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Estimating the Potential for Natural Ecosystem Recovery at the Pietersielieskloof Palmiet Wetland, Western Cape.

By

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II. ABSTRACT

Recent research has highlighted the importance of cut-and-fill cycles in valley-bottom wetlands. This study considers the impact of longitudinal and lateral sediment connectivity on the natural recovery potential of valley-bottom wetlands. Pietersielieskloof is a *Prionium serratum* (commonly known as palmiet) dominated discontinuous valley-bottom wetland. *P. serratum* is considered to be a peat-forming ecosystem engineer that enhances sediment infill in valley-bottom wetlands. Due to its ecological importance and potential as a carbon store, this wetland has been earmarked for rehabilitation by Working for Wetlands. The study ascertains the importance of including sedimentological and geomorphological input in wetland rehabilitation and management strategies. A study of wetland geomorphology was conducted to develop an understanding of the natural dynamic of cut-and-fill processes as context for recent erosion and deposition events. Sediment samples from gully walls and cores were collected for organic content and particle size analysis and five sediment samples predating the current phase of erosion were radiocarbon dated. The valley form was surveyed using cross-sections and long profiles, and historical change was digitised using 30 m – 5 to 30 mm resolution aerial imagery from 1938-2016 in ArcMap. The Pietersielieskloof wetland valley floor is near-horizontal and widening in the upstream reaches. Bedrock is exposed on the gully floor in some places. Recent erosion has widened the valley floor which is now 15 m wide and cut 6m deep into alluvium in parts of the meandering reach. The study also found that *P. serratum* has not formed thick peat deposits compared to other palmiet wetlands, and the sediment deposits are predominantly medium-grained sand. The dating revealed 5 palaeo-depositional cycles ranging in age from 329 - 6098 BP from carbon dating. Impoundment by the road caused a scoured supply of sediment from upstream erosion that appears to have overwhelmed the flow path through culverts, and the sediment has accumulated behind the road fill, reducing sediment supply to downstream reaches. The loss of catchment surface vegetation may have intensified the persistence, duration, and

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severity of erosion. Recovery in Pietersielieskloof depends on the improvement in longitudinal sediment supply from upstream of the road, thus reducing sediment-load carrying capacity and increasing the speed of flow. Sediment must be deposited in lower wetland reaches, and the capacity of peak season wetland flows must be low enough to favour sediment deposition in sink zones within the wetland. Informed catchment management, such as improving and defining appropriate designs for road crossing and for managing run-off after alien vegetation has been cleared is essential for the recovery of cut-and-fill wetlands, whether there is active on-site restoration or not.

KEYWORDS: Cut-and-fill cycles, Geomorphic Controls, Palmiet, Rehabilitation.

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This thesis is dedicated to my supervisor, Dr Suzanne Grenfell.

"As long as I live, I will hear waterfalls, birds and wind sing. I'll interpret the rocks and learn the language of the flood, storm and the avalanche. I'll acquaint myself with the glaciers and wild gardens and get as near to the heart of the earth as I can." --- **John Muir**

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VI. LIST OF TABLES

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VII. ACRONYMS, TERMS AND ABBREVIATIONS

AMS	: Accelerator Mass Spectrometry
BP	: Before Present
CARA	: Conservation of Agricultural Resources Act
CHIRPS	: The Climate Hazards Group Infrared Precipitation with Station data
DGPS	: Differential Geographical Positioning System
ECA	: Environment Conservation Act
MYO	: Million Years Old
NEMA	: National Environmental Management Act
NFA	: National Forests Act
NGI	: National Geo-spatial Information
NSMA	: Nuwejaars Special Management Area
NWA	: National Water Act
OSL	: Optically Stimulated Luminescence
SANBI	: South African National Biodiversity Institute
WfWetlands	: Working for Wetlands
WRC	: Water Research Commission

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GLOSSARY/TERMINOLOGY IN THE THESIS

Abrasion: The action of water eroding away bedrock and the banks and transporting heavy sediment loads as the river flows downstream.

Aggradation: Sediment accumulation where the amount of sediment exceeds the energy the river has to transport the sediment load.

Allogeneic: Sediment transported to its present location from elsewhere.

An active river: A river that is actively eroding and depositing sediments

Autogenic: Self-generated sediments/controls

Avulsion: The process of channel abandonment for a new channel due to change in slope and water supply

Cut-and-fill cycles: repeated successions of erosion and deposition

Cut-off: Usually of a meandering river isolated from the main channel creating an oxbow lake.

Degradation: The fragmentation of a system including lowered bedrock through erosional processes.

Extrinsic: Outside of the system's natural behaviour.

Floodout: Occur where a channel deposits sediment along its banks in wetlands, especially after high rainfall.

Lateral erosion: Erosion along the bank-channel direction, widening the valley.

Natural recovery: Recovery from erosion without external intervention.

Peat soil: In South Africa, peat soils have more than 10% organic carbon.

Resilience: The capacity of a system to resist or recover from a disturbance.

Sediment connectivity: The ability of sediment to be transported and deposited across the reaches within the system.

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Sediment slug: The movement of volumes of sediment.

Threshold: The intensity or amount of change a system must surpass before a major change in equilibrium occurs and the system loses resilience.

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VIII. SOURCES OF DATA

Table 1: A summary of the data gathered for this research

SECONDARY DATA	PRIMARY DATA
Aerial photos	Sediment samples collected
Carbon dating results	Cross-sectional and long profile data
5m contours	
Geology, land cover and quaternary catchment shapefiles	

In the instance of the carbon data, although the sediment was collected by the researcher, the data was analysed by AMS Dating

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Table 2: Sources of the data used in the thesis

DATA	SOURCE
5m Contours and trig beacons	Department of Rural Development and Land Reform National Geospatial Institute (DRDLR NGI) digitised from 1:50 000 topographic maps
Overberg Wetlands shapefiles	South African National Biodiversity Institute Biodiversity-GIS (SANBI-BGIS)
Aerial Photos (1949-2016) 1938 - 1949 – 1:60 000 Job 228 1961 – 1:35 000 Job 461 1989 – 1:50 000 Job 931 2003 – 1:50 000 Job 1074 2010 – GSD 0,5 Job 3419B_2010_326 2014 - GSD 0,5 Job 3419B_2014_708 2016 - GSD 0,5 Job 3419B_2016_1154	Department of Rural Development and Land Reform National Geospatial Institute (DRDLR NGI) Cape Town and Pretoria Offices
G50B Nuwejaars Quaternary Catchment Shapefile from 1:50 000 scale	Department of Rural Development and Land Reform National Geospatial Institute (DRDLR NGI) - digitised from

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	3418_2010_326 ortho-rectified aerial photos
Roads, Forests and woodlands, Orchards and Vineyards shapefiles from 1:50 000 scale	Department of Rural Development and Land Reform National Geospatial Institute (DRDLR NGI) - digitised from 3418_2010_326 orthorectified aerial photos
Geology contacts and lithology data from 1:100 000 scale	Council for Geoscience (CGS) website
Rainfall data 1981-2018 CHIRPS 0,5 resolution	United States Geological Survey (USGS)
SRTM 30m DEM data	United States Geological Survey (USGS) Explorer

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IX. STRUCTURE OF THE THESIS

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CHAPTER SEVEN	**CONCLUSIONS**

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X. OVERVIEW OF THE CHAPTERS

CHAPTER ONE

This chapter introduces the scope of the research and its limitations. This chapter will explain how the study will attempt to highlight the importance of understanding geomorphic controls prior to wetland rehabilitation.

CHAPTER TWO

This chapter is the literature review section which looks at different perspectives on the topic, including literature on some of the methodologies employed in the past, some of the debates and limitations and the gaps present in these types of studies.

CHAPTER THREE

Chapter three introduces the regional setting of the study area, including the climate and geology. It provides a background to the type of landscape and environment under which the area of focus is found.

CHAPTER FOUR

Chapter four is the Methods section and focuses on the methods and materials, procedures, types of data and how the data will be collected including consideration of previous research methods from other studies.

CHAPTER FIVE

This section puts forward the results from the data collected and attempts to display the important categories and relationships shown by the results.

CHAPTER SIX

This chapter concludes the thesis, discussing and analysing the results with possible recommendations and way forward.

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I. CHAPTER ONE

1. INTRODUCTION AND THEORETICAL FRAMEWORK

1.1. Background to the Research Question

Globally, wetland research has tended to focus on ecology (e.g. Zedler, 2000; Lubke and Hertling, 2001; Sieben, *et al.*, 2016), which is often ranked as of greater importance in the assessment of wetland health in comparison to wetland geomorphology. Water and sediment are two very important drivers of wetland ecosystems but management tends to focus on the wetland hydrology and often neglects the importance of sediment (Wohl *et al.*, 2005). As a result, management strategies do not often include an assessment of wetland geomorphology. As a result, they risk the chance of imposing a one-size-fits-all rehabilitation approach along wetlands of varying hydrogeomorphic types, which can render rehabilitation a fruitless and wasteful expenditure should the wetland system's natural processes and dynamics not be properly understood.

Wetlands in drylands such as those in South Africa are climatically complex, sensitive and it is difficult to predict their behaviour (Tooth, 2018), and they are prone to degradation from both natural and anthropogenic activities (Knight and Holmes, 2018). Since dryland wetlands are climatically and geologically complex in Southern Africa (Tooth and McCarthy, 2007), it is often important to first understand each one in terms of what aspects are the most crucial for its ecosystem integrity and biophysical functioning. In dryland wetlands, geomorphology is a fundamental driver that is at least of equal status to hydrology, and it is, therefore, essential to improve our understanding of geomorphic processes in different wetlands.

Fluvial studies on wetland geomorphology and sediment processes have been increasing more recently (e.g. Tooth and McCarthy, 2007; Grenfell, *et al.*, 2009a; Tooth, 2018; Pulley *et al.* 2018; Wohl, 2018). However, further research on how geomorphological and sedimentological dynamics of valley-bottoms influence wetland erosion and deposition cycles is still required, especially with regards to understanding geomorphic thresholds and wetland resilience (Tooth, 2018). South Africa, through the Department of Environment, Forestry and Fisheries (DEFF)'s Working for Wetlands (WfWetlands) initiative, has invested millions of rands into wetland

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protection and rehabilitation (Working for Wetland Programme, 2018). The WfWetlands initiative was created to support, guard, rehabilitate, and protect the integrity of wetlands in South Africa through the collaboration between government and state entities, and other stakeholders such as the collaboration with SANBI and WRC (Cowden *et al.,* 2014). By understanding how a system works, we can attempt to predict a system's processes, its resilience, and its ability to naturally recover from disturbances that warrant these rehabilitation interventions. The most widely used South African wetland classification system is likely the one from Ollis *et al. (*2013) called 'The Classification System for Wetlands and Other Aquatic Ecosystems in South Africa'. This classification system categorises wetlands only according to their respective hydrogeomorphic units. In this classification system, two types of valley-bottom wetlands are identified; unchanneled and channelled valley-bottom wetlands.

Palmiet wetlands are a type of valley-bottom wetland common within the Cape Fold Belt; however, there is a paucity of published research on understanding palmiet valley-bottom wetlands in terms of their geomorphology, or their capacity to naturally recover from disturbances such as intense erosion. The Pietersielieskloof Wetland is degrading and interventions are being put in place, and yet there is inadequate knowledge about wetland geomorphology and wetland processes. This research characterises sedimentological processes of the Pietersielieskloof palmiet valley-bottom wetland and attempts to unpack the relationship between its extrinsic and intrinsic controls. The research considers historical changes in the wetland and the impact of humans on wetland processes in comparison to the wetland's natural processes. By understanding long-term geomorphic processes, we may be able to use this knowledge to evaluate the potential for natural ecosystem recovery from the ongoing erosion that has currently sparked rehabilitation interest.

1.1.1. Motivation for this research

This research will reflect upon the need for catchment management while ensuring that rehabilitation interventions do not impede the natural processes of the wetland. By understanding the geomorphology of the wetland, there is a chance to firstly reduce the cost of rehabilitation, and secondly to include geomorphic processes of palmiet valley-bottom wetlands in rehabilitation. This will ensure that rehabilitation strategies' desired trajectories are aligned with natural processes of the wetland and that they are relevant and specific to that type of wetland.

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There is a need therefore prior to undertaking rehabilitation to first understand whether the intended rehabilitation methods are likely to promote system recovery or if they will impose a false ‘stability’ on a wetland; creating conditions with geomorphic processes that do not reflect the real character of the wetland and changing the wetland’s structure and original functioning.

There are many different reasons to undertake wetland rehabilitation, including recreating lost habitats necessary for rare species. The selection and prioritisation of rehabilitation sites depend on a variety of different factors such as the possibility of success of the rehabilitation process, how rare or valued an ecosystem is the cost of an intervention approach, as well as the benefit to the communities that benefit from the ecosystem services provided by the wetland. All these factors are weighted; however, managers should also consider the ability of the degraded wetlands to naturally recover and whether the geomorphic controls necessary to influence this natural recovery are still in place. Current trends in restoration are not focused on allowing the natural geomorphic fluvial processes to assist the recovery of the wetland, but natural ecosystem recovery has proven possible in areas of larger floodplains where lateral erosion and deposition processes control the delivery of ecosystem services (e.g Kondolf, 2012’s Deer Creek River where a braided river had been straightened to control flooding). This natural recovery process has many advantages; the most important being reduced long-term maintenance costs as the river can continually modify itself dynamically to on-going changes in the catchment. Natural cutting and filling is common in valley-bottom wetlands and this erosional and depositional cycle occurrence is often disregarded in rehabilitation and restoration management.

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1.1.2. Research Question

What are the inherent geomorphic controls within the system that influence the wetland’s natural recovery? The underlying questions from that research question therefore are: should geomorphological and sedimentological processes at Pietersielieskloof be considered in rehabilitation interventions and management strategies, and to what extent; when is it appropriate to intervene and when must we wait to intervene?

The biggest challenge encountered in natural recovery approaches often relates to the long recovery time, or if there are physical impediments or barriers to the recovery such as flow and

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loss of sediment connectivity within the wetland. In the South African context where wetlands tend to form along drainage lines, it is not just the lateral floodplain or valley connectivity that is important for the complete and successful functioning of the ecosystem. Longitudinal connectivity results in an upstream-downstream exchange of sediment which is crucial to the ecosystem. Understanding wetland geomorphic processes responsible for the formation of valley-bottom wetlands is a key consideration in the design of rehabilitation interventions and in the creation of conservation strategies (Tooth and McCarthy, 2007). Many of South Africa's wetlands have been degraded or fragmented (Nduru, 2004 in Tooth and McCarthy, 2007).

1.1.3. Research Statement

Using different analysis tools and techniques; the research attempts to understand the wetland's geomorphic processes and to test the idea that gully erosion may be an important erosional process for peat-forming palmiet valley-bottom wetlands as opposed to always being considered as a sign of wetland degradation (Pulley *et al.*, 2018). The study uses historical imagery, rainfall data, field observations, sediment analyses, and radiocarbon geochronology, to understand the natural geomorphological dynamic of the system. Cross-sections and longitudinal profiles are used to evaluate lateral and longitudinal connectivity.

1.2. Aim and Objectives

AIM

The aim of this research is to investigate the natural geomorphic processes and dynamics of the Pietersielieskloof Wetland, its potential to naturally recover from erosion, the implications, and suitability of the rehabilitation interventions.

This will be carried out through three key **OBJECTIVES:**

1. To understand the sedimentological and geomorphic processes of the wetland system;

2. To study the longitudinal and lateral connectivity of the wetland; and

3. To estimate the potential implications of the above processes/features on rehabilitation interventions on the geomorphic recovery potential of the wetland.

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II. CHAPTER TWO

2. LITERATURE REVIEW

2.1. Valley-Bottom Wetlands – Hydrology and Sedimentology

Valley-bottom wetlands are wetlands that occur at the bottom of a mountain valley and are often extensively vegetated (Grenfell *et al.,* 2019). Valley-bottom wetlands are classified between those without a distinct channel and those with a discontinuous channel flowing through them. Discontinuous valley-bottom wetlands typically have features such as floodouts, and experience periods of extensive erosion of the valley floor and periods of sediment infilling on the valley floor (Grenfell *et al.,* 2019). It is during the infilling phase that wetlands may form. Unchannelled valley-bottom wetlands, however, appear to be characterised by slower rates of erosion and deposition. It is not known what discriminates them, although it is likely related to sediment and water supply. Water input into valley-bottom wetlands can be from rainfall, groundwater seepage and from channels above the wetland (Ollis *et al.*, 2013).

2.1.1. Palmiet Valley-bottom Wetlands

Palmiet valley-bottom wetlands are a type of valley-bottom wetland common to the south-Western Cape where *Prionium serratum* (common name: palmiet) is the dominating vegetation (Rebelo *et al.,* 2015). These wetlands occur in wider reaches of what are overall relatively narrow valleys associated with the fault areas of the Cape Fold Mountains (Ellery *et al.,* 2009). Rebelo (2018) found that only 10 % of South African wetlands comprise peat, and argued that palmiet was a large contributor to organic sediment accumulation. Peat soils will form in saturated anaerobic conditions where the rate of the plant decomposition is slower than the accumulation of the organic matter (Moore, 1987, 1989 in Ellery *et al.*, 2012).

Drylands have low annual rainfall and are often distinctly seasonal, and as a result, these regions are not always suitable for peatland formation (Ellery *et al.*, 2012). As a result, dryland wetlands are usually characterised by clastic and chemical sedimentary processes rather than organic accumulation (Tooth and McCarthy, 2007). Nonetheless, South Africa has peatlands and sixty percent of South Africa's peat-forming fluvial systems can be found in Maputaland in Coastal Kwa-Zulu Natal from forest vegetation, the biggest threat being deforestation and drainage of

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lakes and wetlands in the area (Faul *et al.*, 2016) and most of the peat is stored within unchannelled valley-bottom wetlands (Gabriel *et al.*, 2018).

Palmiet is considered an ecosystem engineer, with its thick sheathed stems and robust leaves that can trap bed sediment, thus creating environments that could be favourable for peat accumulation (Job, 2014; Rebelo *et al.*, 2017; Rebelo, 2018). In the Goukou; one of the largest palmiet valley-bottom wetlands in the Western Cape, the highest organic contents are found toward the wetland head with peat depths up to 8 meters (Job, 2014). Rebelo (2018)'s organic contents varied between 4.8 and 43.2 %, with an average value of 24.7 % across 21 sample sites in three palmiet valley-bottom wetlands along the Cape Fold Belt. Palmiet is thought to stabilise channel banks (Rebelo, 2018) but requires ample space and sunshine to grow, flourishing only in saturated habitats. Despite the importance of peatlands for carbon storage, most peatland wetlands are under threat due to vegetation clearing, and land reclamation and degradation (Grundling and Grobler, 2005, in Job and Ellery, 2013).

Alien vegetation invasion and human activity in palmiet wetlands have resulted in ecological degradation, affecting wetland integrity in terms of sediment and water flow (Boucher and Withers, 2004). South Africa has lost approximately 1/3 of its palmiet wetlands due to farming activities and roads cutting wetlands especially during the 1940-1980 period, and these changes leading to a knickpoint change in slope that can accelerate erosion during peak flow (Rebelo, 2018). During the wet season, gullies can form when erosion cuts vertically into the valley and widens it such that the valley floor is lowered over time. Palmiet can colonise incising valleys where it is able to continue to encourage sediment infill and slow down peak flows (Job, 2014).

Palmiet establishes itself along vertically-eroding streams during periods of reduced rainfall and traps sediments, creating conditions that encourage peat formation (Sieben, 2012; Job and Ellery, 2013). Grenfell *et al.* (2010) and Ellery *et al.* (2012) at Lake Futululu and Mkuze Wetland respectively, found that to encourage peat-forming conditions, or at least to sustain high peat carbon contents, the system requires low clastic sediment inputs, reduced energy in water flow, and base level aggradation as the geomorphic controls. The Futululu Lake consisted of fine silt to medium sand and organics (less than 30 %), and the fill was dated to have accumulated between

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3980-140 BP at a rate of 0.13 cm per year. The Mkuze wetland is made up largely of fine silt sediments, and the organic content ranges between 10 and 20 %.

2.2. Dynamics of Valley-Bottom Wetlands

2.2.1. Disturbances in Wetlands in Drylands: Resilience and Thresholds

To adequately appreciate sediment connectivity in a system, an understanding of thresholds governing the system is required (Fryirs and Brierley, 2012). Understanding the overall geomorphology of the wetland includes the origin and development of landforms, hydrology, and the response to changes in climate and geomorphology (Tooth *et al.,* 2005 in Tooth and McCarthy, 2007). In geomorphology, the term resilience is often explained as the ability of a system to endure and persist despite a disruption in processes (Fryirs and Brierley, 2007), to successfully recover from the disturbance (Fryirs, 2017), and to reach a stable state (with minor dynamic adjustments), in response to a change in the system (Tooth, 2018). Fryirs and Brierly (2014) explained disturbance in terms of stream sensitivity and resilience where a sensitive system will undergo extreme adjustments after a modification while a resilient one can adjust easily without dramatic changes. A disturbance intrudes on the 'stability' of an ecosystem by changing the shape, form, structure, or resource supply and accessibility within the system (Wohl, 2017).

River systems are complex and dynamic (Wohl, 2016), and thus the issue of how resilient systems are, is often open for debate. Tooth (2018) gave examples of the erosion of bedrock, channelisation and excavations of wetlands, and natural climatic stressors such as droughts as examples of factors that can affect wetland resilience. In drylands, change in a climatic variable such as rainfall resulting in drought or a very large flood can leave a lasting impact on a system, even long after they have passed, and the system may take a long time to recover, or it may never recover at all (Tooth and McCarthy, 2007). Tooth (2018) further recommended that if we are to evaluate the nature of wetland resilience, it is best to first consider the relationships within the system including geomorphological lifecycles and thresholds, the role of human impacts on the wetland and channel-floodplain dynamics. Wetlands in dryland regions can also go through unique geomorphic processes, (for example avulsion in floodplain wetlands) and the plants and animals are equally critical in influencing the geomorphology of the wetlands (Tooth and

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McCarthy, 2004), and an understanding of resilience requires that a study site is clearly defined both spatially and temporally (Tooth, 2018).

In dryland regions, wetland resilience can be driven by extrinsic and intrinsic controls that push a system over a threshold. However, changes do not always threaten resilience unless they are related to large extrinsic disturbances, such as a change in sediment supply or water discharge for instance (Tooth, 2018). "*After any disturbance event, the sensitivity of a system (and its components) may shift"* (Fryirs, 2017, p. 65*,)* thus suggesting that *"sensitivity in itself is adjustable over space and time"* (Schumm, 1991 in Fryirs, 2017, p. 65). Floodplain wetlands have been widely studied in comparison to discontinuous (unchanneled and partially channelled) valley-bottom wetlands (Tooth, 2018; Grenfell *et al.*, 2019). To fill the gap, an understanding of valley-bottom origins and an appreciation of their geomorphological processes are required in management and restoration efforts (Tooth *et al.*, 2009; Tooth, 2018).

Sensitivity (or resilience) to changes and their ability to adjust to changes at different rates and under varied conditions can be explained geomorphology and associated erosional and depositional characteristics of the different landscapes (Fryirs, 2017). Modifications and adjustments are an indication that the system is reacting to changes in factors that influence wetland structure (Dardis, *et al.*, 2012). Therefore, the tendency of a system to change depends on its form, shape, and how variables change at the geomorphic level (Brunsden, 1993 in Fryirs, 2017) and this is termed 'morphological sensitivity' or 'morphological resilience' (Fryirs, 2017).

Schumm (1979; 1994), Grenfell *et al.* (2009a), Wohl (2017; 2018), and Tooth (2018) have all argued that fluvial systems have geomorphic thresholds. These thresholds can be exceeded in response to self-induced changes or external controls such as natural disasters, leading to changes to the wetland's geomorphic processes (Grenfell *et al.*, 2009b; Tooth, 2018). Schumm (1979) explains geomorphic thresholds as a state in which a major change to a physical landscape takes place, such as when a channel experiences sudden erosion of its bedrock, or a change in climatic conditions, such as intense drought or increased rainfall. How wetlands respond to this change will vary largely depending on local climate, land surface processes and the intensity of change conditions may exceed a threshold for the wetland in its current state

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(Tooth *et al.*, 2015). Fryirs *et al.* (2007b) suggest that understanding both the internal and external thresholds of landforms to be able to foresee the direction and intensity of the change is a valuable tool for monitoring and management. Cowden *et al.* (2014) go on further to argue that to understand the system; we must not only understand its thresholds but also its response to adjustments and lags in their response before rehabilitation is considered.

2.2.2. Cut-and-Fill Processes and Dynamics of Valley-Bottoms

Wetlands are constantly changing (Ellery *et al.*, 2003; Mitsch and Gosselink, 2007; Tooth and McCarthy, 2007). Channel dynamics such as erosion and depositional processes in river systems create a variety of habitats that are essential for indigenous flora. However, vertical erosion which results in more rapid bedrock incision due to increased energy supply will increase erosion and sediment supply by widening the channel and eroding the banks until they fail (Kondolf, 2012). Pulley *et al.* (2018) argued that gully erosion is a by-product of sediment instability and is a vital process in which the setting of valley-bottom wetland formation is created by eroding the valley and supplying sediment to downstream reaches where new wetlands can be formed. Fryirs and Brieley (1998) found three depositional stages aged 6000 BP in the Wolumla Creek, while Pulley *et al.* (2018) found four depositional cycles dated between 7060 and 470 BP in the South African Upper Krom wetland. At the Matitimani unchanneled valley-bottom wetland, their cycles started nearly 6260 BP in coastal Kwa-Zulu Natal where the vegetation is swamp forest (Gabriel *et al.*, 2017). At the Northington valley-bottom wetland in Kwa-Zulu Natal, Grenfell *et al.* (2009a) described the presence of repetitive incision process of cutting-and-filling and depositional features like floodouts as naturally occurring rather than being attributed to anthropogenic factors.

Pulley *et al.* (2018) found a near-horizontal bedrock profile in the Upper Krom palmiet valley-bottom wetland while Grenfell *et al.* (2009a) found the Northington valley-bottom wetland to also have an 'even' valley floor. Although Northington was not a palmiet wetland, it possessed similar processes to the Upper Krom of palaeo-channels and several cut-and-fill cycles dating over long periods. While this process may be accelerated by human activity, it was not the primary cause. In the Klip River wetland studied by Tooth and McCarthy (2007), incisional avulsion is also a natural process and channel abandonment takes place every 3-6 ky.

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Since wetlands are regarded as areas where deposition takes place (Grenfell *et al.*, 2009a; Grenfell *et al.*, 2009b; Joubert and Ellery, 2013; Pulley *et al.*, 2018), the formation of erosion features such as gullies in valley-bottom wetlands may be regarded as a risk to their existence (e.g. Rebelo *et al.*, 2017) in cases where drastic gully erosion events result in the loss of sediment deposited in the valley-bottom (Rebelo, 2018). Valley-bottom wetlands have been reported, however, as areas of both erosion and deposition cycles. Brierley and Fryirs (1998 in Grenfell *et al.,* 2009a; p.11) described valley-bottom wetlands as '*cut-and-fill features'* of our landscapes where vertical erosion and down-cutting is an important aspect of the wetland's dynamics and processes. During high rainfall seasons when wetlands experience inundation, it is not unusual to have vertical erosion, avulsion and an increase in erosion of sediments which are then deposited downstream (Tooth and McCarthy, 2007).

Natural processes such as erosion and deposition can create lasting features and these can vary from wetland to wetland, depending on the wetland are setting (Grenfell *et al.*, 2009a). The steeper a wetland is, the more vulnerable it is to incision (Ellery *et al.,* 2016). Valley-bottom wetlands can exhibit cut-and-fill nature due to aggradation and incision while floodplain wetlands can go through their own different natural processes such as avulsion due to variations in flow and sediment supply. In wetlands were aggradation results in avulsion of a channel, for example, the floodplain system receives increased sediment infill and causes slope instability, causing the channel to shift and resulting in erosion, incision, and eventually a drop in base level where new channels form through the extension of channel breaches in a downstream direction (Grenfell *et al.,* 2009b).

2.2.3. Connectivity and sediment (dis)connectivity

Connectivity can influence the manner in which fluvial systems respond to changes in processes and dynamics, and connectivity can be described from a hydrological, sedimentological, ecological, and functional perspective (Wohl, 2017). Sediment connectivity concerns the linkages between the drainage line and different parts of the catchment (Fryirs, 2013) and the reworking of sediment from the upstream to the downstream reaches (Fryirs and Brierley, 2012; Cavalli *et al*, 2013; Cavalli *et al.,* 2019). Fryirs and Brierley (2005) and Kondolf *et al.* (2006) studied longitudinal and lateral sediment connectivity as the different sediment linkages in the Bega Catchment of Australia from a landscape perspective. In contrast, Fryirs (2013), Wohl

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(2017) and Wohl *et al.* (2017) described connectivity in relation to longitudinal, lateral, and vertical sediment movement, as the ability of other components such as plant matter and organisms to freely be linked to different reaches in the system. Depositional features like floodouts in valleys with discontinuous stream channels can act as sediment sink buffer zones interrupting sediment supply until a breach occurs (Fryirs, 2013). Vertical connectivity is the relationship between sediments and water as controlled by the substrate and surface flow interactions (Fryirs, 2013; Wohl, 2017).

Fryirs *et al.* (2007a), Fryirs (2013), Bracken *et al.* (2015) and Heckmann *et al.* (2018) provided concepts and frameworks for the modelling of sediment (dis)connectivity. Kondolf (2006), Fryirs (2013), and Wohl (2017; 2018) explained the importance of looking at sediment connectivity from both spatial and temporal perspectives. Heckmann *et al.* (2018) added that the emphasis of these frameworks of connectivity should be on understanding connectivity indices in relation to geomorphology. Climate variability, catchment size, geology and tectonics, land-cover, and land-use all have an impact on a system and can influence the spatial distribution of sediment, as sediment delivery will depend on the type and location of available barriers (Fryirs and Brierley, 2012). These sediment exchanges also occur over varying periods in response to different disturbances, as such, the quantity and transport distance of sediment rely on the rate of recurrence and the magnitude of water flow over time (Fryirs and Brierley, 2012).

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Sediment disconnectivity occurs as a result of "*barriers, blankets and buffers"* (p.46) that interrupts the longitudinal, lateral and vertical transfer of sediment within the catchment (Fryirs et al., 2007b). Sediment disconnectivity can be explained as the extent to which obstructions and buffers can disrupt the effectiveness of sediment transport and delivery exchanges within a catchment (Fryirs *et al.*, 2007b). This can be caused by barriers creating sediment sink zones that prevent sediment from entering the channel from the slopes and the floodplain and vice versa, and gullies, alluvial fans, and slope wash being unable to contribute to sediment delivery (Fryirs, 2012). Longitudinal connectivity refers to the link between upstream and downstream reaches and this relationship is influenced by the channel and its ability to effectively transport and deposit sediments of different grain sizes through the system (Fryirs, 2012; Fryirs and Brierley, 2012; Fryirs, 2013).

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Impediments to longitudinal and lateral connectivity can include valley restrictions and upstream erosion creating sediment sink zones that trap sediment, the lack of energy from the channel to transport sediments without flood events, extensive channels reducing sediment carrying capacity, and human modifications like dams trapping sediments, and roads disrupting sediment supply and creating barriers (Fryirs, 2013). The main difficulty in measuring the amount of connectivity within a system is the challenging task of trying to quantify interactions and linkage in the systems, to predict disturbance (Wohl, 2017). Deposition and erosion cycles in fluvial systems are the main drivers of geomorphic change and modification but human disturbances and climate change as extrinsic controls also have the capacity to impact on these processes. Therefore, extrinsic controls can also influence sediment connectivity and alter landform sensitivity by reducing or enhancing the effectiveness of flow and sediment supply (Fryirs, 2012).

2.3. Implications of Geomorphology for Wetland Rehabilitation and Restoration

There is an on-going debate among wetland experts as to when and if intervention should occur (Kondolf, 2012). The severities and magnitudes of wetland degradation are diverse and vary according to wetlands and wetland processes and, therefore, require different extents of intervention. Choosing the appropriate methods relies heavily on understanding all controls on wetland processes. A better understanding of geomorphic processes prior to arranging for restoration and management strategies is necessary to find those that will deliver optimum benefit (Tooth *et al.*, 2002a, 2002b in Tooth and McCarthy, 2007). Rehabilitation is encouraged where preventing fragmentation and loss of ecosystems is concerned (Russel, 2009). Rehabilitation involves trying to copy or reinstate original processes and controls to maintain the provision of ecosystem services (Jordan *et al.*, 1987 in Russel, 2009).

A large amount of money in South Africa is set aside to remedy the impacts of anthropogenic canalisation and gullies eroded because of agriculture or developments such as the construction of roads (Grenfell *et al.,* 2007). From a governmental, ecological, and societal standpoint, rehabilitation interventions are commendable, but without thorough consideration of the influence of geomorphological and sedimentological wetland processes and dynamics on wetland structure and function, the efforts and expense might be ineffective (Tooth and McCarthy, 2007). Grenfell *et al.* (2007) highlighted that there was a difference between

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‘restoration’ and ‘rehabilitation’ in the South African wetland context. They explain rehabilitation as “*the process of reinstating natural ecological driving forces within part or the whole of a degraded wetland to recover former or desired ecosystem structure, function, biotic composition and ecosystem services”* (p.43). This is somewhat different from restoration which is described as “*the process of reinstating natural ecological driving forces within part or the whole of a completely and permanently altered wetland to recover former or desired ecosystem structure, function, biotic composition and ecosystem services*” (p.43).

The growing interest and concern in preserving and protecting wetlands and wetland ecosystem services they provide have resulted in a growing number of rehabilitation and restoration projects around the world from governments and non-governmental organisations alike (Kotze *et al.*, 2007 in Cowden *et al.*, 2014). However, intervention efforts often focus on building resilience against climate change impacts in fluvial systems and maintaining ecosystems from a biological perspective rather than a geomorphic perspective (Pittock and Finlayson, 2011).

2.3.1. Successes and Shortcomings of Restoration and Rehabilitation Interventions – Case Studies

Cowden *et al.* (2014) studied the long-term response of two channelled valley-bottom wetlands to rehabilitation in the province of Kwa-Zulu Natal. The two wetlands, the Killarney Wetland and the Kruisfontein Wetland were degraded from farming and canalisation. The study found that both wetlands were in better condition after interventions were put in place and the incised channels were stabilised. However, it was found that natural vegetation did not grow on its own after the rehabilitation as was initially expected despite the reinstatement of the original physical drivers. Some plants would have to be manually reintroduced despite the success of improving the hydrology of the wetlands.

In some cases, the unintended consequences of wetland rehabilitation may be harmful. Ellery *et al.* (2003) wrote about the consequences of not properly considering geomorphic processes and how human interventions can result in unintended consequences, using the Mkuze floodplain wetland in the province of Kwa-Zulu Natal as an example. Water canalisation in the 70s and 80s to transfer freshwater into Lake St Lucia from the Mkuze Wetland by dredging had resulted in

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extensive lateral and headward erosion and the avulsion of the Mkuze River into Tshanetshe Canal due to variation in gradient between the river and the canal. Even though avulsion was a natural process in this fluvial system, the canalisation and the presence of hippos in the wetland fast-tracked a process that can take years to occur, resulting in parts of the wetland being deprived of water while other parts experienced new inundation. This was a result of the lack of appreciation of the geomorphic processes of the system and the influence slope can have on flow, regardless of the scale of intervention. The rehabilitation was unsuccessful because the rehabilitation did not consider the importance of long-term geomorphic processes. Similar to Mkuze in Kwa-Zulu Natal is the Okavango in Botswana, where a few years of canalisation had resulted in degradation which will, unfortunately, continue and recovery may not be achieved (Tooth and McCarthy, 2007). At Kondolf (2012)'s Deer Creek, the geomorphic assessment found that the change in geomorphic processes and dynamics caused by rehabilitation interventions of adding levees and straightening the channel to reduce flooding had resulted in the loss of habitat from the reduction in reach variation.

2.3.2. Natural Ecosystem Recovery: An overdue possibility or an unrealistic dream?

While there are many cases of rehabilitation interventions carried out on wetlands such as those already highlighted before, on the far end of the conservation spectrum are some researchers such as Kondolf (2012) and Van Rijen (1998) who propose allowing systems to adjust themselves and for ecosystems to naturally recover from disturbances without the addition of structures. According to Brookes (1987), Binder *et al.* (1993), and Brookes and Shields (1996) in Kondolf (2012), allowing river systems to naturally recover has slowly been gaining momentum in European countries in contrast to North America's rehabilitation-policy preference. This includes allowing headcut erosion or riverbank erosion and allowing the processes of river avulsion to occur as a natural and expected process. Van Rijen (1998) argued that if rehabilitation aims to re-create past ecosystems, it will have to also re-create the climatic conditions under which those ecosystems were formed before the degradation took place.

Kondolf (2012) wrote extensively about Piegay *et al.* (2005)'s proposition of the *espace de liberte* (space of freedom/corridors of freedom) approach, as possibly the most effective form of protection of what already works (not restoration). In this approach, the most intact and least disturbed region within the system with minimal contribution of ecosystem services to humans is

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set aside for protection instead of actively intervening in the whole system. In the corridors of freedom paradigm, firstly consideration is made to preserve spaces that are still intact for conservation. Secondly, is accepting that some changes might be irreversible and their current state may be the new equilibrium. Lastly, that natural process such as channel migration, lateral, and longitudinal connectivity must continue within the system without interruption as part of the system's natural dynamics.

2.4. Approaches to Understanding Wetland Geomorphic Processes

Approaches to understanding geomorphic processes vary from paper to paper depending on the desired end-goal. The common methods used in studying wetland change use sediment dating and historical imagery for palaeoenvironmental reconstruction. Tooth *et al.* (2009) found that the use of remote sensing and sediment chronologies to study quaternary processes and assess human influence can prove to be very useful. There are many studies that have been undertaken to show that wetlands are able to record climatic conditions from the Holocene (e.g. Grenfell *et al.*, 2009b, Gabriel *et al.*, 2018) and date organic deposits (e.g. Pulley *et al.*, 2018). However, wetlands are also vulnerable to environmental and climatic changes such as variations in discharge, and they are formed because of interactions between sediments and their environment (Ellery *et al.*, 2003; Ellery *et al.*, 2016). Nevertheless, Tooth and McCarthy (2007) and Ellery *et al.* (2016) stated that wetlands are paleoenvironmental treasures because they can store information on variations in climate and the environments of the past.

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Gabriel *et al.* (2017) and Elshehawi *et al.* (2019) used radiocarbon dating to assess accumulation rates of peat deposits in Maputaland. Carbon dating was also used alongside historic pollen analysis by Kolka and Thompson (2012) as another method to reconstruct past vegetation communities. Tooth *et al.* (2009) and Tooth (2018) however, used Optically Stimulated Luminescence (OSL) dating on sandy sedimentary deposits within abandoned channels to date deposition timelines and reconstruct avulsion periods, assessing the rate of geomorphic changes in each of them. These dating techniques are useful in understanding how wetlands have changed and using OSL we are able to date how far back the sediments were last exposed to sunlight, and therefore wetland deposition rates. However, Knight and Evans (2018) warned against the use of the OSL method without other confirming data. They suggested that OSL should be

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supplemented by climatic and geomorphic data from the study area to correctly interpret the OSL results.

The use of longitudinal and lateral profiles to study valley geometry and longitudinal channel morphology for varying conclusions is very popular as cross-sectional data provides an image of how the system changes in different reaches and how the channel varies from the headlands to the downstream waters (e.g. Grenfell *et al.*, 2009a; Grenfell *et al.*, 2009b; Grenfell *et al.*, 2010; Grenfell *et al.*, 2012; Ellery *et al.*, 2012; Joubert and Ellery, 2013; Grenfell *et al.*, 2014; Tooth, 2018). This data is important because it shows the geomorphology of the system and how it connects with all its reaches.

In understanding the thresholds of a wetland, Tooth (2018) suggested that one must first consider in space and time, the duration and extent of the fragmentation and the length of time it takes the wetland to recover. Remotely sensed data such as aerial imagery can assist in seeing changes in the general landscape and landforms to see changes in processes over time. Other studies have used aerial photography (e.g. Grenfell *et al.*, 2009b; Kondolf, 2012; Larkin *et al.*, 2017; Tooth, 2018), to study geomorphic changes, reconstruct past environments and compare them to the present. Kondolf (2012) used aerial photos taken before and after flood control measures were put in place at Deer Creek. The imagery was able to show a previously dynamic meandering system that naturally recovers after flooding (creating erosional and depositional features that became a habitat to fauna and flora. Current images show that the river had been modified to a straight channel, resulting in loss of habitat and prompting management to stop straightening the channel.

Climate is a big driver of fluvial systems, and rainfall has a direct influence on geomorphology. Heritage *et al.* (2001) considered a 62-year rainfall discharge record to see the influence of flow on geomorphology in the Sabie River and found that in addition to human impacts, rainfall physically influences bedrock and channel form. In situ precipitation data is not always available and remote sensing has allowed for satellite estimates to fill in the gap. Climate Hazards Group Infrared Precipitation with Station (CHIRPS) data has been used to fill in this gap around the world recently because it provides high-resolution precipitation data. While this approach has not

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been adequately evaluated in Southern Africa, Tote *et al.* (2015) in Mozambique compared 2001-2015 rain-gauge rainfall to CHIRPS and other satellite-derived rainfall data and established that satellite data overestimate low rainfall and underestimates high rainfall areas but CHIRPS was best during high rainfall season.

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III. CHAPTER THREE

3. STUDY AREA

3.1. Regional Setting and Land Use

The study area, the Pietersielieskloof Wetland is in the Upper Nuwejaars Catchment that is part of a rehabilitation project by Working for Wetlands. Pietersielieskloof is a discontinuous *Prionium serratum* (palmiet) valley-bottom wetland that has undergone extensive erosion and alien vegetation invasion at a rate that is considered a threat to the palmiet vegetation within the wetland and its ability to encourage conditions that allow for the accumulation of peat. Wetlands in this upper Nuwejaars catchment are dominated by fynbos which is native to the Cape Floristic Region. Alien vegetation that has established itself in the wetland and the wetland is colonised by *Acacia sp*. (common name Port Jackson, wattles) and *Salix sp.* (common name Willows).

The Pietersielieskloof Wetland is located at 34°32'56.97" S 19°48'30.10" E (**Figure 1**), next to the rural town of Napier and is fed by the Pietersielieskloof River, which is one of the tributaries of the Nuwejaars River under the Nuwejaars Special Management Area (NSMA) (Nieuwoudt, *et al.,* 2018). The Nuwejaars River runs from the Bredasdorp highlands into the Lower Nuwejaars quaternary catchment to form the Heuningnes River, which eventually flows into the Indian Ocean. At the confluence where the Boskloof and Lower Kiersgat wetland arms join, a weir and two chutes have already been put in place to reduce headward erosion and sandbags have been erected to stabilise the banks.

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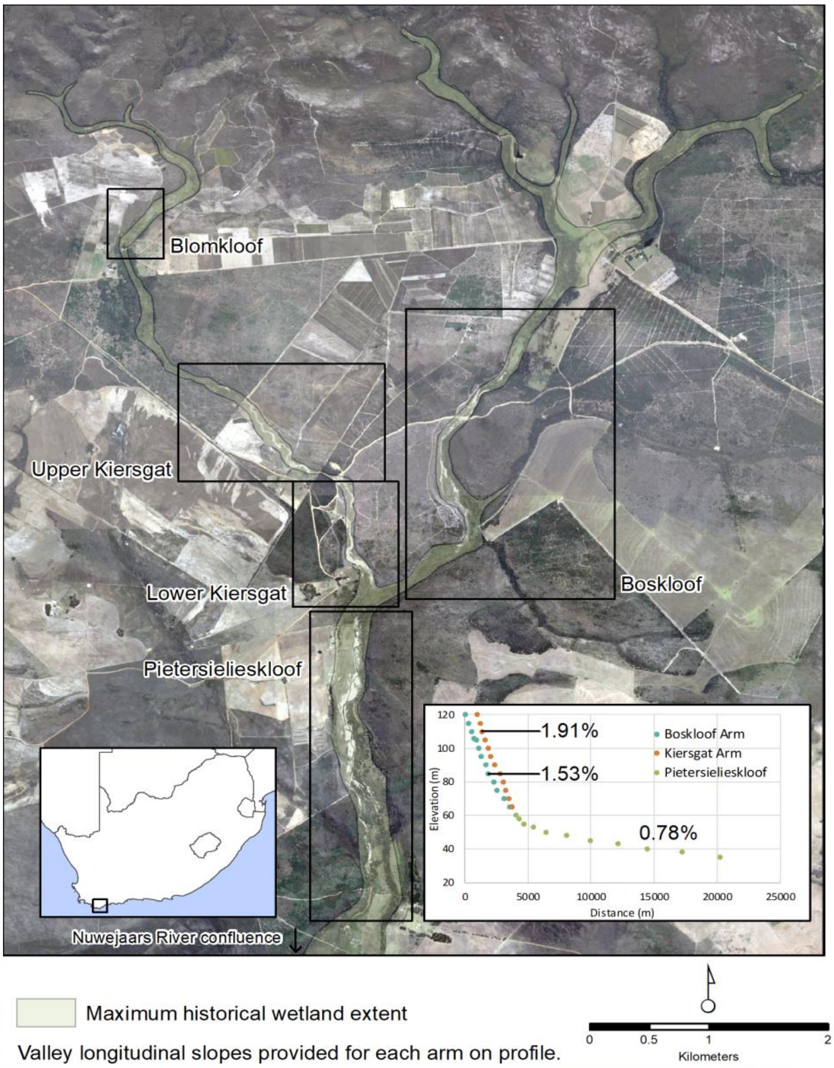

Figure 1: The Study area is divided into 5 reaches for this study based on the farm names along the Pietersielieskloof Wetland.

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The Agulhas Plain is well known for its biodiversity and export of Fynbos flowers, attracting eco-tourists from all over the world. The economic activity of the communities of the Agulhas Plain is largely agricultural, with activities in Pietersielieskloof including intensive wheat farming, cattle and sheep livestock farming, vineyards, orchards, and indigenous flowers such as the *Protea sp*. which are planted for the cut-flower export market (**Figure 2**). The land use in the area is therefore largely cultivated land, grassland and natural fynbos (**Figure 3**).

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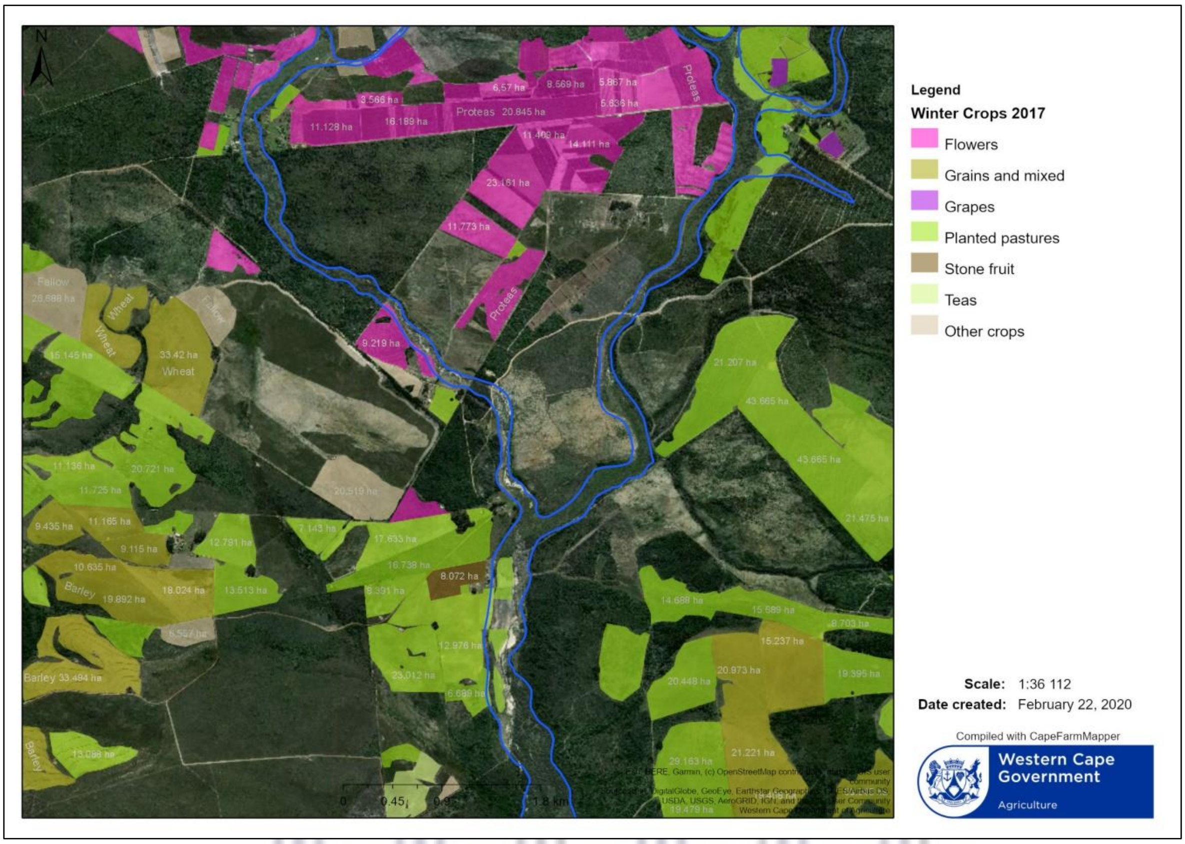

Figure 2: The crop census 2017/2018 in the Pietersielieskloof area generated from Cape Farm Mapper (Source of data: Western Cape Department of Agriculture, 2016).

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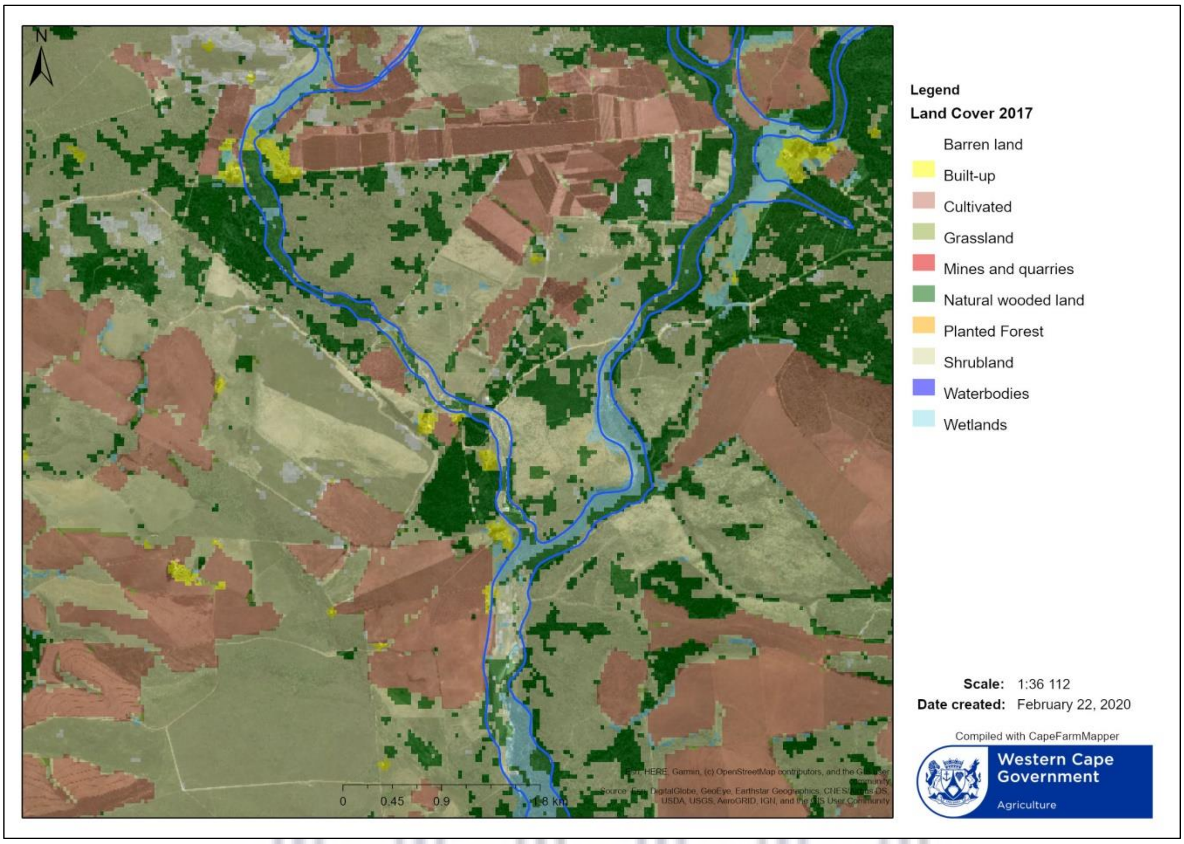

Figure 3: Land cover/ land use in the Pietersielieskloof and surrounding areas created by the National Geospatial Institute from Landsat8 30m imagery and generated from Farm Mapper. In the data, the Kiersgat arm was not classified as a wetland like the Boskloof arm because of degradation (NGI, 2017).

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3.2. Geology and Climate

3.2.1. The Climate of the Agulhas Plain

Southern Africa receives variable rainfall and this varies between countries and the seasons (Knight and Holmes, 2018) and the Agulhas is part of the Western Cape Province’s high winter rainfall zone and is classified as a Csb temperate Mediterranean climate region by the Köppen–Geiger climate classification system. These Mediterranean climate regions are normally located on the western parts of a continent, at 30° and 50° latitudes, and experience rainfall from polar fronts during the winter seasons creating warm moderate temperatures and wet winters. The Agulhas Plain receives the most rainfall in the June, July, and August winter months and the least in the December, January, and February summer months (**Figure 4**), the winters are wet and the summers are warm.

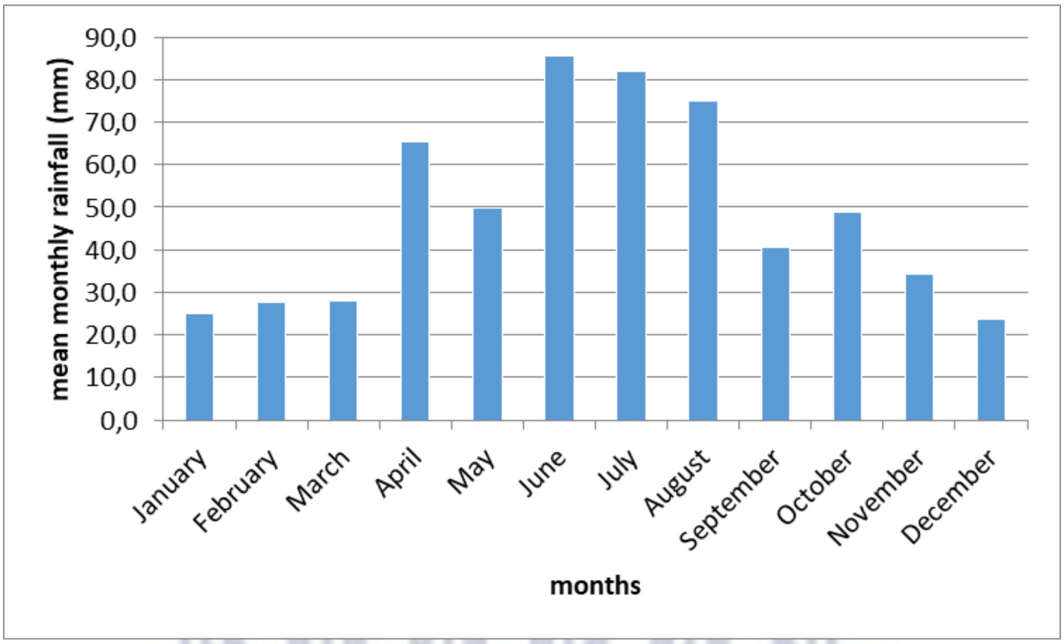

Figure 4: Monthly means of the Agulhas area (CHIRPS data 1981-2018).

This Climate Hazards Group Infrared Precipitation with Station (CHIRPS) winter rainfall results correspond with the South African Atlas of climatology and Agrohydrology study from 1950-2000 (Schulze, 2009), where they found that the Pietersielieskloof area has a mean annual rainfall of 470.97 mm.a^{-1} and a mean annual temperature of 17ºC, lower than the global average of 715 mm.a^{-1}. These low rainfall regions where the rate of evaporation exceeds the rate of precipitation are classified as drylands.

During the 2014 and 2016 rainfall seasons, the Pietersielieskloof Wetland is reported to have received very high rainfall that increased the amount of flow and resulted in flooding. Rainfall recurrence is also an important consideration when evaluating geomorphic controls on fluvial systems, due to the erosive power of increased water inflow (Dardis *et al.*, 2012). Dinku *et al.* (2018) in East Africa evaluated CHIRPS versus rain gauge data from 2006-2010 and concluded that CHIRPS can produce high-quality results in comparison to other satellite-derived data without a station but it is best over larger timescales. Saeidizand *et al.* (2018) in Iran, Paredes-Trejo *et al.* (2016), Le and Pricope (2017) in Kenya, Rivera *et al.* (2019) in Argentina, and Funk *et al.* (2015) in Ethiopia evaluated CHIRPS and agree that although it is not as accurate as direct

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rain gauge data for its overestimation of low rainfall and underestimation of high rainfall, CHIRPS is better than most satellite data over longer timescales.

3.2.2. The Geology of the Pietersielieskloof

The Upper Nuwejaars catchment is underlain by the Malmesbury Group and the Cape Supergroup, and the oldest sedimentary deposits were intruded by the Cape Granite Pluton **(Figure 5**). The Cape Supergroup and Malmesbury rocks range in age between 900 and 300 MA and were all deposited originally as horizontal strata and later underwent folding. The rocks were folded, and later underwent faulting which gave rise to the magnificent mountain ranges of the Cape Fold Belt that extend as far as the Cape Winelands of Worcester and Paarl in the west and into the Eastern Cape Province in the east (Thamm and Johnson, 2006).

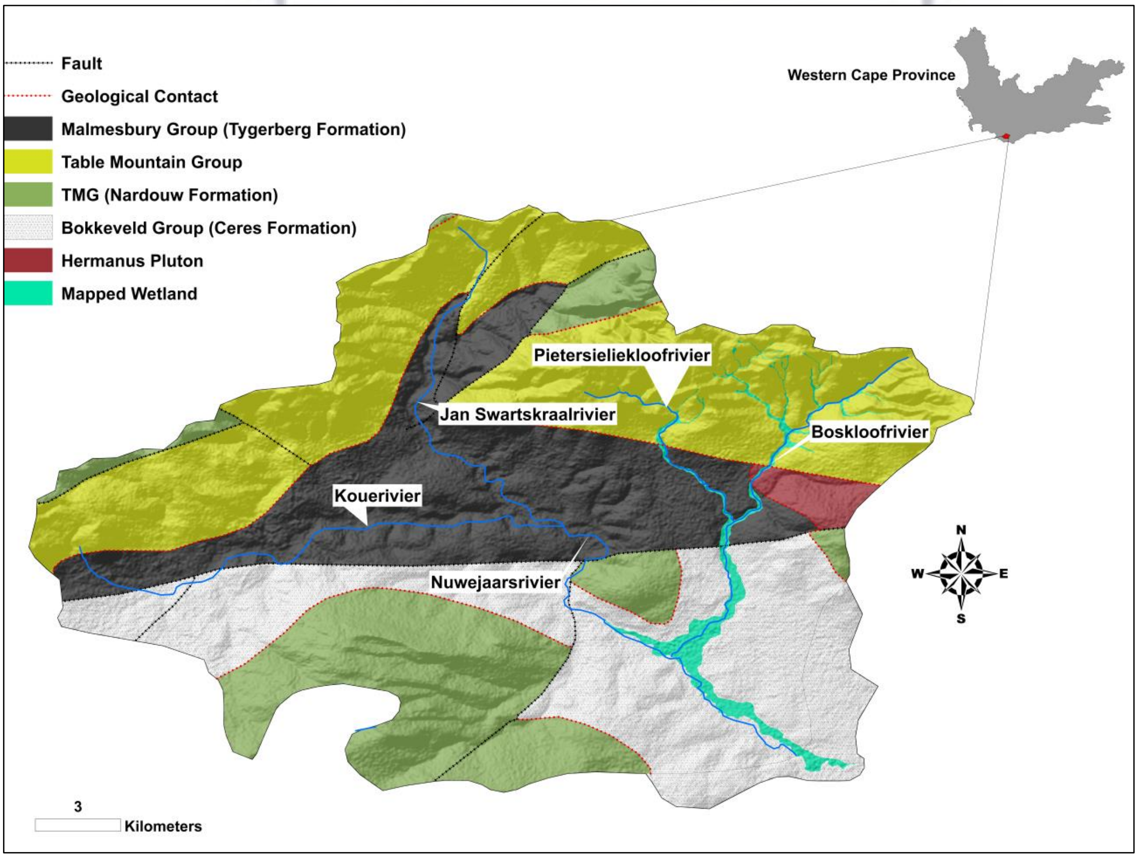

Figure 5: The lithology of the Pietersielieskloof Wetland.

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The Malmesbury Group

The oldest rocks in the catchment area are from the Malmesbury Group which belongs to the Nama/Damara Supergroup dating between 900-545 MA. The Malmesbury Group is made up of three formations; the Piketberg Formation, the Tygerberg Formation and the Porterville Formation. The Tygerberg Formation contains shale, greywacke sandstone and quartzite deposits and dated at 540 MA. The Malmesbury group was intruded by the granite Pluton.

The Granite Suite

The Cape Granite Suite intruded into the Malmesbury group of rocks between 600-500 MA. The Granite Suite is made up of multiple plutons, including the Hermanus Pluton (Scheepers and Scoch, 2006) which is found in the Upper Nuwejaars catchment area. The Hermanus Pluton's granite has in some areas has been metamorphosed into schists. Cape granites have also created extensive granite batholiths which can be seen in Paarl.

The Cape Supergroup

The Upper Nuwejaars catchment area contains two of the three Cape Supergroup groups; the Table Mountain Group and the Bokkeveld Group. The Table Mountain group is dominated by shales, quarzitic sandstones, and conglomerates. The Bokkeveld Group was deposited in a deep marine environment to create three fine-grained units of shale deposits. The youngest of the Cape Supergroup, the Witteberg Group, does not occur in this catchment. The Witterberg Group consists of mudstones and quarzitic sandstones. The rocks of the Upper Nuwejaars Catchment are grouped below in **Table 3 f**rom the most ancient at the base and becoming progressively more recent upwards.

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Table 3: Rocks of the Upper Nuwejaars Catchment

Supergroup	Group and age	Rocks
Cape Supergroup	Bokkeveld 400 MA	Sandstones and fine shale
Cape Supergroup	Table Mountain Group 500-440 MA	Shale, quarzitic sandstones and conglomerates
Cape Granite Suite	Hermanus Pluton 540 MA	granite and schists
Nama/Damara Supergroup	Malmesbury Group 900-545 MA	Shale, greywacke sandstones, quartzites

In the mapped Pietersielieskloof Wetland area of Kiersgat, Boskloof and Blomkloof (**Figure 5**), the valley floors are underlain by these Malmesbury Group sedimentary rocks from the Tygerberg Formation. This includes shale, greywacke, sandstone, and quartzite deposits. The Boskloof tributary, in addition, has some of the granite intrusion that was later metamorphosed into schist. Although farm borehole data indicate the availability of groundwater at 100 m below, the wetland is primarily fed by interflow and episodic base flow water supply and not underground water.

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IV. CHAPTER FOUR

4. MATERIALS AND METHODS

The method process followed in the thesis to achieve the objectives is summarized below in **Figure 6.**

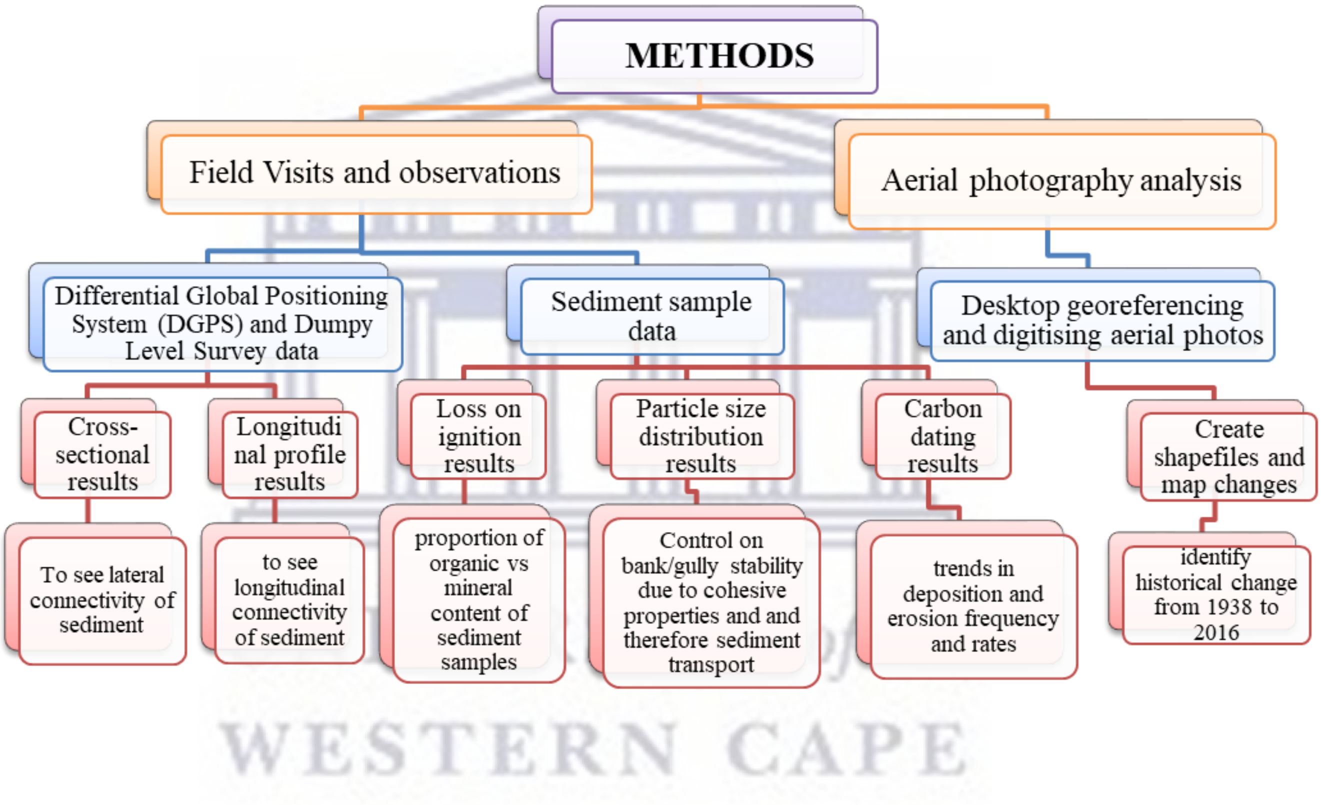

Figure 6: A summary of the methods used in the thesis.

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4.1. Data Collection

This research uses several scientific approaches of collecting data, analysing them to use the findings to gauge what these results will potentially mean for rehabilitation interventions. The methods chosen for this thesis are aimed at identifying patterns, timescales, frequency, style and rates of processes and dynamics at Pietersielieskloof and how they are influenced by extrinsic and intrinsic controls, including land-use change. 5 m contours from National Geospatial Information (NGI), Differential Global Positioning System (DGPS) and dumpy level surveys were used to draw cross-sectional and longitudinal slope profiles. Six historical aerial images from 1938 to 2016 covering 78 years from NGI were also digitized and georeferenced in ArcGIS WGS84 projection and location names were imported from Google Earth to show geomorphological features.

Data was collected for analysis and presented by grouping them into the farms closest to them as the identified reaches of the wetland (**Figure 7**) *i.e.*; Blomkloof, Upper Kiersgat, Lower Kiersgat and Boskloof.

- The Blomkloof tributary is located upstream in the headwaters of the valley-bottom where the palmiet wetland is still intact. The agricultural activity around this area includes vineyards and orchards where wildflowers are planted for export.

- Upper and Lower Kiersgat are downstream of Blomkloof and are divided by a gravel road. This is the eroded palmiet tributary. Land use activities include flower farming, grazing for animal pasture, and rooibos farming.
- The Boskloof tributary is in the headwaters of the eastern arm of the wetland where the wetland is largely intact.

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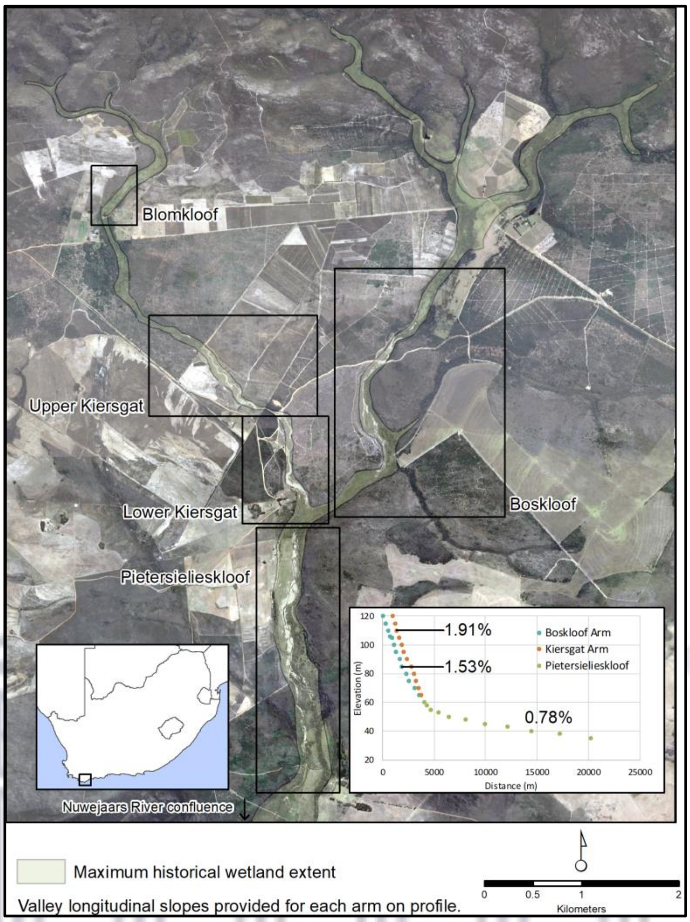

Figure 7: The sampled locations within the wetland. The description of the results is divided according to these sections.

The sediment samples of the wetland were sampled and described from along the gully sidewalls. The results are presented from upstream to downstream. Each sediment log is presented with a cross-section that illustrates the valley geometry at each site. The sampled areas are represented by the blue placemarks (**Figure 8**).

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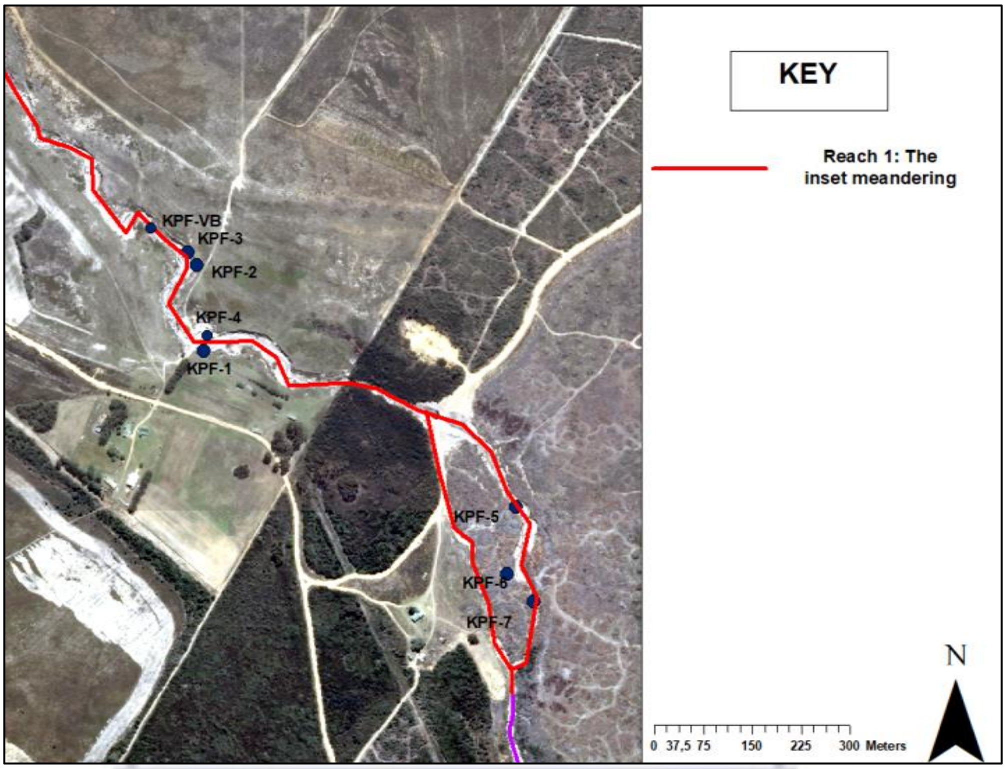

Figure 8: Location of all the Kiersgat sites where sediment samples were collected from the gully walls.

4.1.1. Historical Aerial Photos

Historical imagery from 1938-2016 (**Table 4**) acquired from the National Geo-spatial Information (NGI) were digitized in ArcMap and compared for wetland change. The variation in resolution is also presented.

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Table 4: The images used for geomorphic change analysis

Aerial Photos (1949-2016)	Resolution
1938	1:35 000. Job 461
1961	1:60 000. Job 228
2003	1:50 000. Job 1074
2010	0.5 m Job. 3419B_2010_326
2014	0.5 m Job. 3419B_2014_708
2016	0.5 m Job. 3419B_2016_1154

4.1.2. Rainfall Record

Pietersielieskloof does not have rain-gauge stations capturing rainfall for the South African Weather Service (SAWS) and for the Agricultural Research Council (ARC). The nearest available station is in the Napier area (**Figure 9**), which captures the headwaters from some of the rivers supplying the area of interest. Napier only has a ten-year rainfall record that could not be adequately used to cover the 80-year timescale for this study. Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data provided an opportunity to have access to slightly longer rainfall records because it combines satellite data with gauge station data to give at least thirty years of rainfall record. A CHIRPS daily rainfall record was extracted using Google Earth Engine. Although other authors have found errors in daily and monthly rainfall data compared with direct rain-gauge data, the data set is still considered useful when considering longer-term trends and records.

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Figure 9: The ARC and SAWS Stations in the Agulhas indicated by placemarks.

4.1.3. Topographical Survey

To look at valley morphology and connectivity, 27 cross-sectional transects were surveyed using a DGPS every 20-30 meters along Lower Kiersgat in May 2018**.** The method used is described by Heritage *et al.* (2009)'s survey strategy for digital elevation models, which is when multiple points are taken at changes in slope, with fewer points in flat areas. Care was taken to include the thalweg points for the longitudinal slope and slope inflexions. The culverts along the road were also measured and the road was surveyed in both arms. The same base station was set up for the week of the survey to give results that are relatively accurate to within a centimetre.

4.1.4. Sediment Sample Collection

Sediment samples were collected from 2.5-6 m deep gully faces sitting on bedrock, one was sampled on the bedrock, and one within the channel. The gully faces were logged to note observable changes in grain size, sorting or colour. Samples were taken at observable changes, or every 0.5 m if no observable change was detected. Seventy-six sediment samples were taken and described. A GPS point was taken for each sampled gully face, including measuring the height of the gully relative to thalweg using an automatic level and staff using standard methods and taking pictures of any notable features.

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4.2. Data Analysis

4.2.1. Rainfall Data and Historical Imagery

Rainfall recurrence was calculated using standard methods based on the CHIRPS data from 1981-2018, covering a span of 38 years. The data was used to calculate rainfall recurrence intervals by orders of magnitude to rank the severity of each rainfall year events in comparison with each other. The recurrence interval was then used to calculate the magnitude and probability percentage based on the ranking. This data will give the probability of such rainfall events in the past.

Image Analysis

The older images (1938–2003) were georeferenced using the 2014 5 m resolution imagery, in WGS84 to get them to the same orientation and scale before digitising. Seven classes were used to denote the identified features in the imagery; the main road crossing the wetland, alluvium, the water (the main channel and isolated pools), the gully sidewalls, the floodplain and vegetation.

4.2.2. Topographical Analysis

Transects KPF 1-27 (**Figure 10**) were taken along Lower Kiersgat with a DGPS and input into ArcMap. Cross-sectional valley profiles were drawn from left to right, facing downstream. From this data, the longitudinal thalweg slope was calculated. The coordinates and elevation data are accurate to sub-cm in relative elevation, but not to a known surveyed datum.

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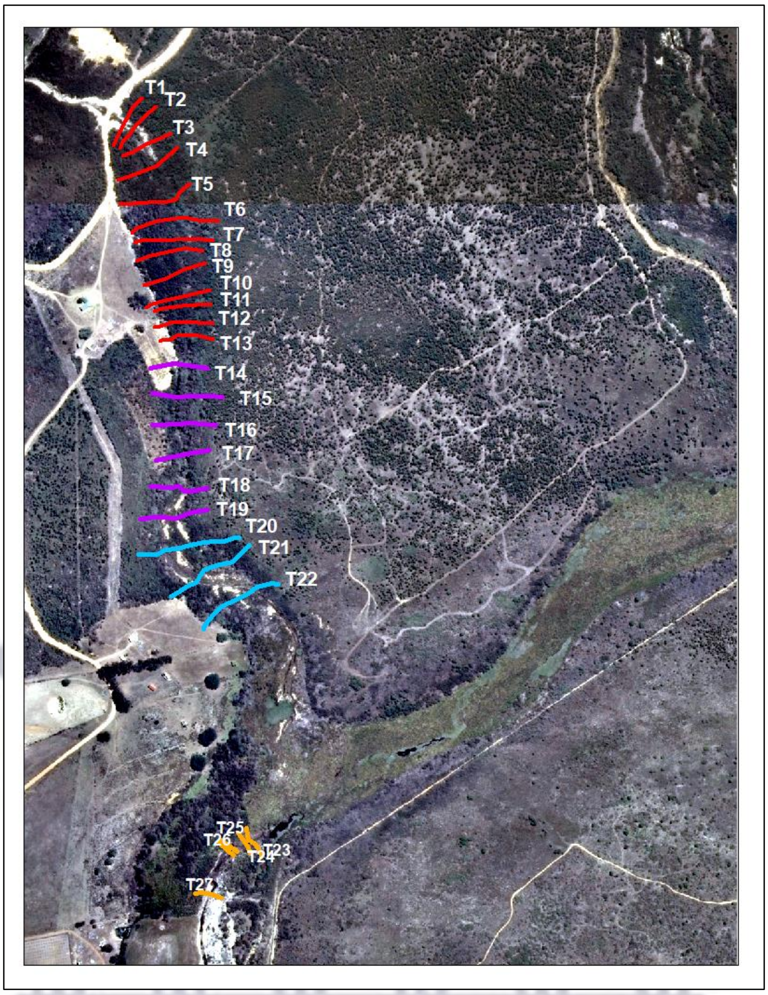

Figure 10: The Locations and numbering of transects representing the different reaches along Lower Kiersgat using the DGPS survey at 20-30m intervals (Image from NGI, 2010).

4.2.3. Sediment Analysis

Soil Preparation

The sediment samples collected in the field were put into labelled pie cups and dried in an oven for twenty-four hours at 105˚C. Before sieving, organics are removed from the sediment samples by addition of hydrogen peroxide and using a 1:1 ratio to digest the organic carbon in the sample whist on a hotplate within the fume hood. This was done until the organics had been removed from the sediment sample and the reaction ceased.

Organic Content by Loss on Ignition

The organic content percentage was calculated using Loss-on-Ignition (LOI). Approximately 3 grams of dry sediment was placed in clean, labelled porcelain crucibles and transferred to a

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muffle furnace and burned at 550˚C for 12 hours, and left to cool before they were reweighed. The loss of mass is presented as organic content. The organic content was calculated as shown in the equation below.

$$Organic\ content\ \% = (mass\ of\ sediment\ after\ 105\ drying - mass\ after\ 550\ ignition) \div mass\ after\ 105\ * 100$$

Particle Size Determination

The sieving method was used to determine the particle size distribution. Approximately 40 grams per sample was used and the sieve shaker was shaken for 10 minutes to pass through a series of graded sieves from 2 mm to 25 µm as shown in **Table 5**. The fine silt and clay were reported together. Samples with organics of more than 30 % organic content were not sieved for particle size.

Table 5: The particle size Wentworth classification used (Wentworth, 1922).

Sieve size	Description
2 mm	Very coarse sand
1 mm	Coarse sand
500 µ	Medium sand
250 µ	Fine sand
125 µ	Very fine sand
63 µ	Coarse silt
25 µ	Medium silt
Less than 25 µ	Fine silt and clay

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Carbon Dating

Five sediment samples with high organic content were sent to Direct AMS Radiocarbon Dating for carbon dating. These were the only samples from the organic deposits found within the wetland. Accretion rates of deposits at different parts of the wetland can be used to compare the rate of organic rate accumulation and for palaeoenvironmental reconstruction.

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V. CHAPTER FIVE

5. RESULTS

Results are described in terms of the three sites that have been identified at the Pietersielieskloof Wetland based on their location namely the Blomkloof tributary (BK), the Kiersgat tributary (KPF) and the Boskloof tributary (UP). The primary region of interest was the eroded reach at the Upper and Lower Kiersgat where seven gully cross-sections were surveyed and sampled. One core was taken from an intact palmiet wetland at Blomkloof (BK-1), and one gully face adjacent to an otherwise intact wetland was sampled in the Boskloof tributary (UP).

5.1. The Kiersgat Tributary

5.1.1. The Current Geomorphology Kiersgat (2010-2016)

The Longitudinal Profile of the Tributary

The wetland may be subdivided into several reaches based on channel shapes identified within each reach (**Figure 11).**

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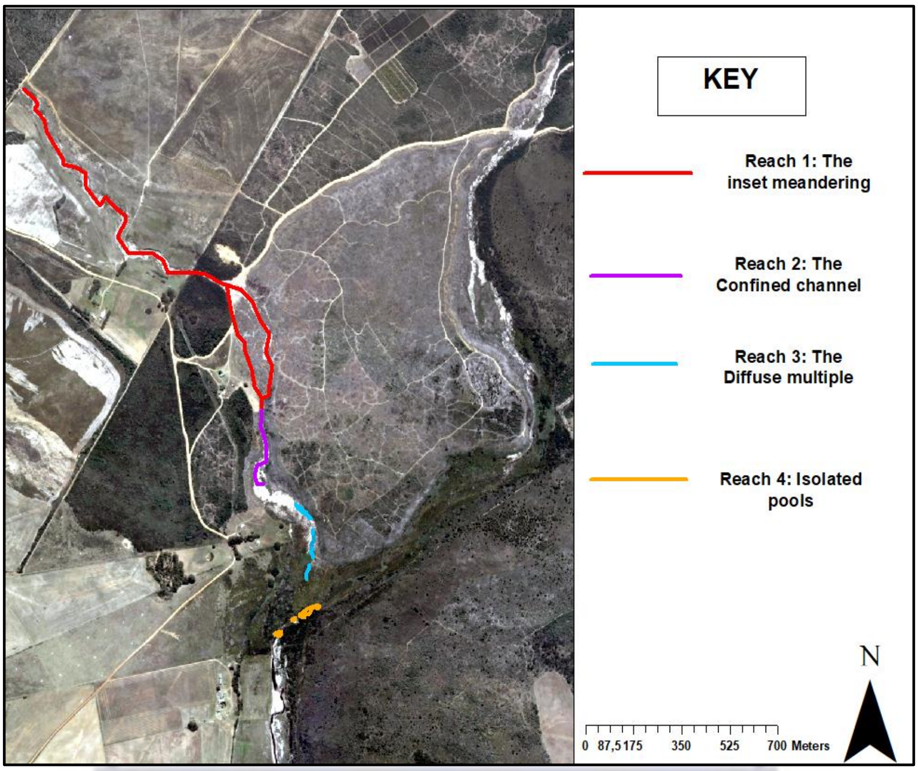

Figure 11: The reaches identified within the Kiersgat tributary based on channel features (Image, NGI, 2014).

The detailed longitudinal profile allows the wetland to be separated into six zones based on the slope (**Figure 12**). Immediately upstream of the road, an incision is prevented resulting in localised steepening (slope 2.89 %). Immediately downstream of the road, the slope is reduced by erosion (slope 1.3 %). Below this reach, the slope steepens once again (slope 2.5 %), before reducing at the head of the floodout feature (0.78 %). At the toe of the floodout, the slope steepens to 1.95 %, and immediately above the confluence weir, it reaches 2.7 %.

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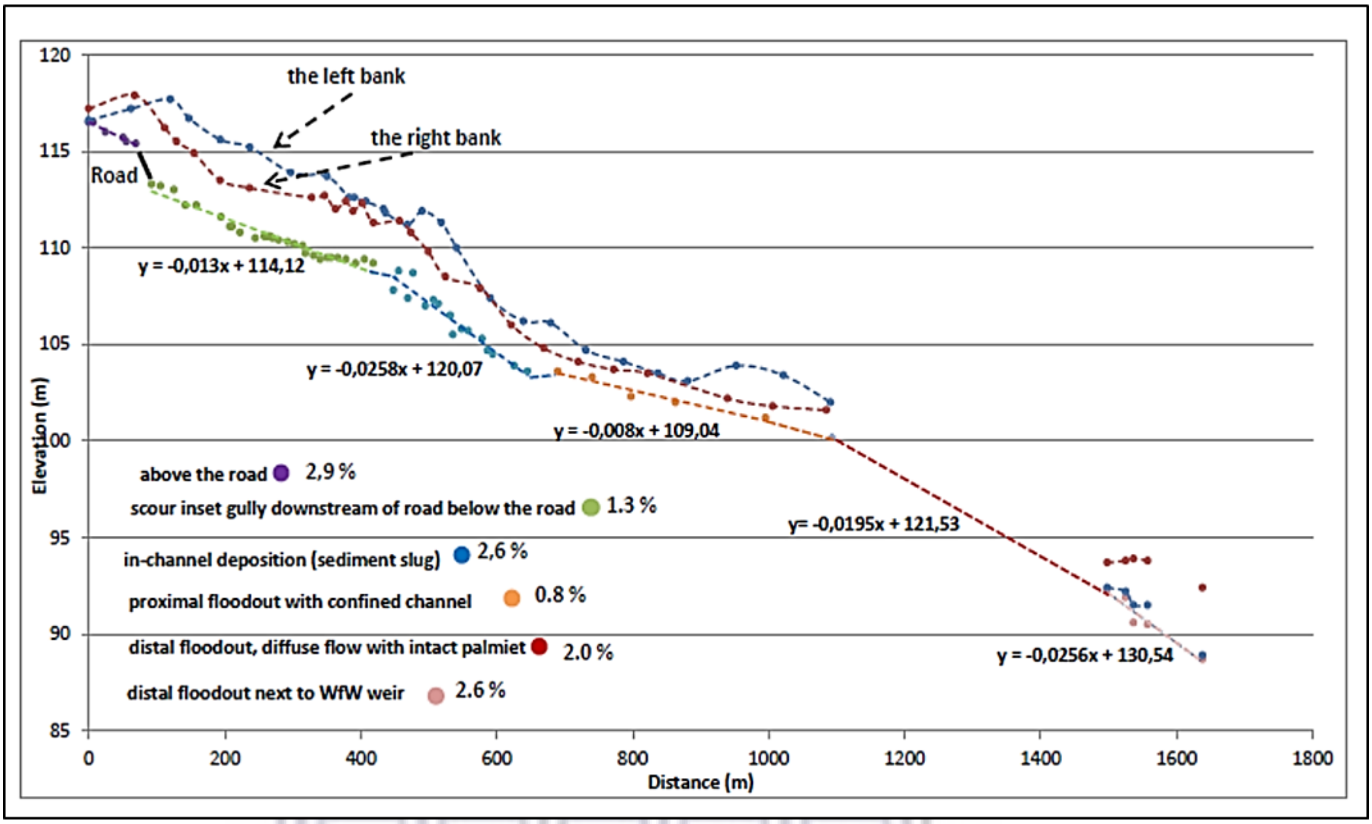

Figure 12: The longitudinal profile of the Lower Kiersgat. The road is indicated in black.

Upstream in the inset meandering channel from the headwaters indicated in blue above which is above the road, and in the reach highlighted in red, sediment is produced where gullies are eroded and valley floor scouring occurs (**Figure 13**) for downstream deposit.

Figure 13: The inset meandering reach is characterised by deep scouring and erosion up to 6 m deep into alluvium.

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The differences in slope before and after the inset meandering reach can be attributed to the channelisation of the water by the 16 culverts put in place at the Pietersielieskloof. The culverts in the road are 58 cm in diameter, 8 on the side of the Kiersgat tributary and 8 on the Boskloof arm. Concrete has been added to raise the road as well (**Figure 14**). The road creates a boundary between the Upper and Lower Kiersgat reaches and acts as a local base level. In Lower Kiersgat, sediment is also eroded vertically and laterally from the wetland valley fill. The sediment scoured at the head and the gully walls create a depositional feature immediately downstream (indicated green in the longitudinal profile) due to the in-channel deposition of sediment, which has a steeper slope than reaches upstream and downstream.

Figure 14: The area below the road indicated by the red colour in the long profile shows deep scouring.

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The wetland is dominated by clastic sediment, with some unconsolidated colluvium sediments underlying the alluvium sandy wetland deposits in some locations. Several gravel bars can also be found upstream of the valley-bottom wetland at Upper Kiersgat. The alluvial deposits at Upper and Lower Kiersgat valley floor are largely consolidated cobble and gravel bars that predate the wetland, as well as sand and coarse silt. The channel has eroded the valley floor in some areas which has created knickpoints in the inset meandering reach causing a sudden change in slope. In this portion of the wetland, the thalweg intersects consolidated gravel and cobble alluvial sediment that predates the intact wetland (**Figure 15**).

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Figure 15: Cobbles and colluvium are found in the Upper Kiersgat tributary.

During the 2010-2016 period (**Figure 16)** the channel morphology has become strongly influenced by flow, sediment and by plant cover and the variations in these three factors have influenced channel geometry, creating distinct reaches that have become increasingly visible. The imagery show concentration of flow at the road, causing downstream incision In 2010, the wetland is still very much vegetated and it is hard to distinguish wetland boundary from terrestrial vegetation. Isolated pools are visible at confluence when looking at higher resolution imagery. The road was also flooded by alluvium and the historical imagery indicates that the erosion has gullied the Upper Kiersgat Farm as the farm had lost all vegetation.

In 2010 the gully downstream of the road was very limited in extent and the wetland still had a lot of the vegetation. By 2014, the entire length of the wetland reach had been eroded along the eastern side and, although not continuous, had also taken place down the western margin. A semi-continuous channel had formed on the eastern side of the gully by 2014, which had become continuous in 2016.

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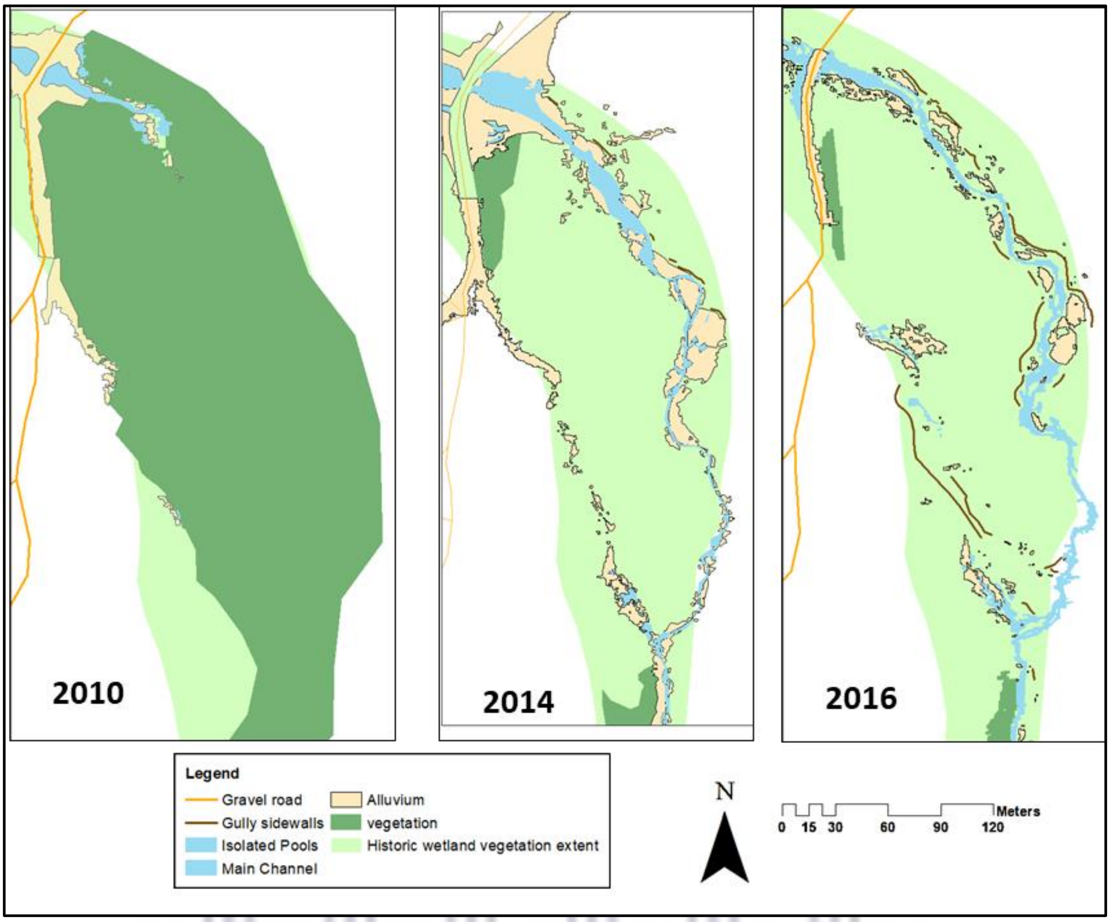

Figure 16: Geomorphic change between 2010 and 2016.

Current Valley Morphology of the Kiersgat Tributary

The current morphology description considers valley cross-sections, the location of which is indicated in **Figure 10** which were used to draw cross-sections in the Lower Kiersgat tributary based on the identified reaches.

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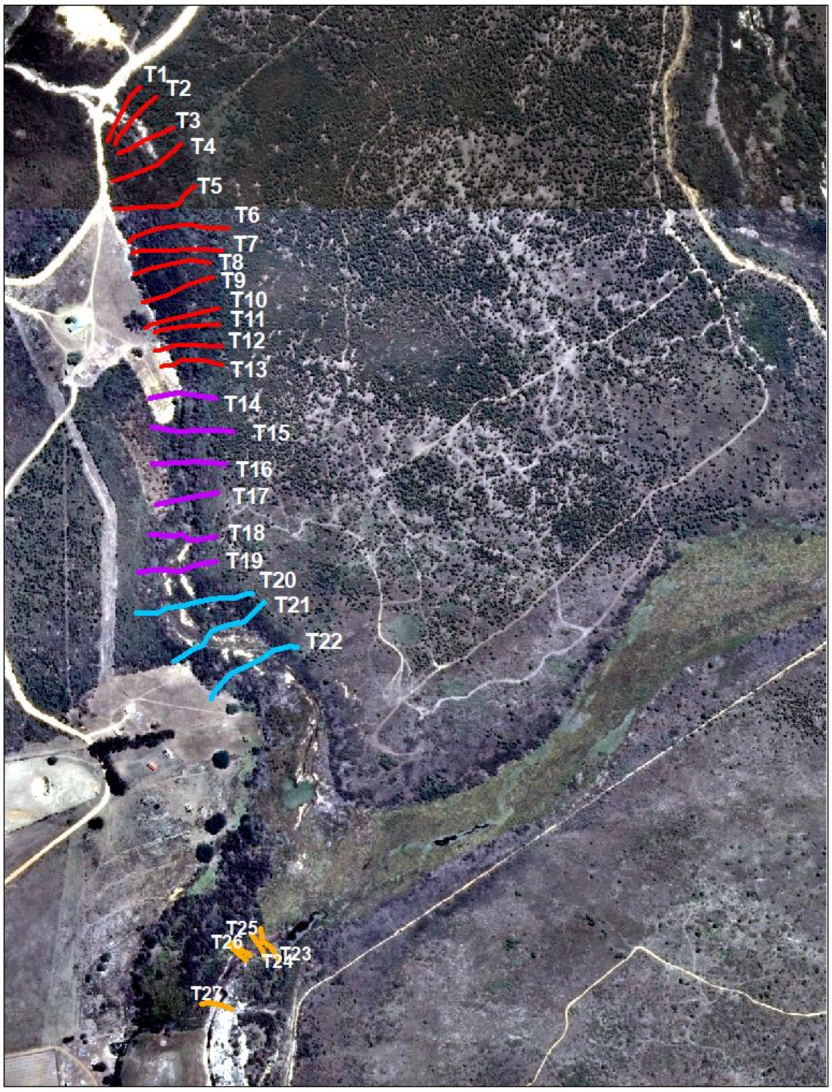

Figure 10: The Locations and numbering of transects representing the different reaches along Lower Kiersgat using the DGPS survey at 20-30m intervals (Image from NGI, 2010).

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<u>The Inset meandering Reach</u>

The inset meandering reach has been transformed into an active laterally eroding channel with a gravel-bed which is inset into alluvial fill (**Figure 17**). The gully upstream of the road is 15m wide and 6m deep on average. Vertical erosion is currently limited by occasional bedrock outcrops and the gravel bed. Lateral erosion is active. The Pietersielieskloof Farm portion of the wetland presents the most meandering portion of the wetland with lots of alluvium around the channel and an extensive colluvium outcrop.

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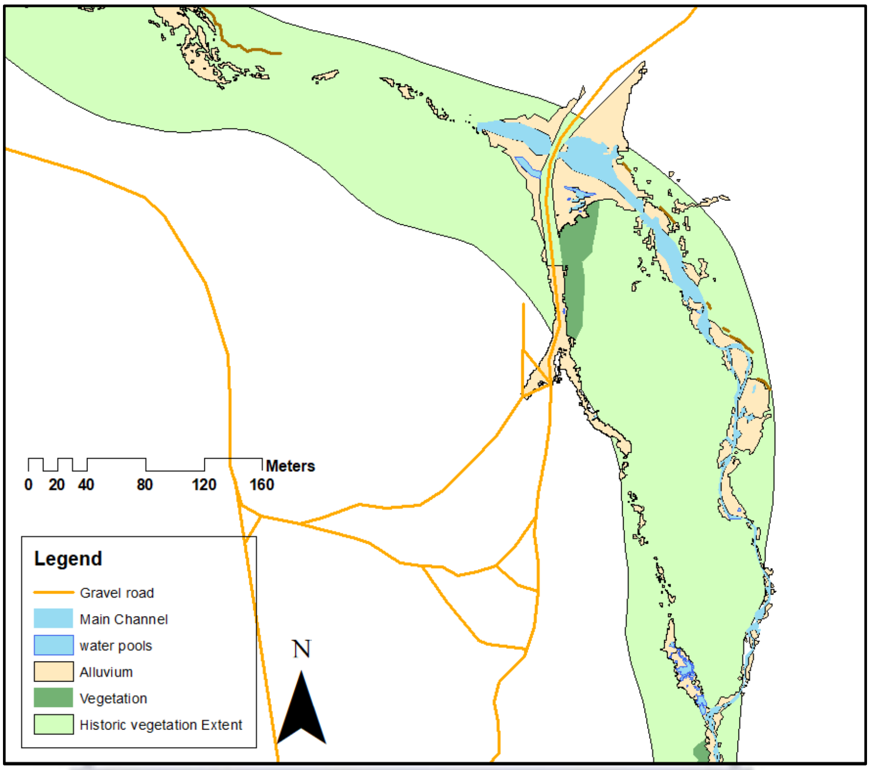

Figure 17: The inset reach where the channel meanders.

Below the road in the inset meandering reach, flows have created another gully. The two parallel gullies join at a point downstream (**Figure 18**) just before the confined-channel reach.

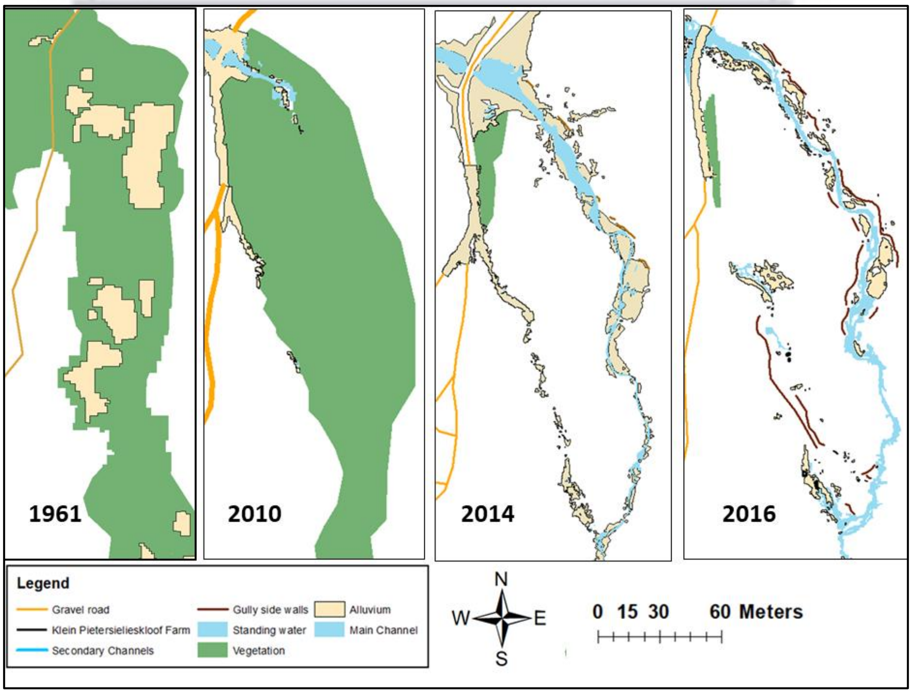

Figure 18: The progression of the two incised gullies and their progression since 1961.

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The valley is dominated by clastic sandy sediment. Old gravel and cobble beds that have been exposed by erosion can be found in this reach of the incised channel (**Figure 19**).

Figure 19: The widened gully inset within the valley floor.

The cross-sections taken along the Lower Kiersgat's meandering reach below the road (**Figure 20**) show a vertically eroding reach where the main channel occupies the main gully.

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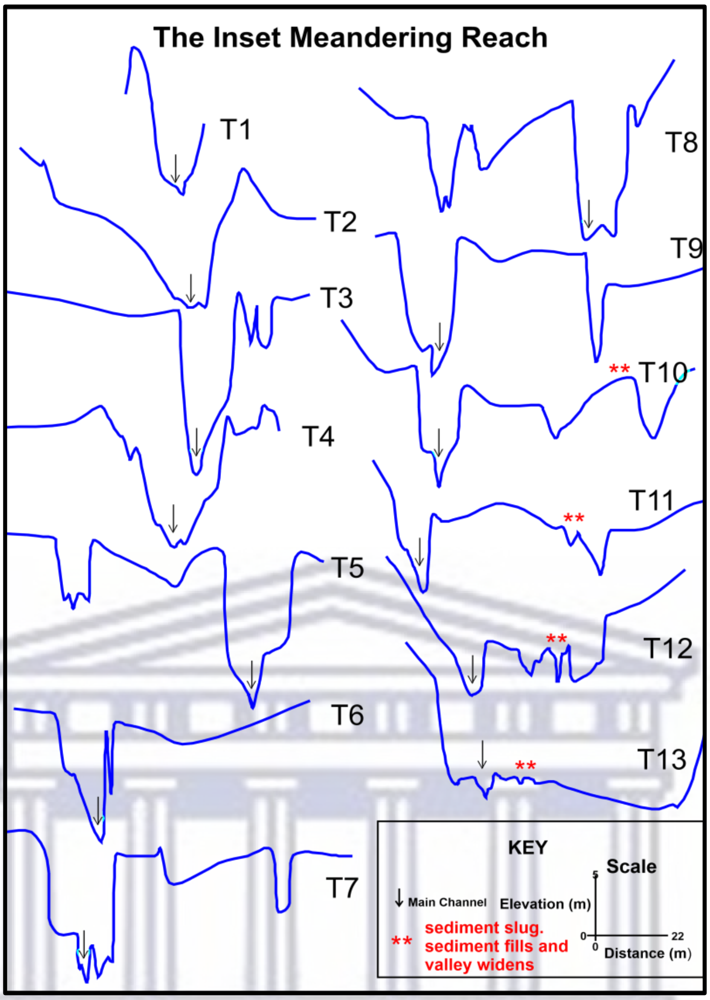

Figure 20: Cross-sections in the inset meandering reach. The sediment slug is in T10-T13.

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<u>The Confined-Channel Reach</u>

The confined-channel reach is a stretch of fairly straight, narrow floodplain (**Figure 21**). The original wetland surface was laterally confined in this reach by adjacent hillslopes. Wetland vegetation growth is currently restricted to the single, narrow channel.

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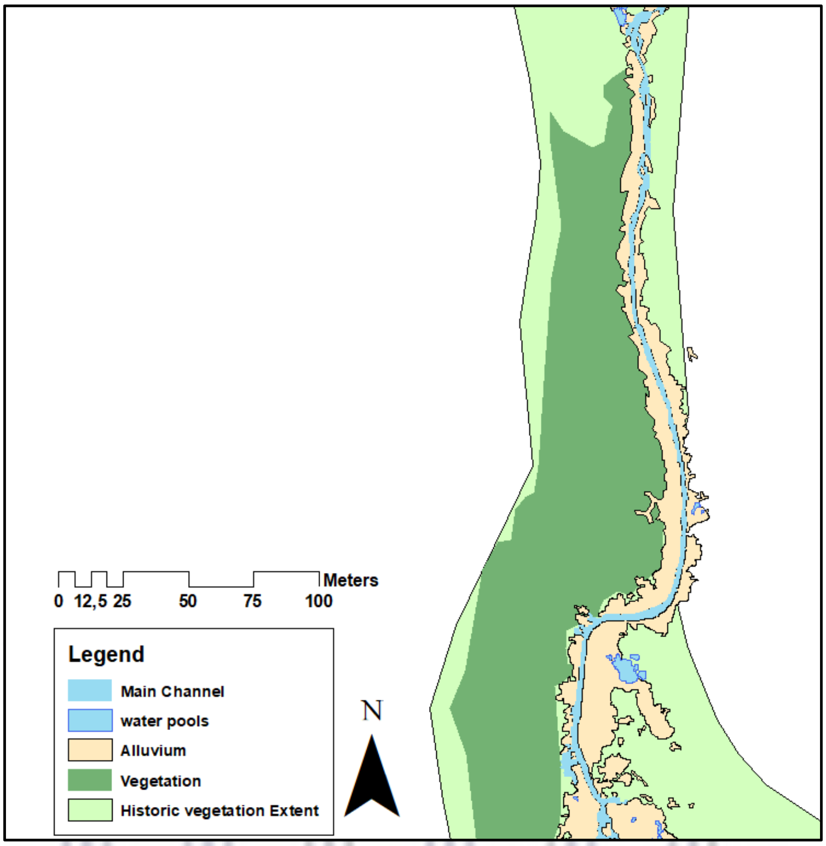

Figure 21: Geomorphology of the confined reach.

The 6 transects taken along the confined-channel reach show a single, narrow channel, and in some areas, a levée is weakly developed. Towards transect T17; the proximal floodout is reached as indicated by widening and flattening of the slope profile (**Figure 22**).

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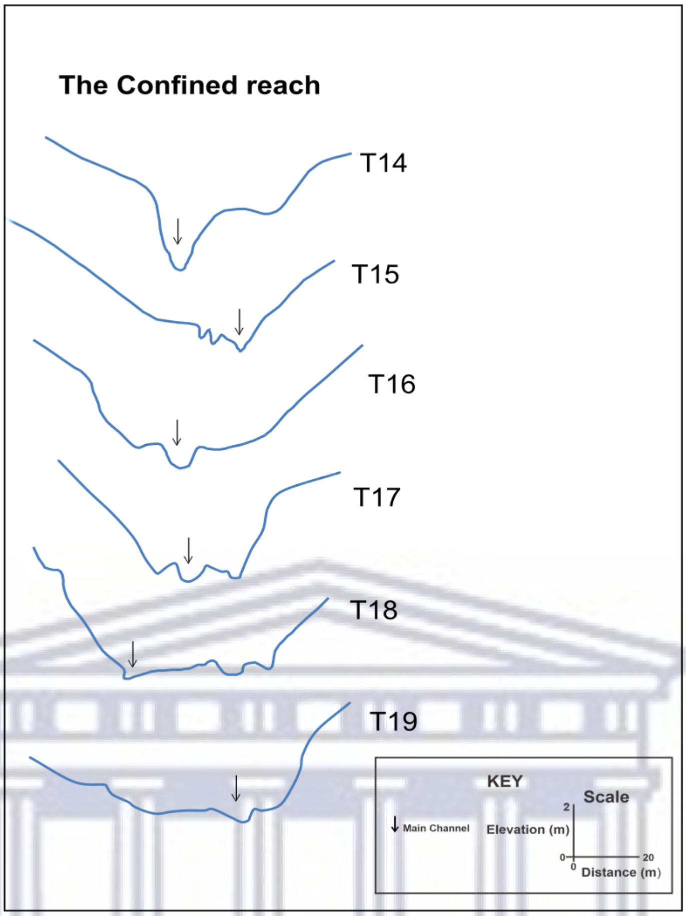

Figure 22: Transects that were taken at the confined reach show a narrow channel.

Diffuse flow Reach

Following the confined-channel reach, the channel spreads out forming multiple channels that appear and disappear into the vegetation, creating a network of weakly concentrated flows (**Figure 23**).

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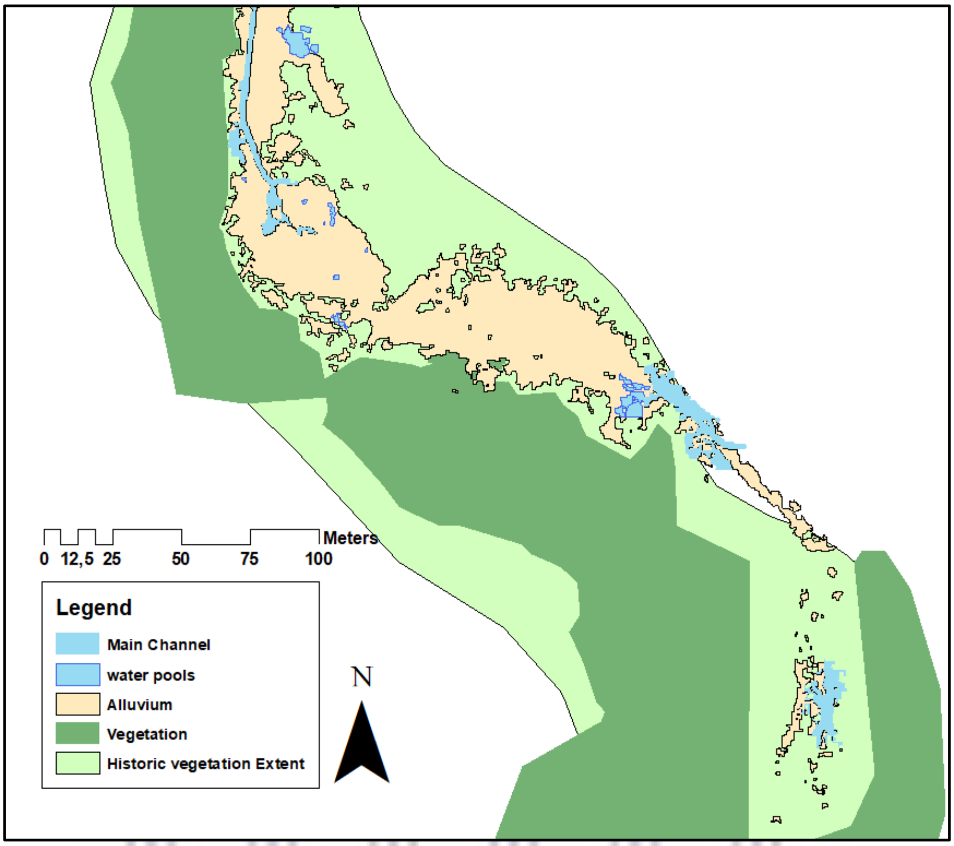

Figure 23: The reach is characterised by a multiple channel diffuse flow network.

The cross-sectional transects .show a channel that moves from bank to bank in a vertically eroding, widened valley (**Figure 24**) before the channel disappears into vegetation. The cross-sections indicate an older pre-existing channel elevated above the surrounding valley floor which has been abandoned.

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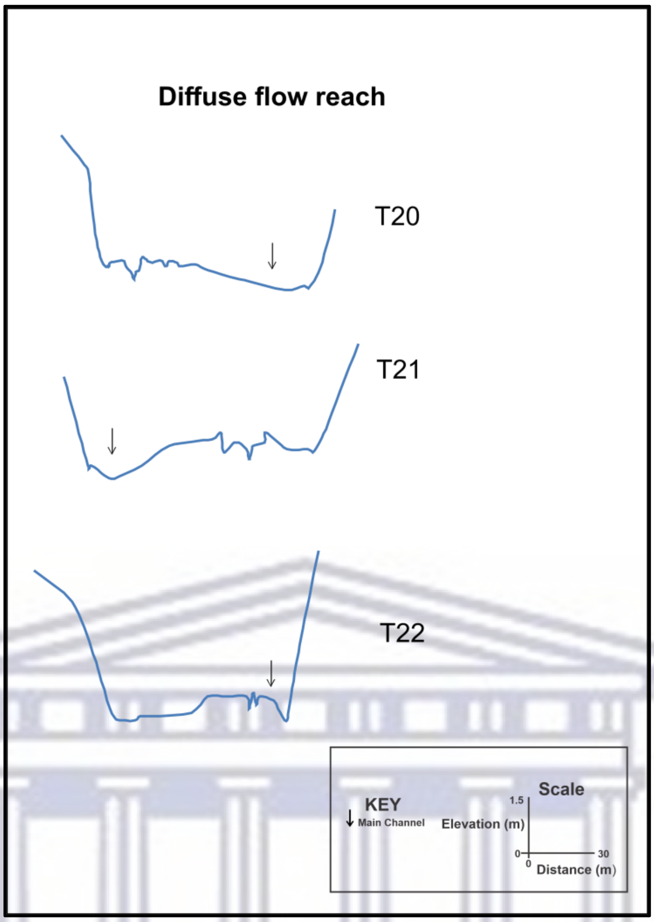

Figure 24: Transects were taken in distal floodout reach as flows become diffuse flows before the channel disappears.

<u>Isolated Pools Reach at the Confluence</u>

Above the Working for Wetlands weir, the channel loses confinement and a series of isolated pools of standing water are visible on aerial photography (**Figure 25**).

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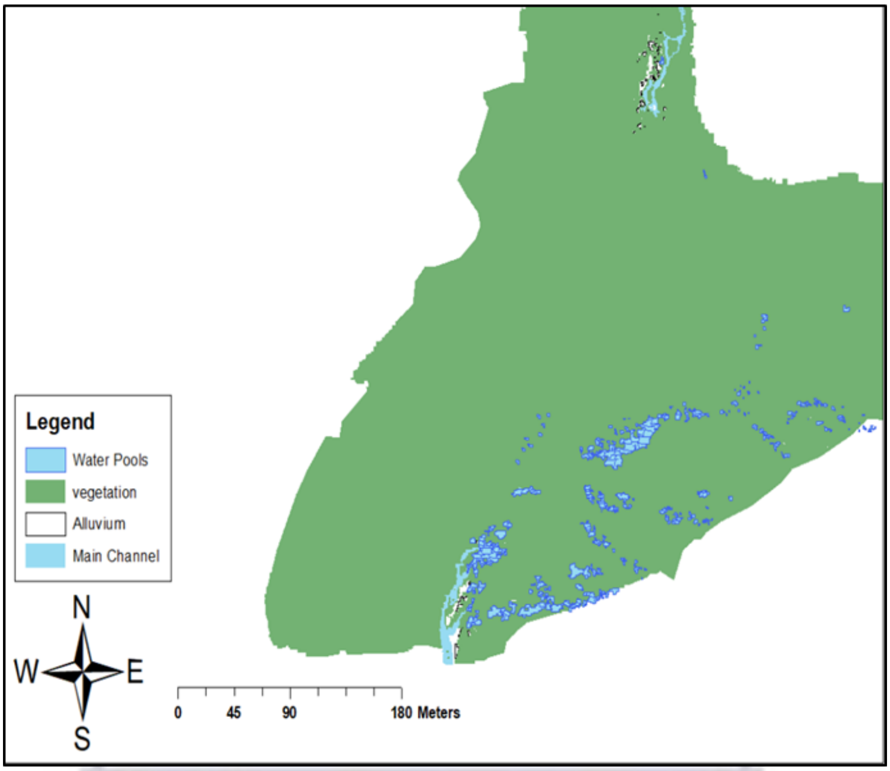

Figure 25: The last reach is the downstream confluence where Lower Kiersgat and Boskloof join.

At the confluence, the left bank has been eroded and sandbags have been put in place. At T25, the cross-section crosses a chute that has been put in place for rehabilitation efforts (**Figure 26**).

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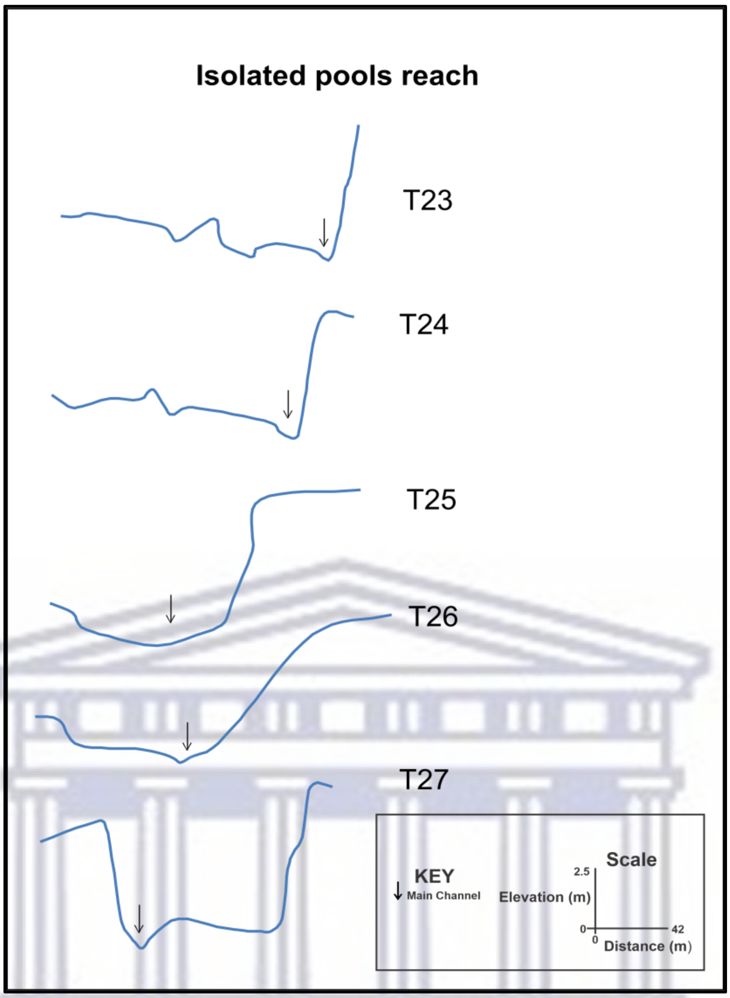

Figure 26: Transects at the confluence are taken before (T23, 24), at (T25, T26) and after (T27) the rehabilitation structures.

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Two weirs and a chute have been constructed to prevent headward erosion from a gully downstream (**Figure 27**).

Figure 27: The rehabilitation structures at the confluence of the Boskloof and Kiersgat.

5.1.2. Historical Geomorphology (1938-2003)

The geomorphology of the wetland as visible in aerial photography between 1938 and 2003 is indicated in **Figure 28**. In 1938, alluvium is visible along a channel over almost the whole length of the wetland, by 1961, large alluvial flats are visible. By 2003, active deposition appears to have ceased, and the region is completely vegetated. The exception is the stretch at the wetland head, where a small scour hole has developed at the road crossing, as evidenced by a pool of open water. These changes reflect a period of erosion in 1938, where visible alluvium is restricted to a linear channel feature, to accumulation in 1961, whereby large alluvial flats are visible as depositionary features, followed by vegetation recovery until 2003.

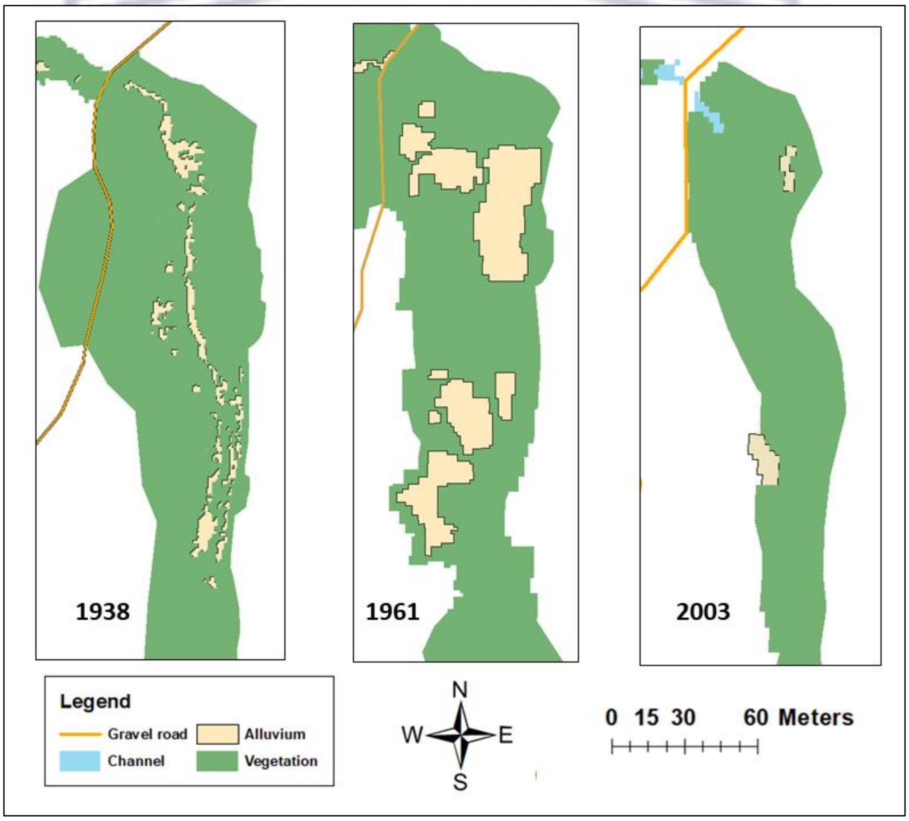

Figure 28: Geomorphic change in Lower Kiersgat between 1938 and 2003.

5.1.3. Wetland sedimentology at Kiersgat

The valley-floor (**Figure 29**) was dated at 3311 years BP and are buried by cobbles and gravel bars while in other parts they are exposed by erosion.

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Figure 29: A buried organic layer on the valley-floor exposed by erosion.

The floor's organic matter in **Figure 29** was found to extend up to 3 m deep and the cross-section of the valley is displayed by **Figure 30**. Above the organic clay, there was gleyed sand and a cobble layer topped with soil. The valley floor's minimum accumulation rate at this site is 0.09 cm. yr^{-1}.

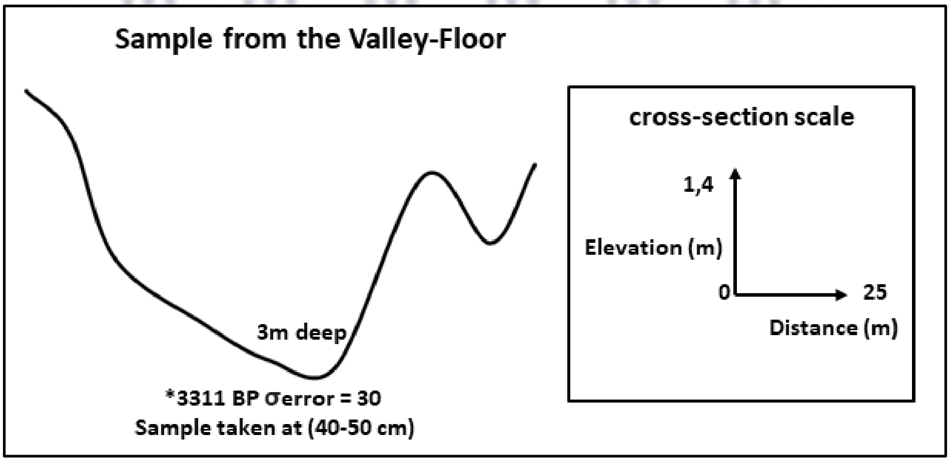

Figure 30: The cross-section of the organic sample that was dated using carbon-dating from the floor.

The base of KPF 3 (**Figure 31**) was characterised by colluvial cobble beds, overlain by alluvial deposits of fine to coarse sand with extremely low organic contents with a widening valley.

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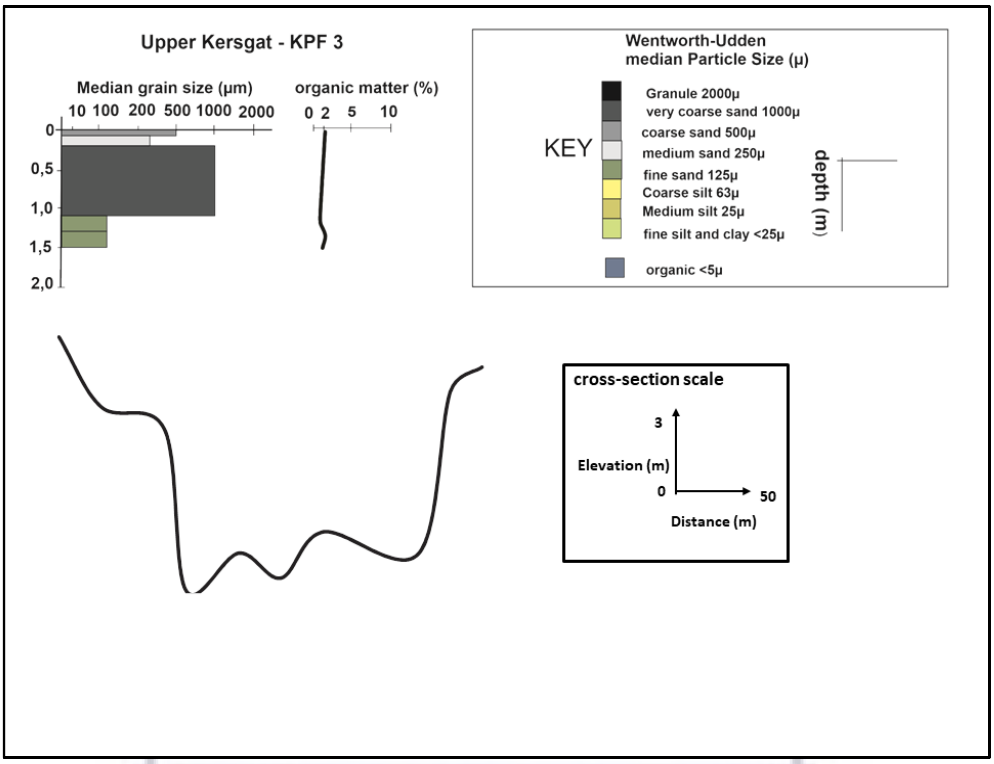

Figure 31: Sedimentology and cross-section at KPF 3.

Similarly, KPF 2 (**Figure 32**) was also characterised by organic contents of less than 6 %. The base of the sequence constituted of medium sand which fined up and then 2 upward coarsening sequences. The overall sedimentology of KPF 2 was distinctly finer than that of KPF 3.

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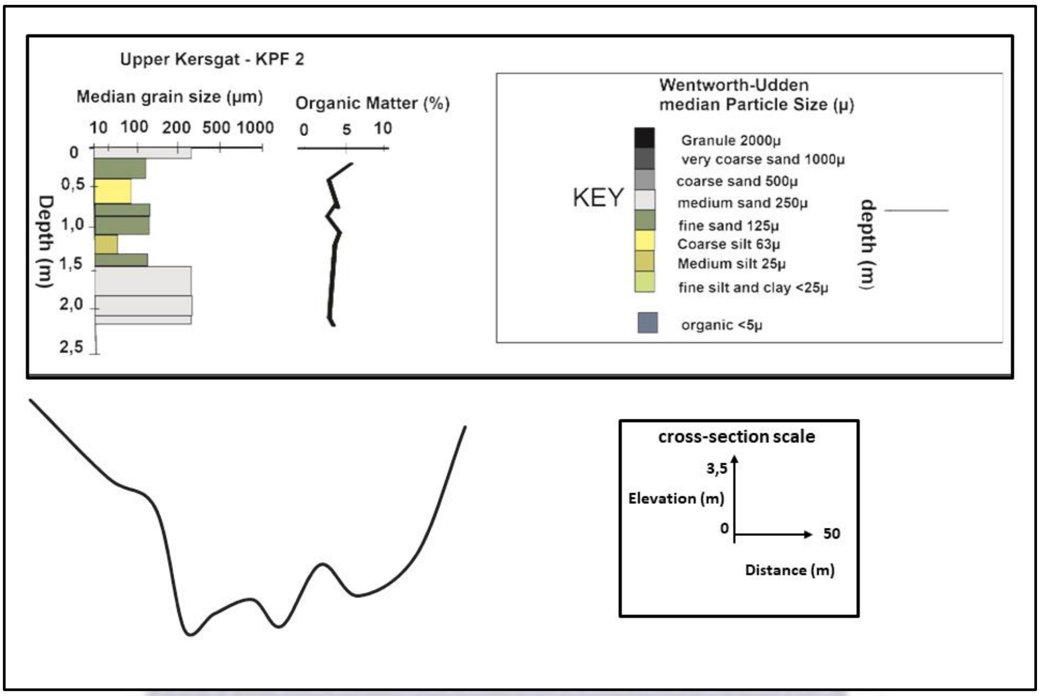

Figure 32: Sedimentology and cross-section at KPF 2.

KPF 1 in **Figure 33** was taken on the right bank opposite the rooibos farm at Upper Kiersgat farm, where the gully cuts 4.6 m deep into alluvium and a laterally eroding gully floor. The stratigraphy indicates multiple flood sequences.

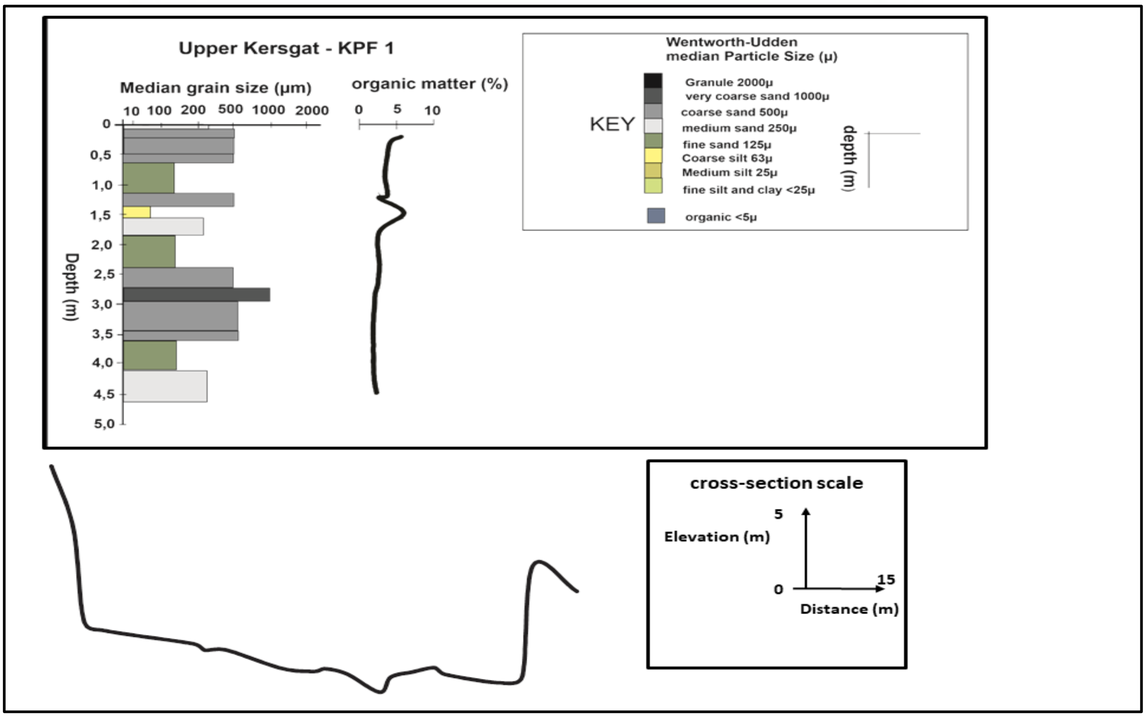

Figure 33: Sedimentology and cross-section at KPF 1 on the right bank.

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KPF 4 was sampled at the opposite gully bank to KPF 1 (**Figure 34**) and despite the proximity, the sedimentology was extremely different. Whereas KPF 1 constituted multiple sequences, KPF 4 displayed much less variation. The base of the gully face was marked by gleyed coarse sand, overlain by almost 1 m of an organic-rich layer (27.2 %). The base of this layer was dated at 5530±42 years BP and overlain by an upward fining sequence of coarse sand to fine sand. Erosion has subsequently eroded this sequence, indicating variability in depositional sequences in a small spatial reach. The minimum rate of sediment accumulation at this site is 0.032 cm.yr^{-1}.

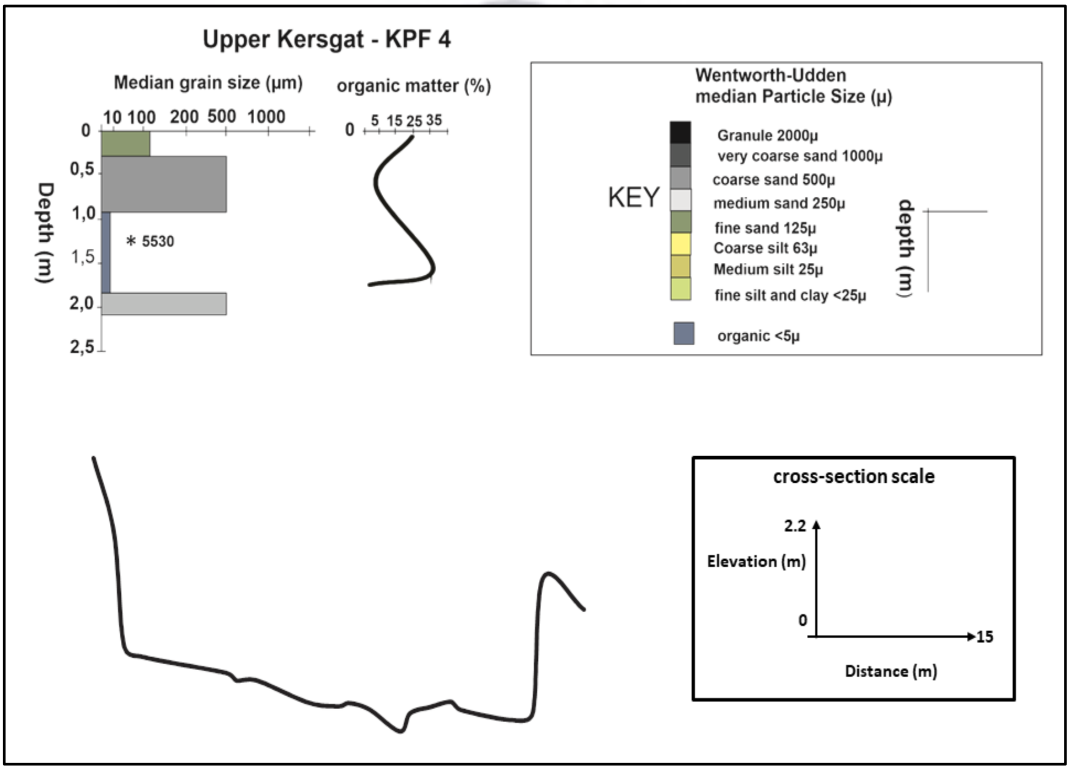

Figure 34: Sedimentology and cross-section at KPF 4 on the left bank.

KPF 5 (**Figure 35**) was described on the scoured gully downstream of the gravel road and is characterised by a fairly homogeneous sequence of medium and fine sand with less than 2 % organic matter throughout.

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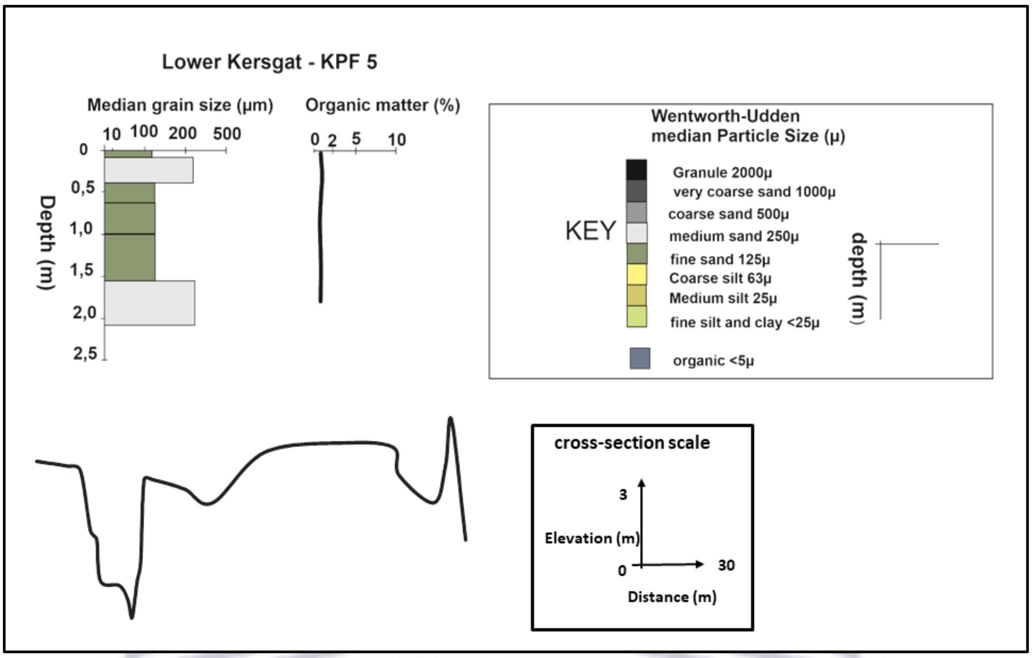

Figure 35: Sedimentology and cross-section sampled at KPF 5.

KPF 6, downstream of KPF 5 is similarly homogenous, with an upward fining sequence from medium to fine sand (**Figure 36**) Organic content decreases from 10 % at the surface.

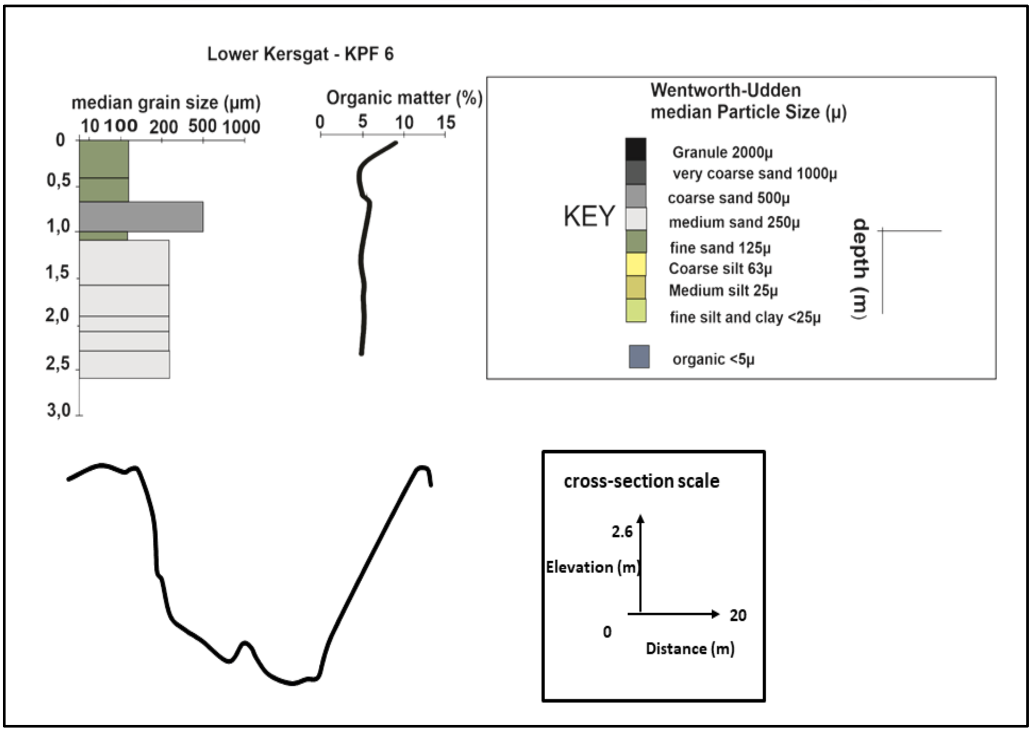

Figure 36: Sedimentology and cross-section sampled at KPF 6.

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KPF 7 is the furthermost downstream of all the described sites (**Figure 37**). Much of the gully face was characterised by fine to coarse sand with very low organic content. However, preserved within the sequence was a thin lens of peat (organic content 62 %) is approximately 6m long and just 20 cm deep. This peat layer was dated at 329 ±28 years BP, the resulting in a minimum accumulation rate for the overlying clastic sediment of accumulation rate of 0.37 cm. yr^{-1}.

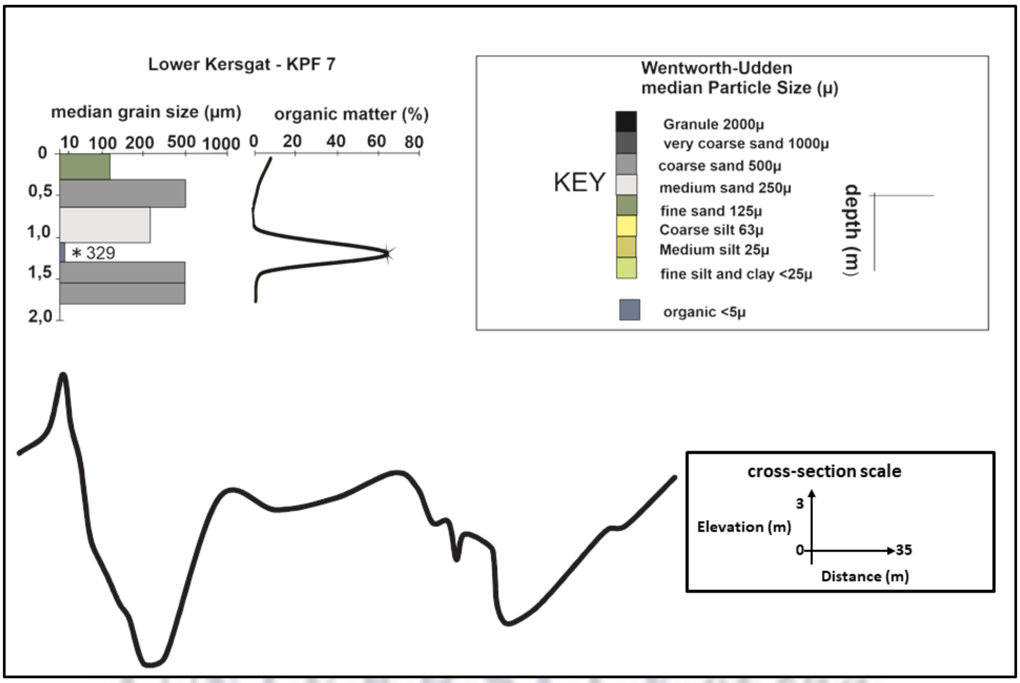

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Figure 37: Sedimentology and cross-section sampled at KPF 7.

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5.2. The Blomkloof Tributary

While the Kiersgat and the Boskloof tributaries have remnants of organics, collected from gully sidewalls, at the Blomkloof tributary, the wetland was found to have organic accumulations sampled from within the palmiet channel (**Figure 38**).

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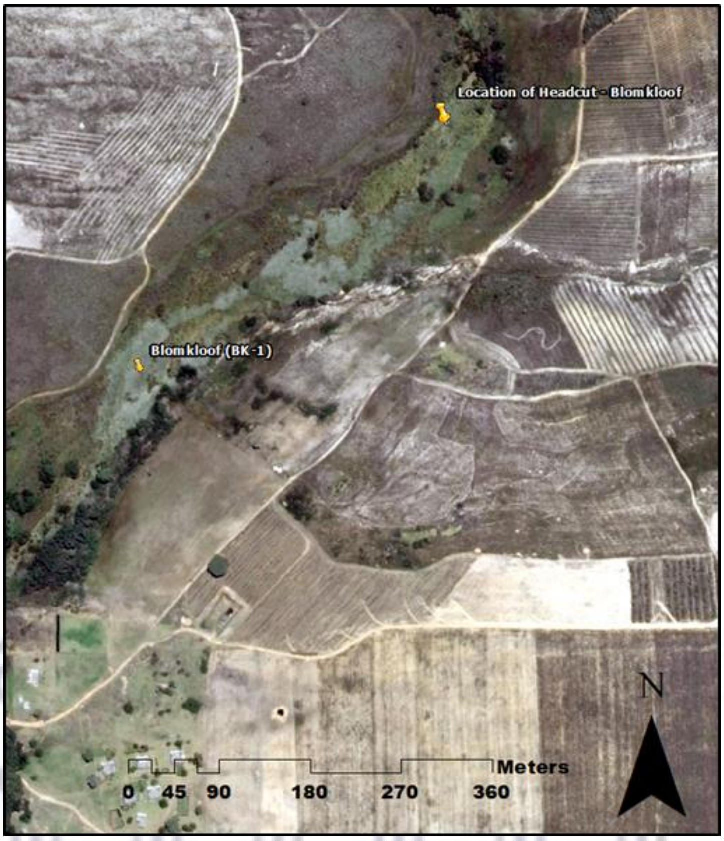

Figure 38: The Blomkloof site is in the intact palmiet wetland (Image from NGI, 2014).

Currently, there are locations within the Blomkloof tributary that have small knickpoints (**Figure 39**) which change the speed and divert the direction of channel flow. Overall, Blomkloof had the most organics as the 9 samples averaged organic matter content of 39 %.

Figure 39: A knickpoint within the Blomkloof tributary causing a drop in elevation and an increase in the amount of flow.

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5.2.1. The Sedimentology of the Blomkloof Tributary

The majority of the augured core were characterised by unconsolidated organic mud (**Figure 40**). A sample from the base of this sequence was sent for radiocarbon dating and was determined to be 814 ±26 years BP, indicating an average rate of sediment accumulation of 0.17 cm.yr^{-1}. The base of the core was marked by medium to coarse sand.

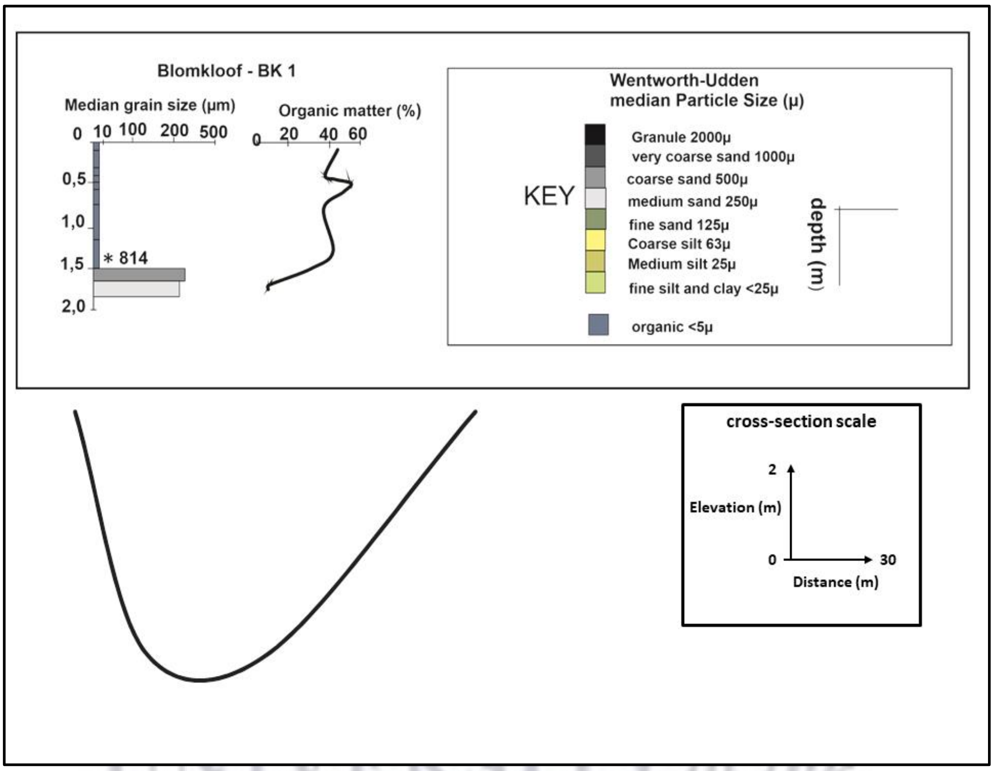

Figure 40: Sedimentology and cross-section at BK 1.

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5.3. The Boskloof Tributary

At Boskloof (**Figure 41**) taken on a 6 m gully wall was made up of mostly sand deposits and only one sample of organics was found and dated.

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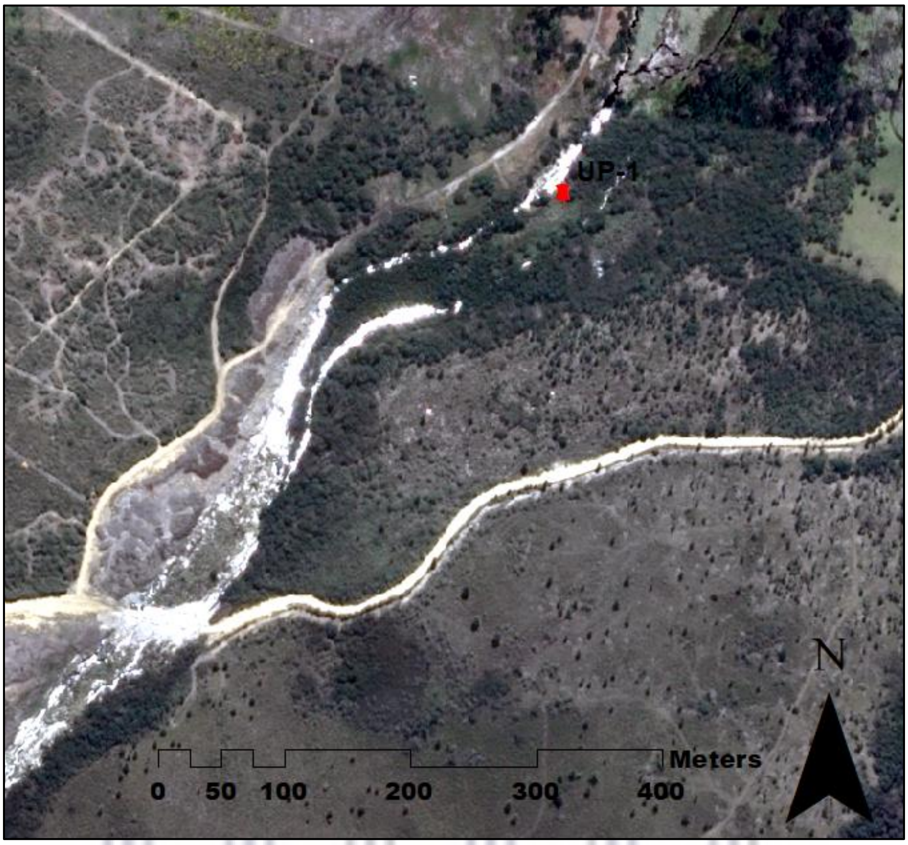

Figure 41: The Boskloof arm has been encroached by alien vegetation trees and the sample was taken on a gully sidewall exposed by erosion (Image from NGI, 2014).

5.3.1. Sedimentology at the Boskloof Tributary

A sample was taken in Boskloof above the gravel road (**Figure 41**) where headward erosion had exposed a gully sidewall 6 m deep. Despite its depth, the gully has not widened, and as a result, the palmiet wetland remains intact on an old valley surface some 6 m above the gully thalweg. Within the gully, palmiet is not as extensive and instead, it has trees that shade the channel creating a forest environment where the woody alien vegetation of wattle trees grows on the river banks. The 11 samples collected from the Boskloof had an average organic content of 12 %.

The base of the profile comprised fine sand topped with a 30 cm thick layer of medium sand. This was overlain by a 70 cm thick accumulation of peat with an organic content of 43.5 %. Radiocarbon analysis dated the base of this layer at 6098±4 years BP. As a result, the minimum rate of sediment accumulation above this layer is 0.07 $cm.yr^{-1}$. The sedimentology of the gully profile (**Figure 42**) indicates an overall trend of upward coarsening, as may be expected in a steepening depositionary environment. This arm is considered a potential future site for wetland

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rehabilitation to reduce headward erosion and remove alien vegetation (Working for Wetlands, 2018).

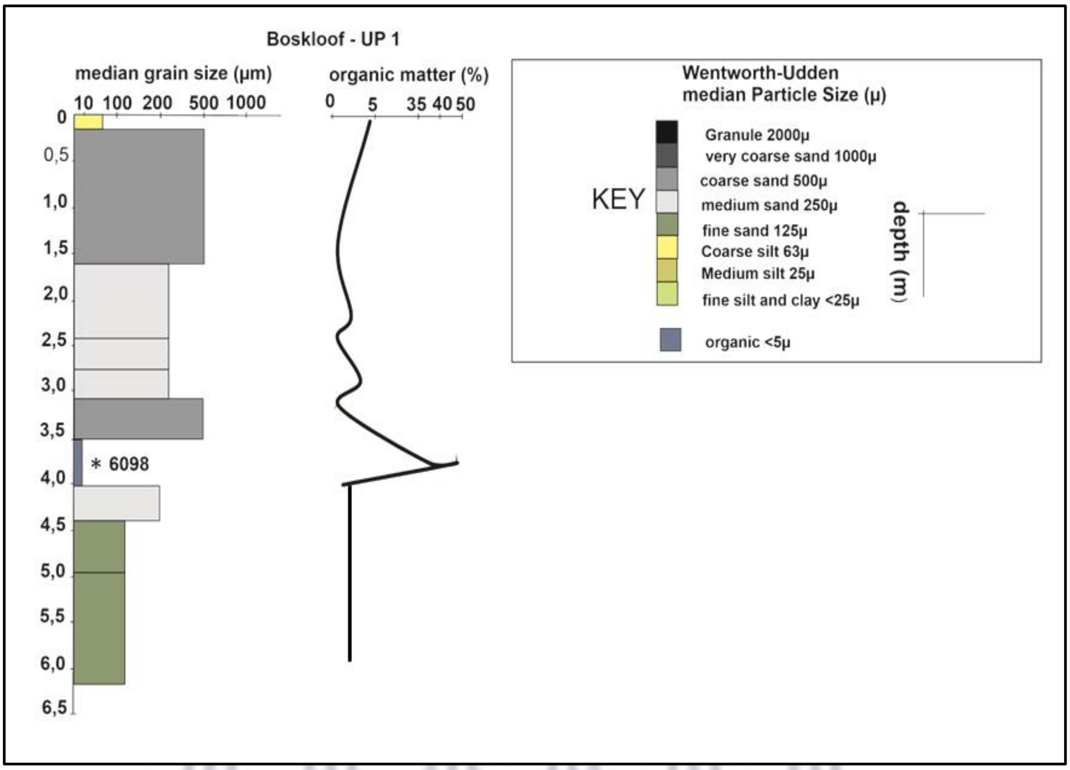

Figure 42: Sedimentology at the Boskloof tributary.

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5.4. Analysis of Historical Rainfall Patterns using CHIRPS Data

The Agulhas Plain has a mean annual rainfall of 470.97 mm.a^{-1}. In **Figure 43**, an analysis of annual rainfall indicates a marginal long-term decreasing trend, although this is not significant. The lowest rainfall year was in the year 2000 with 326.06 mm.a^{-1}. The highest rainfall recorded in a 24-hour period was in 2016 (116.61 mm). The most annual rain was the 640.8 mm.a^{-1} of rain experienced in 1989.

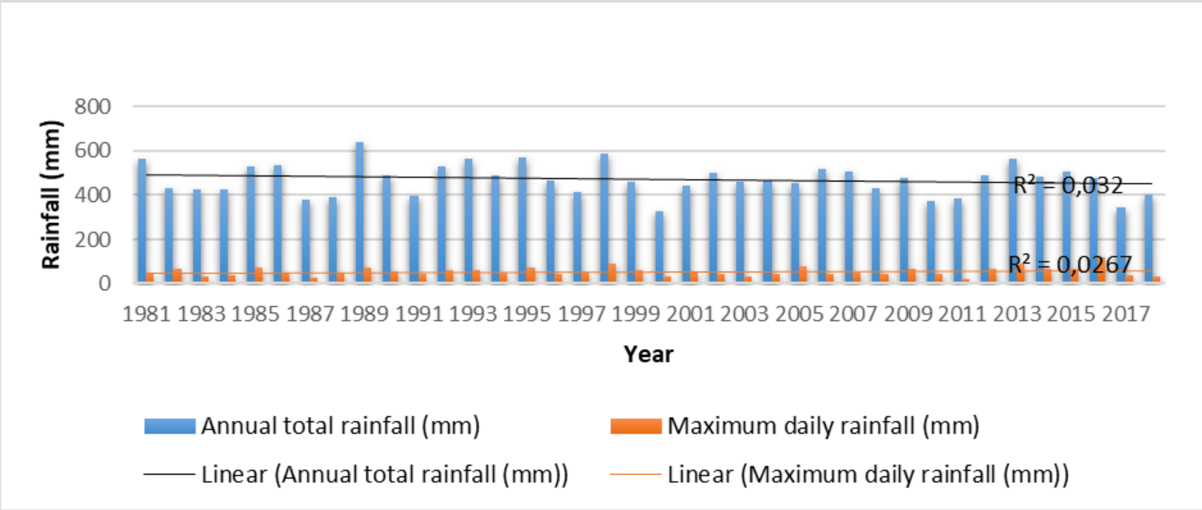

Figure 43: Rainfall over the Agulhas between 1981 and 2018.

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The main erosion below the road occurred between 2000 and 2014. The most annual and 24-hour rain since 2000 were both received in 2013 with an annual total of 563 mm.a^{-1} and 90.7 mm in a 24-hour period. This would be a 1 in 13-year recurrence event (**Figure 44**).

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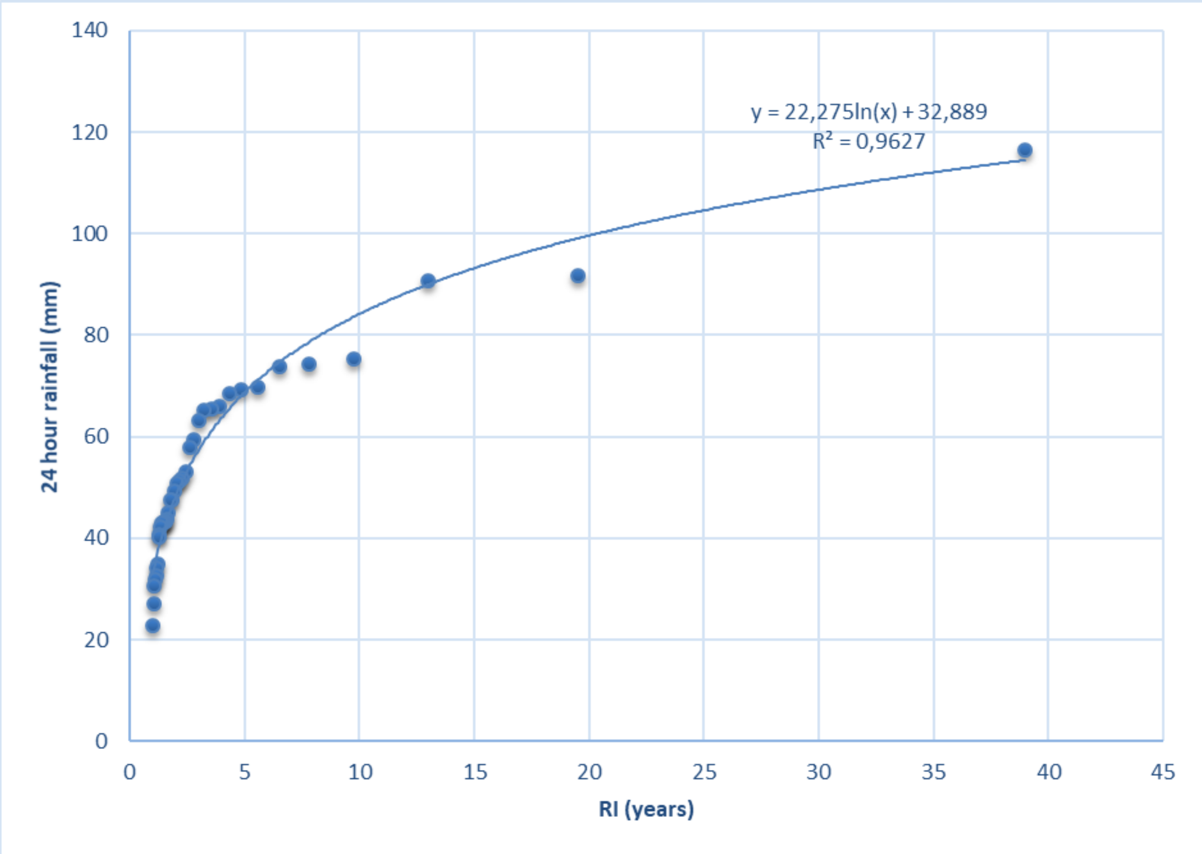

Figure 44: Rainfall recurrence interval

Rainfall in the region is strongly seasonal, occurring predominantly in winter (**Figure 45**). The majority of the rainfall is received during the winter season, followed by autumn and spring, with summer contributing the least rainfall.

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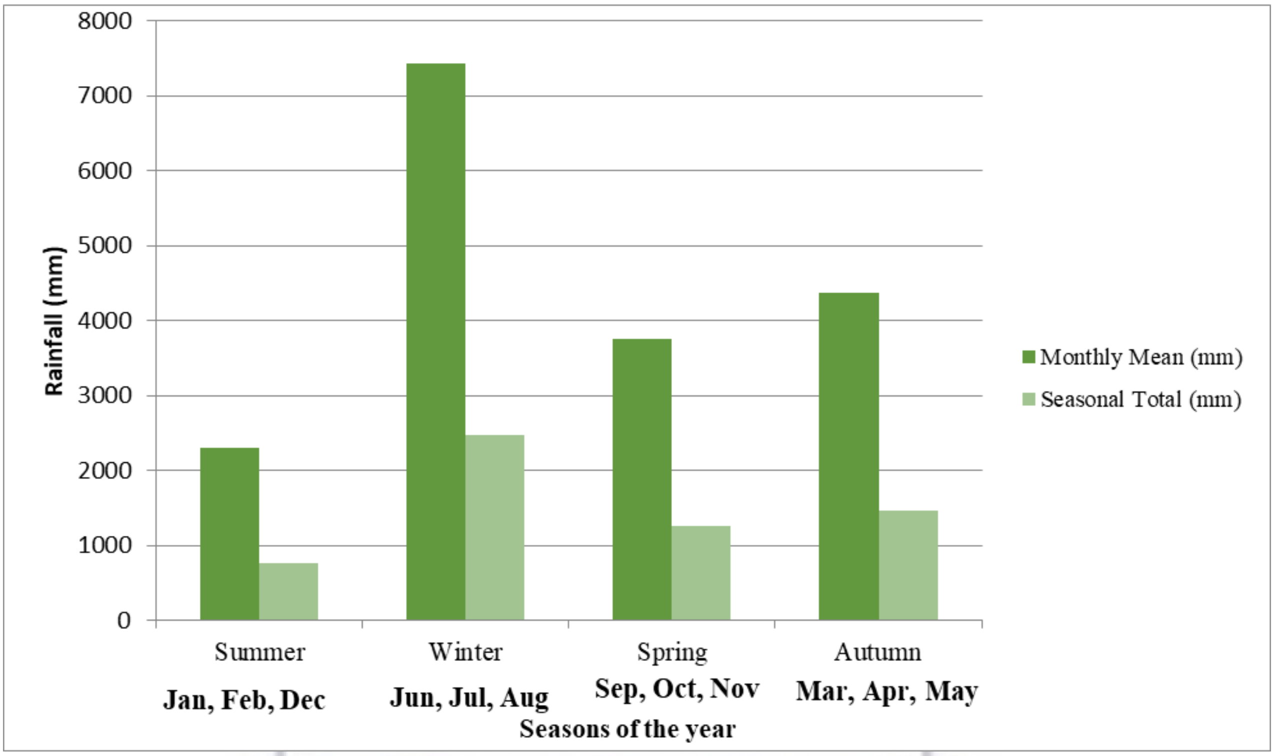

Figure 45: The Rainfall seasonality as determined using CHIRPS data.

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VI. CHAPTER SIX

6. DISCUSSION

6.1. Interaction between Rainfall, Vegetation Cover and Geomorphology at the Pietersielieskloof Valley-bottom Wetland

6.1.1. Historic Wetland Morphology

In Southern Africa, systems with discontinuous channels are common in valley-bottom wetlands along the Cape Fold belt region, forming due to cycles of deposition and erosion (Pulley *et al.*, 2018). Grenfell *et al.* (2019) suggest that valley-bottom wetlands with discontinuous channels result from slow-moving water which allows for extended periods of saturation. The Pietersielieskloof wetland has oscillated between a fully vegetated valley-bottom wetland to valley-bottom with a discontinuous channel. Following incisional events in the last two decades, the wetland has been transformed into a deeply incised gullied wetland that is eroding laterally in parts. As discussed by Wohl (2017), disturbances to a system can result in dramatic changes which will affect wetland shape and form depending on wetland sensitivity. The Kiersgat arm of the wetland has been transformed upstream by erosion, changing the wetland significantly.

Aerial photography from 1938 shows large alluvial floodouts, which are typically deposited at the downstream end of the channel, indicating that erosion was occurring further upstream within the valley during the early part of the twentieth century. Due to the resolution of the imagery (~30 m), the channel itself was not fully visible. By 1961, vegetation cover had increased and vegetation had encroached the floodouts. This suggests that the wetland had gone from an erosional and depositional phase to one of relative stability. The wetland was extensively vegetated in both arms by 2003 but a small part of the channel can be seen locally upstream and downstream of the road crossing in Lower Kiersgat. Boskloof and Blomkloof have remained intact in terms of vegetation cover since 1938 and are not characterized by floodouts to the extent of Lower Kiersgat.

6.1.2. Current Wetland Morphology

The wetland is currently dissected by the gravel road. As a result, the lateral position of the flow of water across the road has been permanently fixed. The gravel road has created a barrier to the

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downstream movement of sediment, and aerial photography shows that the road has been in place since the 1930s. Upstream of the road crossing, erosion has transformed Upper Kiersgat into an inset meandering reach in response to the energy excess created by base-level fall downstream, and because of the limitation in vertical incision. The system is expressing the energy excess laterally by migrating into the valley fill which is inset into the pre-existing alluvium by between 2 and 4 m. Scour has cut the alluvial fill within this meandering reach, a gully that is within 15-20 m wide and up to 6 m deep into. Vegetation in this reach is not extensive.

As the upstream portions of the wetland have become increasingly eroded due to causes that cannot be definitively explained, sediment has been accumulating. Erosion upstream of the road appears to have been impounded by the road crossing, which caused flooding of the road. The impounding effect of the road is further evident in the forced avulsion emanating from a diversion of flow and sediment across the road toward the right-hand valley margin downstream of the road, with traces of deposition and incision evident in imagery and field observations (**e.g. Figure 11**). The Alluvium is visible on the road in 2014 and 2016. The response to road flooding has been to dig out sediment downstream of the road, putting in boulders, culverts and cement which then starve the wetland below of sediment supply. The aim of this work was to improve the flow of water downstream, although the problem was incorrectly diagnosed. Sediment from upstream is blocking the culverts, causing flooding. There is now a meter drop from the road to the base of the channel downstream. As a result, the Kiersgat arm is visibly more eroded in contrast to Blomkloof and Boskloof arms', whose vegetation cover has remained relatively consistent in historical times compared to the Kiersgat.

Downstream of the road in Lower Kiersgat, the wetland is predominantly channelled, with vertical incision on-going in some reaches. The Lower Kiersgat portion of the wetland is currently made up of four distinct reaches; the inset meandering reach made up of gravel bars, floodouts, extensive gullies, fast-flowing water and loss of vegetation; the second is a confined-channel reach, the third reach has diffuse flows and the confluence with isolated pools where the channel disappeared into the vegetation. Boskloof on the eastern arm has seen an encroachment of alien and woody vegetation in the place of fynbos vegetation, and palmiet is not very

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extensive in this wetland. In contrast, Blomkloof in the headwaters remains intact with the palmiet vegetation.

6.1.3. Longitudinal Connectivity and Rainfall Recurrence at Pietersielieskloof

The longitudinal profile of Lower Kiersgat (**Figure 12/Figure 46**) was created using elevation and coordinates collected using DGPS and the longitudinal profile captures the presence of in-channel sediment deposition creating steepening sediment slug. The longitudinal profile of the Pietersielieskloof system is steep at the source of the erosion where the channel is meandering. The longitudinal profile from Pietersielieskloof does not show the usual fall in the gradient from headwaters to the downstream, generally displayed by most river systems. It shows a change from steepness after the road due to scour and in channel deposition. It alternates from steep to gentler slope as sediment moves downstream.

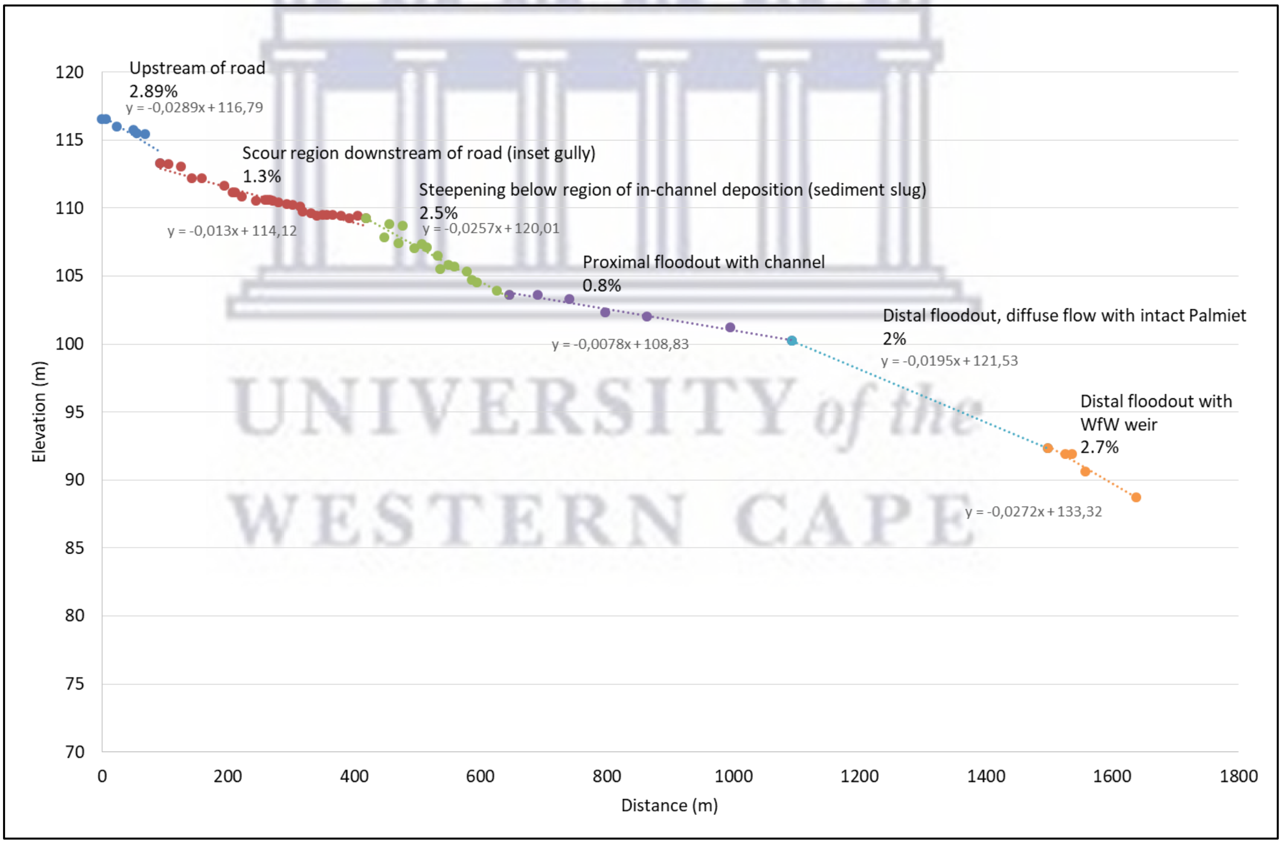

Figure 46: The thalweg longitudinal profile of Kiersgat.

As the gradient lowers, the channel becomes progressively confined and then spreads out into multiple channels eventually flows toward the confluence where rehabilitation structures have

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been put in place. This profile is not uniform, with the presence of the floodouts and has a stepped profile upstream. Downstream at the confluence where Kiersgat and Boskloof join, rehabilitation structures of chutes and a weir have been installed. Similar to the palmiet valley-bottom wetland Upper Krom described in Pulley *et al.* (2018), Pietersielieskloof is also eroding from the toe, while rehabilitation structures aim to reduce headward erosion. However, in addition to the headward erosion, Pietersielieskloof is also eroding from the head below the road through downstream incision. In this reach, valley widening is fairly limited.

Historical images and the rehabilitation plan from WfWetlands indicate that the region immediately adjacent to the currently rehabilitated wetland was cleared of alien vegetation between 2012 and 2014, with no riparian buffer in place. This reduced local infiltration and increased the amount of runoff when compared to a natural, vegetated catchment. According to the geomorphic threshold concept, valley slopes are typically stable for a specific runoff volume, and if there is an increase in the runoff volume while the slope remains the same, the slope will become unstable, resulting in erosion (Tooth, 2018). The magnitude and intensity of flow once a threshold has been crossed will dictate how the system adjusts to the new state.

The main erosion below the gravel road occurred between 2000 and 2014 period. The largest annual rainfall total and biggest 24-hour rainfall event during that 14-year period were both received in 2013, with an annual total rainfall of 563 mm.a^{-1} and 90.7 mm in a 24-hour period. This would be a 1 in 13-year recurrence event as high, intense rainfall years were experienced in 1989 (20-year interval), 2013 (13-year interval) and 2016 (39-year interval). The combination of high rainfall, removal of catchment vegetation, the intervention of the roads agency to consistently remove sediment below the road, as well as the road's impact as knickpoint and sediment barrier, have resulted in catastrophic erosion of the wetland. The next section will contextualize the magnitude of this erosional event with historical and sedimentological evidence. It is therefore likely that sediment starvation of the reach downstream of the road, coupled with intense flood events made worse by catchment surface clearing of vegetation, have collectively driven the erosion and within-wetland deposition observed below the road over the past decade.

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6.2. Sediment (Dis) Connectivity and Wetland Processes and Dynamics

6.2.1. Wetland Processes and Dynamics at Pietersielieskloof

The system has shown sensitivity to loss of vegetation and changes in run-off volume. Solon *et al.* (2007) argued that there is a clear exchangeable relationship between sediment and plants; and that the soil can control the plants and the plants can influence the soil. As such, vegetation cover can play a critical role in influencing how a channel behaves and can have a strong influence on flow and sediment delivery (Brierley and Fryirs, 2005). This can, therefore, influence connectivity. The Pietersielieskloof gullies have incised in the same locations vegetation had been cleared, affecting flow. Although vegetation was not the sole cause of faster flows, the loss of infiltration and storage potential provided by the presence of vegetation can result in increased erosion.

The concentration of flow by the culverts at the road increased the energy of the water within the wetland, and in terms of connectivity, increasing catchment runoff sporadically increases hydrological connectivity which can also cause erosion. Fryirs *et al.* (2007b) explained that modifications to a system can force them to readjust as the system exceeds its threshold capacity to resist or regulate the introduced change. The gullies displayed by the cross-sectional data indicate that the valley deepened by eroding vertically before finally widening laterally. The channel is currently in its final phase of widening.

Below the road, a reduction in sediment increased erosional capacity. Retention of sediment above the road crossing resulted in increased flow energy downstream due to reduced load relative to capacity (*i.e.* ‘hungry water’; Kondolf, 1997), thereby promoting lateral and vertical erosion within the reach below the road. The road culverts disconnect sediment flux on the hillslopes adjacent to the wetland, and this has led to accelerated erosion between the road and the wetland, with a hydrological concentration of flow with limited flow attenuation, and sedimentological (increased localised points of sediment delivery to the wetland) consequences as a result. The material produced by this erosion has been deposited downstream as a sediment slug within the widening channel. Despite recent events which appear to have exacerbated erosion, historical aerial photography and sedimentological evidence presented earlier support the suggestion of other authors that these systems operate primarily through cut-and-fill processes.

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Schumm (1994) demonstrated cut-and-fill development by using cross-sections to show how a vertically incising channel can laterally widen, infill and return to stability before incising again (**Figure 47**). He attributed the switching between erosive and depositional settings over a long time period variability in the amount of sediment available and gully drainage. The cross-sections at Pietersielieskloof are consistent with the valley-bottom wetlands from Grenfell *et al.* (2009a) in Northington, Job (2014) in the Goukou, and from Pulley *et al.* (2018) in the Upper Krom of a 'uniform', 'evenly uniform' and 'horizontal' valley floor.

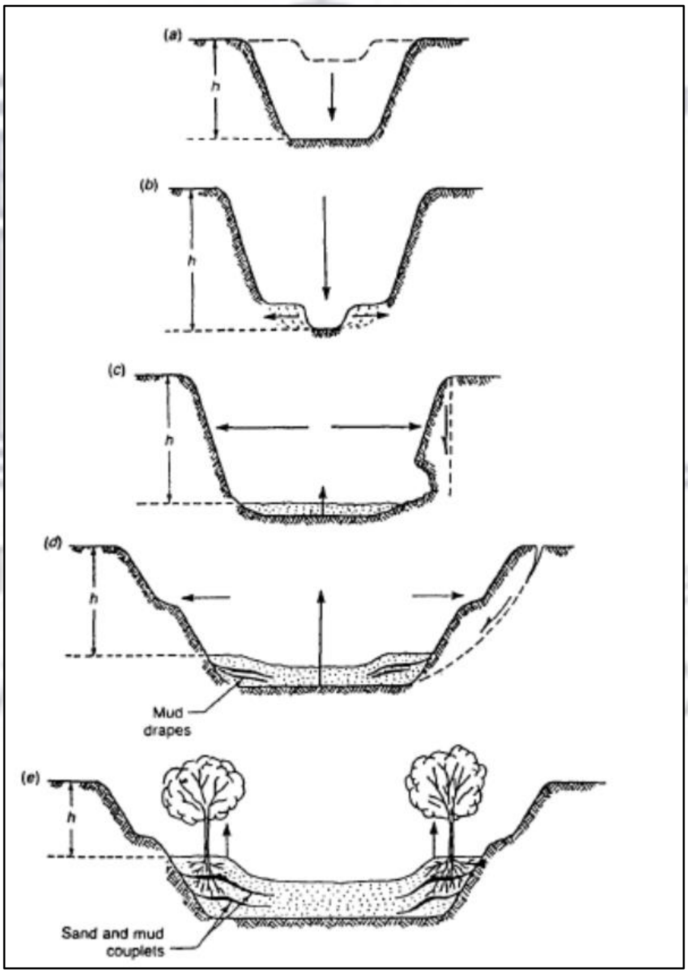

Figure 47: Modelling valley widening in incising channels (from Schumm, 1994: p.134).

6.2.2. Spatial Variability in Sedimentology at the Pietersielieskloof Wetland

In addition to the cut-and-fill process, local variability is introduced into the wetland by the existence of a 'sediment slug', visible on the Pietersielieskloof longitudinal profile. Nicholas *et al.* (1995) described sediment slug as the outcome of "*the generation and propagation*" (p.500) of sediment. The profile shows variations in slope that are related to sediment production and deposition zones of the slug. Sediment is eroded on the upstream end of the slug and deposited on the downstream end. Over time, the sediment slug moves as a unit which in this case has occurred fairly rapidly in response to anthropogenic modifications to the catchment and valley floor and would occur more slowly under natural conditions. As a result of this process, the slopes associated with the slug also move downstream. Sediment infill creates slope instability and sediment imbalance initiates gully erosion exposing buried organics and initiating the process of deposition again downstream where sediment will also be moved again.

In the current setting, sediment input and transport in the wetland are longitudinally reduced by the gravel road cross-cutting the two arms of the wetland and as a result, there is lack of connectivity between the reaches upstream and downstream of the gravel road. This occurs because the road acts as a local base level, causing deposition immediately upstream of the road crossing. Thus, the downstream movement of sediment released from massive valley incision and widening upstream is restricted by the road crossing. This has had two unintended consequences. Firstly, the wetland downstream of the road crossing is sediment starved. As a result, sediment supply is now derived primarily from bank erosion (valley widening) or bed erosion (vertical incision) rather than from upstream catchment sources. The lack of longitudinal sediment supply has therefore been supplemented by increased lateral connectivity between the banks and the channel which has provided locally derived sediment. Secondly, because so much sediment has been eroded from upstream, were it not for the road crossing, this reach would probably be in a phase of sediment accumulation. However, because the road crossing starves the downstream reach of sediment, it has caused erosion. Thus, the road reduces longitudinal connectivity in terms of sediment supply. In contrast, catchment vegetation clearing has increased longitudinal connectivity in terms of hydrology. The two together cause erosion, as an increase in hydrological connectivity locally increases stream capacity to carry sediment, while the impoundment local sediment supply has been reduced.

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With regards to sedimentology, only 10 samples from the entire wetland site were found to contain more than 30 % organic matter, with a combined average of 48.3 %. Overall, samples from the Kiersgat have the least organic matter at an average at 4.1 % and the Blomkloof tributary has the most at 38.6 %. In contrast, samples from one gully sidewalk at the Boskloof had an average organic content of 12.4 %. The sediment faces are dominated by sand, with silt and layer of high organic content forming as small lenses within the chronology. Overall, sample analysis separates the Pietersielieskloof wetland from other palmiet wetlands in the literature. Organic contents for samples taken from the eroded wetland ranged from 0.7 % to 62.3 %, with an average of 9.7 % organic matter. KPF-7, the youngest sample dated, contained the most organic matter compared to other dated sediments, with 62.3 %. This is in stark contrast to Rebelo (2018) who sampled 3 palmiet wetlands at 21 sites and found a range of 4.8 to 43.2 % and an average of 24.7 % in organic content.

Overall, the sedimentology of the Kiersgat wetland is dominated by sandy deposits with low levels of organic matter. The sediment faces exposed on gully sidewalls show a sequence of alternating upward coarsening sequences, indicating a series of depositional cycles in environments of increasing flow. The lack of upward fining sequences suggests that the upper part of these units tend to be eroded by subsequent flows. The wetland has a very small discontinuous amount of peat; the largest lens was 6.3 m wide and less than 20 cm thick and occurred as an isolated patch between sandy deposits. As such, organic accumulation at the Pietersielieskloof is clearly highly localised due to cut-and-fill processes of erosion and deposition. The likely modern analogue environment is in the distal diffuse floodout, which over time is topped by prograding sediment from the proximal floodout characterised by medium to coarse sands, organic accumulations are buried and later exposed by gully erosion.

Radiocarbon dating of these distal floodout organic remnants suggests that the cut-and-fill process occurs approximately every 3000 years. Furthermore, an analysis of sedimentology and a consideration of the radiocarbon dates further suggests that processes of erosion are were historically under natural conditions covers a small spatial extent occurs, occurred over a long period of time (i.e. 3000 years) and that erosion did not occur over the entire longitudinal profile at any one time. In addition, there are no thick peat deposits within this system, in contrast to the

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systems studied by Pulley *et al.* (2018) and Rebelo (2018) which may indicate relatively more rapid cut-and-fill turnover of valley sediments or a drier and more variable hydrological regime.

6.3.Implications of (Dis) Connectivity and Wetland Processes for Rehabilitation

The Pietersielieskloof Wetland is dynamic and constantly changing. By understanding its processes, it is possible to estimate the wetland's potential timelines, potential lags, resilience to disturbance, the existence of thresholds, and natural recovery potential. Due to the dynamics of the wetland, it is imperative that rehabilitation interventions aid natural recovery instead of imposing "stability" such that management and engineers design with an understanding of the wetland's processes. This will assist managers to achieve the set-out rehabilitation objectives more effectively to avoid a one size fits all approach while contributing to better wetland management, balancing wetland ecosystem services with maintaining wetland functionality. The analysis indicates that while the wetland does have the potential to recover geomorphically from erosion, the current situation with a long stretch of a continuous channel where channelisation compromises organic accumulation potential due to constant erosion and faster sediment cycling. Radiocarbon dating suggests a repeat of floodout formation every 3000 years, whereas historical analysis of aerial photographs suggests 3 phases of erosion and infilling within the last 100 years. This rate is clearly dramatically out of step with past process rates not enforced by built infrastructure.

In recent years, the clearing of alien vegetation likely increased storm event run-off volumes, accelerated flows and aggravated erosion. Thus despite the potential for natural recovery, as it has cycled through erosional to depositional phases many times in the past; change has been greatly accelerated, and the potential for natural recovery is limited as current catchment practices intensify the rate of erosion and reduce the availability of sediment supply that is deposited into downstream reaches. Nevertheless, although erosion in this wetland at these current rates appear higher than in previous erosion phases, sedimentological analysis reveals that gully erosion and floodout formation are natural processes in this valley-bottom wetland. When considering approaches to rehabilitation, we need to consider the importance of longitudinal connectivity for sediment supply stormflow Unless the fundamental causes of degradation associated with the road crossing and catchment disturbance are understood and addressed, rehabilitation interventions that focus on symptoms of change at points of headcut

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formation in the lower reaches of the system can only hold the system in a state of false stability over and above a simplistic description of the hydrogeomorphic units (Ollis *et al.*, 2013).

This research examined the geomorphic factors that act as inherent controls influencing the thresholds of the wetland's dynamics, such as vegetation cover, flow energy and sediment supply and connectivity. The wetland's most important identified geomorphic process is cut-and-fill cycles, whereby a series of new wetlands are created by erosion upstream and subsequent floodout deposition where wetland vegetation may re-establish. However, changes in the boundary conditions have changed the frequency and intensity of the natural processes, and impede on the processes of natural recovery. The wetland does not have extensive organic accumulation because of the absence of the right conditions to encourage infill.

The best time for rehabilitation intervention in such systems that go through periods of erosion and deposition is during the recovery phase when the wetland is undergoing sediment infill (Schumm, 1994), although more attention should be given to catchment disturbance and valley-spanning infrastructure that drives disturbance initially. This is the time at which recovery is the least risky and most cost-effective. Lower Kiersgat below the road appears to be in this phase, and the timing of Working for Wetlands interventions is therefore appropriate. However, rehabilitation structures do not necessarily address all catchment problems; they only address the local symptom of erosion.

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While most rehabilitation structures are designed to trap sediment and allow infilling of gullies, in this case, the road barrier is preventing a major source of sediment from reaching the structures. Thus, the full capability of the system's ability to naturally recover is not being harnessed. If this sediment is not allowed to progress downstream, it is likely that the wetland will remain confined to within the base of the gully and will not be able to infill and to allow the wetland to recover to its full potential will take more time. Thus, for interventions to have a higher chance of success, rehabilitation must also embrace natural recovery by ensuring that longitudinal sediment connectivity is not artificially breached. While the road crossing cannot be removed, it could be raised above the valley as a bridge or sediment could be manually supplied

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to the downstream reach so as not to alter flood flows by confinement, or disrupt sediment throughput by impoundment.

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VII. CHAPTER SEVEN

7. CONCLUSION

This research has shown how vegetation cover and land use can impact wetland form and change wetland process and behaviour by influencing the storm flow runoff response, the availability of sediment supply and accumulation, and the capacity of sediment delivery. All these processes are also influenced to a large extent by the road crossing, which is acting as a catchment disturbance, preventing natural recovery and keeping the wetland in the eroding state it is in. This research argues that continuous saturation and slow flows are stronger drivers of peatland formation than a specific vegetation type since at Pietersielieskloof, thick peat accumulations can only occur where there is permanent saturation over long periods of time with low clastic sediment inputs.

While external factors such as floods can produce marked changes within a system, some changes can also be autogenic such as the cut-and-fill cycles and occasional floodouts displayed by some valley-bottom wetlands. In managing ecology and repairing biodiversity in wetlands, management must consider natural processes taking place within the system over varying temporal and spatial scales. In wetlands such as Pietersielieskloof, this would mean that both depositional and erosional processes can be natural; however, it is the frequency, intensity and the extent of erosion that could ultimately degrade the wetland. More attention should be paid to causes of degradation that typically also inhibit natural recovery, and are in many cases located far away from the sites chosen for intervention.

This research considered the likelihood of natural ecosystem recovery with a focus on both lateral and longitudinal connectivity in the Pietersielieskloof Wetland. This was as a result of identifying a gap in sedimentological and geomorphological inputs in rehabilitation methods and strategies for rehabilitation other than just their hydrogeomorphic types. The extent of the research was limited to Pietersielieskloof so results may not be conclusively generalised to apply to other wetlands of the same hydrogeomorphic type since not all unchanneled/discontinuous valley-bottom wetlands are palmiet valley-bottom wetlands and not all palmiet valley-bottoms have the same geomorphic controls.

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LIMITATIONS OF THE STUDY AND RECOMMENDATIONS

This study was able to use carbon-dating to date organic matter and this allowed us to understand previous depositional cycles, and therefore the natural process of filling. This method provided reliable data, although expensive. The lack of extensive organic matter in this palmiet wetland in comparison to others highlights why studying wetlands in their individuality for rehabilitation purposes is so important. The lack of historical imagery from National Geo-spatial Information (NGI) prior to 1938 meant that the study was not able to study the wetland prior to the road crossing. This would have provided a better view of the wetland and the influence of the road on wetland processes. The unavailability of direct rain-gauge rainfall data from the Agricultural Research Council (ARC) and the South African Weather Service (SAWS) allowed for the introduction of the Climate Hazards Group Infrared Precipitation with Station (CHIRPS) rainfall data as a method of analysing rainfall and rainfall patterns. A future study comparing CHIRPS with direct rain-gauge data in South Africa might be worth looking into as CHIRPS provides accessible data to locations that might not have monitoring stations.

Pietersielieskloof could also benefit from a cross-sectional survey of all tributaries. This can be expected to be challenging because the confluence of the Lower Kiersgat tributary, the Blomkloof tributary, and the Boskloof tributary are heavily vegetated and this makes the use of a Differential Global Positioning System (DGPS) difficult to connect. This survey would have provided a good comparison of the tributaries at a higher resolution than using 5 m contours to draw the cross-sections such as the one done for Blomkloof. These wetland origin and wetland process studies can provide leeway for ecologists when considering interventions and resource management strategies.

Similar studies in palmiet valley-bottom wetlands across the Cape Fold Belt can provide an understanding of the functioning of these types of wetlands so that we are able to protect them better. Future studies at Pietersielieskloof looking at the rehabilitation structures, their impact on wetland recovery, and their influence on sediment supply and delivery once they have been in place long enough, would also be interesting.

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9. APPENDIX

Particle Size Error Percentage

SAMPLE #	dry sed (g)	after sieve	Lost sample	w3/w1*100
BK 1 (165-170)	36,382	35,437	0,945	2,60
BK 1 (170-175)	39,684	39,016	0,668	1,68
KPF 1 (0-10)	39,372	37,316	2,056	5,22
KPF 1 (10-20)	39,345	38,604	0,741	1,88
KPF 1 (110-115)	39,407	37,52	1,887	4,79
KPF 1 (115-120)	40,762	39,58	1,182	2,90
KPF 1 (140-145)	39,984	38,868	1,116	2,79
KPF 1 (145-180)	40,633	37,666	2,967	7,30
KPF 1 (180-240)	39,544	38,221	1,323	3,35
KPF 1 (255-275)	42,805	42,55	0,255	0,60
KPF 1 (280-290)	41,255	40,607	0,648	1,57
KPF 1 (320-345)	38,387	37,72	0,667	1,74
KPF 1 (345-360)	42,461	40,624	1,837	4,33
KPF 1 (365-435)	39,404	37,481	1,923	4,88
KPF 1 (40-50)	40,295	39,792	0,503	1,25
KPF 1 (435-465)	39,483	38,637	0,846	2,14
KPF 1 (80,5-81,5)	40,432	39,613	0,819	2,03
KPF 2 (0-20)	38,865	38,288	0,577	1,48
KPF 2 (105-120)	39,058	38,516	0,542	1,39
KPF 2 (125-145)	39,756	38,609	1,147	2,89

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KPF 2 (145-180)	39,674	39,058	0,616	1,55
KPF 2 (180-210)	40,751	39,619	1,132	2,78
KPF 2 (20-40)	40,641	39,864	0,777	1,91
KPF 2 (210-220)	39,497	38,44	1,057	2,68
KPF 2 (40-75)	39,208	37,823	1,385	3,53
KPF 2 (75-85)	41,081	40,246	0,835	2,03
KPF 2 (85-105)	39,713	39,211	0,502	1,26
KPF 3 (0-10)	40,157	39,284	0,873	2,17
KPF 3 (130-135)	40,387	37,667	2,72	6,73
KPF 3 (145-150)	40,534	38,02	2,514	6,20
KPF 3 (15-20)	45,945	45,475	0,47	1,02
KPF 3 (80-110)	41,572	41,521	0,051	0,12
KPF 4 (200-210)	40,608	37,718	2,89	7,12
KPF 4 (20-30)	37,028	29,823	7,205	19,46
KPF 4 (80-90)	39,628	36,234	3,394	8,56
KPF 5 (155-160)	40,138	39,087	1,051	2,62
KPF 5 (200-205)	40,804	38,777	2,027	4,97
KPF 5 (35-40)	40,448	40,109	0,339	0,84
KPF 5 (5-10)	39,82	39,091	0,729	1,83
KPF 5 (60-65)	40,35	39,937	0,413	1,02
KPF 5 (95-100)	48,171	40,744	7,427	15,42
KPF 6 (105-110)	39,78	38,98	0,8	2,01
KPF 6 (160-165)	39,817	38,947	0,87	2,18

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KPF 6 (180-195)	39,52	38,923	0,597	1,51
KPF 6 (205-210)	40,029	39,28	0,749	1,87
KPF 6 (230-235)	39,034	38,808	0,226	0,58
KPF 6 (265-270)	40,132	39,776	0,356	0,89
KPF 6 (40-45)	37,903	37,25	0,653	1,72
KPF 6 (65-70)	39,725	39,081	0,644	1,62
KPF 6 (95-100)	40,071	40,059	0,012	0,03
KPF 7 (105-110)	40,279	38,676	1,603	3,98
KPF 7 (145-155)	39,759	38,793	0,966	2,43
KPF 7 (180-185)	43,712	40,423	3,289	7,52
KPF 7 (30-35)	38,654	36,303	2,351	6,08
KPF 7 (65-70)	40,912	40,811	0,101	0,25
UP 1 (150-160)	40,522	40,401	0,121	0,30
UP 1 (15-20)	34,834	33,389	1,445	4,15
UP 1 (230-245)	37,952	36,963	0,989	2,61
UP 1 (265-270)	39,453	39,176	0,277	0,70
UP 1 (315-320)	37,777	35,855	1,922	5,09
UP 1 (340-350)	40,483	39,671	0,812	2,01
UP 1 (430-440)	39,263	38,206	1,057	2,69
UP 1 (485-495)	19,004	18,111	0,893	4,70
UP 1 (600-620)	19,871	19,052	0,819	4,12

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