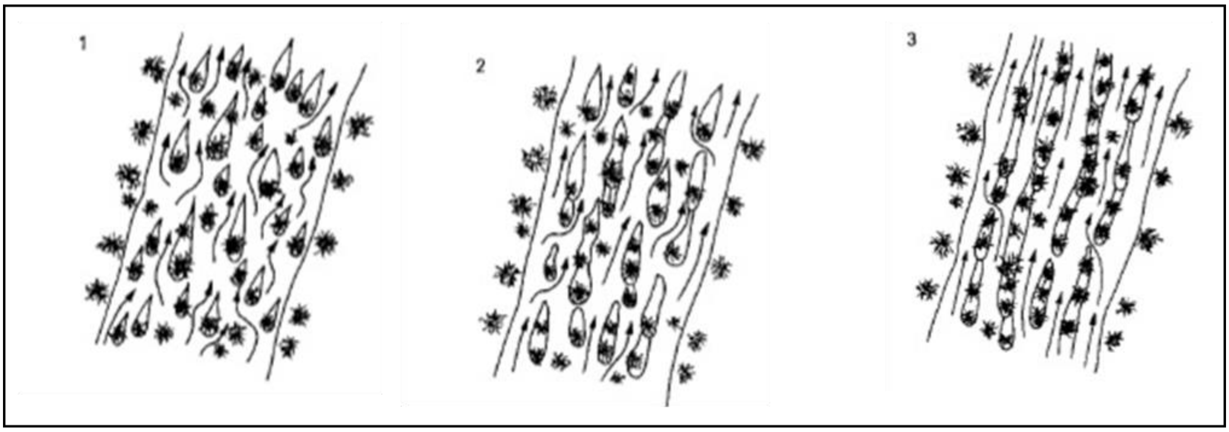


Figure 2. 1: Schematic diagram illustrating how the growth of vegetation can lead to the formation of anabranching river in dryland rivers. (Source: Tooth and Nanson, 2000).

The work of Gibling and Davies (2012) has been pivotal in showing the importance of the relationship between vegetation and geomorphology in the co-evolution of fluvial styles and vegetation through geological time scales. It was found that the appearance of roots in early plants contributed to sediment stabilisation and might have driven Palaeozoic river evolution from braided to meandering and to anabranching planforms .This observation was found to be true for shorter time scales in dryland rivers by Graf (1978), in which the introduction of Tamarisk in the United States resulted in channel narrowing, floodplain renewal and the conversion of multi-thread rivers to straight single channel forms.

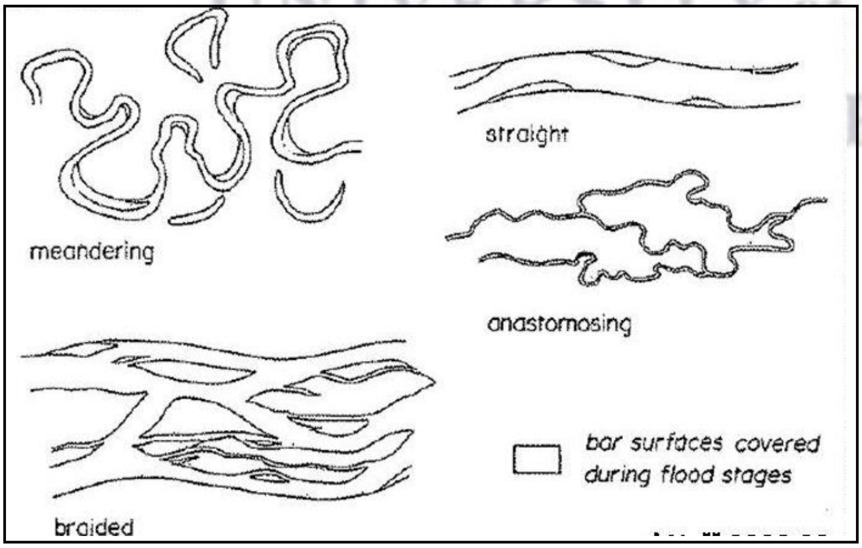


Figure 2. 2: The four basic fluvial channel styles (Source: Miall, 1978)

The interaction between sediment and vegetation is highly influenced by hydraulic conditions which in turn are influenced by the presence of vegetation (James *et al*., 2001). As such one cannot be examined without the other, vegetation being the common factor that influences both sediment process and hydraulic conditions. Brooks and Brierley (2002) noted that in low energy systems, vegetation strongly controls channel morphology, causing the formation of specific fluvial landforms and trapping fine sediments, while in high energy systems the role of vegetation is more limited. The natural flow of a river varies on time scales of hours, days, seasons, years, and longer (Poff *et al*., 2007). River flow regimes show regional patterns that are determined largely by river size, geographic variation in climate, geology, topography, and vegetative cover (Poff *et al*., 2007).

Summary

Although rivers in dryland regions have not received as much attention as those in humid temperate regions, several authors have done a tremendous amount of work in highlighting the ecological importance of these river systems, a large amount of this work has mainly been in South Africa and Australia (see Tooth and McCarthy, 2007). The flow variability in N-PRs is what sets them apart. The interaction between this flow variability, geomorphology and vegetation is what drives the fluvial styles found along these rivers. Vegetation found along N-PRs has adapted to the flow variability provided by these systems, and one such example is the common reed (*Phragmites australis*). The establishment of vegetation along the channels of rivers has various implications. One such example, as highlighted in the review is the change in river channels. The mid-channel bars formed by sediment accumulating either due to vegetation roughness or by a flood as it loses its energy, can lead to braided channels as flow is divided. Various fluvial styles are created due to the establishment of vegetation in and around river channels. However, vegetation is not the only factor affecting change in channel morphology, large flood events also impact the type of channels found along rivers by resetting the geomorphological settings and removing everything within the channel. This therefore highlights the importance of vegetation in channel morphdynamics and the important role played by major flood events.

Chapter 3: Methods

3.1Background to study area

The study area forms part of the Breede-Gouritz Water Management Area (WMA). The area is as a result of the amalgamation of two WMA; the Breede WMA and the Gouritz WMA. These are respectively drained by the Breede and Gouritz Rivers, both rivers discharge into the Indian Ocean. The Gouritz River has three main tributaries, the Groot, Gamka and Olifants Rivers. There are also a number of other smaller rivers in the Gouritz WMA, i.e. Touws, Duivenhoks, Goukou, Hartenbos, Great Brak, Kaaimans, Knysna and Keurbooms (BGCMA annual report, 2016). The Touws River tributary rises in the Matroosberg Mountains and flows east and then south into the Little Karoo, where it joins the Buffels River into the Groot River which confluence with the Gouritz River. The area drained by the Touws/Buffels/Groot area is approximately 13 313 km^2 (River health program, 2007).

The study sites are mainly located in the area drained by the Touws River (herein Touws River Catchment) and its tributaries (Figure 3.1). The Prins River which forms part of the study area, is a tributary of the Touws River and has a number of transverse mountains and joins the Touws River at -33 34.493802 S & 20 51.212508 E (Figure 3.1). Three dams used for irrigation and farming (i.e. the Verkeerdevlei, Prins and Belair dams) can be found in this catchment. The majority of the stored water in this catchment is used for irrigation (DWS, 2014). The catchment has an estimated 98 km^2 (9800 ha) of irrigated land within the total of 13 313 km^2, and of this, it is estimated that an average of only 38 km^2 (3800 ha) is harvested annually. Crops such as Lucerne can lie dormant in certain years when water is not available, as such, much of the irrigation is opportunistic, taking place when water is available (DWARF, 2004).

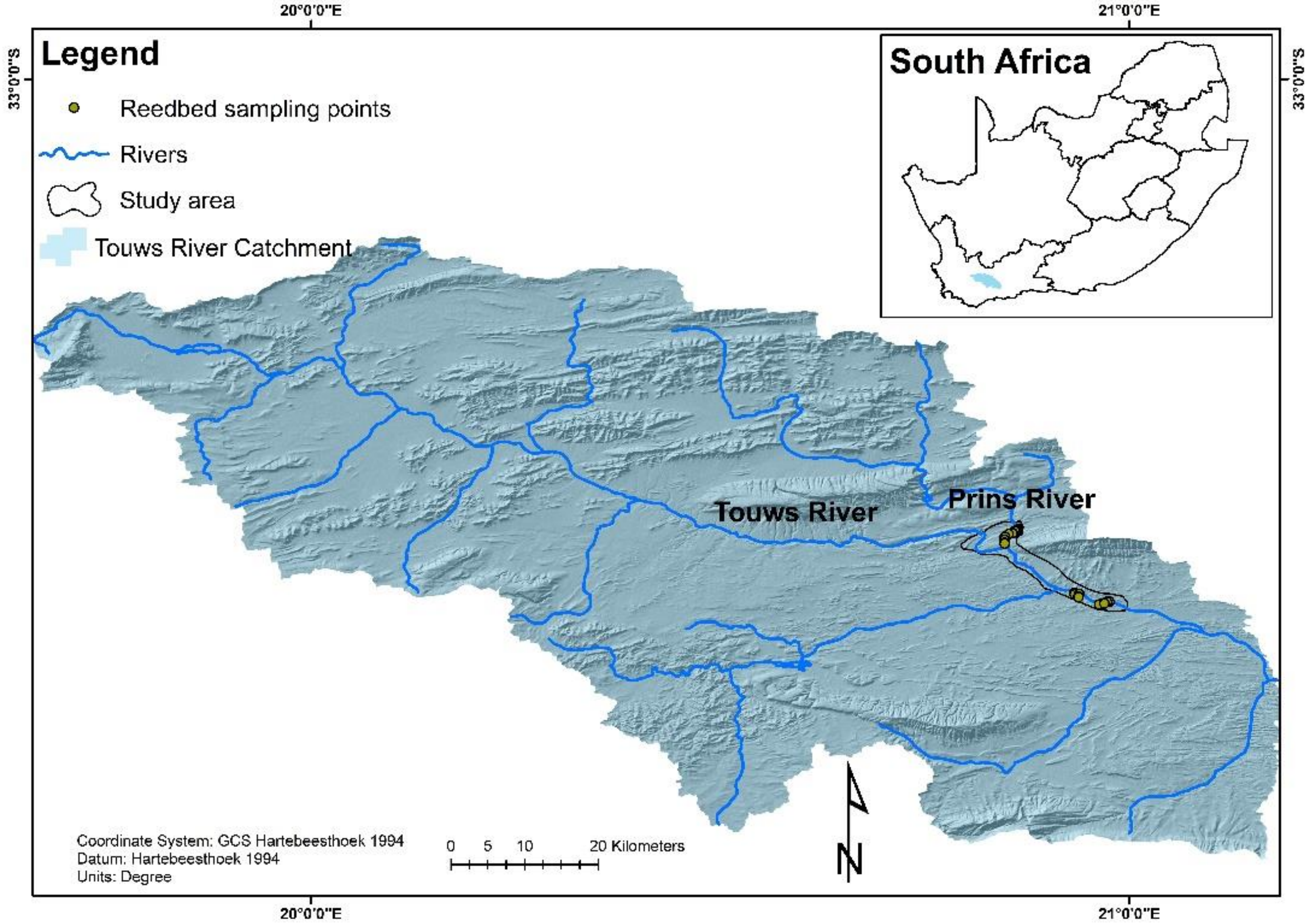


Figure 3.1: Location of the study area within the Touws River catchment.

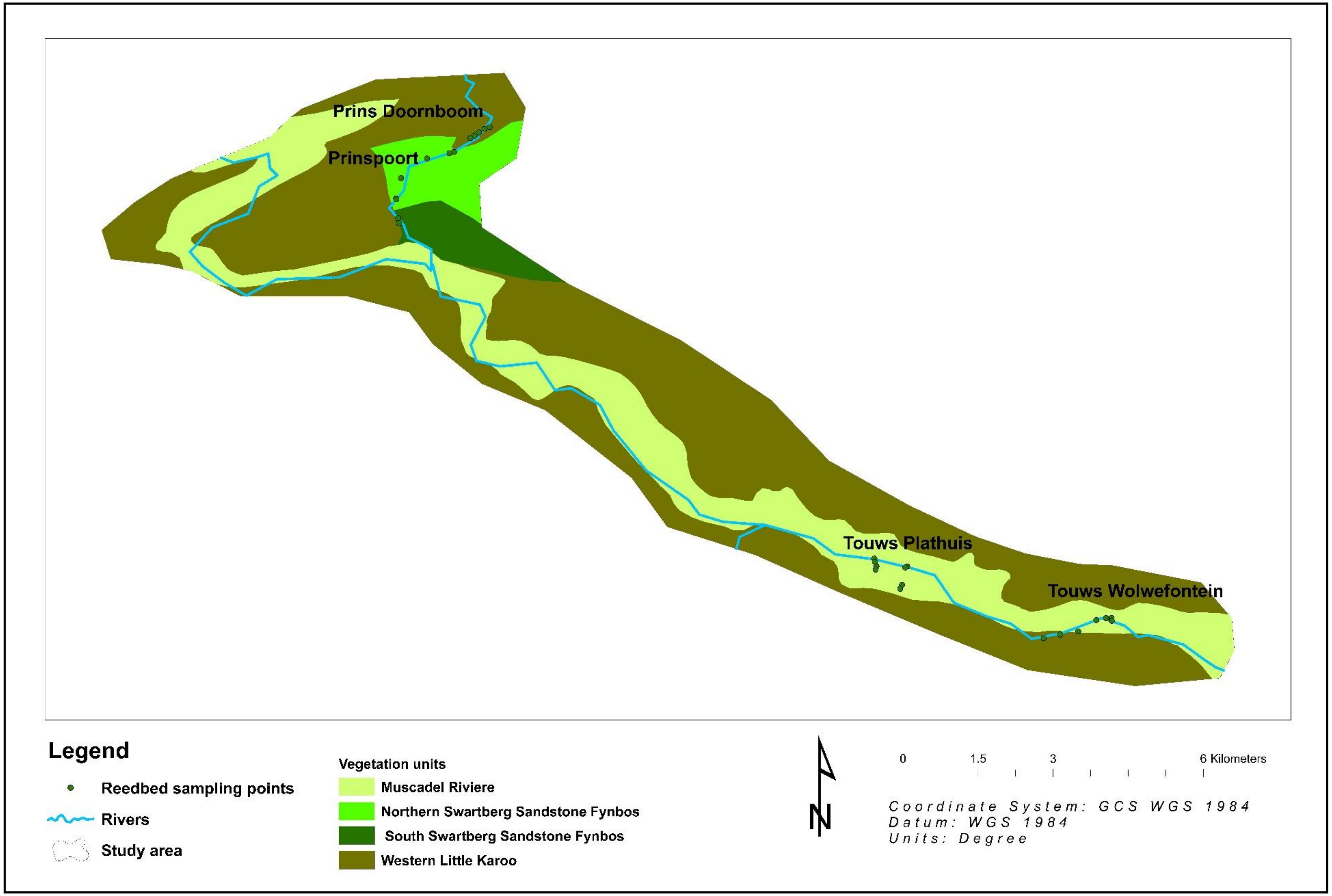


Figure 3.2: Location of the study reaches (Prins Doornboom, Prinspoort, Touws Plathuis and Touws Wolweontein) underlain by vegetation of the study area. Data source: Mucina and Rutheford,2006

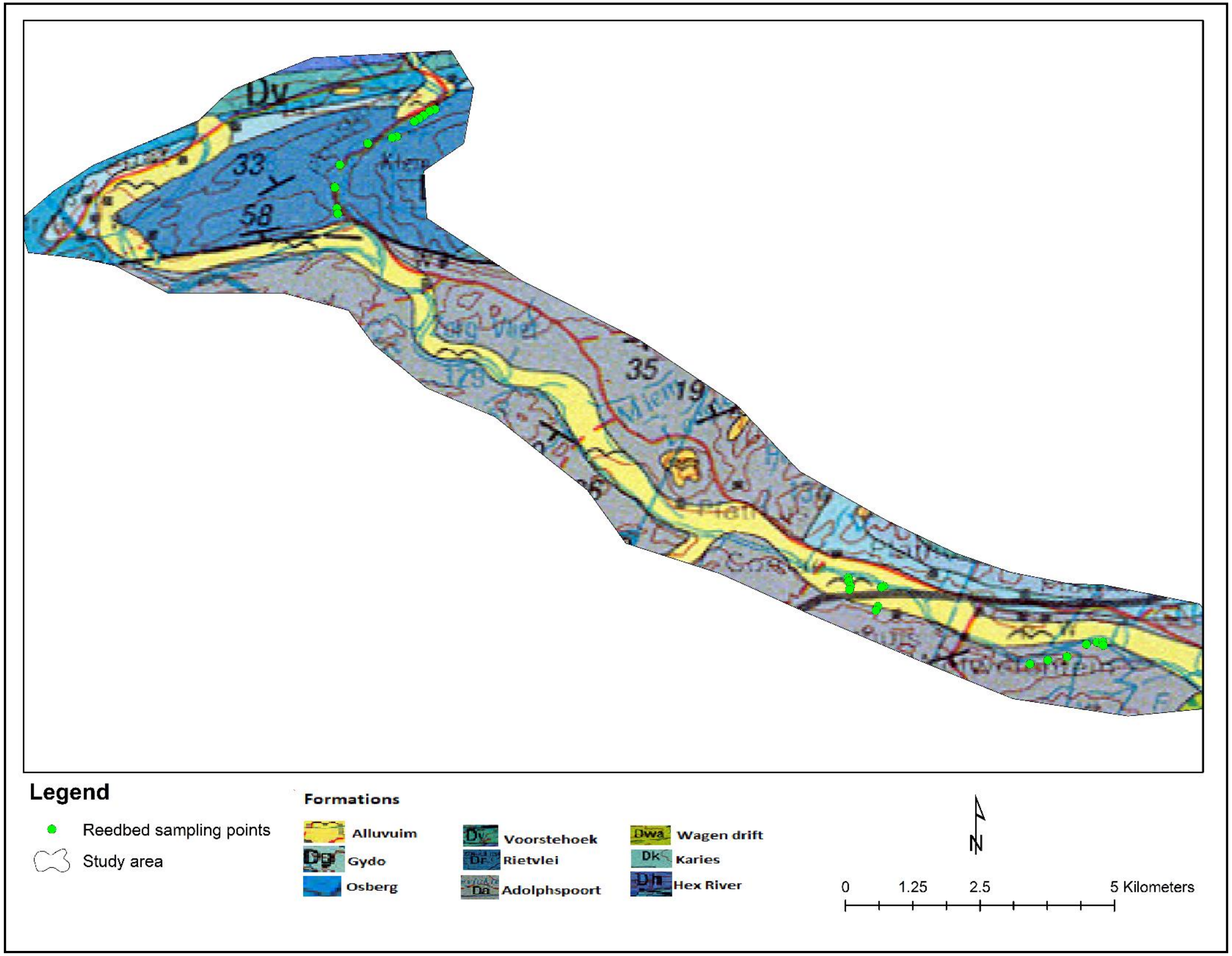


Figure 3. 3: The main rock units in the study area. Modified from Council for Geoscience 1:250 000 geology map (3320 Ladismith)

The study area is divided into four reaches with different fluvial styles. The reaches in the Prins River (Prins Doornboom and Prinspoort) are mainly single thread. The reaches along the Touws River (Touws Plathuis and Touws Wolwefontein) are mainly multithread. In the sites were the Prins Doornboom and Prinspoort reaches are located the North Swartberg Sanstone Fynbos vegetation unit is dominant, occurring at altitudes between 700-1800 m. The endemic vegetation in this unit includes low shrubs such as: *Acmademia fruticose* and *Aspalathus lamarckiana*, succulent shrub such as: *Lampranthus pocockiae*, succulent herbs such as: *Haworthia* (Mucina and Rutherford, 2006). This vegetation unit is categorised as least threatened. The alien plants found here include *Pinus pinaster* and *P. radiate* and the erosion in this area is notably low (Mucina and Rutherford, 2006). The South Swartberg Sandstone Fynbos can also be found towards the Prinspoort reach, occurring at altitudes lower than 550 m. The vegetation is medium tall shrubland and heathland. Proteoid and restioid Fynbos dominate, with ericaceous Fynbos at higher altitudes and shrub Fynbos at lower altitudes. Endemic vegetation includes the tall tree: *Protea nitida*, and the succulent tree: *Aloe ferox*, the tall shrubs *Aspalathus hystrix* (Mucina and Rutherford, 2006). The vegetation is categorised as least threatened with low to moderate erosion. (Mucina and Rutherford, 2006) (Figure 3.2).

The Prins Doornboom and Prinspoort reaches alternate between sandstones, shale and siltstone beds of the Cape Supergroup i.e. the Hex River Formation composed of light-grey protosandstone, feldspathic; thin siltstone beds. The Rietvlei Formation composed of light-grey feldspathic sandstone, siltstone and micaceous shale beds. The Voorstehoek Formation is composed of grey shale, siltstone and mudstone fossiliferous; thin sandstone beds. The Gydo Formation composed of black to dark-grey shale, siltstone, and sandstone and fossiliferous. The Osberg Formation containing quartzitic sandstones, light grey, fleldspathic and micaceous. The current riverbed alluvium in both the Prins and Touws River channels is a mixture of cobble, gravel, sand and finer material (Figure 3.3).

The Touws Wolwefontein and Plathuis reaches are mainly composed of the Succulent Karoo and Azonal group (Mucina and Rutherford, 2006) (Figure 3.2). The vegetation consists of a number of small trees e.g. *Pappea capensis* and is dominated by Succulent shrubs with some endemic species such as *Cotyledon tomentosa* subsp. *Ladismithiensis*, *Crassula atropurpurea var. muirii* (see Mucina and Rutherford, 2006). This vegetation unit is categorised as least threatened. Alien vegetation e.g. *Acacia Cyclops* and *A. saligna* pose a threat to the local vegetation and invasive *Atriplex lindleyi* subsp. Inflate is a serious local problem for grazing. Erosion is categorised as high at 54% (Mucina and Rutherford, 2006). In general, the Mean Annual Precipitation (MAP) the study area is 321 mm with a Mean Annual Potential Evaporation (MAPE) is 2180 mm and a Mean Annual Temperature (MAT) of 16 °C (Mucina and Rutherford, 2006). Azonal vegetation which is divided into Muscadel Riviere and (non-wetland) and wetlands type (Mucina and Rutherford, 2006). The latter which was established in all the study reaches is found along the river valley floors (in pools or longer stretches of concave channel) and experiences waterlogging (seasonal or permanent) and flooding (regular, irregular or catastrophic), leading to formation of wetland soil forms. The vegetation unit is mainly composed of extensive tall reeds of *Phragmites australis* and sedgelands in the study area. The Touws Plathuis and Touws Wolwefontein reaches are mainly made up of the Adolphspoort Formation composed of siltstone, shale and argillaceous sandstone. The Karies Formation composed of dark grey shale forms a section of Touws Plathuis reach (Figure 3.3)

3.2 Data collection and analysis methods

A combination of fieldwork and desktop research approaches were used for this study. In order to identify the study reaches and establish the spatial distribution of reeds along the rivers, WorldView-2 imagery (0.5 m resolution) was used to map the valley width and current distribution of reeds along the rivers, with the aid of verification observations recorded during fieldwork. Longitudinal profiles for both rivers were drawn from 5 m SuDEM data (e.g. Grenfell *et al*., 2014). The SuDEM was also used to determine variation in valley width and to perform the Topographic Wetness Index (TWI), using the TauDEM tool in ArcGIS (10.6) to show the potential for water accumulation. TWI is calculated by evaluating the flow direction, flow accumulation, slope, and various geometric functions derived using ArcGIS software. The output is a raster layer that depicts areas with drainage depressions where water is likely to accumulate. The formula used for calculating TWI at a point is: $I=\ln (a/\tan\beta)$, where I is the index value, a is the upslope contributing area and β is the topographic gradient (Ballerine, 2017; Hojati and Mokarram, 2016). A georeferenced geology map for the study area was captured from the Council for Geoscience 1:250 000 geology map (3320 Ladismith), and digitised lithology and valley width variation were superimposed on the longitudinal profile to aid description of the physiographic setting of the study reaches.

Topographic field surveys, using a Stonex S10 Differential Global Positioning System (dGPS) (~10 mm accuracy), were conducted to construct more detailed valley floor profiles and longitudinal profiles of the valley in each reach (Grenfell *et al*., 2009). Using the WorldView-2 imagery taken a couple of days before the fieldwork work was conducted, the area occupied by the reed beds was then plotted onto each cross section. This was done in order to have an understanding of the relationship between valley physiographic settings and reed distribution.

To gain an understanding of the variation in substrate characterises within the reed beds, field work was conducted and substrate characteristics (using Wolman pebble count for material greater than 2 mm, sampling, and sieving for material finer than 2 mm) were collected on the surface at the sampling points. Particle size distribution (% clay, silt and sand) were determined by the pipette method (Briggs, 1997). D50s of samples comprising N50% sand, as well as the sandy/gravely layer samples were determined by dry sieving in a vibrating sieve stack (e.g. Grenfell *et al*., 2009). D50 values were interpreted (e.g. as fine sand or coarse gravel) using the Udden–Wentworth scale and associated nomenclature (Gordon *et al*., 2004).

The reed stem thickness (diameter of each stem), stem height and stem density (number of stems per unit area) were collected at a 1 m^2 quadrat for each reed bed that was located in an area considered representative of the reed bed as a whole – it was necessary to simplify sampling effort in this way, as the vast number of stems (stem density) in some reed beds meant that stem counts and measurements of height and diameter were very time consuming, and a dataset of several reed bed locations was desired. These data were analysed and fed directly into the mathematical roughness formulae that were used to objectively compare different stands of reeds based on the Chézy value (which is indirectly proportional to the hydraulic roughness) using the approach of Baptist *et al*. (2007).

Figure 3. 1: Collection of reed characteristics data

In order to observe whether the reed beds located in the cross section would be non-submerged or submerged, the maximum flood level (MFL) on each cross section was identified. This was done by observing the point at which the river would overflow its banks from the cross sections constructed from dGPS. To find out the average height of the reed beds on the ground the following was done, using dGPS points which were surveyed in the reed bed area, an average was assumed to be the ground height occupied by reed beds (AHG). Then stem height measurements made in the field in the same reed bed area (in 1m^2 quadrant) were averaged (ASH) and added to the averaged ground height. This was done for each cross section. The following equations were then used to identify if reeds would be non-submerged or submerged:

(MFL)- (AHG+ASH) = non-submerged/submerged vegetation

Therefore: MFL> (AHG+ASH) = submerged reeds

MFL< (AHG+ASH) = non-submerged

These equations were used in the calculation of the Chézy value to determine whether the vegetation is non-submerged or submerged at maximum flood level when the potential for geomorphological work would be greatest.

According to the Chézy formula, the depth-averaged flow velocity (ū) in a channel is influenced by the interaction between river energy – given by the depth (h), and the water surface slope (S) – and resistance given by the hydraulic roughness of the bed and banks, parameterised by the Chézy roughness coefficient (C):

1. $$\bar{u} = C\sqrt{hS}$$

If the Chézy roughness coefficient is known or can be estimated, then it is possible to predict depth-averaged flow velocity from channel hydraulic parameters that can be measured through field survey.

For vegetated surfaces, the Chézy value (C_b) can be estimated from a friction factor (*f*) related to the D_{84} bed particle size (determined by Wolman pebble count), using the two equations below:

2. $$\sqrt{\frac{8}{f}} = 5.75\log_{10}\left(\frac{h}{D_{84}}\right) + 3.514$$

3. $$C_b = \sqrt{\frac{8g}{f}}$$

Where;

h is the water depth (m)

g is acceleration due to gravity, 9.81 m/s^2

For surfaces covered by non-submerged, the Chézy value (C_k) can be estimated using physical properties of the vegetation that influence how the stems interact with the flow to cause resistance:

4. $$C_k = \sqrt{\frac{1}{\frac{1}{{C_b}^2} + \frac{C_D m D h}{2g}}}$$

Where;

C_b is the Chézy value of the bed without vegetation cover, based on the D_{84} particle size (equation given above) (assumed to be negligible)

C_D is a bulk drag coefficient (Table 1) m is the number of stems per m^2, measured in the field by counting stems in a 1m plot

D is the average stem diameter in m (for the 1m plot), measured in the field using a pair of calipers

h is the water depth in m

g is acceleration due to gravity, 9.81 m/s^2

Table 3. 1: Bulk drag coefficient values for different vegetation types (adapted from van Velzen *et al*., 2003).

Vegetation Type	C_D
Trees with a spacing of 1 stem per m^2	1
Forest, shrubland, thornscrub	1.5
Grassland, reed/rush/sedge beds	1.8

In cases where the emergent vegetation dominates the surface cover (e.g. dense reed beds), the effect of bed resistance can be removed, and the equation for C_k can be reduced to:

5. $$C_k = \sqrt{\frac{2g}{C_D m D h}}$$

In cases where vegetation is fully submerged the following equation was used:

6. $$C_r = \sqrt{\frac{1}{\left(1/C_b^2\right) + (C_D m D k/2g)}} + \frac{\sqrt{g}}{\kappa} \ln\left(\frac{h}{k}\right)$$

Where;

C_r is the Chézy value for fully submerged vegetation

κ is the Von Kármán's constant $1/\kappa \approx 2.5$

Based on the conditions prevailing at each cross section (submerged versus non-submerged) at MFL, the various Chézy values were calculated. Using linear regression these values were then compared to the sediment sizes and stem characteristics in order to get an understanding of the relationship between these variables. All these values were then related to the where they occurred along the river. The Chézy value gives an indication of the hydraulic roughness offered by the reeds. As such the Chézy is indirectly proportional to hydraulic roughness / resistance of the reeds. The result was put together into a conceptual model showing the hydrogeomophic controls on reed bed persistence (through enhancement of sediment deposition) in non-perennial rivers.

To map the spatial distribution of reed bed area changes before and after the 2014 flood, a combination of georeferenced aerial photography (0.5 m) taken 14 July 2013, obtained from the National Geo-spatial Information (NGI) and SPOT 6 imagery, obtained from the South African National Space Agency (SANSA) (1.5 m) taken 08 July 2014 were used to digitize the area occupied by the reeds at a scale of 1:5000 (Kotschy *et a*l., 2000; Larkin *et al*., 2017)). Google Earth Pro was also used in conjunction with these images to investigate the area covered by reeds. The 2014 flood peaked at 785.377 m^3/s (357.194 m^3/s day-average) and was recorded on 08 January 2014 for the Okkerskraal station (J1H018) in the Touws River (Figure 3.4). This flow rate data was obtained from the Department of Water and Sanitation (DWS). The average rainfall for the month of January 2014 was recorded as 50 mm by Weather SA, at station [0044050 9] – Touws River. WorldView-2 imagery (0.5 m resolution) taken 17 October 2017 was also used to map the current distribution of reed beds along the Touws and Prins River floodplains. 2003 observed the largest flood peak on the DWS flood record data, however suitable imagery were not available for this type of comparison to be done for 2003.

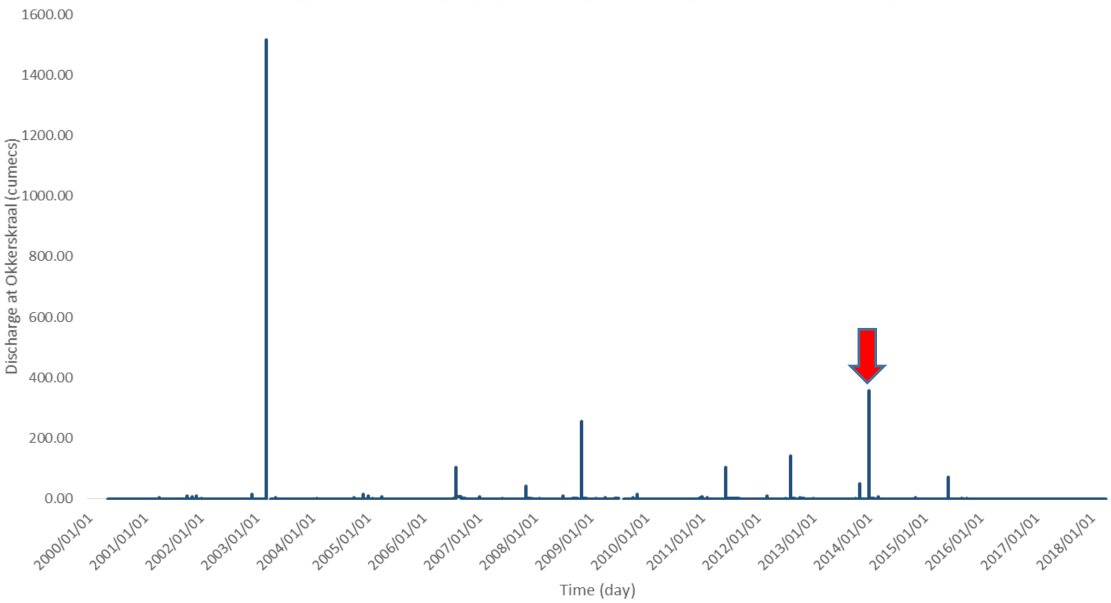


Figure 3. 5: Mean daily flow for the Touws River between 2001 and 2017. (Data source: Department of Water and Sanitation, South Africa).

Chapter 4: Results

4.1 Introduction

The results of this study are presented in two sections: 1) field work and 2) image analysis.

In the field work section, the results are subdivided into two parts: i) valley physiographic settings consisting of the valley width and longitudinal profile of the Touws and Prins River, and physiographic setting examining detailed cross sections of each site. ii) The second subdivision deals with substrate characteristics found within the sampling plots. This is then related to the roughness offered by the reeds in each site. In the image analysis section, this study reports changes in the spatial distribution and area occupied by the reeds along the river channel before and after the 2014 flood event and current reed bed distribution. Moreover, a map of potential water accumulation is presented.

4.2 Description of valley Physiographic Setting

The study area consists of four reaches (the Prins Doornboom, Prinspoort, Touws Plathuis and Touws Wolwefontein). Each reach is subdivided into various study sites where data were collected. The Prins Doornboom and Prinspoort reaches are both located upstream and largely composed of feldspathic sandstones, siltstones and micaceous shale beds of the Rietvlei Formation. The Prins Doornboom reach also has traces of thin sandstone fossiliferous of the Gydo Formation. Both reaches have narrow valleys with steep gradients when compared to reaches found downstream, however, the Prinspoort reach has a narrower valley (Figure 4.1). In contrast, the Touws Plathuis and Touws Wolwefontein reaches both located downstream are mainly composed of siltstone, shale and argillaceous sandstone of the Adolphspoort Formation. The Touws Plathuis is also underlain by dark grey shale of the Karies Formation .Both reaches have wide valleys with moderate gradients, however the Touws Plathuis is much wider than the Touws Wolwefontein (Figure 4.1)

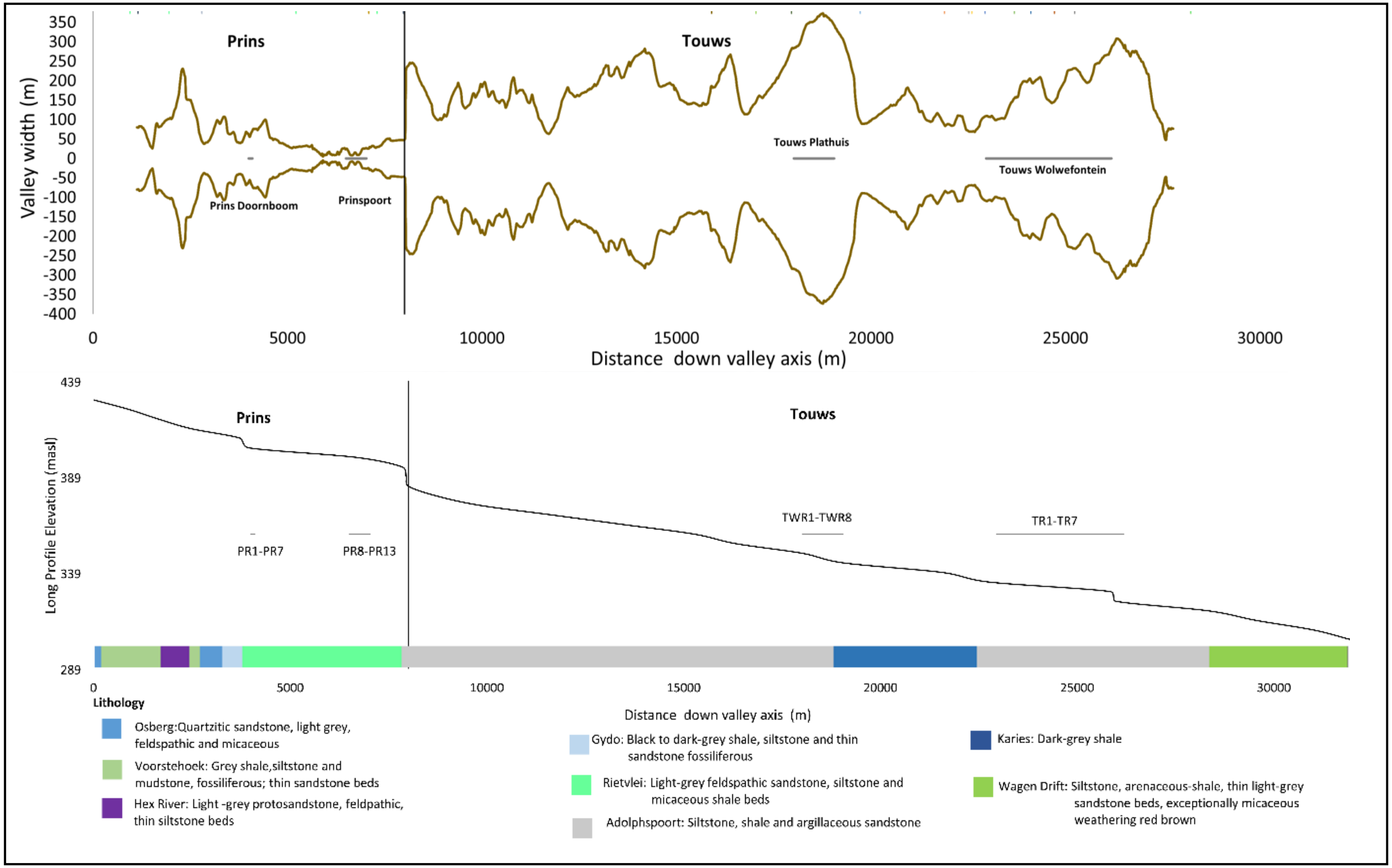


Figure 4. 1: Longitudinal profile of the Prins and Touws Rivers through the reaches surveyed in the field, also showing variation in sub-bed lithology and valley width.

4.3 Description of valley cross sections and reed bed quadrat data

Figure 4.2 a-d and Figure 4.3 e-f, shows cross sections through the Prins Doornboom reach; Figure 4.3 g-l, cross section through the Prinspoort reach; Figure 4.4 m-p and Figure 4.5 q-t cross sections through the Touws Plathuis reach and Figure 4.6 n-x, cross sections through the Touws Wolwefontein reach. The Prins Doornboom reach is a single thread channel characterised by narrow valleys, with the exception of PR1 and PR2 (Figure 4.2 a-b), which are much wider and flatter. *P. australis* in this reach when compared to the other three reaches had moderate (referring to values in between high and low values) stem density and diameter and recorded the highest average stem height (1.2 m) (Figure 4.7). The reeds had low leaf area at the time of the fieldwork and the rhizomes were visible near the channel edge, however at PR6 and 7 (Figure 4.3f) the reeds had green leaves with no rhizomes visible at the surface. Most of the reeds grow along the channel corridors and around depressions. The reeds at PR6 are found within the channel located around a pool of water. This reach recorded the highest stem height on average and the measurements are spread out (Table 4.1) At maximum flood peak most of the reeds in the reach are submerged except for PR2, PR3 and PR5 (Figure 4.2 a, b and Figure 4.3 e). A mixture of cobbles, pebbles and sand had accumulated within the channel. Within the reed beds the sediment were well sorted, having medium sand sized grains (D50 = 0.45 mm). No sign of grazing was observed.

Prinspoort reach has a single thread channel, characterised by very narrow channels. The bedrock was visible through the reach with very little sediment on the surface. The reeds at PR 8 and 9 (Figure 4.3g and h) had low stem density, height and diameter. The reeds did not grow near the pool with water but grew a measurable distance away from the pool. At site PR 10 and 11 (Figure 4.3 J) the reeds were seen growing on top of a rock with sediment near a pool of water. At site PR13 (Figure 4.3 k) the reeds grew within the channel, with low stem diameter, moderate stem density and height (Figure 4.7). All the reeds in this reach are submerged at maximum flood peak. A mixture of cobbles, pebbles and sand had accumulated within the whole channel. The sediment found within the reed beds was extremely poorly sorted, containing medium sand sized grains (D50 = 0.32 mm). No sign of grazing was observed.

The Touws Plathuis reach located in the Touws River has wide and shallow channels. The reach is characterised by multiple mid-channel bars with sharp elevation changes. Recorded a high average in stem diameter (Table 4.1 and Figure 4.7). The reed grew on elevated mid-channel bars in isolated patches. In some of the areas the reeds were grazed upon by cattle and could not be measured (Figure 4.4m). TWR1-5 (Figure 4.5 m-p) had the widest channel covering a distance of up to 1600m. All the reeds were submerged at maximum flood peak. The channel consisted of a mixture of cobbles, pebbles and sand. The sediment within the reeds was poorly sorted, containing fine sand sized grains (D50 =0.10 mm).

The Touws Wolwefontein (Figure 4.6 n-x) reach had wide channel when compared to the Prins Doornboom and Prinspoort reach (with the exception of TR6) and narrow when compared to the Touws Plathuis reach. The channel is similar to the Prinspoort as bedrock is visible to the surface and most of the reeds grow in accumulated sediment found within the bedrock (4.6 w). The reeds in this reach were found growing along channel corridor and around pools, with a high average in stem diameter and low average in stem density when compared to the other reaches. All the reeds are submerged at maximum flood peak. The reach contains medium sand sized grains (D50 = 0.33 mm).

The reeds found within these reaches vary from upstream to downstream. There is a gradual decrease in stem characteristic and sediment sorting. A significant increase in channel width is also visible from upstream to downstream. Mid-channel bars and pools also increase downstream. The reeds found in the upper reaches are well intact and form continuous linear stands, showing increased stem characteristics. The reeds found downstream are not as well intact as those found upstream. The reeds downstream are found in patches along the multithreaded channels. The majority of the reeds are submerged at maximum flood peak, however, there are a few sites where the reeds are not submerged at maximum flood peak. The emergent reeds are found in the upper reaches.

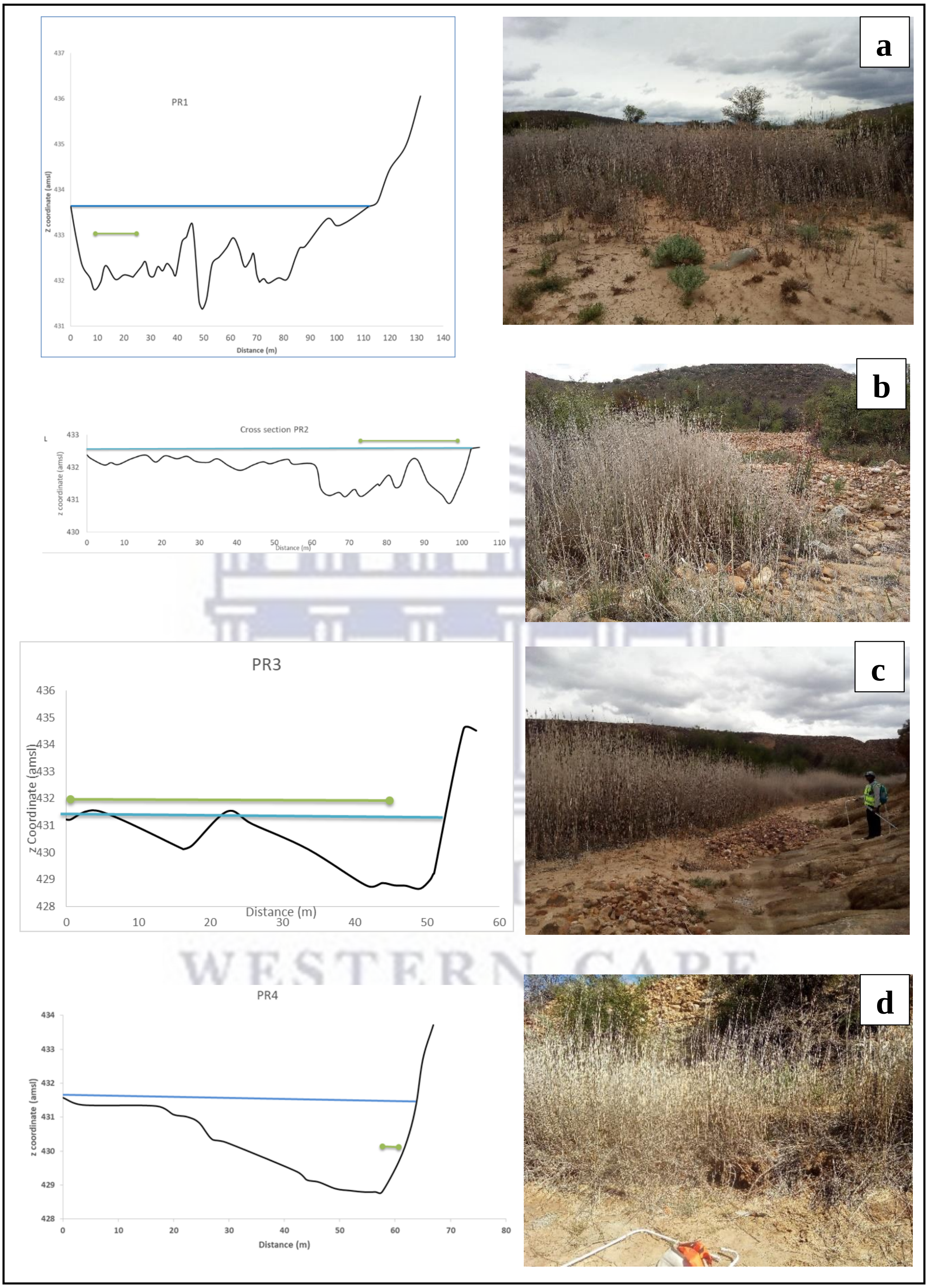
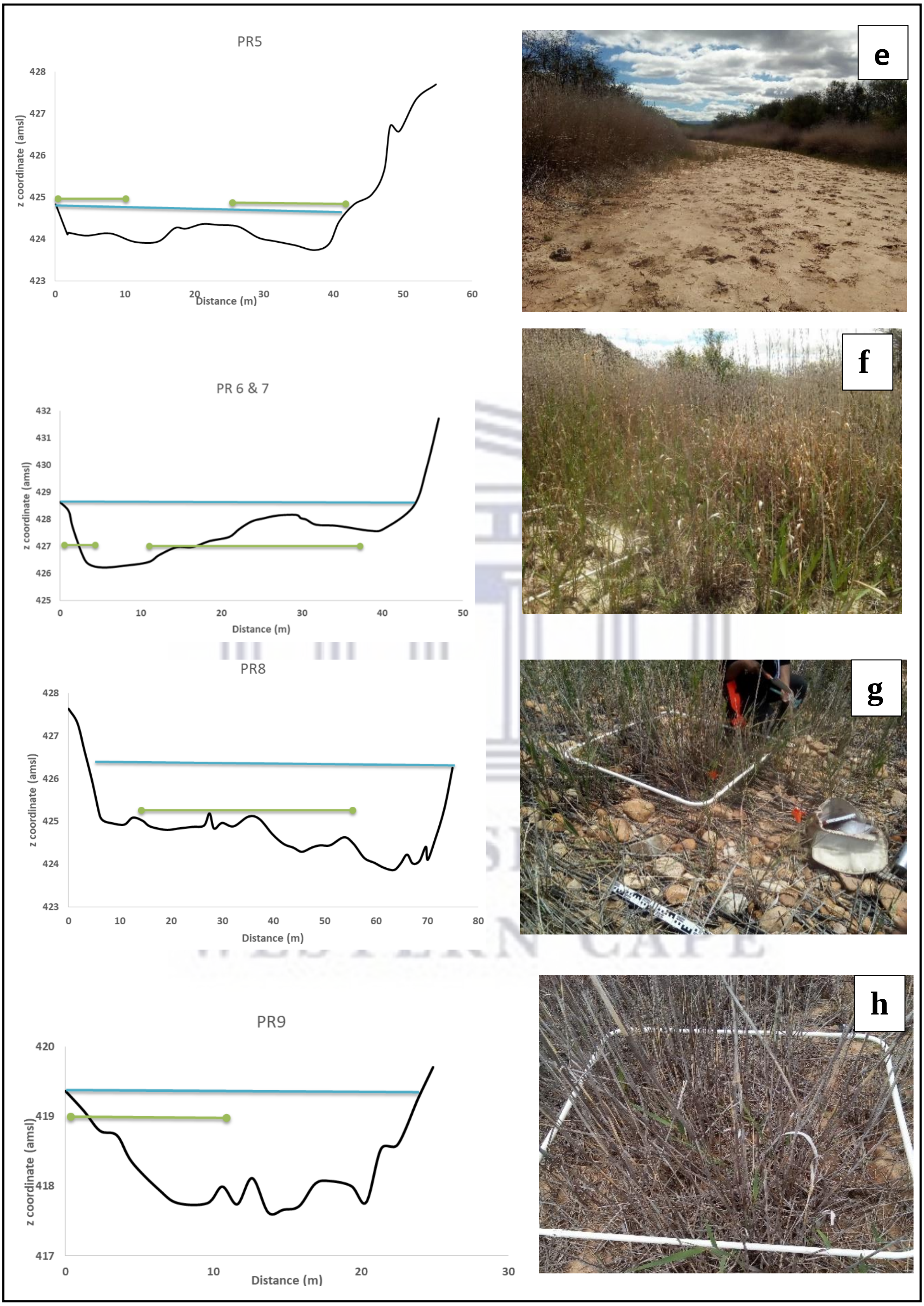


Figure 4. 2: Cross section showing maximum flood (blue line), average height above reed (green line) and photographs of the sites in the Prins Doornboom reach.


PR5
z coordinate (amsl)
428
427
426
425
424
423
0
10
20
30
40
50
60
Distance (m)
e
PR 6 & 7
z coordinate (amsl)
432
431
430
429
428
427
426
425
0
10
20
30
40
50
Distance (m)
f
PR8
z coordinate (amsl)
428
427
426
425
424
423
0
10
20
30
40
50
60
70
80
Distance (m)
g
PR9
z coordinate (amsl)
420
419
418
417
0
10
20
30
Distance (m)
h

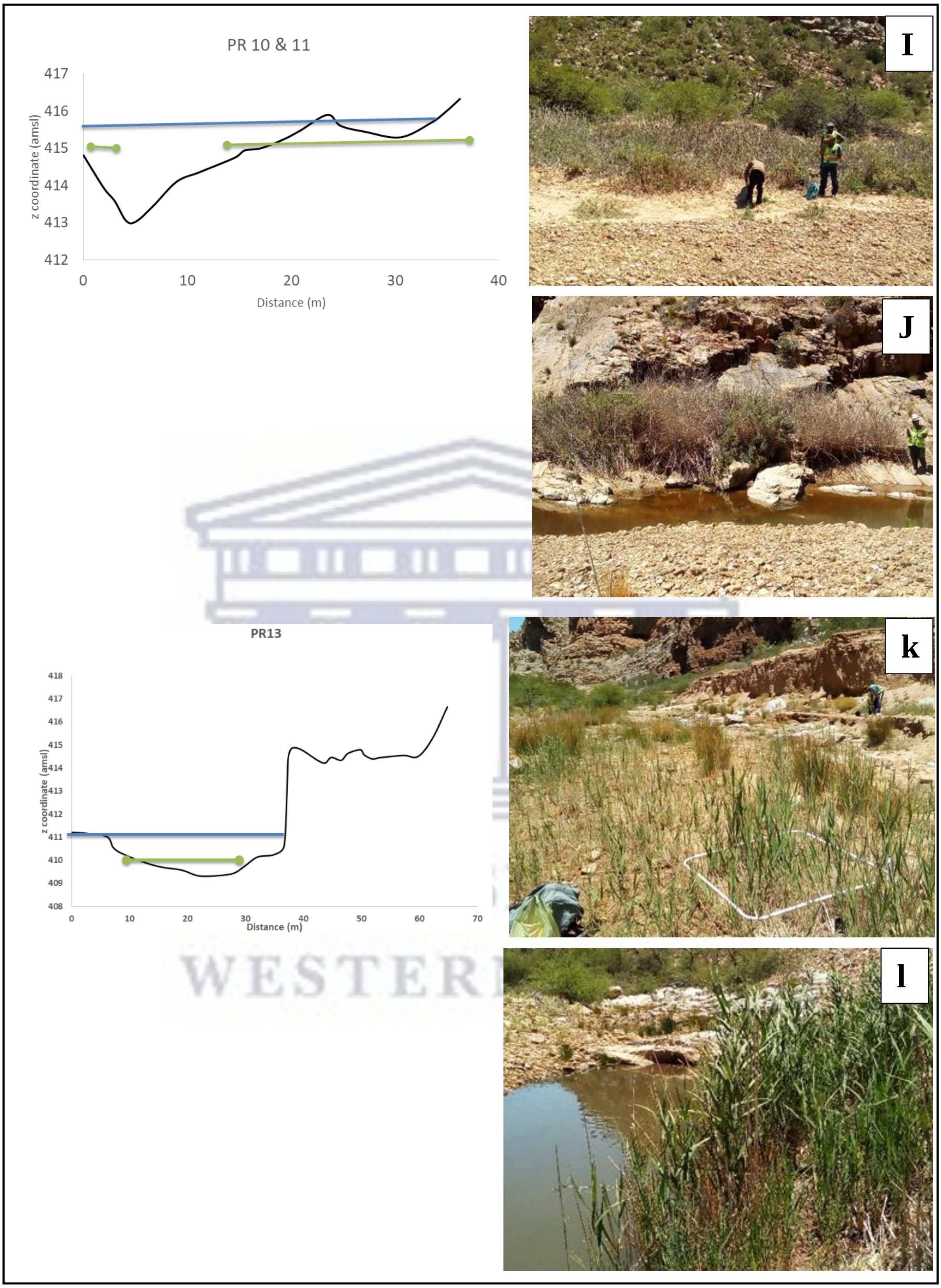


Figure 4. 3: Cross section showing maximum flood (blue line), average height above reed (green line) and photographs of the sites in the Prins Doornboom and Prinspoort reaches.

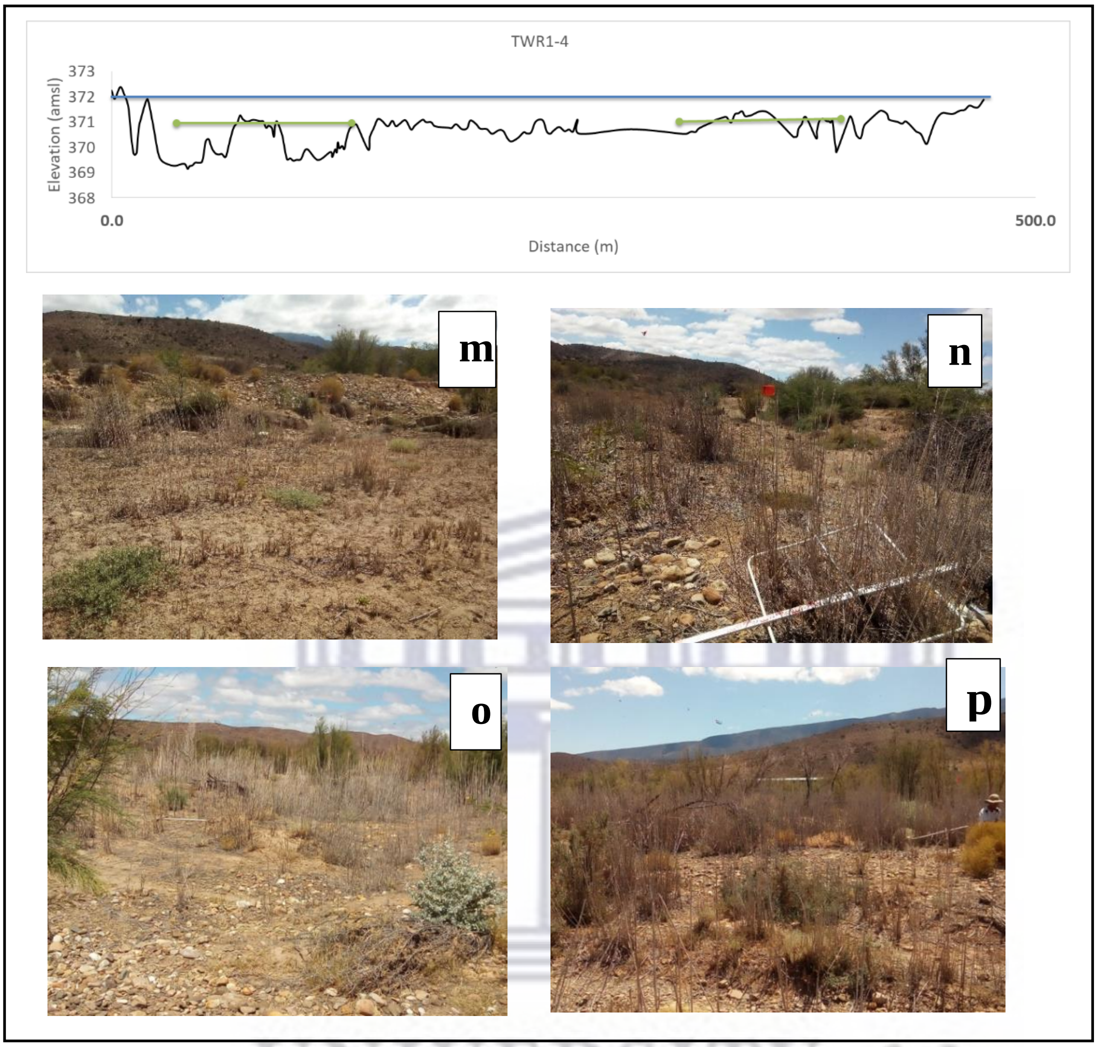


Figure 4. 4: Cross sections showing maximum flood (blue line), average height above reed (green line) and photographs of the sites in the Touws Plathuis (TWR1 m; TWR2 n, TWR3o; TWR4p).

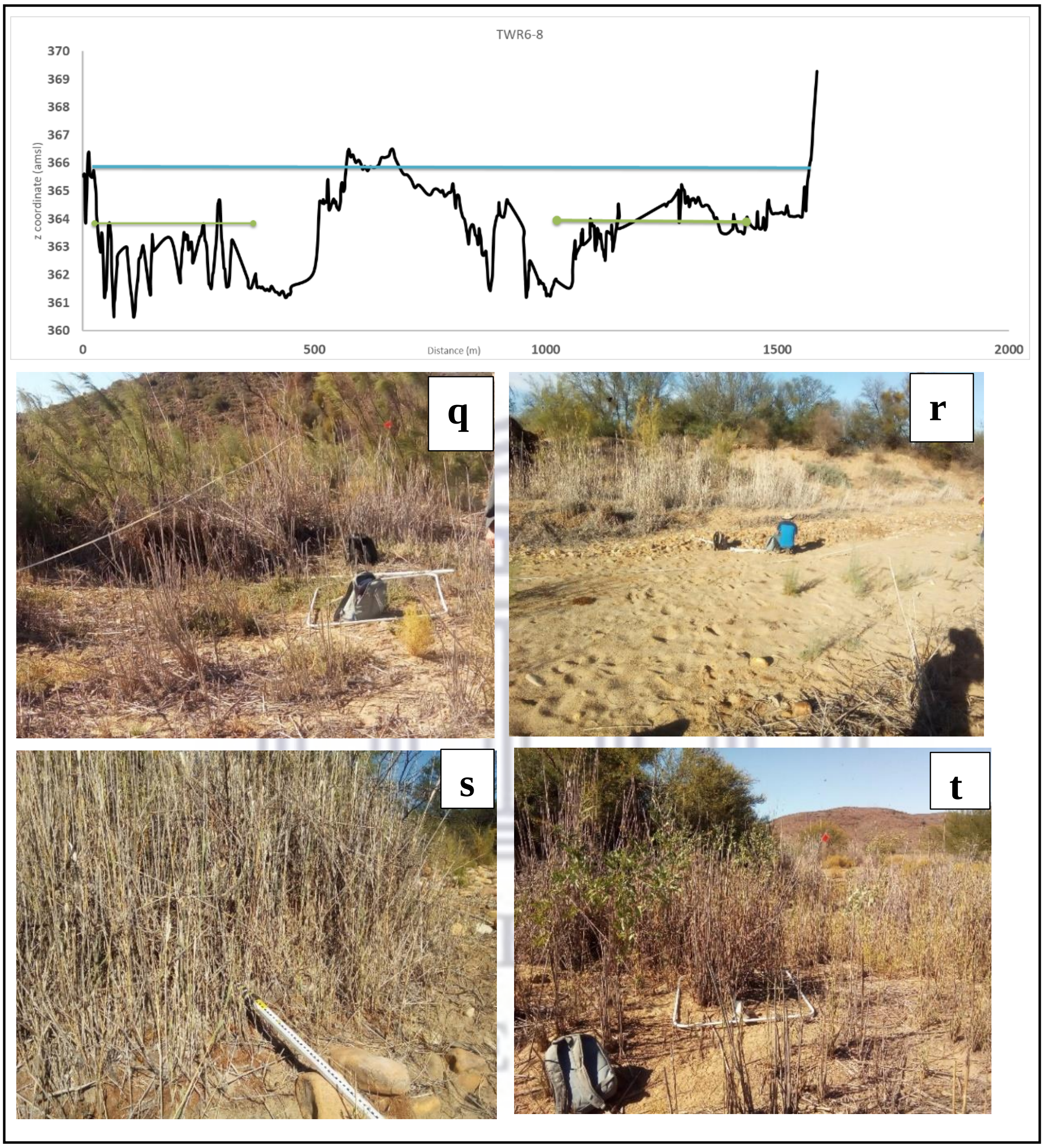


Figure 4. 5: Cross sections showing maximum flood (blue line), average height above reed (green line) and water depth above reed bed (red line) and photographs of the sites in the Touws Plathuis (TWR5 q; TWR6 r; TWR7 s; TWR8 t).

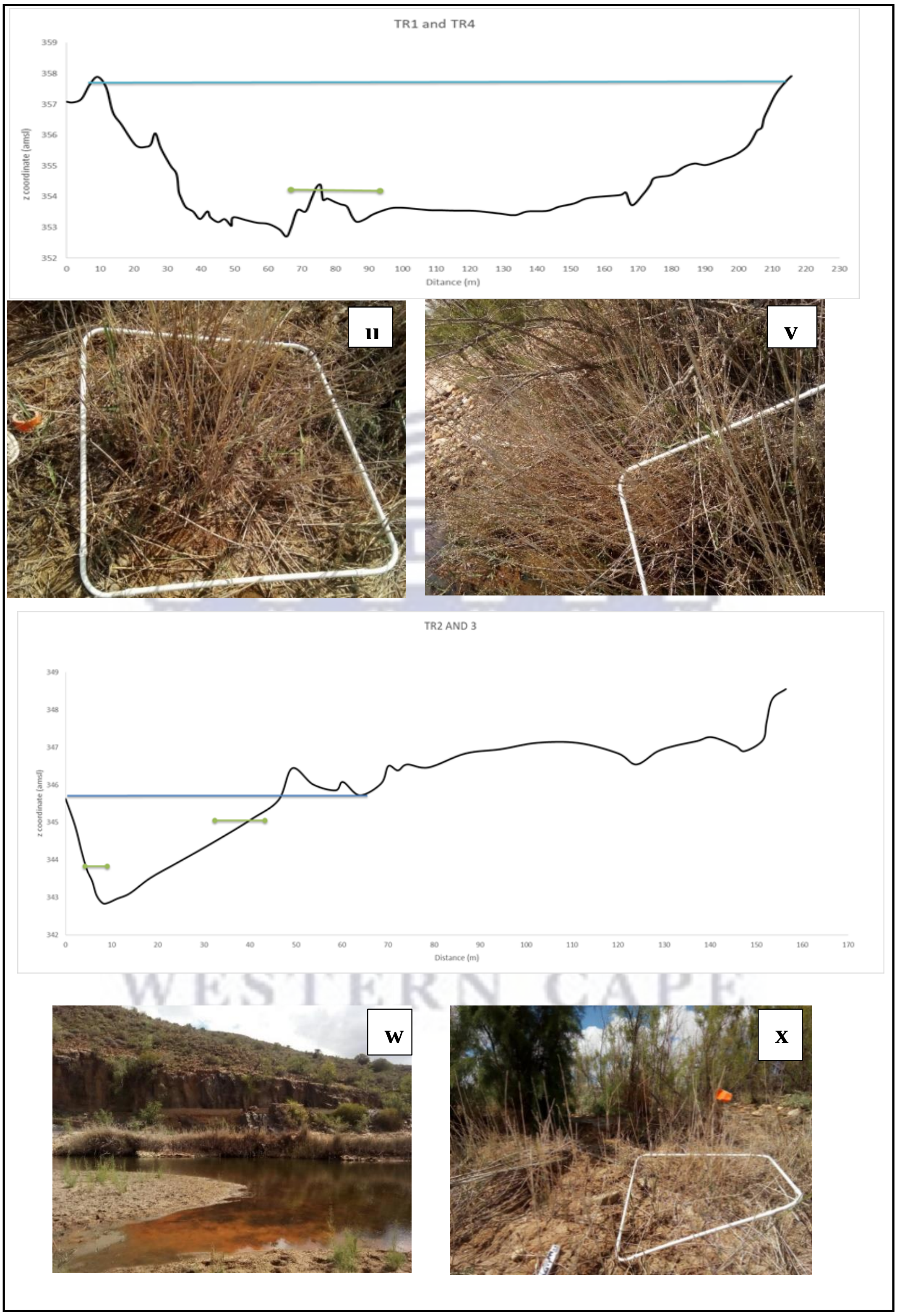
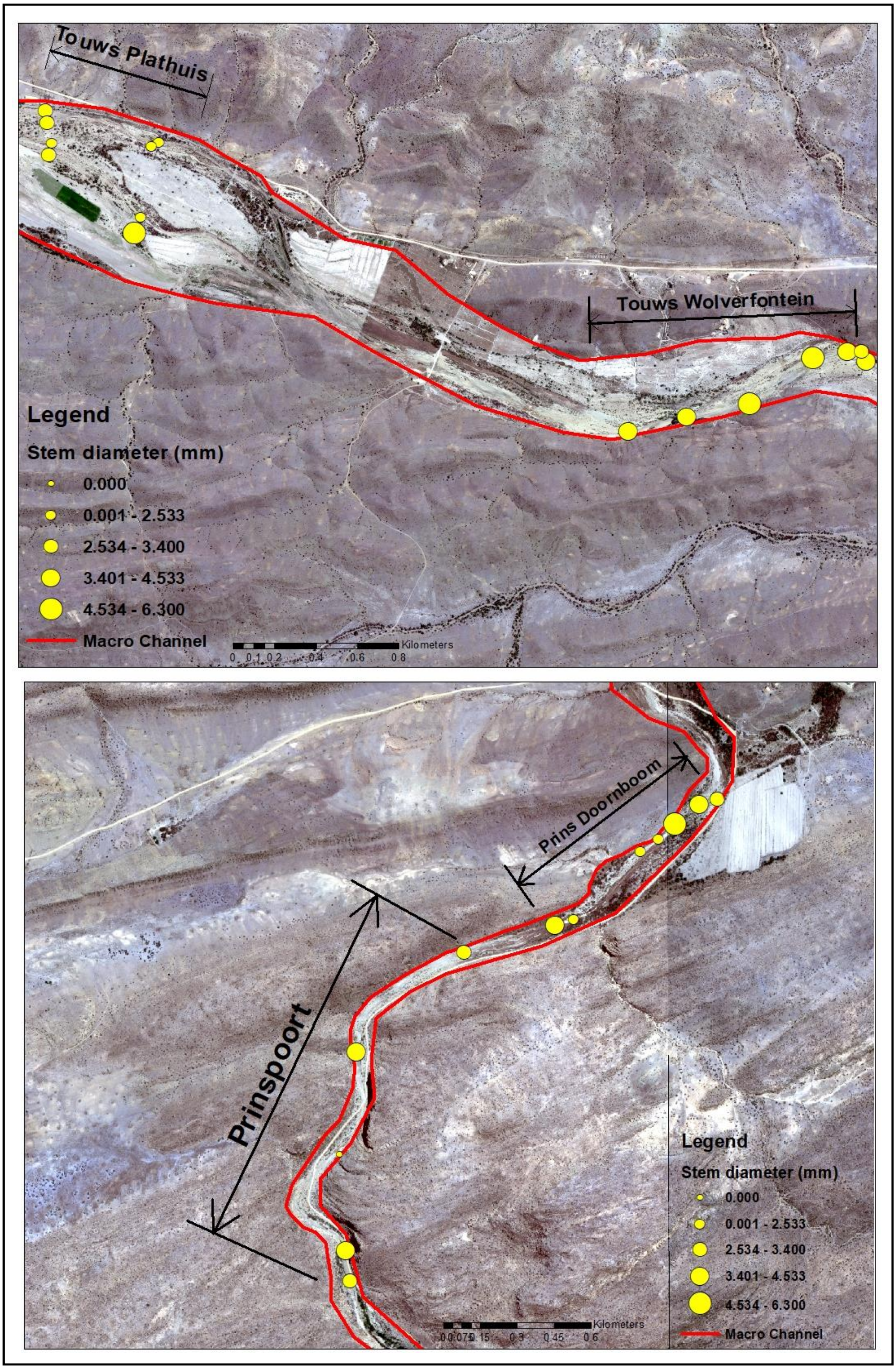
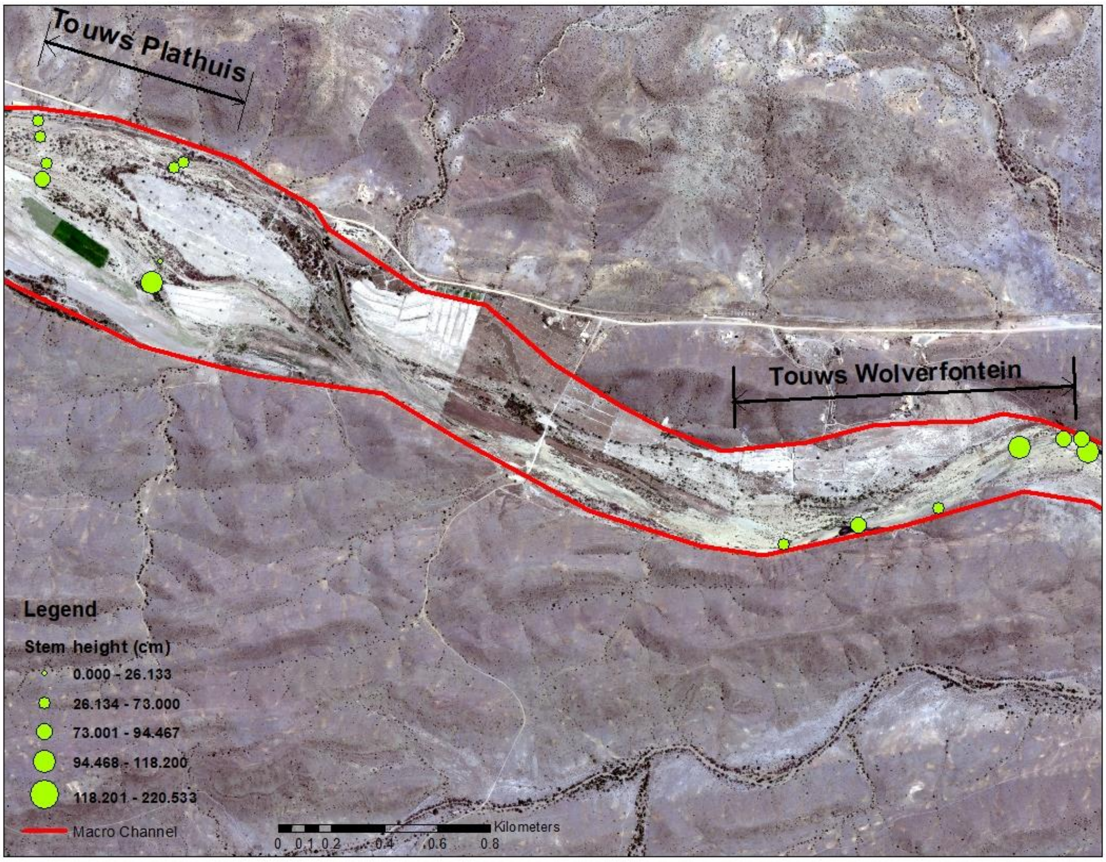
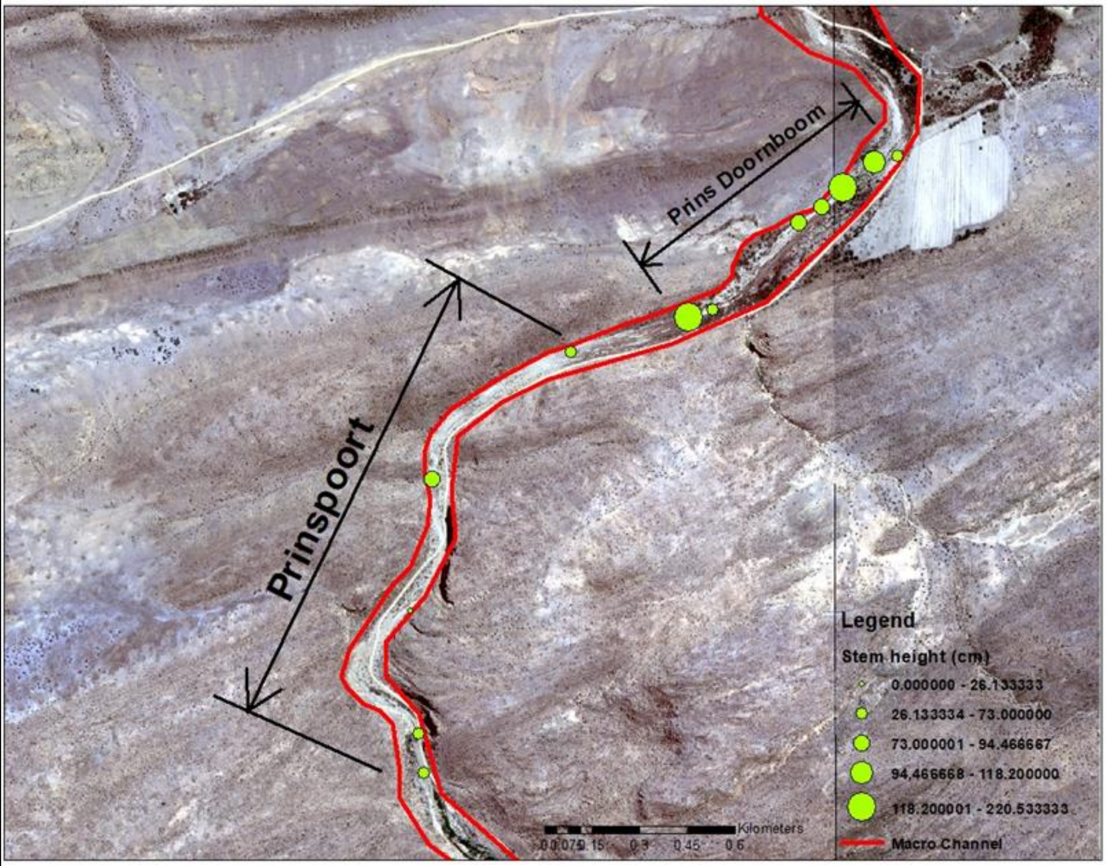


Figure 4. 6: Cross sections showing maximum flood (blue line), average height above reed (green line) and photographs of the sites in the Touws Wolwefontein.



Touws Plathuis
Touws Wolverfontein
Legend
Stem diameter (mm)
0.000
0.001 - 2.533
2.534 - 3.400
3.401 - 4.533
4.534 - 6.300
Macro Channel
Kilometers
0 0.1 0.2 0.4 0.6 0.8
Prins Doornboom
Prinspoort
Legend
Stem diameter (mm)
0.000
0.001 - 2.533
2.534 - 3.400
3.401 - 4.533
4.534 - 6.300
Macro Channel
Kilometers


Touws Plathuis
Touws Wolverfontein
Legend
Stem height (cm)
0.000 - 26.133
26.134 - 73.000
73.001 - 94.467
94.468 - 118.200
118.201 - 220.533
Macro Channel
Kilometers
0 0.1 0.2 0.4 0.6 0.8


Prins Doornboom
Prinspoort
Legend
Stem height (cm)
0.000000 - 26.133333
26.133334 - 73.000000
73.000001 - 94.466667
94.466668 - 118.200000
118.200001 - 220.533333
Macro Channel
Kilometers

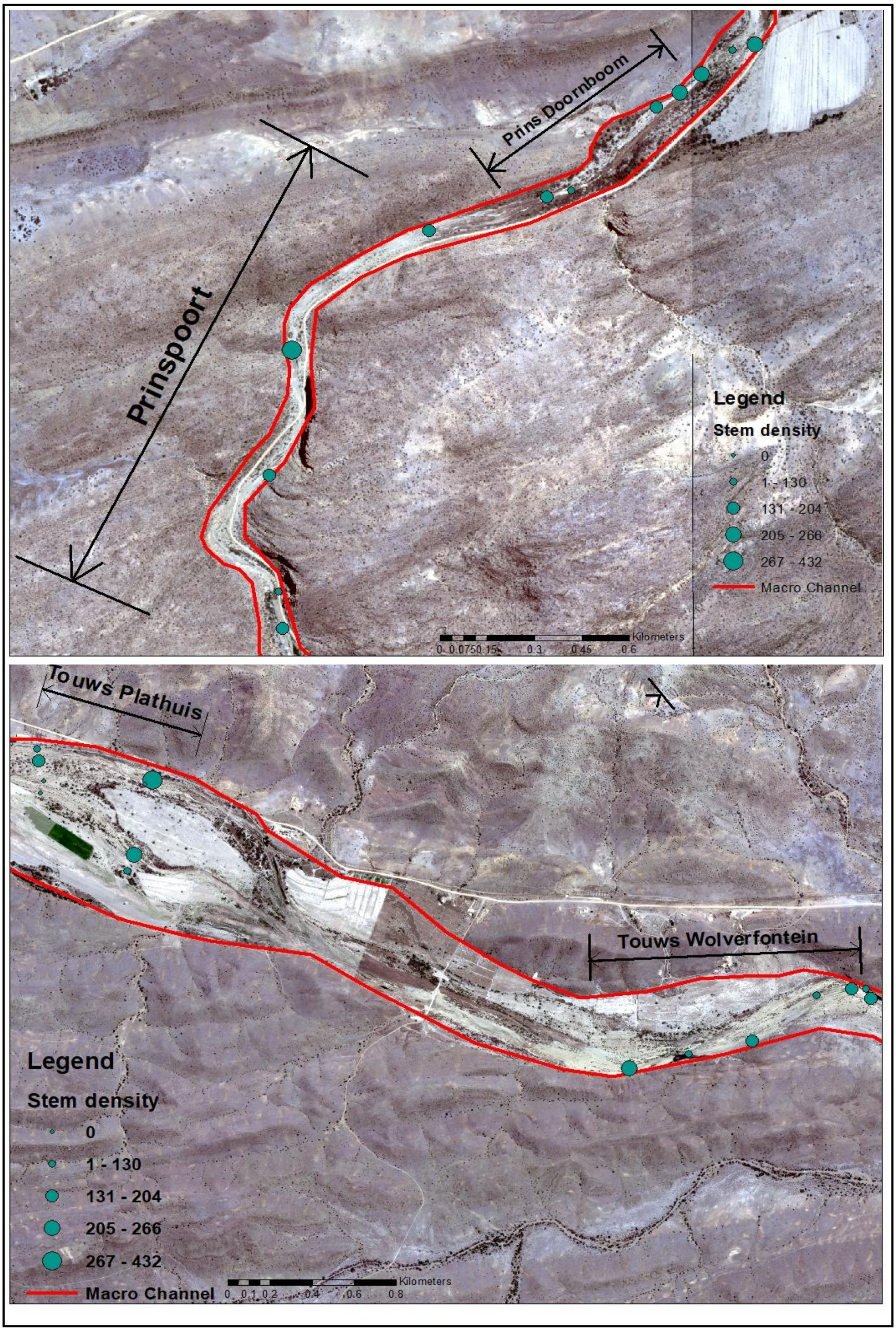


Figure 4. 7: Stem characteristics across reed bed patch boundaries along the Prins and Touws Rivers

Table 4.1: Descriptive statistics of stem characteristics along the Prins and Touws reaches

	Prins Doorboom	Prinspoort	Touws Plathuis	Touws Wolwefontein
Stem Diameter				
Mean	3,33	3,24	4,67	2,73
Median	2,83	3,17	4,38	2,67
Standard Deviation	1,46	0,38	0,86	0,50
Sample Variance	2,12	0,14	0,73	0,25
Range	4,10	0,90	2,63	1,13
Minimum	2,20	2,73	3,40	2,23
Maximum	6,30	3,63	6,03	3,37
Stem height				
	Prins Doorboom	Prinspoort	Touws Plathuis	Touws Wolwefontein
Mean	115,73	60,38	91,58	53,48
Median	94,47	54,40	89,33	60,77
Standard Deviation	57,38	15,66	19,99	18,52
Sample Variance	3292,31	245,28	399,49	342,84
Range	155,80	38,03	51,63	40,10
Minimum	64,73	50,03	66,57	26,13
Maximum	220,53	88,07	118,20	66,23
Stem density				
	Prins Doorboom	Prinspoort	Touws Plathuis	Touws Wolwefontein
Mean	184,57	198,80	155,50	225,00
Median	204,00	172,00	160,00	190,50
Standard Deviation	73,90	97,77	57,43	151,85
Sample Variance	5460,62	9558,70	3298,00	23058,00
Range	190,00	260,00	157,00	345,00
Minimum	76,00	104,00	86,00	87,00
Maximum	266,00	364,00	243,00	432,00

4.4 Interplay between stem characteristics, hydraulic roughness and sediment

In general, the relationship between stem characteristic and Chézy value is not linearly related to stem characteristics; stem diameter (regression test: $F_{1,22}$ = 1,90, P = 0,18), stem height (regression test: $F_{1,22}$ = 1,11, P = 0,30), stem density (regression test: $F_{1,22}$ = 1,43, P = 0,25) . At reach scale, in the Prins Doornboom reach the Chézy value is however, negatively linearly related to stem density (regression test: F1, 6 = 8.32, P = 0, 03). This indicates an increase in hydraulic roughness with an increase in stem density along the Prins Doornboom (Figure 4.9). Some sites as indicated by the red circles cluster together in the Prins Doornboom away from the other sites in the other three reaches as indicated by the black circle (Figure 4.8). In the Touws Plathius the Chézy value was negatively linearly related to stem height (regression test: F1, 7 = 7.10, P = 0, 04), as such hydraulic roughness increases with stem height in this reach (Figure 4.8). The Prinspoort and Touws Wolwefontein reaches observed no significant relationship between Chézy value and any of the stem characteristics.

Figure 4.9 shows the relationship between Chézy value and sediment characteristics. All the sites have a clay percentage which is below 10%, silt values below 20% and very high sand percentage, greater than 70%. An increase in Chézy value (decreases in hydraulic roughness) increases sand sediment (sand; regression test: $F_{1,22}$ = 5,27, P = 0,03). A decrease in Chézy value (increase in hydraulic roughness) however leads to an increase in clay sediment; regression test: $F_{1,22}$ = 7,92, P = 0,01). No significant relationship was observed between Chézy value and silt ($F_{1,22}$ = 2,72, P = 0,11). The Prins Doornboom reach distinctively showed Chézy value to be negatively linearly related to clay (regression test: $F_{1,6}$ = 59.06, P = 0,0006) and Chézy value to be positively linearly related to sand (regression test: $F_{1,6}$ = 8.81, P = 0.04).

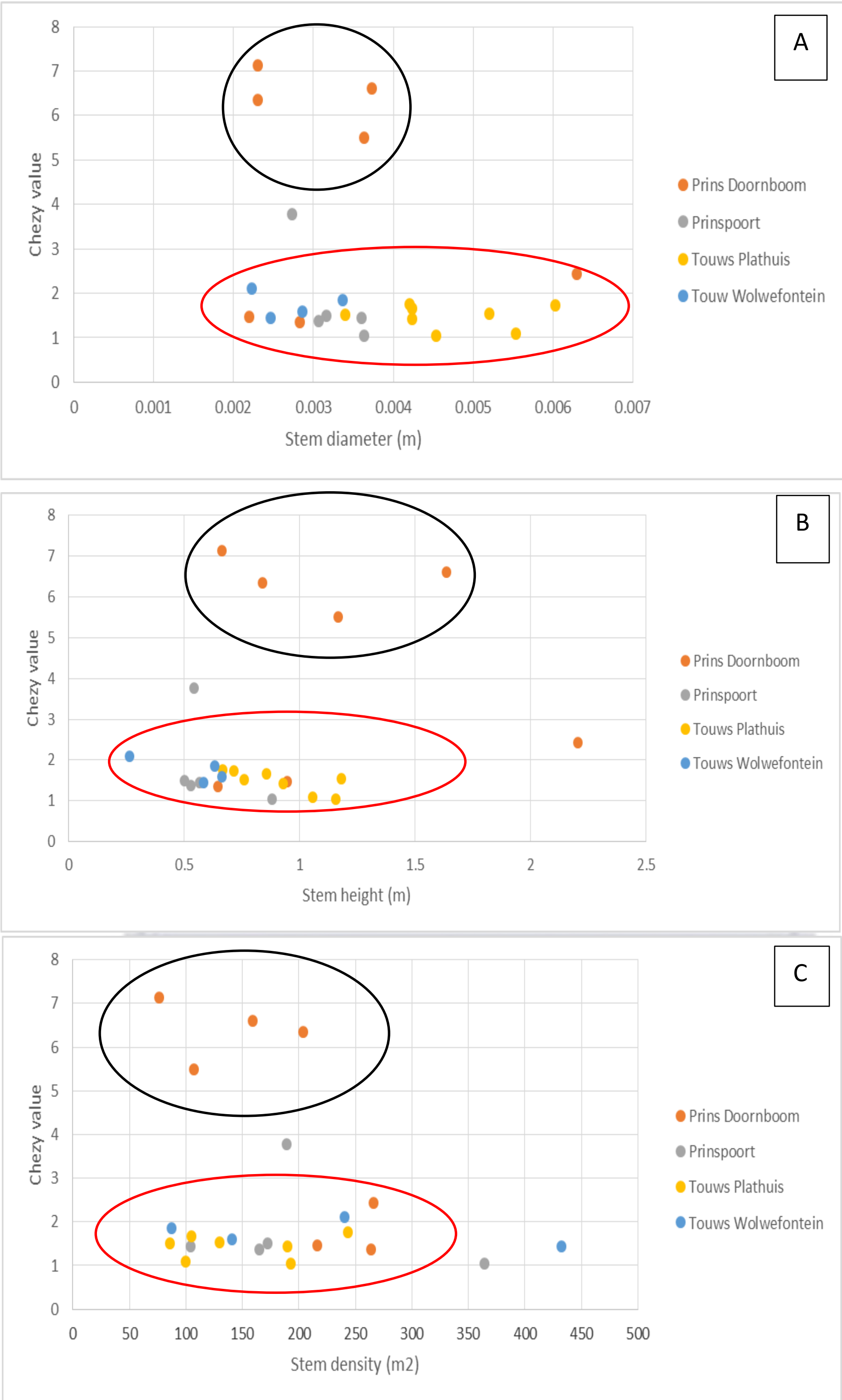


Figure 4. 8: Variation in Chézy value with stem characteristics. (A) Variation in Chézy value with stem diameter, (B) Variation in Chézy value with stem height, (C) Variation Chézy value with stem density.

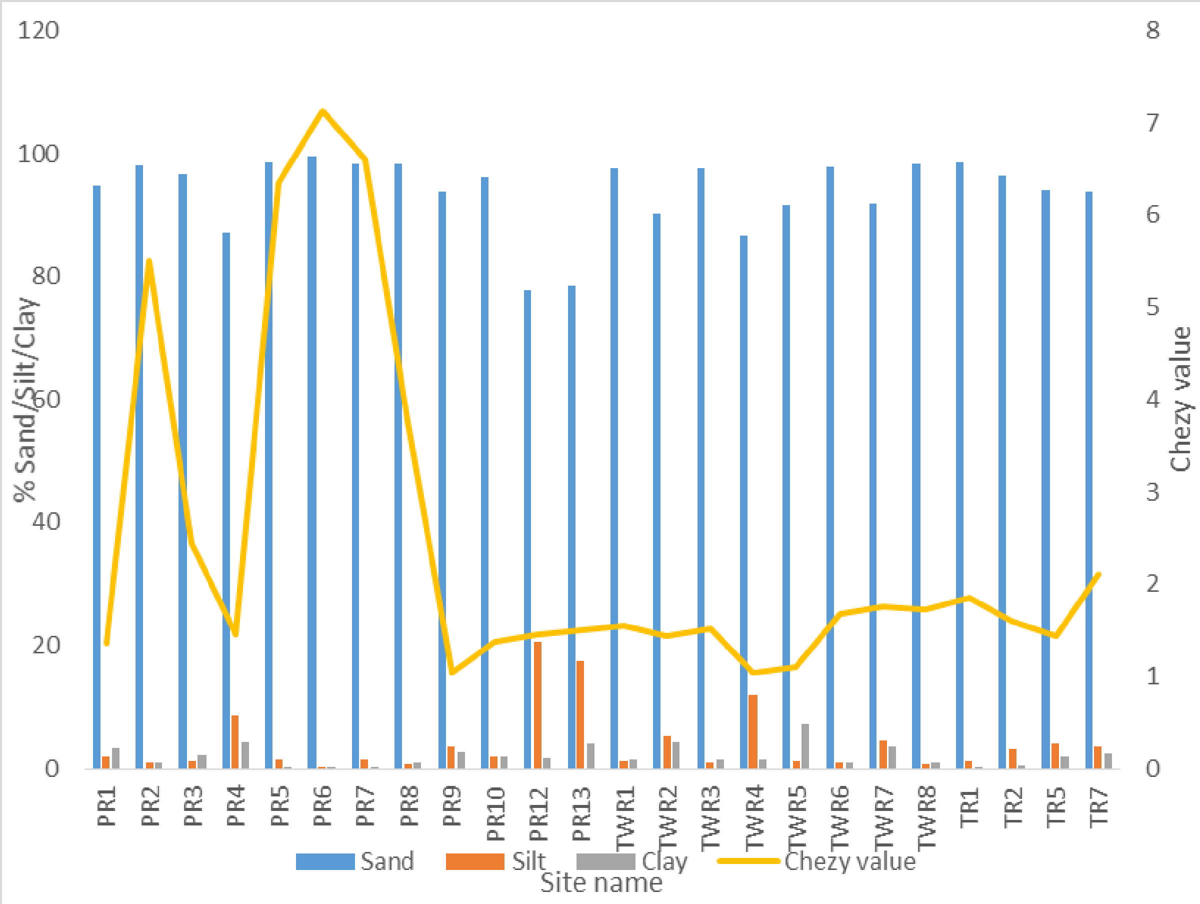


Figure 4.9: Variation in percentage sand/silt/clay with Chézy value. An increase in Chézy value results in a decrease in hydraulic roughness

4.5 Documenting longitudinal changes in reed bed distribution

The mapping of the longitudinal distribution of reed beds along the Prins and Touws Rivers produced the following results. When observing all four reaches, a dramatic increase in reed patch size from 2013 to 2014 can be observed, followed by a dramatic decline in 2017. This applies to only about 10 of the 30 patches described in the study (Figure 4.10-4.17 and Table 4.1). 8 small patches appearing only in 2017 can be observed in the Touws Plathuis and Touws Wolwefontein. No patches which were present in 2013 and 2014 became absent in 2017. However, nearly half the number of patches which appear in 2017 are not present in 2014. In the Prins Doornboom reach which is geomorphologically less confined, patch 1 recorded the highest reed bed area of all the patches in both 2013 and 2014, this was followed by a decline in 2017. Patch 8 is the only patches in which in both 2013 and 2014 no reed patch was observed, however in 2017 a patch is present. Patch 2 shows a gradual increase in reed bed area from 2013, 2014 and 2017. A decrease in reed bed area can be observed at patch 3 in 2014 followed by an increase in 2017 which surpasses 2013. No patches can be observed for 2014 in the last three patches and in patch 8 a reed patch is only found in 2017 (Figure 4.11). Most of the reeds in this reach were found to still be present in 2017 in smaller patches than in previous years, with the exception of patch 2 and 8. Although a few patches peaked in 2014, those that peaked observed drastic peaks.

In the Prinspoort reach which is geomorphologically confined, no patches which were present in 2013 became absent in 2017. A decrease in reed patch area can be observed in reed patch 1 from 2013 to 2014 followed by an increase in 2017. No patches can be observed for 2014 in the last two patches (Figure 4.13). The patches in this reach are isolated hence very few merged following the 2014 flood (Figure 4.12). Patches 4, 5 and 6 in the middle of the reach, observed the highest reed bed area in 2014 followed by a drastic decrease in 2017, with reeds often lower than those observed in 2013. The majority of patches in this reach peaked in 2014. In the Touws Plathuis reach which is geomorphologically unconfined, patch 1 drastically increased from a small patch observed in 2013 to the massive patch found in 2014, however this increase did not last as a decreased was observed in 2017 (Figure 4.14). Patch 2 which was present in 2013, disappears entirely in 2014 and then reappears as a considerably smaller patch in 2017. The last four patches observed a similar trend to each other, as none were present in 2013 and 2014 and only appeared in 2017(Figure 4.15). The majority of patches appear only in 2017 as smaller patches. In the Touws Wolwefontein reach which is also geomorphologically unconfined (Figure 4.16). A similar trend can be seen for patches 1 to 3, in that the reed bed area of the patches increased from 2013 to 2014, however, a decrease followed in 2017. Patch 4 had the highest reed bed area in 2013, followed by a drastic decrease in 2014 and 2017. The remaining four patches only appeared in 2017 (Figure 4.17).

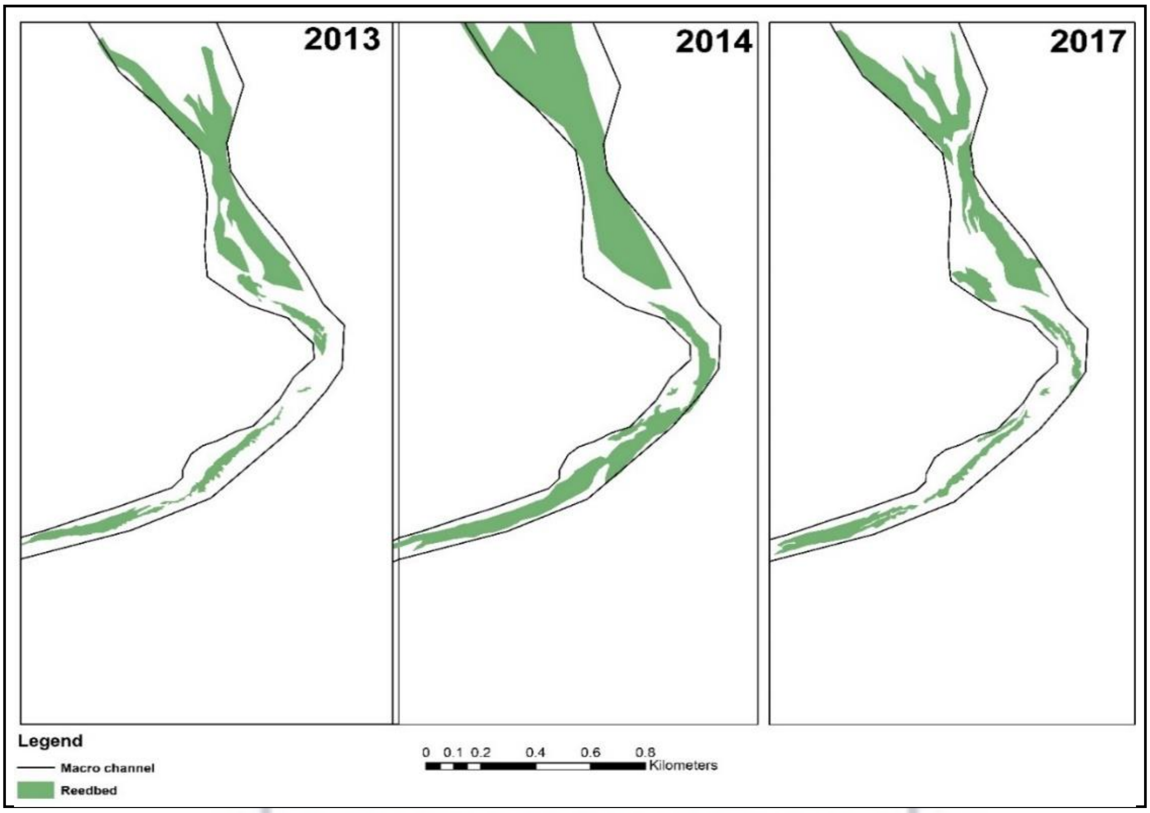


Figure 4. 10: Longitudinal distribution of reed beds along the Prins Doornboom before and after the 2014 flood event, with the current distribution observed in 2017

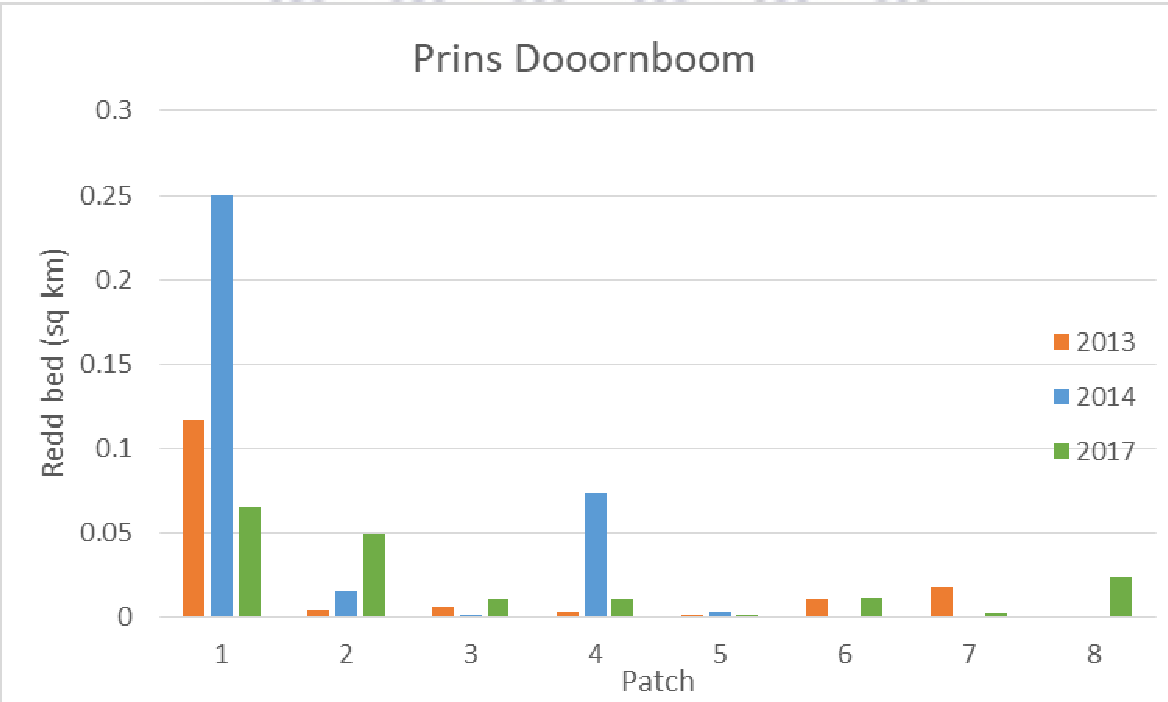


Figure 4. 11: Change in spatial extent of eight selected patches in the Prins Doornboom reach, from upstream to downstream.

Figure 4. 12: Longitudinal distribution of reed beds along the Prinspoort before and after the 2014 flood event, with the current distribution observed in 2017

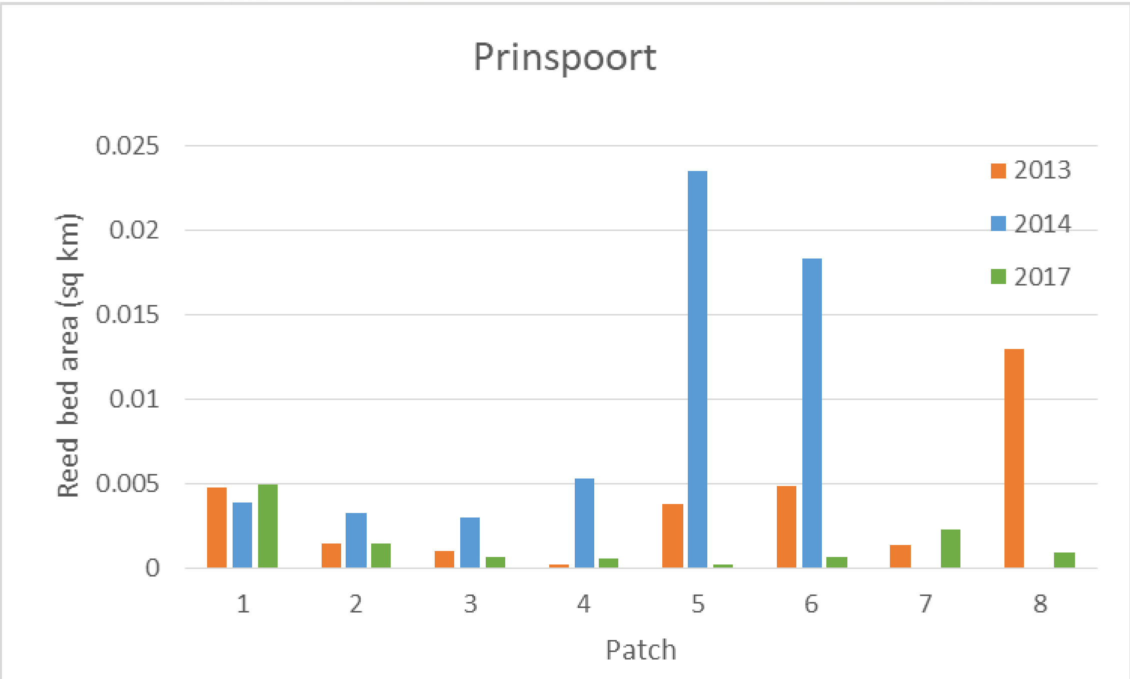


Figure 4. 13: Change in spatial extent of eight selected patches in the Prinspoort reach, starting upstream through to downstream.

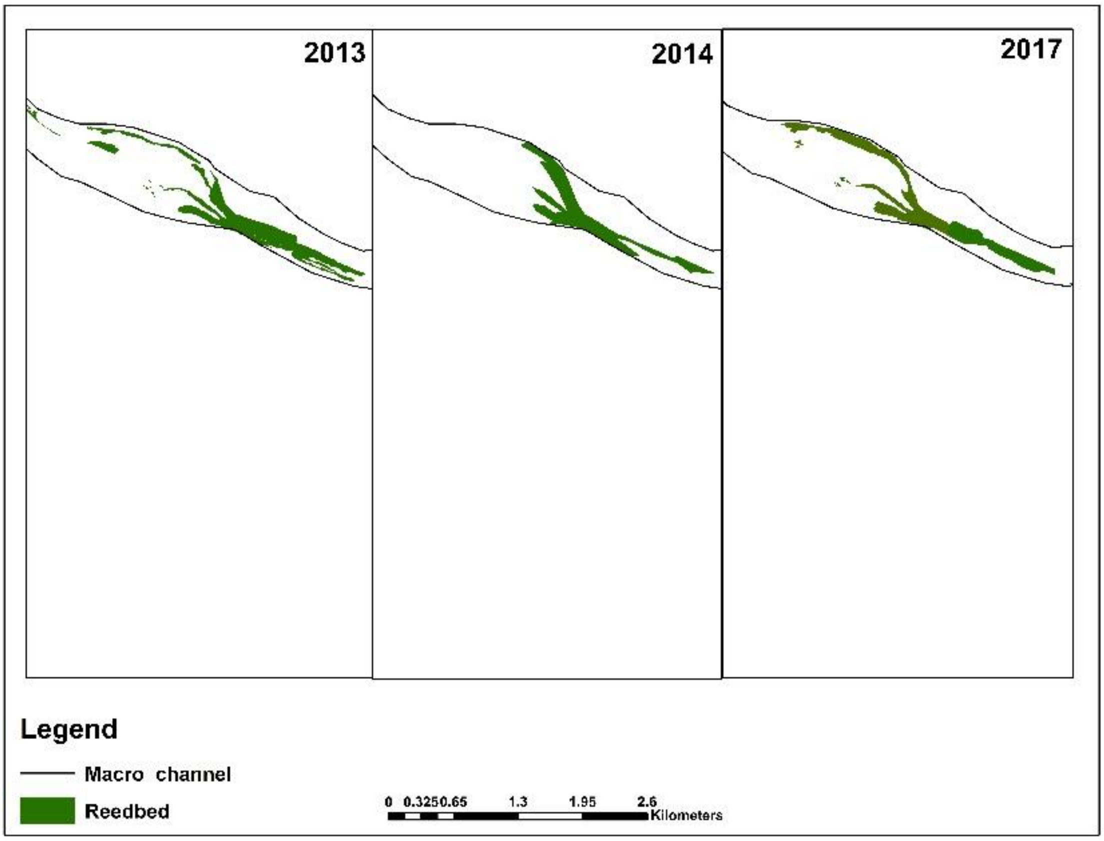


Figure 4. 14: Longitudinal distribution of reed beds along the Touws Plathuis before and after the 2014 flood event, with the current distribution observed in 2017

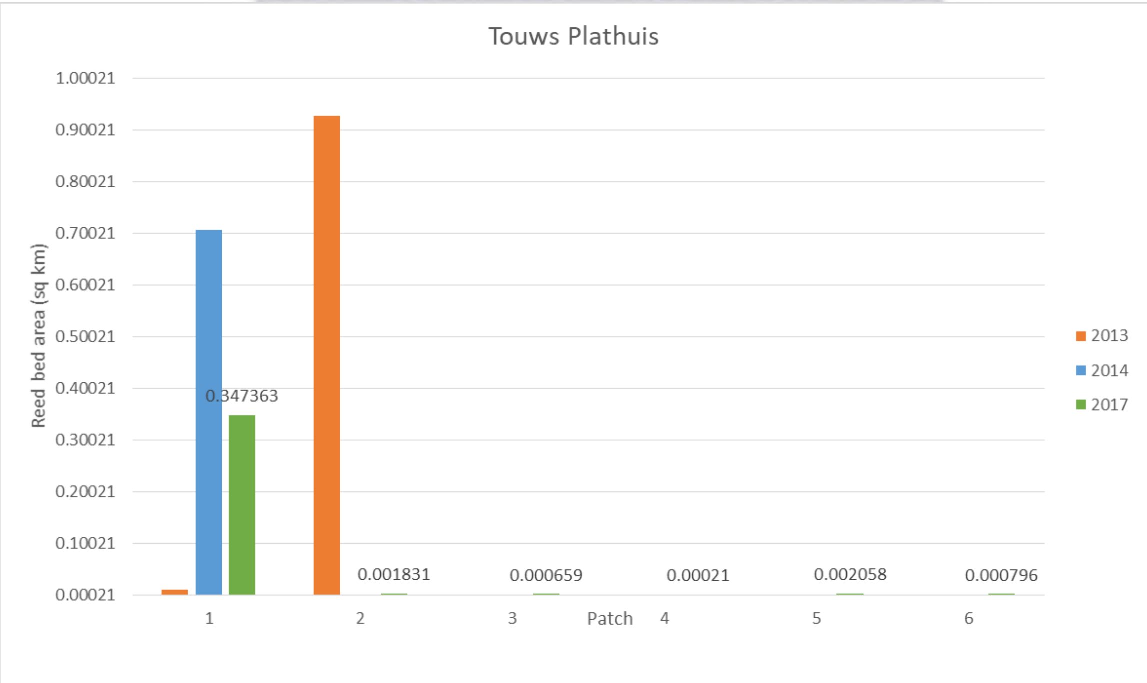


Figure 4. 15: Change in spatial extent of six selected patches in the Touws Plathuis reach, starting upstream through to downstream.

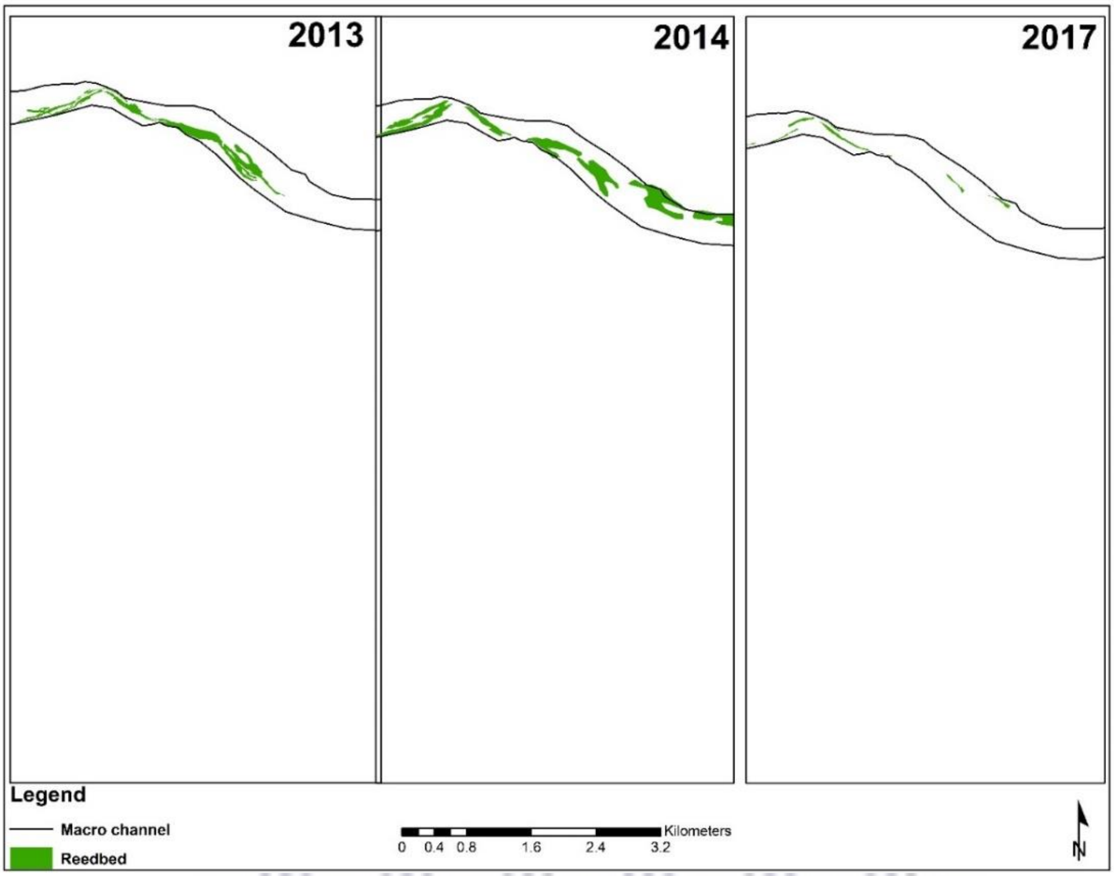


Figure 4. 16: Longitudinal distribution of reed beds along the Touws Wolwefontein before and after the 2014 flood event, with the current distribution observed in 2017

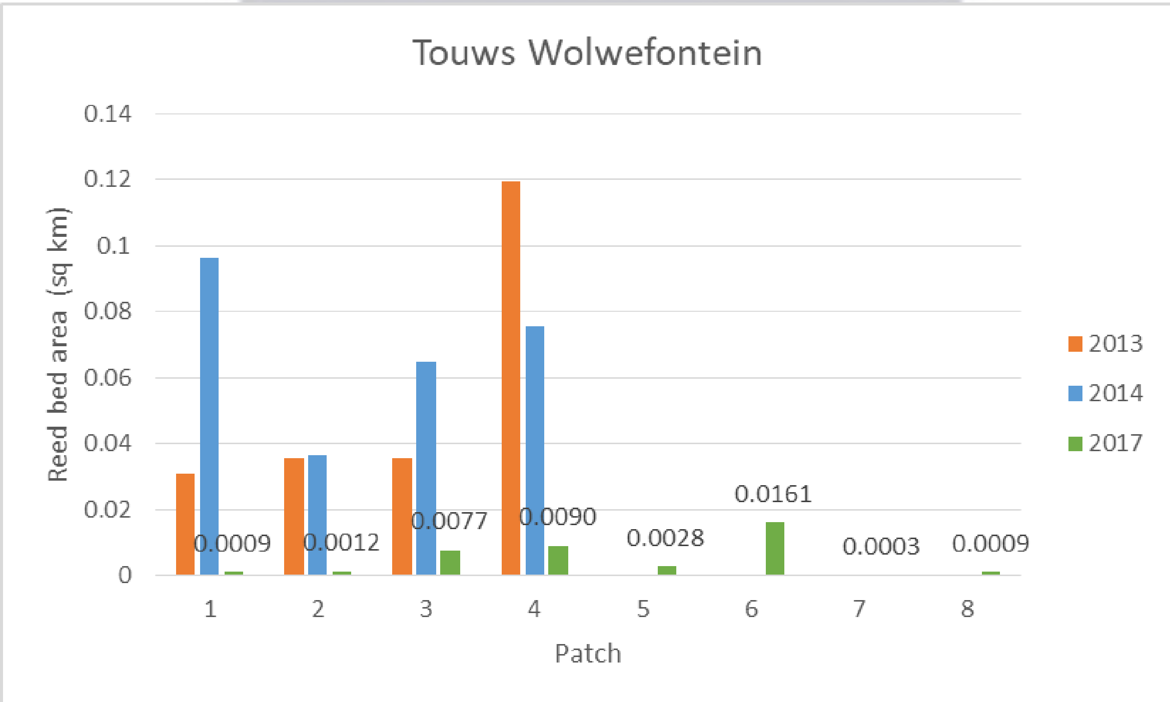


Figure 4. 17: Change in spatial extent of eight selected patches in the Touws Wolwefontein reach, starting upstream through to downstream.

Table 4.2: Change in spatial extent of reed beds along the four reaches

Reach name	Reed patch	Change in spatial extent in 2013 (sqkm)	Change in spatial extent in 2014 (sqkm)	Change in spatial extent in 2017 (sqkm)
Prins Doornbooom	1	0,117	0,250	0,065
Prins Doornbooom	2	0,004	0,015	0,049
Prins Doornbooom	3	0,006	0,001	0,010
Prins Doornbooom	4	0,003	0,073	0,011
Prins Doornbooom	5	0,000	0,003	0,001
Prins Doornbooom	6	0,011		0,011
Prins Doornbooom	7	0,018		0,002
Prins Doornbooom	8			0,023
Prinspoort	1	0,005	0,004	0,005
Prinspoort	2	0,001	0,003	0,001
Prinspoort	3	0,001	0,003	0,001
Prinspoort	4	0,000	0,005	0,001
Prinspoort	5	0,004	0,023	0,000
Prinspoort	6	0,005	0,018	0,001
Prinspoort	7	0,001		0,002
	8	0,013		0,001
Touws Plathuis	1	0,010	0,705	0,347
Touws Plathuis	2	0,926		0,002
Touws Plathuis	3			0,001
Touws Plathuis	4			0,000
Touws Plathuis	5			0,002
Touws Plathuis	6			0,001
Touws Wolwefontein	1	0,031	0,096	0,001
Touws Wolwefontein	2	0,036	0,036	0,001
Touws Wolwefontein	3	0,036	0,065	0,008
Touws Wolwefontein	4	0,119	0,076	0,009
Touws Wolwefontein	5			0,003
Touws Wolwefontein	6			0,016
Touws Wolwefontein				

Topographic Wetness Index

There is not much variation in the TWI values in the different reaches (Figure 4.18), but there is variation in the spatial pattern of flow accumulation. The Prins Doornboom reach is a large low slope area upstream of the poort (confined gorge), that has an extensive reed bed valley-bottom wetland. This can be clearly seen in image analysis in Figure 4.11, by the long stretches of in-channel reed bed. The upper Prinspoort has a more continuous swath of high TWI than the lower part of Prinspoort. The reed beds in the lower Prinspoort have increased in reed patchiness in 2017 (Figure 4.12). The Touws Plathuis and Touws Wolwefontein reaches downstream, have areas with high TWI, resulting in disconnected pools as you move downstream. This affects the distribution of the reeds found downstream, as the patchiness increases downstream at the Touws Wolwefontein (Figure 4.16).

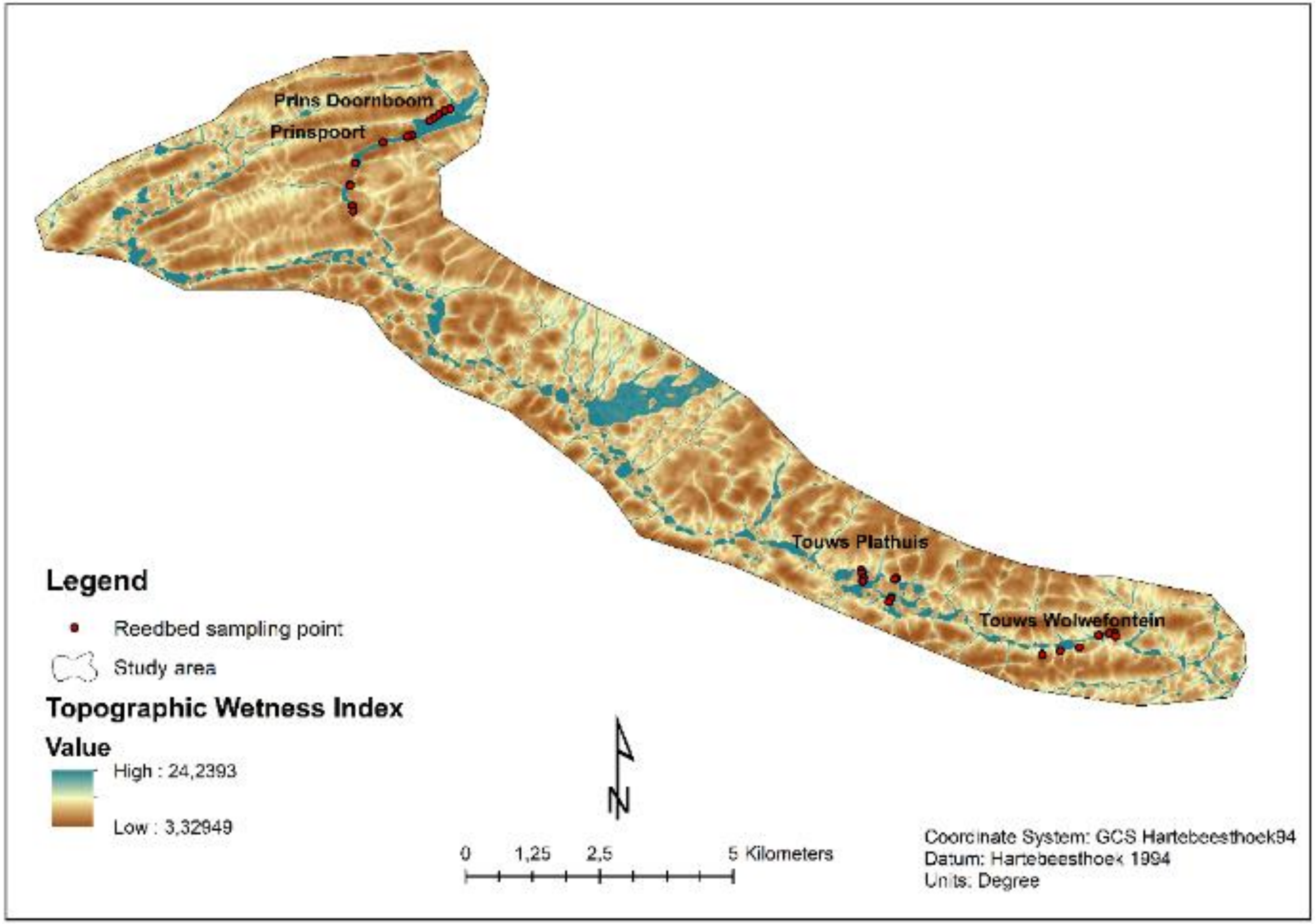


Figure 4. 18: Map showing the Topographic Wetness Index (TWI) along the Prins and Touws rivers. (Data source: SuDEM 5 m, Stellenbosch University)

Summary

The results show that geomorphological setting controls the spatial distribution and patchiness of reeds. In confined, single-thread channels, where the river is dominated by exposed bedrock the reeds are often found a distance away in small patches of sediment deposits, away from the scoured areas which have exposed bedrock with accumulated water. In these areas during flood events some of the patches are removed, however reed bed area does increase after the flood has subsided and fewer patches are observed. This reed bed area declines during periods of no flow. In wider unconfined, multi-thread channels, dominated by high sediment accumulation the reeds are often found linearly distributed along channel margins, within the channel, and across the floodplain. Shortly after a flood event these reeds increase in reed bed area and occur across the entire valley floor. In these reaches the stem characteristics, hydraulic roughness and fine sediment accumulated are positively related.

Chapter 5: Discussion

5.1 Understanding the dynamics of reed patches along non-perennial rivers

The hydrogeomorphic controls on the distribution and dynamics of reed beds in non-perennial river systems are poorly understood. This hampers our ability to manage these systems for the many ecosystem services that they provide to society (e.g. nutrient, sediment and toxicant assimilation, and provision of a reliable grazing resource in a highly climatically variable environment (Kotze *et al*., 2009)). Understanding how hydrogeomorphic controls influence the distribution and dynamics of reed beds in non- perennial rivers, will facilitate decision making related to ecological and social consequences of changes in flow of non-perennial rivers. This will lead to improved methods and management strategies for non-perennial rivers.

In this study, field measurements of the variation in channel morphology, substrate and reed bed characteristics were examined, this was coupled with the analysis of a terrain model of the landscape and aerial imagery of the variation in reed bed size and location along the Touws and Prins Rivers. Based on the results of this study, the study proposes the following sequences of changes in the longitudinal distribution and dynamics of reed beds in non-perennial river systems in response to hydrogeomorphic controls (Figure 5.1):

5.2 Reed bed distribution along geomorphological zones

Due to the valley physiographic settings that exits along non-perennial rivers, reed bed distribution also varies along the channel. Jaeger *et al*. (2017) has described different physiographic settings found along idealized non-perennial rivers as zones (Figure 5.1). The authors described the geomorphological character and sediment transport processes along non-perennial rivers within the context of four geomorphological zones – upland, piedmont, lowland and floodout.

The upland zone similar to the Prinspoort reach, is mostly characterised by a narrow channel with exposed bedrock and very little alluvium. The reed beds in this reach are often found along pool margins in areas with sufficient sediment often a distance away (e.g. Figure 4.3 g; Figure 4. 12) from the pools. These pools are often found in areas where sediment has been eroded away and only the exposed bedrock remains. Due to the lack of sufficient water and sediment the reeds in this reach do not completely fill the channel (Figure 5.1 (**1**)). During large flood most of the reeds are removed.

The Piedmont zone like the Touws Wolwefontein reach is characterised by wider valley floors than the upland zone and is dominated by alluvium and/ or bedrock (Jaeger *et al*., 2017). The majority of reeds found here grow along channel margins with a few growing within the channel on accumulated sediment (e.g. Figure 4. 6; Figure 4. 16. The presence of reeds growing on this accumulated sediment increases sediment deposition due to the increase vegetation-related hydraulic roughness (Busari and Li, 2016). Backfilling is limited in these channelled valley bottoms (Figure 5.1 (**2**)).

The Lowland zone much like the Prins Doornboom and Touws Plathuis is characterised by alluvial valleys and tends to become wider than the upland and Piedmont zones. The lowland zone is characterised by a variable mixture of alluvium and bedrock based on catchment characteristics (Jaeger *et al*., 2017). Reed beds can be found growing across the whole channel with partial backfilling (e.g. Figure 4.4; Figure 4.10). . Due to abundant sediment (the water is easily lost due to transmission losses (Jaeger *et al*., 2017) and pools do not stay long (Figure 5.1 (**3**))

The floodout zone although not covered within the reaches identified for the study is characterised by wide unchanneled valley bottom with a mixture of coarse and fine sediment load. Reeds beds can be found growing across the whole channel with complete filling and valley-bottom wetlands (Figure 5.1 (**4**)). Due to the sediments accumulated flow accumulation is divided within this reach, often leading to patchy distribution when there is insufficient water. Due to changes in lithology along N-PRs, these systems often do not follow the expected trend in zones from upstream to downstream as demonstrated by Jaeger *et al*. (2017). As the upland zone can be preceded by a zone that would ideally be locate downstream etc. This can also be observed in the Prins and Touws River systems, e.g. the Prinspoort is more upland like in structure than Prins Doornboom, yet it is located downstream.

5.3 Conceptual model of the hydrogeomorphic controls on reed bed persistence in non-perennial river systems.

The following conceptual model explain the changes in reed bed distribution. A large flood event arrives at a time when reed bed area is low after a period of no flow and grazing pressure, which limit aboveground production. Such flow causes damage to stem characteristics and some rhizomes are buried and/ or uprooted and carried away by the floods and establish elsewhere ((Mal and Narine, 2004; Meyerson *et al*., 2009), (Figure 5.2 (A)). The central part of the of rhizome system in a reed patch however is not removed due to the deep rhizome network system which has accumulated with clay cores as demonstrated by Kotschy *et al*. (2008). The sediment deposited by the floods favour the establishment of Phragmites rhizome, as buried rhizomes are able to survive and re-establish (Ailstork *et al*., 2001). These subsurface rhizome network extends beyond the pre-flood reed bed area and responds to the flood very quickly by sprouting stems up from the rhizomes (Figure 5.2 (B)). The newly established reed patches quickly join with older patches and create bigger reed patches so that soon after a large flood there is a large reed bed area.

Over time, without more floods, reed bed area shrinks again due to grazing, and due to the fact that small flows only inundate the channel or near-channel environment, so that reeds further away are reduced and cannot recover (although the rhizomes remain intact) until the next big flood. During this period there is minimal growth in biomass, rhizome growth, number of buds and offspring shoots in the older reeds during this time (Figure 4.12; Figure 4.13, patches 7 and 8) (Zhang *et al*., 2018). The large sediment deposit after a large flood event also create large channel-dividing bars in wider reaches (characterised by a less resistant rock layer) that create distinct threads of flow accumulation separated by a dry area of floodplain (Jaeger *et al*., 2017; Rountree *et al*., 2000).

The reeds then grow in these areas which have accumulated in sediment and water. The situation changes when there is some confinement (due to a resistant rock layer) and a predominantly single-thread channel exits. In these areas reeds often grow on the margins of pools but not all the way across as there may not be sufficient substrate depth in the pools for rhizomes to move across completely. The removal of reeds is also extensive in these areas. Rhizome persistence allows reed bed area to respond rapidly to large floods, and these rhizome network need a substrate to grow in. As such reeds are favoured in areas where sediment accumulates and are more likely to persist due to the buried rhizome which can extend 2 m to reach deep down water (Mal and Narine, 2004). A positive feedback between fine sediment accumulation and vegetation-related hydraulic roughness exists, which increases with sediment characteristics. Rountree *et al*. (2000) noted that during large flows, sediment is deposited in dense reed stands resulting in increased elevation. Sediment can also be deposited during periods of no flow within the reed beds through mechanisms such as wind (Rountree *et al*., 2000). This sediment accumulation therefore provides protection for the rhizome when a large flood event occurs.

5.4 Reed beds as ecosystem engineers in non-perennial river systems

As explained in the conceptual model reed beds act as ecosystem engineers in non-perennial rivers. These reeds are often the first to occupy the scoured areas with little sediment through their rhizome network. Overtime these areas accumulate sediment due to the establishment of reeds. The reeds increase the hydraulic roughness of these areas due to the dense monocultures and result in increased sediment accumulation. The accumulation of sediment can lead to different flow paths as can be seen downstream in the Touws Plathuis and Touws Wolwefontein (Figure 4.18), resulting in different bar formations. The rhizome network aids in stabilising these bar formations. Overtime other plant species can occupy some of the bars. During period of flow, reed bed also important during flood attenuation as they slowing down the floodwaters. In the Karoo reeds also offers a reliable source of grazing for cattle and offer shelter to a variety of fauna.

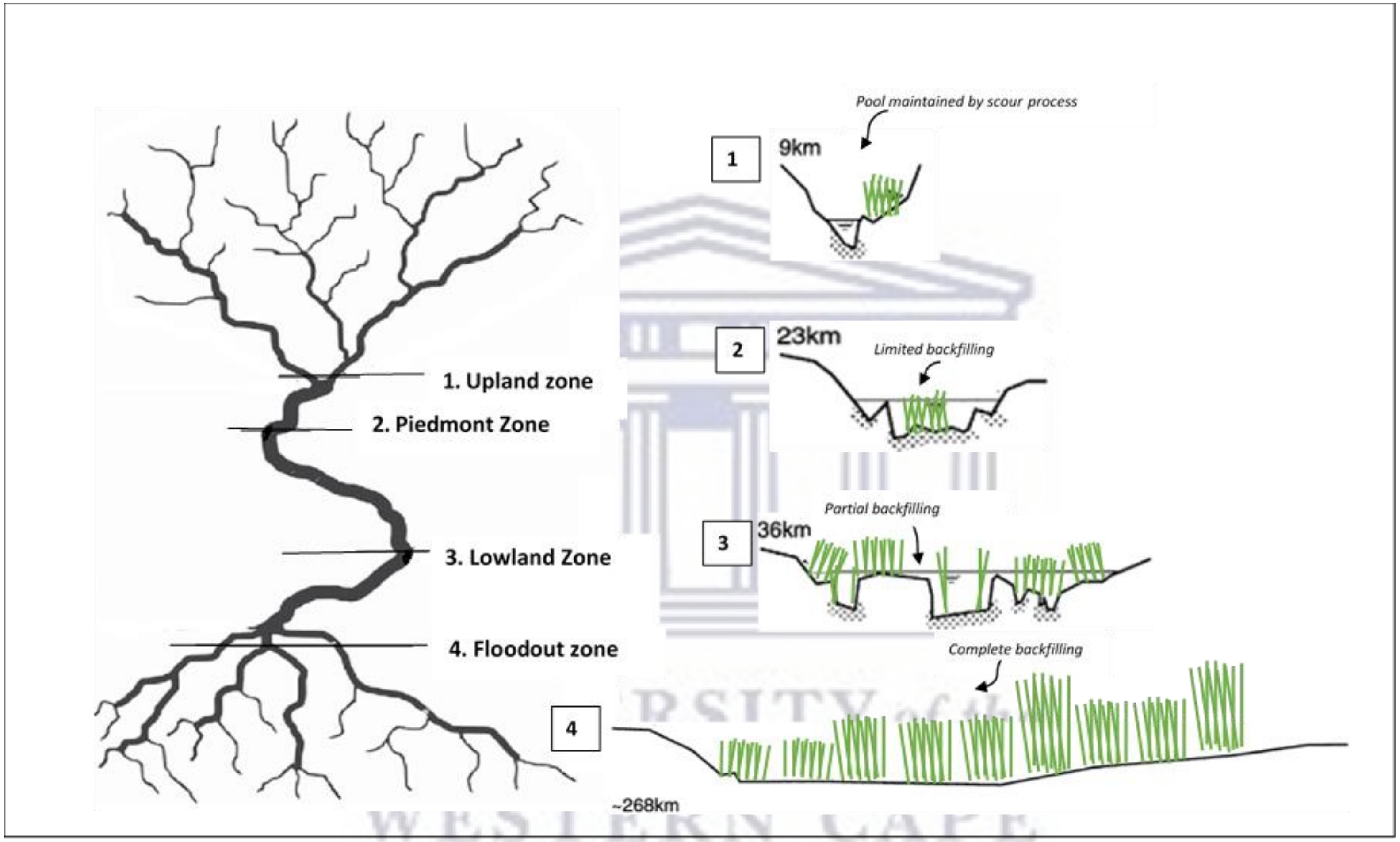


Figure 5. 1: Conceptual model showing the four geomorphological zones of an idealized non-perennial river system. (**1**) upland zone characterised by reeds growing on pool margins where sediment has accumulated. (**2**) Piedmont zone characterised by reeds within the channel. (**3**) Lowland zone characterised by reeds growing across the channel where sediment has accumulated. (**4**) floodout zone characterised by unchanneled valley bottom, reeds occupy the whole channel. The conceptual model is modified from Jaeger *et al*. (2017) and Tooth *et al*. (2000).

Figure 5. 2: (A) Exposed rhizomes from an established reed patch in the Prinspoort reach. (B) Rhizome growth in the Touws Wolwefontein reach.

Chapter 6: Conclusion and recommendations

6.1 Conclusion

The aim of this study was to understand hydrogeomorphic controls on reed bed persistence in non-perennial river systems. To achieve the aim, the study set out four objectives. The first was to characterize the valley physiographic setting, distribution, substrate characteristics and hydraulic roughness characteristics of reed beds. Secondly to document changes in the distribution of reed beds. Thirdly to investigate relationships between the identified parameters. Lastly to develop a conceptual model of the hydrogeomorphic controls on reed bed persistence in non-perennial river systems.

The results showed that reeds located in upper reaches, where the reaches are dominated by resistant rock layers, exposed bedrock with little to no sediment, most of the reeds grow along channel corridors on small heaps of sediment . These reed patches undergo slight changes in reed bed area. The reed bed patches found in these reaches remain persistent through dry and wet periods. The reeds show a reduction in area during periods of no flow . During wet periods an increase in area is observed with a slight decrease in the number of patches. Due to the low hydraulic roughness the reaches are dominated by a mixture of sediment, mainly course sediments. As a result of the lack of substrate very few in-channel bars form as the dominating process during a flood is scouring. Reaches located downstream dominated by less resistant rock layers with wider valleys were found to be multi-threaded. The reed beds here are distributed across the channel in masses of mainly fine sediment. These reaches have very large patches of reeds. However, this reed bed area decreases dramatically during periods of no flow, resulting in an increase in reed patches. Due to high hydraulic roughness, multiple in-channel bars are present and the main process taking place within these reaches is filling. This results in sharp elevational changes over short distances.

From this study it can be deduced that flooding favours the re-establishment of the reed *Phragmites australis*. As indicated by the increase in reed bed area following a flood event. The sediment and water supply provided by these flood events promotes the growth of this reed bed. No flows events are also important in reed bed persistence as they affect the accumulation of fine sediment within the reed beds, the fine sediment provide for anchorage of rhizome in preparation for a flood event. It can also be noted that the physical geomorphological setting controls the spatial distribution and patchiness of reeds. For example, in areas with no sediment, no reed beds established and in areas with abundant sediment reeds are found distributed across the channel. Therefore, in this study the presence of water in particular flood waters and sufficient fine sediment often determined by underlaying geology plays an important role in reed bed persistence in dryland rivers.

Thus, a holistic management approach is needed in the management of non-perennial river systems. One that not only looks at average flow but mimics the original flow conditions of a river should there be anthropogenic changes to the river system. As highlighted by the study all flows, including large flood events and no flow periods are important for the persistence of reed beds which provide a number of ecosystem services along non-perennial rivers. This study looked at hydrogeomorphic controls on reed bed persistence, however there a combination of factors that lead to changes in reed beds, such as eutrophication, wave action, insect attack, low genetic diversity, grazing, stem strength etc (Busari *et al*., 2016; Ostendorp, 1989; Rea, 1996). A number of these controls were not examined in this project as they are not within the scope of this project. In conclusion several interconnected factors play a role in reed bed persistence, these factors are interconnected, and management needs to take into consideration all these factors. Incorporation of a river's specific natural flow regime in environmental water allocation is necessary to ensure ecosystem functioning.

6.2 Recommendations

Results from this study resulted in interesting debates and assumptions as there is a lack of knowledge concerning the important of flooding for vegetation dynamics in non-perennial rivers, more so the lack of knowledge in the functioning of N-PRs. Some of the interesting debates include the importance of floods for reed bed growth and persistence. Flood have mainly been looked at as destructive forces, however in many cases floods are important for ecosystem functioning as highlighted by the study. In developing the conceptual model, several parameters were identified i.e., stem characteristics, flood, physiographic setting, , stem characteristics, hydraulic roughness, reed bed distribution, rhizome network, grazing pressure and draught. However, the latter three parameters were not intensity investigated and quantified in the study. Therefore, the recommendations from this study are:

- An in-depth investigation and quantification of the effects of rhizome network, grazing pressure and draught on reed bed persistence.
- Doing the same study in other dry land rivers in order to see if there is an observed pattern in all dry land rivers
- Increasing the number of quadrats per reed bed

- Investigate the influence of the water table on reed bed persistence.
- Using Drone footage in order to accurately map the distribution of reed bed, in order to clearly distinguish *P. australis* from other plant species.

Reference list

Adams, J. B., & Bate, G. C. (1999). Growth and photosynthetic performance of *Phragmites australis* in estuarine waters: a field and experimental evaluation. *Aquatic Botany, 64*(3-4), 359-367.

Ailstock, M. S., Norman, C. M., & Bushmann, P. J. (2001). Common reed Phragmites australis: control and effects upon biodiversity in freshwater nontidal wetlands. *Restoration Ecology*, 9(1), 49-59.

Albayrak, I., Nikora, V., Miler, O., & O'Hare, M. (2012). Flow-plant interactions at a leaf scale: effects of leaf shape, serration, roughness and flexural rigidity. *Aquatic sciences*, *74*(2), 267-286.

Asaeda, T., & Karunaratne, S. (2000). Dynamic modelling of the growth of *Phragmites australis*: model description. *Aquatic Botany*, *67*(4), 301-318.

Baker, V. R. (1977). Stream-channel response to floods, with examples from central Texas. *Geological Society of America Bulletin*, *88*(8), 1057-1071.

Baldwin, A. H., Kettenring, K. M., & Whigham, D. F. (2010). Seed banks of *Phragmites australis*-dominated brackish wetlands: relationships to seed viability, inundation, and land cover. *Aquatic Botany*, *93*(3), 163-169.

Ballerine, C. (2017). Topographic Wetness Index Urban Flooding Awareness Act Action Support, Will & DuPage Counties, Illinois. Illinois State Water Survey.

Baptist, M. J., Babovic, V., Rodríguez Uthurburu, J., Keijzer, M., Uittenbogaard, R. E., Mynett, A., & Verwey, A. (2007). On inducing equations for vegetation resistance. *Journal of Hydraulic Research*, *45*(4), 435-450.

Baptist, M. J., de Groot, A. V., & van Duin, W. E. (2016). Contrasting biogeomorphic processes affecting salt-marsh development of the Mokbaai, Texel, The Netherlands. *Earth Surface Processes and Landforms*, *41*(9), 1241-1249.

Biggs, B. J. (1996). Hydraulic habitat of plants in streams. *Regulated Rivers: research & management*, *12*(2-3), 131-144.

Bonada, N., & Resh, V. H. (2013). Mediterranean-climate streams and rivers: geographically separated but ecologically comparable freshwater systems. *Hydrobiologia*, *719*(1), 1-29.

Breede-Grouritz Catchment Management Agency, (2016). Annual Report. South Africa. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwi

XlOrG0cDjAhWYSBUIHTJgBxUQFjAAegQIAhAC&url=http%3A%2F%2Fbgcma.co.za%2Fwp-content%2Fuploads%2F2017%2F02%2FBGCMA-Annual-Report-2015-2017.pdf&usg=AOvVaw146YRSDfxzcFZGeSb4GlLW, Accessed 19 July 2019.

Briggs, D. (1997). Sediments. Butterworths, London, UK. 190 pp.

Brooks, A. P., & Brierley, G. J. (2002). Mediated equilibrium: the influence of riparian vegetation and wood on the long-term evolution and behaviour of a near-pristine river. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 27(4), 343-367.

Burdick, D. M., Buchsbaum, R., & Holt, E. (2001). Variation in soil salinity associated with expansion of Phragmites australis in salt Fmarshes. *Environmental and Experimental Botany*, *46*(3), 247-261.

Busari, A. O., & Li, C. W. (2016). Bulk drag of a regular array of emergent blade-type vegetation stems under gradually varied flow. *Journal of Hydro-environment Research*, *12*, 59-69.

Carter, A. J., & Rogers, K. H. (1995). A Markovian approach to investigating landscape change in the Kruger National Park Rivers. *Report*, *2*, 95.

Chambers, R. M., Mozdzer, T. J., & Ambrose, J. C. (1998). Effects of salinity and sulfide on the distribution of Phragmites australis and Spartina alterniflora in a tidal saltmarsh. *Aquatic Botany*, *62*(3), 161-169.

Cheng, K., Zang, R., Zhou, X., Zhang, W., & Bai, Z. (2007). Influence of floods on natural riparian forests along the Ergis River, west China. *Frontiers of Forestry in China*, *2*(1), 66-71.

Coombes, M. A. (2016). Biogeomorphology: diverse, integrative and useful. *Earth Surface Processes and Landforms*, *41*(15), 2296-2300.

Corenblit, D., Steiger, J., Charrier, G., Darrozes, J., Garófano-Gómez, V., Garreau, A., & Lambs, L. (2016). Populus nigra L. establishment and fluvial landform construction: biogeomorphic dynamics within a channelized river. *Earth Surface Processes and Landforms*, *41*(9), 1276-1292.

Corenblit, D., Steiger, J., Gurnell, A. M., Tabacchi, E., & Roques, L. (2009). Control of sediment dynamics by vegetation as a key function driving biogeomorphic succession within fluvial corridors. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *34*(13), 1790-1810.

Costa, J. E. (1987). Hydraulics and basin morphometry of the largest flash floods in the conterminous United States. *Journal of hydrology*, *93*(3-4), 313-338.

Datry, T., Larned, S. T., & Tockner, K. (2014). Intermittent rivers: a challenge for freshwater ecology. *BioScience*, *64*(3), 229-235.

Department of Water Affairs (DWA), (2014). Reserve Determination Studies for Surface Water, Groundwater, Estuaries and Wetlands in the Gouritz Water Management Area: Desktop EcoClassification Report. Prepared by Scherman Colloty & Associates. Report no. RDM/WMA16/00/CON/0213.

Department of Water Affairs and Forestry, South Africa. (2004). Gouritz Water Management Area: Internal Strategic Perspective. Prepared by Ninham Shand (Pty) Ltd in association with Jakoet & Associates and Umvoto Africa, on behalf of the Directorate: National Water Resource Planning. DWAF Report No P WMA16/000/00/0304.

Edmaier, K., Crouzy, B., Ennos, R., Burlando, P., & Perona, P. (2014). Influence of root characteristics and soil variables on the uprooting mechanics of Avena sativa and Medicago sativa seedlings. *Earth Surface Processes and Landforms*, *39*(10), 1354-1364.

Engloner, A. I. (2009). Structure, growth dynamics and biomass of reed (*Phragmites australis*)–A review. *Flora-Morphology, Distribution, Functional Ecology of Plants*, *204*(5), 331-346.

Erskine, W., Chalmers, A., Keene, A., Cheetham, M., & Bush, R. (2009). Role of a rheophyte in bench development on a sand-bed river in southeast Australia. *Earth Surface Processes and Landforms*, *34*(7), 941-953.

Folkard, A. M. (2011). Vegetated flows in their environmental context: a review. *Proceedings of the Institution of Civil Engineers-Engineering and Computational Mechanics*, *164*(1), 3-24.

Frankenberg, J. (1997). Guidelines for growing *Phragmites* for erosion control. *Murray-Darling Freshwater Research Centre.*

Gibbs Russell, G.E., Watson, L., Koekemoer, M., Smook, L., Barker, N.P., Anderson, H.M. & Dallwitz, M.J. (1990). Grasses of southern Africa. M*emoirs of the Botanical Survey of South* Africa, No. 58.

Gibling, M. R., & Davies, N. S. (2012). Palaeozoic landscapes shaped by plant evolution. *Nature Geoscience*, *5*(2), 99.

Gordon, N. D., McMahon, T. A., Finlayson, B. L., & Gippel, C. J. (2004). Stream hydrology: an introduction for ecologists. *John Wiley and Sons*.

Graf, W. L. (1978). Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. *Geological Society of America Bulletin*, *89*(10), 1491-1501.

Graf, W. L. (1988). Fluvial processes in dryland rivers (p. 346). New York: Springer-Verlag.

Gran, K. B., Tal, M., & Wartman, E. D. (2015). Co-evolution of riparian vegetation and channel dynamics in an aggrading braided river system, Mount Pinatubo, Philippines. *Earth Surface Processes and Landforms*, *40*(8), 1101-1115.

Grenfell, M. C., Ellery, W. N., & Grenfell, S. E. (2009). Valley morphology and sediment cascades within a wetland system in the KwaZulu-Natal Drakensberg Foothills, Eastern South Africa. *Catena*, 78(1), 20-35.

Grenfell, S. E., Grenfell, M. C., Rowntree, K. M., & Ellery, W. N. (2014). Fluvial connectivity and climate: A comparison of channel pattern and process in two climatically contrasting fluvial sedimentary systems in South Africa. *Geomorphology*, 205, 142-154.

Gurnell, A. (2014). Plants as river system engineers. *Earth Surface Processes and Landforms*, *39*(1), 4-25.

Gurnell, A. M., Bertoldi, W., & Corenblit, D. (2012). Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel Bed Rivers. *Earth-Science Reviews*, *111*(1-2), 129-141.

Gurnell, A. M., O'Hare, J. M., O'Hare, M. T., Dunbar, M. J., & Scarlett, P. M. (2010). An exploration of associations between assemblages of aquatic plant morphotypes and channel geomorphological properties within British rivers. *Geomorphology*, *116*(1-2), 135-144.

Harvey, G. L., Henshaw, A. J., Moorhouse, T. P., Clifford, N. J., Holah, H., Grey, J., & Macdonald, D. W. (2014). Invasive crayfish as drivers of fine sediment dynamics in rivers: field and laboratory evidence. *Earth Surface Processes and Landforms*, *39*(2), 259-271.

Haslam, S. M. (2009). (Eds.). The reed. Brown & Co., Old Bank of England Court, Queen Street, Norwich.

Haslam, S.M., 1972. Phragmites communis Trin. (Arundo phragmites L.,? *Phragmites australis* (Cav.) Trin. ex Steudel). *Journal of Ecology*, 60(2), pp.585-610.

Heritage, G. L., Large, A. R. G., Moon, B. P., & Jewitt, G. (2004). Channel hydraulics and geomorphic effects of an extreme flood event on the Sabie River, South Africa. *Catena*, *58*(2), 151-181.

Hesp, P.A., 1991. Ecological processes and plant adaptations on coastal dunes. J. Arid Environ. 21, 165–191

Hojati, M., & Mokarram, M. (2016). Determination of a topographic wetness index using high resolution digital elevation models. European Journal of Geography, 7(4), 41-52.

Holmes, N. T. H., Boon, P. J., & Rowell, T. A. (1998). A revised classification system for British rivers based on their aquatic plant communities. *Aquatic Conservation: marine and freshwater ecosystems*, *8*(4), 555-578.

Jacobs, K., & Jangle, R. (2008). Ecosystem Management Plan: Guide Tool. *Unpublished, The Nature Conservation Corporation, Cape Town*.

Jacobson, P. J., & Jacobson, K. M. (2013). Hydrologic controls of physical and ecological processes in Namib Desert ephemeral rivers: implications for conservation and management. *Journal of Arid Environments*, *93*, 80-93.

Jaeger, K. L., Sutfin, N. A., Tooth, S., Michaelides, K., & Singer, M. (2017). Geomorphology and sediment regimes of intermittent rivers and ephemeral streams. In *Intermittent Rivers and Ephemeral Streams* (pp. 21-49).

James, C. S., Birkhead, A. L., Jordanova, A. A., Kotschy, K. A., Nicolson, C. R., & Makoa, M. J. (2001). Interaction of reeds, hydraulics and river morphology. *Water Research Commission Report*, *856*(1), 01.

Jones, C. G. (2012). Ecosystem engineers and geomorphological signatures in landscapes. *Geomorphology*, *157*, 75-87.

Jones, C. G., Lawton, J. H., & Schachak, M. (1994). Organisms as ecosystem engineers Oikos 69, 373–386. *Google Scholar*.

Junk, W. J., Bayley, P. B., & Sparks, R. E. (1989). The flood pulse concept in river-floodplain systems. *Canadian special publication of fisheries and aquatic sciences*, *106*(1), 110-127.

Kawasaki, M., Nobuchi, T., Nakafushi, Y., Nose, M., & Shiojiri, M. (2015). Structure and biomechanics of culms of Phragmites australis used for reeds of J apanese wind instrument "hichiriki". *Microscopy research and technique*, *78*(4), 260-267.

Köbbing, J. F., Thevs, N., & Zerbe, S. (2013). The utilisation of reed (Phragmites australis): a review. *Mires & Peat*, *13*.

Kotschy, K. A., Rogers, K. H., & Carter, A. J. (2000). Patterns of change in reed cover and distribution in a seasonal riverine wetland in South Africa. *Folia Geobotanica*, *35*(4), 363-373.

Kotschy, K., & Rogers, K. (2008). Reed clonal characteristics and response to disturbance in a semi-arid river. *Aquatic Botany*, *88*(1), 47-56.

Kotze, D., Marneweck, G., Batchelor, A., Lindley, D., & Collins, N. (2009). WET-EcoServices: a technique for rapidly assessing ecosystem services supplied by wetlands. *Water Research Commission*, report TT 339/09.

Larkin, Z. T., Ralph, T. J., Tooth, S., & McCarthy, T. S. (2017). The interplay between extrinsic and intrinsic controls in determining floodplain wetland characteristics in the South African drylands. *Earth Surface Processes and Landforms*, 42(7), 1092-1109.

Larned, S. T., Datry, T., Arscott, D. B., & Tockner, K. (2010). Emerging concepts in temporary-river ecology. *Freshwater Biology*, *55*(4), 717-738.

Leigh, C., Boulton, A. J., Courtwright, J. L., Fritz, K., May, C. L., Walker, R. H., & Datry, T. (2016). Ecological research and management of intermittent rivers: an historical review and future directions. *Freshwater Biology*, *61*(8), 1181-1199.

Lytle, D. A., & Poff, N. L. (2004). Adaptation to natural flow regimes. *Trends in ecology & evolution*, *19*(2), 94-100.

Mal, T. K., & Narine, L. (2004). The biology of Canadian weeds. 129. Phragmites australis (Cav.) Trin. ex Steud. *Canadian Journal of Plant Science*, *84*(1), 365-396.

McDonough, O. T., Hosen, J. D., & Palmer, M. A. (2011). Temporary streams: the hydrology, geography, and ecology of non-perennially flowing waters. *River Ecosystems: Dynamics, management and conservation*, 259-290.

Meyer, J. L., Strayer, D. L., Wallace, J. B., Eggert, S. L., Helfman, G. S., & Leonard, N. E. (2007). The contribution of headwater streams to biodiversity in river networks1. *JAWRA Journal of the American Water Resources Association*, *43*(1), 86-103.

Meyerson, L. A., Saltonstall, K., Chambers, R. M., Silliman, B. R., Bertness, M. D., & Strong, D. (2009). Phragmites australis in eastern North America: a historical and ecological perspective. *Salt marshes under global siege*, 57-82.

Miall, A. D., & Gibling, M. R. (1978). The Siluro-Devonian clastic wedge of Somerset Island, Arctic Canada, and some regional paleogeographic implications. *Sedimentary Geology*, *21*(2), 85-127.

Mucina, L., & Rutherford, M. C. (2006). The vegetation of South Africa, Lesotho and Swaziland. *South African National Biodiversity Institute*.

Murray, A. B., & Paola, C. (1994). A cellular model of braided rivers. *Nature*, *371*(6492), 54.

Nanson, G. C., Tooth, S., Knighton, A. D., Bull, L. J., & Kirkby, M. J. (2002). A global perspective on dryland rivers: perceptions, misconceptions and distinctions. *Dryland rivers: hydrology and geomorphology of semi-arid channels*, 17-54.

Nilsson, C., & Svedmark, M. (2002). Basic principles and ecological consequences of changing water regimes: riparian plant communities. *Environmental management*, *30*(4), 468-480.

O'Hare, M. T., Mountford, J. O., Maroto, J., & Gunn, I. D. M. (2016). Plant traits relevant to fluvial geomorphology and hydrological interactions. *River Research and Applications*, *32*(2), 179-189.

Oliveira, P. C. D., Torezan, J. M. D., & Cunha, C. N. D. (2015). Effects of flooding on the spatial distribution of soil seed and spore banks of native grasslands of the Pantanal wetland. *Acta Botanica Brasilica*, *29*(3), 400-407.

Palmer, A. R., & Ainslie, A. M. (2005). Grasslands of South Africa. *Grasslands of the World*, *34*, 77.

Parker, G. (1976). On the cause and characteristic scales of meandering and braiding in rivers. *Journal of fluid mechanics*, *76*(3), 457-480.

Philipp, K. R., & Field, R. T. (2005). *Phragmites australis* expansion in Delaware Bay salt marshes. *Ecological Engineering*, *25*(3), 275-291.

Poff, N. L., & Ward, J. V. (1989). Implications of streamflow variability and predictability for lotic community structure: a regional analysis of streamflow patterns. *Canadian journal of fisheries and aquatic sciences*, *46*(10), 1805-1818.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., ... & Stromberg, J. C. (1997). The natural flow regime. *BioScience*, *47*(11), 769-784.

Poff, N. L., Olden, J. D., Merritt, D. M., & Pepin, D. M. (2007). Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences*, *104*(14), 5732-5737.

Polvi, L. E., Wohl, E., & Merritt, D. M. (2014). Modeling the functional influence of vegetation type on streambank cohesion. *Earth Surface Processes and Landforms*, *39*(9), 1245-1258.

Powell, D. M. (2009). Dryland rivers: processes and forms. In *Geomorphology of desert environments* (pp. 333-373). Springer, Dordrecht.

Puijalon, S., Bouma, T. J., Douady, C. J., van Groenendael, J., Anten, N. P., Martel, E., & Bornette, G. (2011). Plant resistance to mechanical stress: evidence of an avoidance–tolerance trade-off. *New Phytologist*, *191*(4), 1141-1149.

Rea, N. (1996). Water levels and Phragmites: decline from lack of regeneration or dieback from shoot death. *Folia Geobotanica*, *31*(1), 85-90.

Reinecke, M. K., Brown, C. A., Esler, K. J., King, J. M., Kleynhans, M. T., & Kidd, M. (2015). Links between lateral vegetation zones and river flow. *Wetlands*, *35*(3), 473-486.

River Health Programme (2007). State of Rivers Report: Rivers of the Gouritz Water Management Area. Department of Water Affairs and Forestry, Pretoria ISBN No: 0-620-38676-0

Robertson, H. A., & James, K. R. (2007). Plant establishment from the seed bank of a degraded floodplain wetland: a comparison of two alternative management scenarios. *Plant Ecology*, *188*(2), 145-164.

Rossouw, L., Avenant, M. F., Seaman, M. T., King, J. M., Barker, C. H., Du Preez, P. J., ... & Watson, M. (2005). *Environmental water requirements in non-perennial systems*. Pretoria: Water Research Commission.

Rountree, M. W., Rogers, K. H., & Heritage, G. L. (2000). Landscape state change in the semi-arid Sabie River, Kruger National Park, in response to flood and drought. *South African Geographical Journal*, *82*(3), 173-181.

Seaman, M. T., Avenant, M. F., Watson, M., King, J., Armour, J., Barker, C. H.,... & Van Tonder, G. (2010). Developing a method for determining the environmental water requirements for non-perennial systems. *Water Research Commission Report No. TT459/10, ISBN*, 978-1.

Skoulikidis, N. T., Sabater, S., Datry, T., Morais, M. M., Buffagni, A., Dörflinger, G. ... & Rosado, J. (2017). Non-perennial Mediterranean rivers in Europe: status, pressures, and challenges for research and management. *Science of The Total Environment*, *577*, 1-18.

Stanley, E. H., Fisher, S. G., & Grimm, N. B. (1997). Ecosystem expansion and contraction in streams. *BioScience*, *47*(7), 427-435.

Surian, N., Barban, M., Ziliani, L., Monegato, G., Bertoldi, W., & Comiti, F. (2015). Vegetation turnover in a braided river: frequency and effectiveness of floods of different magnitude. *Earth Surface Processes and Landforms*, *40*(4), 542-558.

Thornes, J. B. (1990). The interaction of erosional and vegetational dynamics in land degradation: spatial outcomes. *Vegetation and erosion. Processes and environments.*, 41-53.

Thrush, Paul W. (ed.), 1968, A Dictionary of Mining, Mineral and Related Terms. U.S. Bureau of Mines, *Department of the Interior*. https://www.mindat.org/glossary/feldspathic_sandstone

Tooth, S. (2000). Downstream changes in dryland river channels: the Northern Plains of arid central Australia. Geomorphology, 34(1-2), 33-54.

Tooth, S. (2000). Process, form and change in dryland rivers: a review of recent research. *Earth-Science Reviews*, *51*(1-4), 67-107.

Tooth, S. (2018). The geomorphology of wetlands in drylands: Resilience, nonresilience, or…?. *Geomorphology*, 305, 33-48.

Tooth, S., & McCarthy, T. S. (2007). Wetlands in drylands: geomorphological and sedimentological characteristics, with emphasis on examples from southern Africa. Progress in Physical Geography, 31(1), 3-41.

Tooth, S., & Nanson, G. C. (2000). The role of vegetation in the formation of anabranching channels in an ephemeral river, Northern plains, arid central Australia. *Hydrological processes*, *14*(16-17), 3099-3117.

Tooth, S., McCarthy, T. S., Brandt, D., Hancox, P. J., & Morris, R. (2002). Geological controls on the formation of alluvial meanders and floodplain wetlands: the example of the Klip River, eastern Free State, South Africa. Earth Surface Processes and Landforms: *The Journal of the British Geomorphological Research Group*, 27(8), 797-815.

Tooth, S., McCarthy, T., Rodnight, H., Keen-Zebert, A., Rowberry, M., & Brandt, D. (2014). Late Holocene development of a major fluvial discontinuity in floodplain wetlands of the Blood River, eastern South Africa. *Geomorphology*, 205, 128-141.

Tooth, S., Nanson, G.C., 2011. Distinctiveness and diversity of arid zone river systems. In: Thomas, D.S.G. (Ed.), Arid Zone Geomorphology: Process, Form and Change in Drylands, third ed. *Wiley-Blackwell*, Chichester, pp. 269–300.

Van Dijk, W. M., Teske, R., Van de Lageweg, W. I., & Kleinhans, M. G. (2013). Effects of vegetation distribution on experimental river channel dynamics. *Water Resources Research*, *49*(11), 7558-7574.

Weisner, S. E., & Ekstam, B. (1993). Influence of germination time on juvenile. *Aquatic Botany*, *45*(1), 07-118.

Wolman, M. G., & Gerson, R. (1978). Relative scales of time and effectiveness of climate in watershed geomorphology. *Earth surface processes*, *3*(2), 189-208.

Zhang, N., Zhang, J., Li, Z., Chen, J., Zhang, Z., & Mu, C. (2018). Resistance strategies of *Phragmites australis* (common reed) to Pb pollution in flood and drought conditions. *PeerJ*, 6, e4188.