THE MORPHODYNAMIC CHARACTERISTICS OF EROSIONAL HEADCUTS IN PALMIET (*Prionium serratum*) WETLANDS

by

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Declaration

I declare that the thesis entitled "*The morphodynamic characteristics of erosional headcuts in Palmiet (Prionium serratum) wetlands"* is my own work, that it has not been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by means of complete references."

Afeefah Williams 2018

Signed:……………………………

Abstract

Gully erosion and headcut migration has been at the crux of wetland degradation in South Africa. The resulting erosion and draining effect has seen more than 50% of wetlands in the country degraded. This study investigated the degradation of indigenous Palmiet, peat forming, wetlands through headcut erosion. This was done by exploring the relationship between headcut migration rate and morphodynamic characteristics through the use of multiple regression analysis. Wetlands investigated in this study occurred in the Kromme River catchment and Nuwejaars River catchment, in the Eastern Cape and Western Cape respectively. Morphodynamic characteristics assessed include headcut dimensions, gully characteristics, soil characteristics and drainage basin characteristics. These parameters were determined either through infield assessment, image analysis or laboratory analysis. Three headcut migration rate types were calculated through a combination of infield measurements and image analysis techniques executed within ArcGIS. These migration rate types include apex advancement (m/a), gully expansion (m^2/a) and volume erosion (m^3/a). Statistical analysis revealed significant relationships between morphodynamic characteristics and both volume erosion and gully expansion. Morphodynamic characteristics such as drop height, apex width, gully width, drainage rate and sand content were found to have a direct relationship with migration rates, whereas characteristics such as average drainage basin slope, clay content, silt content, SOM content and soil saturation were found to have an indirect relationship with headcut migration rates. Results provide insight into the headcut migration process, its influencing factors and the potential for headcut migration rate prediction. An evaluation of these results using WET-Health found that the wetland management tool captures wetland geomorphic controls to an accuracy of 68% and 70%. Furthermore, the influence of morphodynamic characteristics on migration rates contributes to the wetland rehabilitation process as it allows for the identification of headcut sites most susceptible to erosion. This will then allow for timely wetland rehabilitation, decreasing the rate of net wetland degradation and improving the management and efficiency of wetland restoration.

Key words: Degradation, drainage basin, ecosystem, gully erosion, Headcut migration, management, Palmiet, peat, rehabilitation, WET-Health, wetland.

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Abbreviations

Appd	Average plunge pool depth
Aw	Apex width
BD	Bulk Density
CFB	Cape Folded Belt
CFR	Cape Floristic Region
CHIRPS	Climate Hazards Group InfraRed Precipitation with Stations
DEM	Digital Elevation Model
Dh	Drop height
GMC	Gravimetric Moisture Content
Gw	Gully width
LoI	Loss on Ignition
NGI	National Geo-spatial Information
NRCS	Natural Resources Conservation Service
PPMCC	Pearson's Product-momentum Correlation Coefficient
SANSA	South African National Space Agency
SOM	Soil Organic Matter
SUDEM	Stellenbosch University Digital Elevation Model
TMG	Table Mountain Group
USDA	United States Department of Agriculture
VIF	Variance Inflation Factor
VMC	Volumetric Moisture Content
WMA	Water Management Area

Measurements:

cm	Centimetre
cm.hr	Centimetre per hour
cm^2	Squared centimetre
g	Grams
$g.cm^3$	Grams per centimetre cubed
ha	Hectare
km	Kilometre
km^2	Square kilometres
m	Metre
m^2	Square metres
m^3	Metres cubed
Ma	Mega-annum
m.a.s.l	Metres above sea level
ml	Millilitre
mm	Millimetre
m/a	Metres per annum
m/a^2	Metres squared per annum
m/a^3	Metres cubed per annum
µm	Micrometre

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Chapter 1: Introduction

1.1) Background

The country of South Africa is known for its water scarcity due to its semi-arid nature and average rainfall of about half of the world average (Nel et al., 2013). The available water resources are subject to the influence of high potential evaporation, over abstraction and pollution. Many Water Management Areas (WMA) have been put under stress as demand far surpasses the supply of available water resources and is projected to worsen due to population growth and industrial development (Colvin et al., 2016). This has resulted in increased attention on conservation and protection of our already limited fresh water resources.

1.1.1) Water and wetlands in South Africa

As a developing country, the dependency on water for social and economic progression has led to ecological regression. This is especially the case for wetlands; wetlands are globally defined by the Ramsar convention as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres". In terms of South Africa's National Water Act of 1998, wetlands are defined as, "Land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil".

Although South Africa is regarded as a semi-arid region it boasts a variety of wetlands, contrary to its negative water balance with potential evaporation exceeding precipitation (Ellery et al., 2009; Job, 2014). Tooth and McCarthy (2007) described wetlands in a southern African context characterising them as wetlands in drylands. Drylands are characterised by high but variable levels of aridity. South Africa generally has a negative water balance with a mean annual potential evapotranspiration that far exceeds the, lower than global, mean annual precipitation. This means that wetlands in the country can only occur in small pockets that have a positive water balance for all or part of the year (Tooth and McCarthy, 2007).

Peatlands are amongst the most rare wetlands types usually having a topogeneous origin (Sieben, 2012). Topogeneous origin implies that groundwater flows through a mineral substrate before it enters the peat; topogeneous wetlands form under climatic conditions of reduced rainfall with lower humidity and summer drought and occur where water naturally accumulates (e.g. hollows and valleys) (Seneviratne, 2014). The characteristics surrounding and defining wetlands make them ecological hotspots as they provide habitat for a distinctive variety of fauna and flora. This distinctive habitat plays a key role in the diversity of indigenous and endemic plant and animal species.

Wetlands have been at the epicentre of various types of development on both a local and national scale. They provide various ecological goods and services to mankind. These include a wide range of ecosystem services that contribute to human well-being, such as fish and fibre, water supply, water purification, climate regulation, flood regulation, coastal protection, recreational opportunities and increasingly tourism (Butchart et al., 2005). With the loss of wetland and wetland habitat it is expected that these goods and services will be lost too.

1.1.2) Ecosystem goods and services

Ecosystem services are divided into four categories based on the type of benefit they provide mankind. These categories includes provisioning services (e.g., food, fibre, fuel, water, medicine); regulating services (e.g., climate, sediment, floods, disease, waste and water quality); cultural services (e.g., recreation, aesthetic enjoyment, tourism, spiritual and ethical values); and supporting services necessary for the production of all other ecosystem services (e.g., soil formation, photosynthesis, nutrient cycling) (Butchart et al., 2005; Turpie et al., 2010). Of these services, the supply of fish and water availability have been identified as the two most crucial benefits (Butchart et al., 2005). Though this is the case wetlands are recognised as being degraded and lost at a more rapid rate than any other ecosystem type, thus diminishing these services and deteriorating the status of both fauna and flora species (Ramsar Convention Secretariat, 2013). This is due to the complex relationship and dependence of mankind on the goods and services wetlands provide coupled with the increasing population and need for economic sustainability (Macfarlane et al., 2009).

Fresh water resources such as surface water bodies provide a large number of ecological goods and services. Wetlands in particular provide an array of benefits to our welfare (Butchart et al., 2005). Wetland areas cover 3% of South Africa’s land surface area and are essential to the existence of various indigenous fauna and flora (Haigh et al., 2004). Besides being ecological hotspots, wetlands also contribute to the hydrogeology of rivers regarding morphology, water quantity and water quality.

Wetlands tend to originate in environments with relatively low energy as they rely on a prolonged supply of water in the root zone for their existence. When the requirement for prolonged supply of water is met vegetation growth and densification promotes diffuse flow, enhancing deposition and decreasing erosion, in that way regulating river morphology. Wetlands store water during both wet and dry seasons therefore, contributing to freshwater water storage and regulation of river flow. Organisms such as micro-organisms and invertebrates that inhabit wetlands improve the quality of water by naturally chemically and biologically decomposing pollutants (Turpie et al., 2010).

1.1.3) Wetland degradation and rehabilitation

Although the importance of wetlands has been recognised, wetland degradation and collapse has been a recurring problem in South Africa, with approximately 50% of wetlands area already lost and 65% of the remaining wetland ecosystem types classified as threatened, 48% of which are critically endangered (Driver et al., 2012; Haigh et al., 2004). The need for wetland rehabilitation in South Africa is compelling. The loss and degradation of wetlands have been ubiquitous and national policy and legislation provides clear direction and support for rehabilitation. The various ways in which wetlands can be degraded and the complex relationship between wetlands and humans makes wetland rehabilitation a challenging task. In order to protect and restore wetlands from threats it is important to understand the natural processes of wetlands and equilibrium thereof.

Wetlands can be degraded both biologically and morphologically, though degradation is not limited to the degradation of either. Once the wetland undergoes biological changes, undoubtedly morphological changes will follow and vice versa. Biological changes in wetlands directly influence the occurrence, type, density and proportion of plant and animal species, thus indirectly influencing the morphological state of the wetland as vegetation plays a key role in river and wetland morphology (Grabowski and Gurnell, 2016). This happens due to the complex nature of ecosystems making rehabilitation of wetlands a challenging task.

The Kromme River catchment and Nuwejaars River catchment have both been identified as catchments undergoing rapid fluvial geomorphological degradation to both their river channels and wetlands. The Kromme catchment, Eastern Cape, and the Nuwejaars catchment, Western Cape, have been sites of extensive research regarding wetland degradation and wetland restoration.

The Kromme River forms part of the Fish to Tsitsikamma water management area (WMA) and is one of five catchments that provide water to the Nelson Mandela Metropolitan Municipality via the Churchill Dam. The source of the river is in the Tsitsikamma Mountains, which form part of the Cape Folded Belt (CFB), flowing in an east-southeast direction with an outlet into the Indian Ocean at St. Francis Bay estuary west of Port Elizabeth. The Nuwejaars catchment, one of five quaternary catchments in the Heuningnes catchment, is located in the adjacent Breede-Gouritz WMA. The Nuwejaars River and Kars River drain the upper catchment in a general south-eastern direction and converge to produce the Heuningnes River which drains the entire catchment into the Indian Ocean at the De Mond estuary. The catchment is home to an array of wetland types most of which have been exposed to various levels of alien tree infestation.

Many wetlands in the Kromme and Nuwejaars catchments host Palmiet (*Prionium serratum*) vegetation which is a key characteristic of wetlands selected for this research project. Historically Palmiet has been seen as a nuisance by farmers who removed it under the misperception that they blocked rivers, used lots of water and caused inundation of farms established on floodplains (Job, 2014). Palmiet wetlands are wetlands that are host to robust semi-aquatic Palmiet vegetation which belongs to the Prioniaceae family and is endemic to South Africa (Mucina and Rutherford, 2006). Palmiet vegetation is regarded as an ecological engineer due its erosion deterrence and wetland forming characteristics (Jones et al., 2010; Sieben, 2012; Sieben et al., 2017a). The flexible stems bend and protect stream banks during high flow events and its clonal root structure provides resistance to flow velocity largely decreasing the effect of fluvial erosion on the river bed. These plant properties allow for the formation and persistence of wetlands in upper-catchment areas in which wetlands would not normally occur due to steep slopes resulting in high stream power (Job, 2014). These wetlands are currently undergoing severe gullying and headcut erosion which has caused a reduction of the vegetation. Reduction in the occurrence of Palmiet vegetation directly affects the sustainability of wetlands in these upper-catchment areas which provide habitat for a diversity of biota, as well as water storage and flood attenuation to the rest of the catchment downstream.

1.1.4) Wetland gully erosion

Erosion of wetlands through gully incision has been identified as one of the most serious problems facing South African wetlands (Ellery et al., 2009). The degradation of these habitats will consequently cause the degradation of the ecosystem goods and services they provide to society. Wetland health is dependent on the interrelation between three components namely hydrology, geomorphology and vegetation as seen in Figure 1.1. This complex nature of wetlands results in a domino effect when one of these components is altered. These resulting changes to wetland systems are the habitat's response to readjust to a new found balance. Wetlands incision through headcut erosion and gullying can be a result of changes to one or more of these factors (Macfarlane et al., 2009).

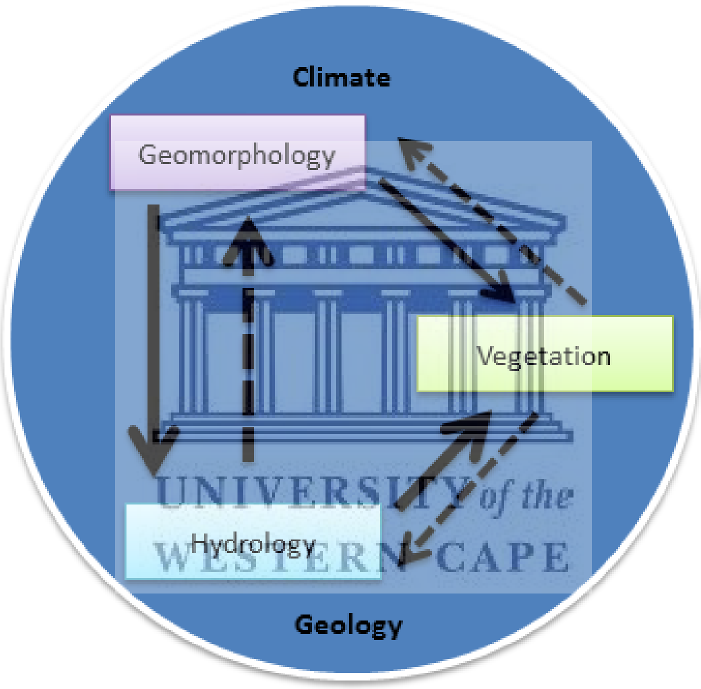

Figure 1.1: Interrelationships with respect to magnitude of impact between hydrological, geomorphological and vegetation state of wetlands. The width of the lines indicates the likely strength of interactions (Macfarlane et al., 2009).

Gully incision is an erosional process which removes soil along drainage lines creating new drainage networks or extending the existing drainage network. The most active point along a gully feature is the gully-head which is the most upstream reach of a gully where large scale erosion takes place. The gully head is characterised by a knickpoint and headcut face. A headcut refers to the step-like feature or near vertical reach in the gully head long profile and a knickpoint is the exact point where the original stream bed intersects the near vertical face of the headcut (Figure 1.2). The abrupt increase in slope at the knickpoint increases the velocity of water as it flows across the headcut; therefore, increasing the water's erosive force when it collides with the stream bed resulting in erosion. Gullies erode through various mechanisms, namely, seepage erosion, mass wasting and plunge pool erosion (Flores-Cervantes et al., 2006; Rengers and Tucker, 2014). The mechanism and rate of erosion are dependent on various infield controls and site characteristics. These controls and characteristics include overland flow, drainage area, slope, soil type, soil stratigraphy and vegetation.

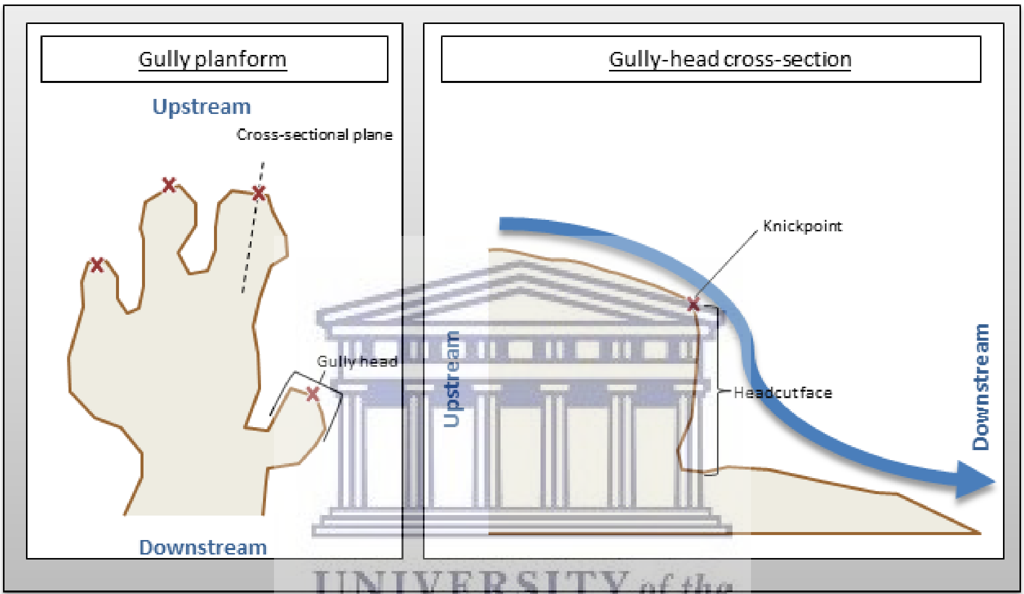

Figure 1.2: Schematic depicting gully form a) Gully planform, with knickpoints and cross-sectional plane and b) Gully cross-section with knickpoint and flow path across a headcut.

Headcut erosion differs to gully erosion as it refers the displacement of the headcut face, being the most dynamic part of a gully, therefore not necessarily taking gully widening into account. Headcut and gully erosion is degrading Palmiet wetlands in both the Kromme and Nuwejaars catchments. Erosion results in the upward migration of the headcut which intercepts upstream wetlands resulting in the diminution of the wetland and eventually their destruction as the headcut reaches the top of the wetland. There have been many attempts by government organisations and landowners to slow down wetland degradation caused by headcut migration, many of which have proved unsuccessful. Working for Wetlands has been at the forefront of wetland restoration by means of rehabilitation and the implementation of various structures. A number of these restoration initiatives are specifically aimed at halting further headcut migration and geomorphological degradation of wetlands. Regardless of the large amount of capital and time spent on these interventions many of them have proven to be unsuccessful and this could be a result of a lack of understating of the processes that take place during headcut migration (Kotze and Ellery, 2009).

Alien vegetation encroachment is prevalent in both catchments, known for disrupting wetland disrupting morphology by out-competing native wetland vegetation for the available water resource, subsequently causing the drying of wetlands. The presence of both alien vegetation and headcut erosion in Palmiet wetlands has led to the deterioration of wetland vegetation health and geomorphological health, resulting in the collapse of many Palmiet wetlands and loss of natural capital (Rebelo, 2012). Based on the interrelationship between wetland hydrology, geomorphology and vegetation it is safe to assume that the degradation of hydrological component will soon follow (Figure 1.1).

1.2) Rationale

Controls on headcut morphodynamics are not well known due to the logistical difficulties that surround the monitoring of actively migrating headcuts (Robinson et al., 2000). Continuous uncontrolled channelization and erosion of wetlands could lead to severe degradation or destruction of wetlands and ecosystems downstream. This will impact the ecological state of biodiversity and offset the hydrological and ecological interrelationships of wetland ecosystems as well as any and all activities benefiting from an ecosystem's existence. The loss of habitat ultimately means the decline of biodiversity in the area and could also result in the obliteration of an entire species endemic to the area. The degradation and channelization of a wetland compromises its hydrological health in terms of both water quality and quantity (Cox et al., 2016). Water quality will be affected as the degradation of wetlands will diminish its water storage and biodiversity capacity. This will subsequently decrease the capacity of microbes, nematodes and vegetation capable of improving water quality and also the residence time of water within the wetland during which these species metabolise and filter sediments. The quantity of water will be affected due to the loss of water retention and flood attenuation properties associated with wetlands. This could result in insufficient water availability during the dry season and flooding during the wet season. Indigenous Palmiet wetlands with their associated headcut erosion typically occur in the upper reaches of river catchments. Therefore, degradation of wetlands will have knock-on effects to the entire catchment from the headwaters all the way down to the estuary.

A paper written by Bergonse and Reis (2016) identified two main scientific gaps that should be included in future research on the evolution of landforms to further increase the knowledge of factors controlling the size and location of gully systems. The first being the dating of gully system fills which would contribute to the chronology of the development of these features, shedding light on the corresponding environmental context, rates of evolution and possible human influence. The second is to present work based on primary data, infield measurements, taking into account the lithological setting of the gully system due to its control on gully erosivity/stability, the mechanism responsible for gully erosion and its influence on subsurface hydrology (Bergonse and Reis, 2016).

Vanmaercke et al. (2016) identified various important research gaps surrounding gully headcut retreat rates. These include lack of continuous monitoring and additional data, understanding the temporal variability of gully erosion rates, the role of land use and other factors at a local scale and the differentiation between gully headcut retreat and gully erosion in terms of factors that affect them (Vanmaercke et al., 2016).

Based on the gaps identified by the above mentioned researchers this project aims to partially fill these gaps by researching the relationship between headcut migration rate and various headcut characteristics at a local scale. This will be achieved by quantifying the effect various headcut characteristics have on headcut migration rate. This study also assesses the influence of factors on both headcut retreat rate and gully erosion potentially providing differentiation between these two erosion types. Establishing these relationships will provide insight to the key driving forces behind the migration of specific headcuts. Lack of adequate understanding of factors influencing headcut migration will ultimately result in limitations regarding further understanding and management of river and wetland geomorphology. Improving the understanding of headcut migration and its associated processes will provide a better basis for the development of adequate restoration interventions for headcut stabilisation, thus decreasing the rate of wetland degradation.

1.3) Aim

This study aimed to improve knowledge and management of headcut erosion by understanding the morphodynamic characteristics of erosional headcuts.

1.4) Objectives

1. To develop a conceptual model of controls on headcut migration
2. To investigate the rate of headcut advancement and gully expansion in Palmiet wetlands.
3. To explore relationships between headcut erosion rate and:
    i. Headcut and gully geometry
    ii. Sediment characteristics of the lowest sediment horizon along the headcut face
    iii. Regional controls (slope and drainage area)
4. Refine the conceptual model for Palmiet wetlands based on the findings and evaluate the application of current wetland management tools in headcut assessment.

1.5) Methodological approach

The leading method for obtaining data was through field visits and time series image analysis. Data analysis was primarily empirical-statistical. The analysis and further exploration of the relationships within the dataset followed an inductive approach in which repeated measurements allow prediction of "what will happen next". The methodological approach was based primarily on the statistical use of correlation and regression analysis.

1.6) Thesis outline

Chapter 1 introduces the subject matter being investigated and establishes the problem statement, rationale, aims, objectives and the general research approach.

Chapter 2 provides a background of the research topic through a literature review. This chapter covers previous research on Palmiet wetlands, headcut and gully erosion and wetland degradation.

Chapter 3 provides the necessary information of the research projects study areas including aspects such as climate, geology, topography, hydrology, vegetation and land use.

Chapter 4 describes the various methods and materials used for data collection and analysis used in this research project.

Chapter 5 illustrates and describes the results generated in this study.

Chapter 6 discusses the significance of the results with reference to existing knowledge base and considers its contribution to existing knowledge.

Chapter 7 concludes the study by considering the significance of the findings in a broader context than presented in the discussion.

Chapter 2: Literature review

2.1) Introduction

The following chapter will cover previous research done on headcut erosion, establishing a background on this erosion process, factors affecting the rate of erosion and also identify gaps in literature. This chapter will also review research on Palmiet wetlands, the process of headcut and gully erosion and lastly factors that influence headcut migration rate.

2.2) Palmiet wetlands

Wetlands naturally provide a dynamic setting for both fauna and flora species due to their ability to host both terrestrial and aquatic species. Furthermore the presence of wetlands occurring in drylands, such as Palmiet wetlands, provides moisture in climatically variable conditions allowing for the sustenance of diverse species. This results in a large ecological diversity within these wetland ecosystems. These wetlands are therefore, referred to as ecological hotspots/niches (Tooth et al., 2015). Peatlands are particularly rare in South Africa, occurring along the southern and eastern coast and along the mountain escarpment inland. Sieben (2012) suggested Palmiet plays an important role in the formation of peatlands in South Africa, dominating the wetlands they occur in, as they have no functional equivalent, thus making it a successful competitor. Furthermore its ability to alter an environment to suit its needs establishes Palmiet as an ecosystem engineer (Sieben, 2012). Peat is defined as accumulated soils containing a minimum 30% dead organic matter of its dry mass and a peatland is defined as an area both vegetated and un-vegetated that naturally accumulates organic matter having a peat layer with a minimum thickness of 300 mm (Joosten and Clarke, 2002; Ollis et al., 2013). Palmiet vegetation influences the formation in peatlands in two ways; 1) it plugs foothill streams with is clonal growth-form, forming valley-bottom wetlands and 2) it produces peat and traps sediments and debris in an anoxic zone promoting organic material accumulation. Peat forms when the rate of decomposition is less than vegetation production, resulting in a carbon surplus (Joosten and Clarke, 2002). Peat produced by Palmiet vegetation decomposes slowly and has a low humification index, therefore, making Palmiet is a good peat-forming plant (Sieben, 2012). Another benefit of peatland formation is the carbon sequestration function (Turpie et al., 2010), offsetting carbon emissions, thus making the conservation of Palmiet wetlands and other peatlands alike a matter of global importance.

The evolution of Palmiet wetland morphology is described by Job (2014) as a cut and fill process following climate cycles. Palmiet wetlands originate when Palmiet vegetation colonizes V-shaped valleys during periods of reduced flow. The ecosystem engineer plugs valleys, providing an area for water storage, diffused flow and sediment storage, ultimately forming a valley bottom wetland. When the region is subjected to increased flow due to high precipitation in the catchment, gully erosion starts incising the wetland. During this phase the wetland stream bed and valley sides are eroded to the local bed level and widening and planing of the valley floor occurs. Once flooding becomes less frequent, Palmiet recolonizes the gullies and promotes diffuse flow, sedimentation and peat accumulation. As the cycle of flooding and low flow continues with time, the phases of the cutting and filling process also continue through the entire width of the wetland. This subsequently results in a valley floor of cross-sectional uniform elevation, for a given distance from the head of the wetland, transforming the valley to a wider U-shaped valley (Job, 2014).

Alien vegetation encroachment is a common threat to the existence of Palmiet wetlands. Apart from abstracting large quantities of available water, these alien species also shade out lower growing indigenous plants, thereby out-competing natural vegetation. Once the native Palmiet is displaced, the underlying peat beds are exposed, dry out, and rapidly erode. This effect of alien vegetation on natural vegetation also causes a reduction in vegetation ground-cover, increasing the occurrence of bare soil, consequently increasing sediment entrainment when runoff occurs (Rebelo et al., 2015).

2.3) Headcut and gully erosion

A headcut is defined as an erosional near vertical step-like feature along a reach of stream bed or flow path that undergoes a sharp drop in elevation over a short distance in a downstream direction. Headcuts generally migrate upstream with time, thereby lengthening the gully (Stein and Julien, 1993). These features occur in areas of concentrated flow typical of upland areas and have been associated with rill and gully erosion, erosion of bedrock channels and the initiation of drainage systems and landscape evolution (Bennett et al., 2000). Headcut erosion occurs when flow occurs across the step-like feature, locally increasing stream-power due to the increased slope, thus eroding soil. Headcuts have been known to occur both naturally and due to anthropogenic activity. Headcut initiation and the accompanying gullying of the landscape have been at the crux of South African wetland geomorphic transformation and degradation for several decades (Macfarlane et al., 2009).

Gullying destroys the wetland habitat it incises, by uprooting vegetation and draining the wetland. Gully and headcut erosion are responsible for up to 94% of sediment yield in catchments and for soil and farmland loss (Osborn and Simanton, 1986; Poesen et al., 2003; Rieke-Zapp and Nichols, 2011). These erosional features are of great concern to wetland rehabilitation practitioners because of their observed potential to migrate headward at rates of metres per year under normal flow conditions.

Wetlands are naturally aggrading features undergoing three types of sedimentation, namely clastic, organic and chemical. These sedimentation processes are responsible for shaping the gradient of a wetland however; these processes of sedimentation are not synchronized leading to gradient variability. The gradient of wetlands is a threshold such that an increase in discharge will result in erosion. Because discharge and gradient are sensitive to many external changes (e.g. climate fluctuation, human activity) this means that wetland stability is also subjected to these changes, often resulting in wetland degradation, often in the form of gullying (Figure 2.1) (Ellery et al., 2009).

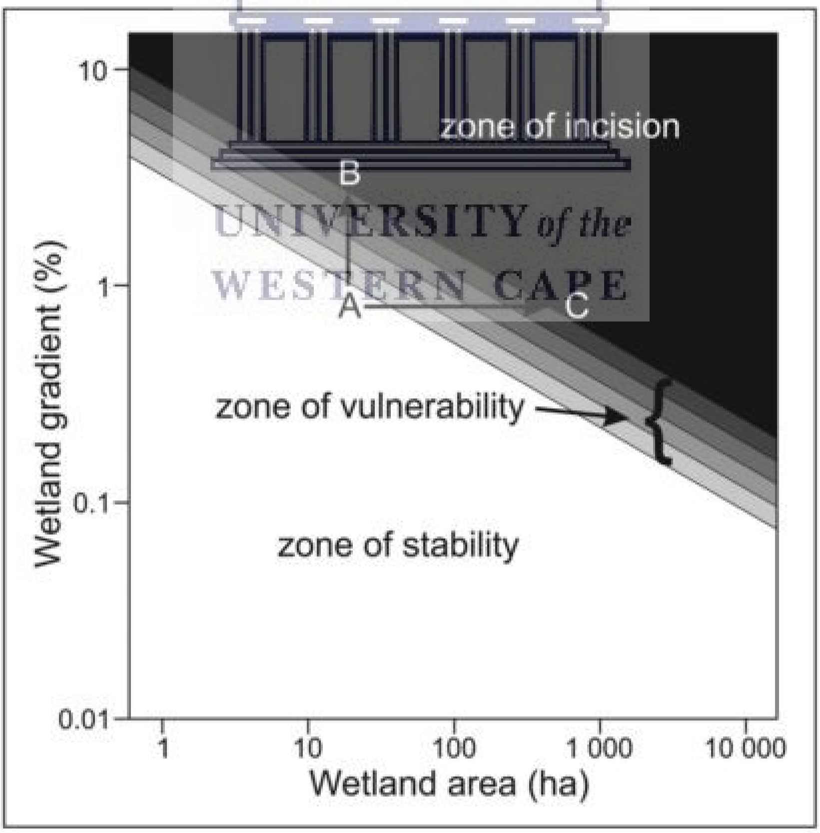

Figure 2.1: Zones of stability, vulnerability and incision for southern African valley-bottom wetlands (Ellery et al., 2016).

Headcuts range in size from as small as a drop within a rill to as large as waterfalls, each leading to the deepening and extension of channel environments. This process of erosion can be divided into two main processes namely knickpoint and headcut erosion, both of which have similar controls but varies depending on the stream bed setting in which they occur. Knickpoints are formed through the influence of tectonics, climate history and/or lithological variation and erodes river channels with bedrock river profiles (Crosby and Whipple, 2006; Mackey et al., 2014; Tooth et al., 2004). Headcut erosion on the other hand forms and occurs in alluvial rivers. Though both processes provide good background and insight on the factors that influence channel/gully incision, headcut erosion is the process under examination in this research project due to the prevalence of alluvial stream beds in wetland environments. Experimental studies by Bennett (1999a) and De Ploey (1989) indicate that headcuts in alluvial fill originate from small scarps along a flow path and evolve through the process of plunge pool erosion (Rieke-Zapp and Nichols, 2011). Headcut initiation is a result of vegetation, geomorphic and hydrologic variations along channel beds. Vegetation variations refer to changes in vegetation type along the length of a river. Geomorphic variations refer to changes in the stream bed structure such as channel modification and heterogeneous stream bed composition caused by the natural geologic and topographic setting in which wetlands occur. When flow intercepts a point where there is a change in stream bed material, erosion can occur when one of the stream bed material types erode at a faster rate than the other (Simon and Thomas, 2002). Hydrologic variations refer to both the climatic setting, flow and sediment regime, which have a natural influence on the occurrence of headcuts. Increased rainfall and runoff lead to increased stream power, which increases erosion rates (Macfarlane et al., 2009). Anthropogenic factors such as furrows, drainage lines and culverts directly have the potential to result in the development of headcuts by altering natural hydrologic processes of the stream, such as the direction and magnitude of flow at specific points, which lead to higher than normal erosion rates at that given point, resulting in stream bed variation (Bennett and Casali, 2001; Poesen et al., 2003; Robinson et al., 2000). Manmade structures affect processes such a flow velocity and orientation, altering the natural flow and sediment regime of the stream. Hydrologic variations may include natural or artificial tributaries such as irrigation furrows, or flow diversions. These natural or artificial inconsistencies may result in the formation of headcuts (Poesen et al., 2003; Valentin et al., 2005).

River rejuvenation refers to a fluvial system's natural response to changes in its longitudinal profile. This mechanism occurs over a very long length of river and time-scale, shaping an entire river system by means of erosion. River rejuvenation occurs when environmental and topographic variations cause the formation of a knickpoint, incised meander and river terrace. Of these features the knick point, is the most relevant to this study as it is the starting point for headcut and gully erosion. A convex reach or point of increased stream bed slope has been identified as a key factor in headcut and gully initiation along valley floors (Schumm and Hadley, 1957). In response to this longitudinal profile irregularity, or knickpoint, the stream bed starts to erode vertically to the local base level, compensating for excess energy within the hydrological system, until a balance between forcing and resistance is re-established (Rieke-Zapp and Nichols, 2011). This process of erosion is powered by the increased slope at the knickpoint, which increases the gravitational force on the water across the knickpoint. As the stream bed re-establishes to a new local base-level, through erosion, transportation and deposition, the knickpoint migrates upwards, lengthening the gully, and the channel becomes incised (i.e. headcut and gully erosion). Sediment production will increase as the length of the gully increases, causing a decline in water quality (Osborn and Simanton, 1986; Schumm, 1994). This process of headcut formation and erosion over long time-scales at the scale of a drainage basin, informs headcut migration over shorter time-scales in wetlands or smaller river reaches, as similar processes can be observed across both scales, suggesting universal controls. However, the way in which gully incision and headcut migration takes place may vary.

Schumm (1994) developed a cross-sectional channel incision model that describes gully evolution from initiation to channel stabilization as a result of natural and anthropogenic changes to the environment (Figure 2.1a). The evolution of incised channels forms an integral part to this study as gully and headcut erosion leads to channelization, which evolves through this process. Gullying causes the channelization of a landscape, thus the process of channel incision can be used to describe the cross-sectional evolution of gullies. According to the model the gully/channel first and foremost undergoes a process of incision through vertical erosion, lowering the elevation of the flow path. Thereafter, the gully begins to widen, which might be a result of the flow eroding into a less erosion resistant soil horizon, and as a result the flow undercuts the banks causing mass failure of the unsupported bank soil, leading to deposition along the stream bed. As gully widening occurs, flow concentration decreases leading to lower flow velocity, subsequently resulting in increased deposition. The now reduced erosion and flow condition yields a renewed relative stability and increases the opportunity for vegetation re-establishment in the gully (Schumm, 1994) (Figure 2.2b). This model was adapted by Ellery et al. (2009) and is presented below (Figure 2.2b).

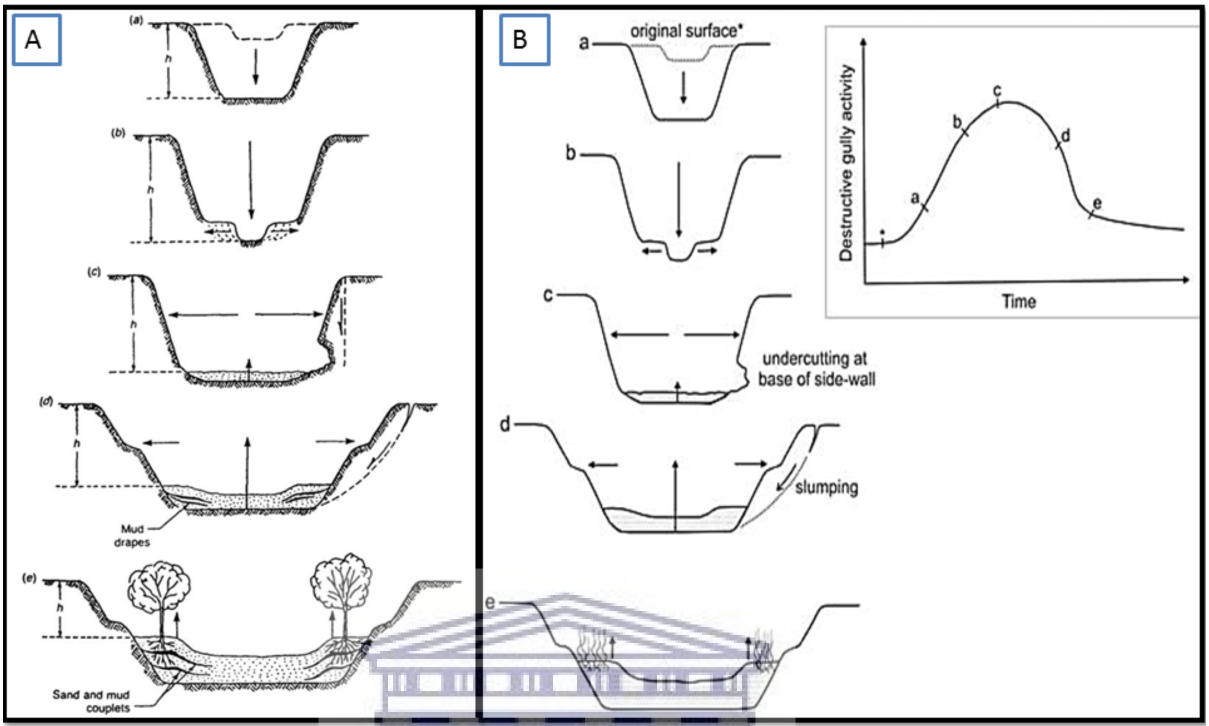

Figure 2.2: A) Evolution of incised channels from initial incision (a, b) and widening (c, d) to aggradation (d, e) and eventual relative stability (e) (Schumm, 1994). B) Evolution of a gully from initial incision (a, b) and widening (c, d) to aggradation (d) and eventual relative stability (e). Inset: curve showing changes in destructive gully activity with time (Ellery et al., 2009).

The process of gullying within a landscape leads to increased connectivity of the landscape through the development of a more intricate drainage system (Bennett and Casali, 2001; Poesen et al., 2003). These gully systems drain an area more rapidly than under natural circumstances and concentrate flow within the gullies. Flow concentration, through gullying, increases flow velocity which ultimately increases the erosive potential of water in the drainage system. When gullies are formed through headcut initiation the dominating erosional process extending gullies is gully headcut retreat, and less often through gully wall retreat; this is due to the fact that headcuts are the most dynamic feature of gully erosion (Cox et al., 2016; Poesen et al., 2003). This could also be explained by the natural evolution of gullies where it has been noticed to first deepen, then widen through bank undercutting and slumping (Ellery et al., 2009; Schumm, 1994). Gully headcut retreat refers to the longitudinal migration of the gully apex in an upstream direction increasing the gully area in length rather than width, whereas gully wall retreat refers to the lateral extension of gully area (Figure 2.3).

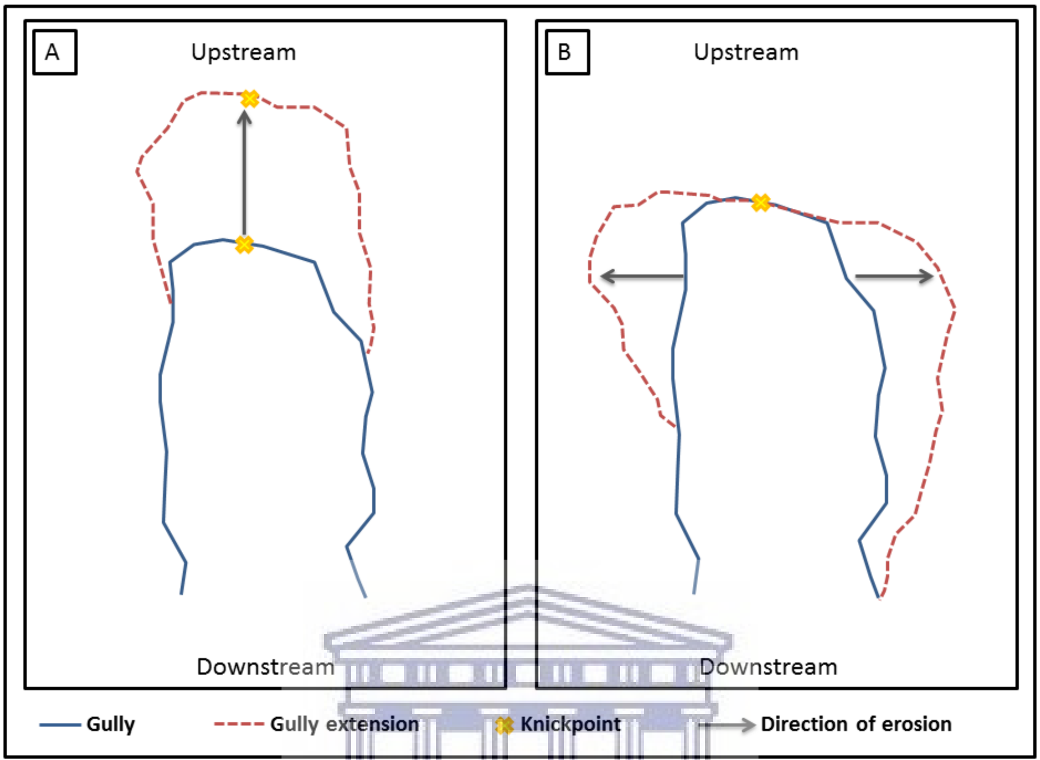

Figure 2.3: a) Gully headcut retreat, longitudinal gully extension. b) Gully wall retreat, lateral gully extension.

Rengers and Tucker (2014) provide a comprehensive review of literature regarding the potential mechanisms of headcut migration and the key relationship between headcut retreat rate and the square root of drainage area. The potential mechanisms of headcut retreat include seepage erosion, mass wasting and plunge pool erosion (Figure 2.4). Several researchers have proposed that seepage erosion is a key factor in headcut retreat rate expressed by the differential pressure at the interface between the saturated headcut and the atmosphere. This causes the movement of sediments away from the headcut face decreasing the soil layers bulk density, thus leading to erosion (Chu-Agor et al., 2008; Rengers and Tucker, 2014). However, Lamb et al. (2006) noted that there is little definitive evidence of seepage erosion as a primary driver of headcut erosion in consolidated material. A prior study by Oostwoud Wijdenes (1999) in semi-arid Spain also hypothesised that subsurface flow and seepage seemed not to be a major factor in gully head erosion (Oostwoud Wijdenes et al., 1999).

In contrast, both mass failure and plunge pool erosion have been shown to be key processes extending gully networks and generating sediments (Rengers and Tucker, 2014). Mass failure refers to the collapse or slumping of soil along the headcut face. This type of erosion occurs due to the effect of the continuous force of flow and gravity on the face of the headcut weakening the cohesive forces existing between sediments which make up the headcut feature. Mass-failure increases as the weathering process weakens the soil (Robinson et al., 2000). Istanbulluoglu et al. (2005) and Montgomery (1999) conceptualized a headcut as a fracture-bound 3-D slab of sediment subject to Coulomb failure. Mass failure of the 3D sediment slab will occur when the sum of the soil weight and hydrostatic pressure force exceeds that of the resisting force of soil cohesion (Rengers and Tucker, 2014). Mass failure and plunge pool erosion often occurs in association in that plunge pool erosion undermines soil strata making them more susceptible to the force of gravity.

Plunge pool erosion occurs when water, flowing across the headcut face, is subjected to gravitational force increasing its velocity and therefore, its erosive potential on the soil base of the plunge pool. This force diminishes according to the amount of standing water present in the plunge pool, which decreases the impact of flow by cushioning the waters impact on the plunge pool base. Plunge pools reach a stable equilibrium depth when erosive shear stress equals the resisting strength in the pool (Stein et al., 1993). Headcut migration through plunge pool erosion has been observed occurring through two mechanisms depending on soil stratigraphy (Flores-Cervantes et al., 2006). The mechanism of plunge pool erosion observed in homogenous soils occurs in such a way that the headcut reaches a geometrically steady state as the headcut migrates upstream (Bennett, 1999a; Bennett et al., 2000). The second mechanism, applicable to this study, occurs in stratified soils and was investigated by Stein and La Tray (2002). This process of erosion occurs due to the presence of a cohesive topsoil horizon and a lower more easily erodible sub-soil horizon, characteristic of wetlands, resulting in undercutting. The impact of flow will be more effective at eroding the lower soil horizon and thus undercutting the cohesive top soil stratum. With sufficient undercutting and weathering, the overhanging top soil cohesive stratum undergoes cantilever/mass failure detaching from the headcut face, producing a restored near vertical face (Figure 2.4) (Robinson et al., 2000; Stein and LaTray, 2002). This mechanism of headcut migration results in a higher migration rate as cantilever failure dislodges large volumes of wetland bed material during a single event. This mechanism of headcut migration is most likely to occur in wetlands based on its heterogeneous soil stratigraphy. Stratified soils are characteristic of wetlands because during the formation of wetlands the sediments deposited become finer as lower energy conditions prevail and also continuously trap various sediments transported during different flow stages, resulting in further soil stratification of the wetland bed (Rengers and Tucker, 2014). Another mechanism of plunge pool erosion, not mentioned in Rengers and Tucker's (2014), is headcut migration through tension cracks. This mechanism however, is usually a secondary process occurring in association with one of the above mentioned mechanisms, only taking place if there is sufficient undermining of top soil horizons (Figure 2.4) (Stein and LaTray, 2002).

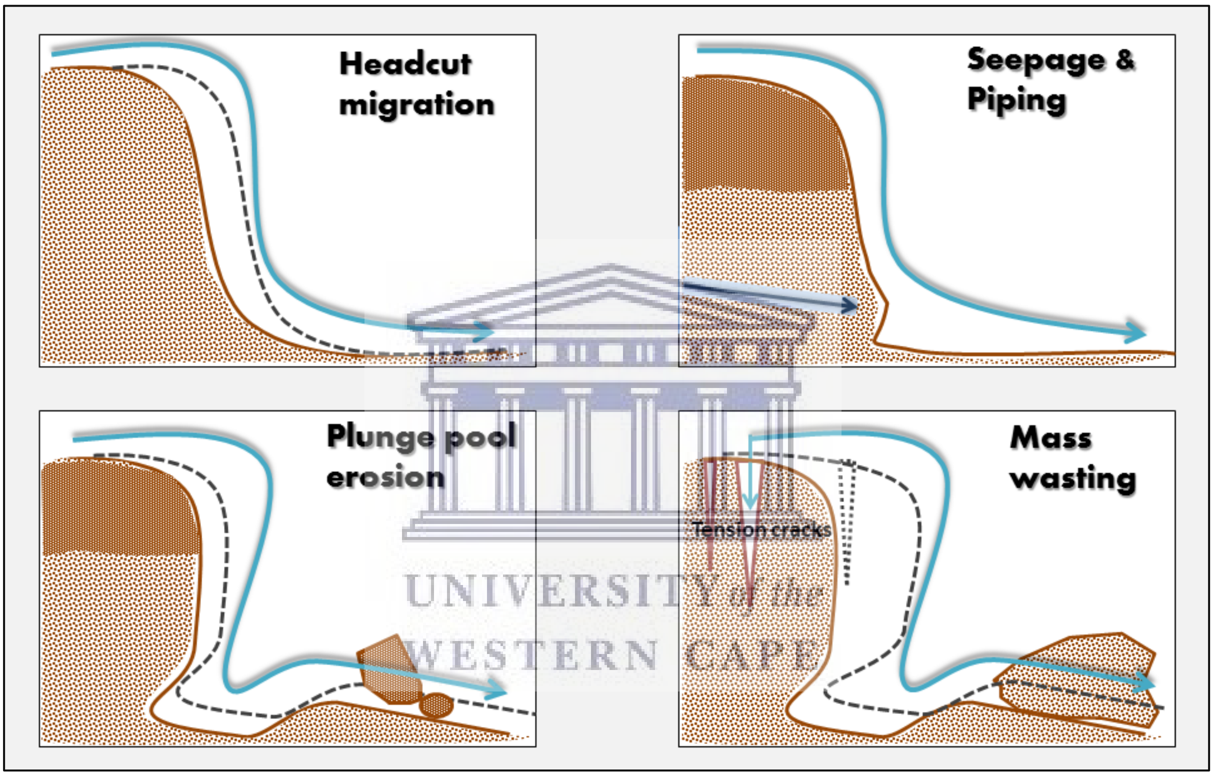

Figure 2.4: Mechanisms of headcut erosion based on literature (Bennett, 1999a; Rengers and Tucker, 2014; Stein and LaTray, 2002).

The draining effect gullies have on wetlands severely alters the functions of wetlands. The draining of wetlands also changes their natural processes (e.g. floodplain inundation, carbon sequestration), affecting the ecological and hydrological cycles that depend on them (Tooth and McCarthy, 2007). The vulnerability of valley bottom wetlands undergoing gully incision can be determined by the indirect relationship that exists between wetland slope and area, with wetland slope being the key control on erosion. The vulnerability of a wetland to incision increases with increasing slope and area as illustrated in Ellery et al., (2016) (Figure 2.1). The graph illustrates the likelihood of a wetland incision (Ellery et al., 2016). Figure 2.1

is based on the principle that source area above a channel head decreases with increasing local valley gradient (Montgomery and Dietrich, 1988). Erosion has been strongly correlated with discharge and slope. Both the high variability of the South African climate and necessity of continuous infield monitoring, for discharge determination, make determining discharge tedious and lengthy. Therefore, an alternative being drainage area has been established as an appropriate proxy for discharge (Bennett et al., 2000; Burkard and Kostaschuk, 1997; Sidorchuk et al., 2003).

2.4) Factors influencing headcut migration

There are many factors that affect the rate at which a headcut migrates, such as upstream drainage area, slope, vegetation type, soil type, rainfall events, land-cover, headcut height, plunge pool depth, and anthropogenic activity (Flores-Cervantes et al., 2006; Macfarlane et al., 2009; Sieben, 2012; Tooth et al., 2004; Tooth and McCarthy, 2007; Vandekerckhove et al., 2000). In order to properly understand how headcuts behave in various settings it is important to understand the factors surrounding and influencing headcut and gully erosion. Understanding the relationships between headcut migration rate and these factors is vital in establishing a means of determining how fast and how much a headcut will erode in future. The figure below (Figure 2.5) provides a visual representation of factors to influence headcut migration rate.

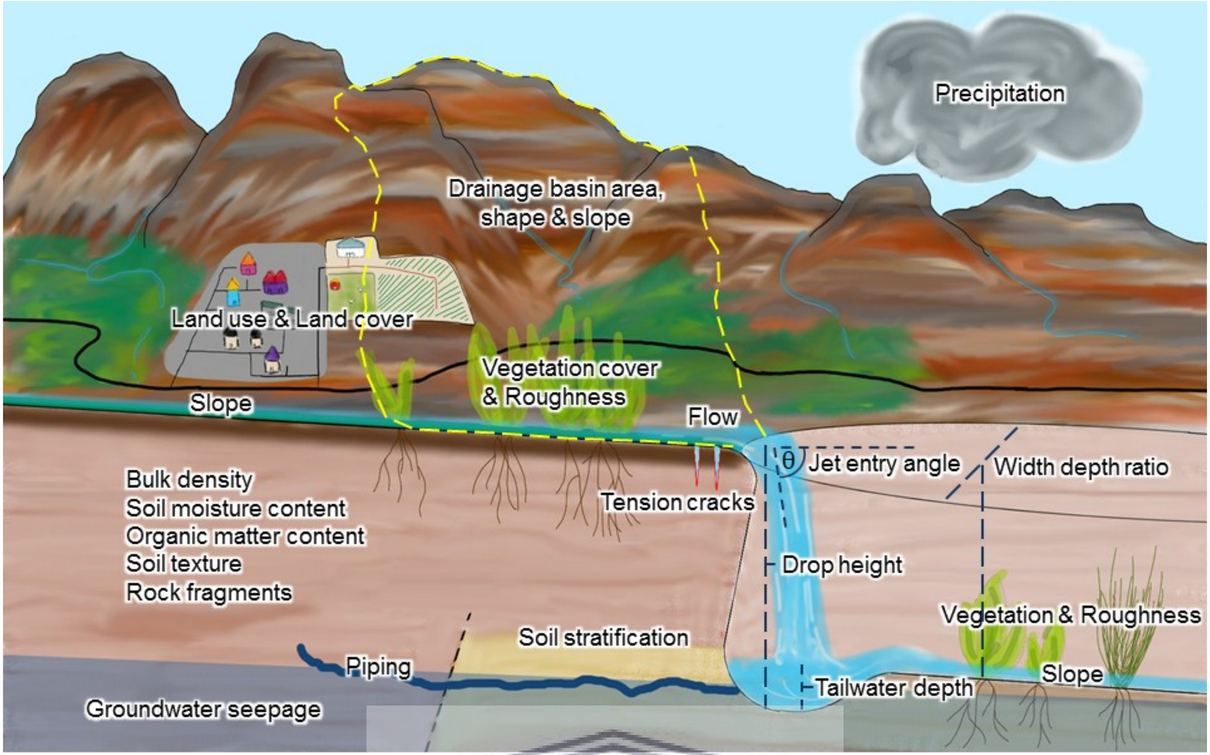

Figure 2.5: Conceptual diagram of factors influencing headcut migration rate and gully erosion adapted from literature.

Gully expansion is affected by a variety of factors including drainage area, gully dimension parameters, indices of surface runoff and precipitation, antecedent precipitation, soil moisture, and indices of piping (Burkard and Kostaschuk, 1997). However, recent literature primarily focuses on the impact of drainage area, slope, headcut height and soil characteristics. Overland flow concentration is the most evident and widely recognised factor directly affecting headcut migration (Bennett et al., 2000; Bennett and Casali, 2001). Changes in overland flow paths upstream cause some headcuts to receive more flow than others, causing variation in headcut migration rate. This variation is attributed to an increase or decrease of drainage basin area feeding each headcut. Headcut initiation along a flow path is a precursor to gully incision; when flows exceed the critical shear stress threshold of the material making up the soil surface gullies begin to form. Gully erosion continues until the balance between forcing and resistance is re-established (Flores-Cervantes et al., 2006). Because overland flow varies dramatically from place to place and requires infield measurements to adequately determine the discharge at specific sites, drainage area has been identified as an adequate proxy for discharge. This substitution is based on the strong correlation that is known to exist between flow and drainage area.

The same principle is applied to drainage area and gully growth rate. Drainage area, as a proxy for discharge, is the most commonly researched factor related to gully growth rate. Researchers have suggested that there is a finite limit to gully growth resulting in its natural stabilization. This will occur when the flow velocity is less than the threshold value needed for erosion initiation, but greater than the critical velocity of wash load sediments and/or when a headcut has advanced upstream to a threshold level in terms of catchment size. This suggests that decreasing catchment size leads to a reduced discharge across a headcut; subsequently lowering the erosive force the gully head is subjected to, therefore, decreasing headcut migration rate. Once the catchment threshold is reached channel slope will become shallow enough that the gully slopes become vegetated and stabilize (Bennett et al., 2000; Burkard and Kostaschuk, 1997; Sidorchuk et al., 2003).

Vanmaercke et al. (2016) provided a recent review of the processes and factors controlling gully head retreat rates through an extensive study on global headcut retreat rates. The study reviewed previous site specific studies on gully erosion on various continents, thereby aiming to get a global perspective of gully erosion and the factors affecting this. Gully erosion rates reviewed were reported as linear retreat rates (i.e. the distance along the slope (m) over which the gully head retreated per unit of time), as area retreat rates (i.e. the area expansion (m^2) of the gully head over time), as volumetric retreat rates (i.e. the eroded volume (m^3) of soil per unit time) or the mass retreat rate (i.e. the mass of eroded soil material per unit time). Vanmaercke et al. (2016) categorised the factors affecting gully erosion into six groups namely; climate, maximum contributing area, topography, land use, soil characteristics and gully age. The processes that have been identified as affecting gully erosion are tension crack development, piping, plunge pool and splash erosion, fluting and mass failure. These processes are in turn affected by other factors which indirectly influence gully erosion rate. This review identified drainage area, drainage area shape, weather and climate conditions, soil moisture content, land use, soil characteristics and topography as factors influencing gully erosion. However, it was surmised that the last three factors mainly control the initiation of gullies and are not necessarily crucial for explaining differences in gully retreat rates, thus substantiating their limited inclusion in gully head retreat (Vanmaercke et al., 2016). A further two factors, namely vegetation and soil characteristics, were identified for the role they play in terms of soil resistance to erosion, thus influencing gully retreat rate (Vanmaercke et al., 2016).

Oostwoud Wijdenes et al. (2000) estimated the contribution of bank gully head erosion to the overall sediment yield in a catchment, the spatial distribution and the rate at which gullies retreat in a Mediterranean environment, in southeast Spain. They established that in order to estimate the sediment contribution an understanding of the factors that control the spatial variation in bank gully erosion was necessary. The activity of 458 gully heads was assessed in field with predefined criteria such as sharp edges, presence of plunge pools, tension cracks, recent deposited sediment, flow marks and vegetation regrowth. Factors discovered to influence gully head activity included land use (runoff production), lithology (runoff production and erodibility) and topography. Active gully frequency was observed to be higher in almond groves and marls than in abandoned and conglomerate areas, thus implying that the influence of land-cover on runoff largely influenced the spatial distribution of gullies. Contributing flow and therefore, drainage area largely controlled the overall activity of the gully head. However, gully head erosion at a local scale showed considerable variation, related to local conditions such as the erodibility of the lithology and the land-use type. The paper concluded that the expansion of agricultural area and the introduction of different vegetation or crop cover types have changed the runoff potential dramatically over the last decades exacerbating the rate and distribution of gully head erosion (Oostwoud Wijdenes et al., 2000).

Oostwoud Wijdenes et al. (1999) aimed at determining if gully head morphology can be used as an indicator for gully development in semi-arid Spain. Gully head characteristics investigated that potentially affect gully development were morphologic and pedologic properties, ground surface, channel and catchment characteristics. Gullies included in the dataset were subdivided into four gully types namely; gradual, transitional, abrupt and rilled-abrupt (Figure 2.6). The statistical analysis showed that gully-head characteristics have an effect on the development of gradual and abrupt gully head types. Abrupt headcuts were found to always form in multi-layer soils with at least one erosion resistant layer. The most resistant layer was not limited to the topsoil layer. Analysis of width-depth ratios indicated that gradual headcuts were controlled by fluvial processes and abrupt headcuts were controlled by a combination of both fluvial and mass-wasting processes (Oostwoud Wijdenes et al., 1999).

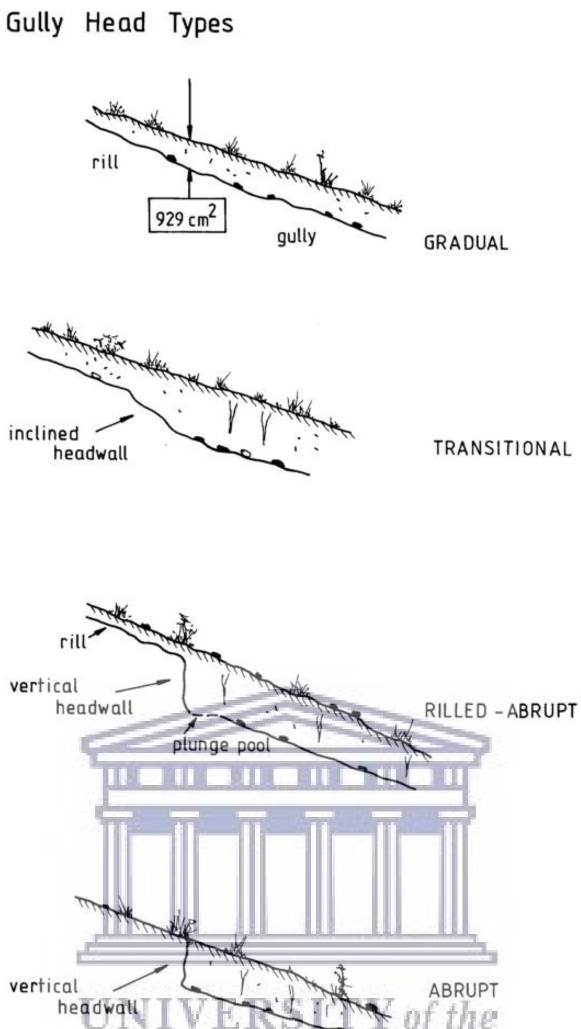

Figure 2.6: Gully-head morphology, longitudinal profile of gully types (Oostwoud Wijdenes et al., 1999).

Crosby and Whipple (2006) investigated knickpoint initiation and distribution in bedrock rivers, in New Zealand, in reference to drainage area. It was found that approximately 70% of the knickpoint dataset was located at drainage areas between 1×10^5 m^2 and 1×10^6 m^2, of that more than half were located <1 km upstream of tributary junctions. A correlation was found between knickpoints <1 km from tributary junction and tributary drainage area. With this established relationship Crosby and Whipple developed two end-member models, the first investigating knickpoints initiated at basin outlet migrating upstream and distributing the signal throughout the entire network at a rate that is the power law function of drainage area. The second model investigated knickpoints initiated near a threshold drainage below which the channel cannot incise with the same efficiency capable in downstream reaches.

Comparison between modelled data and observed data showed small differences in knickpoints with a drainage area below $1\times10^{6}m^{2}$ and large differences with drainage area exceeding $1\times10^{6}m^{2}$. They concluded that the presence of observed knickpoints, in the Waipaoa River basin, is largely a consequence of thresholds in channel incision at low drainage areas. Therefore, establishing a relationship between knickpoint retreat and drainage area though neglecting the influence of stream variation in substrate and knickpoint form (Crosby and Whipple, 2006). Even though this study covers knickpoint erosion in bedrock rivers the same principles governing this process may apply to headcut erosion which could lead to the formulation of headcut erosion drainage area thresholds.

Vandekerckhove et al. (2000) provide good insight for this research project because they too aim at understanding the influence of headcut characteristic on headcut migration and also utilize the same method of analysis, being multiple regression. Although Vandekerckhove et al. (2000) research differs as the primary focus is bank gully retreat; it provides a good understanding of the key influencers on gully retreat. This could potentially provide justification to results in this research project. Vandekerckhove et al. (2000) analysed gully geometrical characteristics, topographical site characteristics, material characteristics and climate. The results of the regression analysis concur with literature in that drainage area is again the most influential factor on the rate of gully retreat and that a significant relationship (indirectly proportional) exists between slope and drainage area. Soil characteristics were found to have a relationship with the presence of fluting and piping however, it did not express a strong relationship with the volume of soil lost through gully erosion in the long run. Piping refers to conduits formed naturally in soil stratum due to existence of a lateral preferential pathway for flow in the vadose zone, whereas fluting follows a vertical preferential pathway (Wilson et al., 2017). The effect of these topographical and soil characteristics on total eroded volume was used to establish a multiple regression model which ultimately explained up to 83% of variation in eroded volume (Vandekerckhove et al., 2000).

Vandekerckhove et al. (2001b) provided a good understanding of the relationship between short-term headcut retreat rate (1 to 5 years) and headcut characteristics in Mediterranean environments. This study makes reference to, the same methodology used in this research project, the multiple regression analysis and the analysis of headcut characteristics (which includes; drainage area, runoff, slope, drop height and sand content). Drainage area was identified as the most important topographic factor contributing to headcut retreat rate in terms of volume of soil loss and linear retreat rate. However, this relationship was not observed for original drainage area. The second most important factor contributing to annual eroded volume was headcut height. Linear retreat rates was also explained by the average slope of the drainage basin, because it influences flow velocity, and sand content as increasing sand content decreases the soil materials resistance to erosion (Vandekerckhove et al., 2001b). Vandekerckhove et al. (2003) explores these relationships further but in relation to medium-term retreat rates (5 to 50 years). Headcut characteristics investigated during this study include various slope measurements, drainage area, soil characteristics and headcut height. Statistical analysis showed that medium-term retreat rates are best correlated with drainage-basin area. Differences in individual gully-head retreat rates measured at short-term and medium-term time scales showed the importance of anthropogenic activity on gully-head retreat rates and the episodic nature of gully-head retreat. Higher gully head retreat rates were observed during medium-term time scales as opposed to short-term time scales; however, the difference was not significant. The medium-term method generated more, high gully retreat rates but less extreme values compared to the short term method. This is explained by a more equal distribution of extreme rainfall events both in space and time at a longer-term time scale, and hence a higher probability of measuring the average effect of both small and extreme rainfall events at each gully. Clay and soil rock fragment content had a positive correlation with headcut height indicating a stabilizing effect of these measures on the headcut height, thus increasing the effect of gully erosion (m^3/a) when headcut retreat takes place. This assumption was confirmed when it was found that linear retreat rates were not correlated with soil parameters (Vandekerckhove et al., 2003).

Bennett (1999) investigated the effect of slope on headcut retreat rate by simulating headcut migration at a range of slopes (1% to 10%) in laboratory channel while keeping all other variables, such as headcut height, soil material, overland flow and simulated rain, constant. Through this experiment Bennett found that slope has an indirect relationship with headcut migration rate, thus higher slope percentages resulted in a decrease in headcut retreat (Bennett, 1999a). Bennett et al. 2000 investigated headcut growth and migration in concentrated flows typical of upland areas with the use of laboratory channel packed with sandy loam and sandy clay loam. A key result showed that after the period of initial adjustment of the soil bed to the simulated constant overland flow headcut migration rate remained constant and headcut shape and sediment efflux remained unchanged (Bennett et al., 2000). A similar laboratory channel experiment conducted by Stein and LaTray (1997) also observed a constant headcut advancement rate in stratified soil materials. Further research by Bennett and Casali (2001) investigated the effect of initial step height on headcut development in upland concentrated flows and found a relationship between initial step height and the rate of headcut stabilization both spatially and temporally. They achieved this by conducting lab experiments to examine the effect of initial step height on growth, development and upstream migration of headcuts. In a laboratory channel packed soils were constructed with preformed headcuts between 5 mm and 50 mm. The channel stratigraphy, slope, rainfall and overland flow were kept constant for each experiment to allow for the absolute observation of the influence of headcut height on headcut evolution. It was found that the increase in initial step height decreased the time and space needed for a headcut to reach a steady state. On the contrary an increase in steady state scour hole dimensions, sediment yield and the slope of the sediment deposit was observed with increased initial step height however, sediment sorting patterns downstream of the migrating headcut remained unchanged. It was found that as headcut initial height increased; headcut migration rate increased, maximum scour depth increased, length to maximum scour depth decreased and jet entry angle increased. Jet angle refers to the acute angle the jet centreline forms with the water surface as it enters the backwater pool. Initial step height of the headcut and tailwater were observed as having both a positive and negative relationship. The increasing headcut height increased the erosive effect of the impinging jet of water on the scour hole in the absence of tailwater, whereas the presence of tail water decreased the erosive impact of the impinging jet thereby limiting the depth of scour. However, this relationship did not have a significant impact on migration rate and scour lengths (Bennett and Casali, 2001).

A known association between soil type and erosion rate exists as substantiated by various studies exploring the effect of soil characteristics on gully erosion. Heavier textured soils are known for their resisting force against erosion due to the cohesive forces that exist between fine grained sediments. However, it has been found that these erosion resistant soil layers can influence extreme headcut erosion rates when plunge pool erosion occurs in stratified soils. When a headcut erodes into stratified soils containing cohesive soil layers the cohesive soil layer is undermined by plunge pool erosion of the lower less erosion resistant soil layer resulting in drastic headcut migration rates when the cohesive soil layer succumbs to the force of flow and gravity through cantilever mass failure detaching large sections of soil bed in a single event (Gordon et al., 2007; Stein and LaTray, 2002). Robinson et al. (2000) investigated migration characteristics and failure mechanisms in cohesive materials and examined the roles of stratigraphy, overfall height, flow discharge, and backwater level in headcut migration, highlighting the significant impact of soil characteristics, especially soil moisture content, on headcut migration (Hanson et al., 2001; Robinson, 1996; Robinson et al., 2000). A study done by Radoane et al. (1995) investigated the influence of soil characteristics on headcut migration and gully cross-section with the use of the *M* parameter as formulated by Schumm (1960), where *M* is the weighted mean percentage silt-clay for the sediment making up the perimeter of river channels (Schumm, 1960). Results obtained showed that low silt-clay percentage along the headcut soil face determines the maximal height of respective headcuts and that the *M* parameter determines gully cross-sectional shape. Gullies with low *M* values characterized by low silt-clay percentage were found to be deeper and narrower whereas high *M* values characterized by high silt-clay percentage were found to be shallower and wider. Soil characteristics also influenced a headcut's erosion rate, migrating at >1.5 m/y in sandy soils and <1 m/y in marl/clay soils (Radoane et al., 1995).

Tooth et al, (2004) evaluated the influence of geological controls, in the form of dolerite sills and dykes, on the behaviour of gully incision in upstream alluvial reaches. The case study was investigated along three tributaries of the Vaal River, each transgressing varying geologic settings. The variation in stream bed geology across these rivers allowed for the investigation of the influence of geologic controls on channel incision. Results of an analysis of the upper Klip River found that river reaches above an intact major dolerite intrusion actively meandered through extensive near-pristine floodplain wetlands. The case study of the Schoonspruit River showed that areas where the dolerite has been partially breached formally meandering reaches started incising, floodplain wetlands started desiccating and dongas began to form in the valley fill. However, the case study of the Venterspruit River showed that the absence or complete breaching of dolerite resulted in deep incision, wetland abandonment and the formation of multiple dongas. These results proved the implication of geologic controls on modern river forms and processes and also long-term landscape development. These findings also have important implications for interpretations of river and landscape response to environmental change and for identifying the primary controls on channel, floodplain wetland, and donga erosion (Tooth et al., 2004).

Several studies also make reference to the influence of anthropogenic activity on the formation and retreat of headcuts. Anthropogenic practices which most impacts headcut formation are land-use and land cover (LULC) changes. The transformation of natural land to agricultural area or housing settlements affects the amount of overland flow experienced in an area. Built up or paved areas decrease infiltration rates and increase runoff, increasing the natural erosive potential of water and thus degrading natural habitats downstream of construction. Agricultural practices influence runoff in the same way and additionally cause changes to the natural flow and sediment regime of a hydrological system through the alteration of soil characteristics and Manning's roughness coefficient (e.g. tillage and application of compost). Research done by Rebelo (2012) found that the main drivers of headcut formation and retreat, among other things, in Palmiet wetlands along the Kromme River, were LULC changes and wetland transformation (Rebelo, 2012). A factor highlighted by Rebelo for inducing headcut and gully erosion was the construction of roads and railways. This relationship was investigated along the Pikes Peak highway in Colorado (Katz et al., 2014). Katz et al. (2014) found that the presence of roads in steep mountainous terrain changes the surface hydrology of the area by changing the magnitude and direction of runoff. Road induced gullies occurred through the concentration of runoff, changes in runoff pathways and the rearrangement of drainage networks (Katz et al., 2014). Another anthropogenic factor identified for the role it plays in the development of headcuts is cattle grazing. McCloskey et al. (2016) found that gullies along the Victoria River in Australia were of human origin through the introduction of cattle to a natural habitat. Cattle have long been identified as a geomorphic agent due to their influence on land cover through grazing. Overstocking of cattle reduces the resistance to erosion by removing vegetation and disturbing the soil, and rainfall-runoff drives erosion, thus leading to the development of badlands. McCloskey et al. (2016) further hypothesized that gully erosion features are initiated from cattle tracks and that gullies are also used by cattle to gain easy access to the river, thus causing further erosion along existing gullies (McCloskey et al., 2016).

Chapter 3: Study area

3.1) Introduction

This chapter will provide a description of the study area. The study area for this research project falls within the Western and Eastern Cape provinces of South Africa. Though separated by a provincial border and 397km from one another they are similar in that they occur in a single ecoregion, the Southern Folded Mountains ecoregion (Herdien et al., 2005; Kleynhans et al., 2005). Furthermore, similarities in land use and degradation of these wetlands, in terms of geomorphology and alien invasion, substantiates their selection as appropriate research sites for this study. Due to the fact that the two areas are geographically separate, each area is discussed under separate headings. Ultimately, however, the data collected in each area was analysed collectively based on the study area similarities previously stated. The general study area is first described based on ecoregion classification. Each sub-area is described in terms of climate, topography, geology, hydrology, land use and ecology is discussed. Thereafter, the characterising vegetation, Palmiet, is described.

3.2) Regional setting

Based on work by Kleynhans et al. (2005) with respect to ecoregion classification both the Kromme and Nuwejaars sites are grouped together in the Southern Folded Mountains ecoregion. This classification is based on similarities of climate, rainfall, mineral availability (geology and soils), vegetation and physiography (Kleynhans et al., 2005). The Southern Folded Mountain ecoregion primary boundary determinants are terrain morphology consisting of low and moderate relief, lowlands, hills and mountains that have a moderate to high relief at an altitude of 300-1900 m.a.s.l (Herdien et al., 2005; Kleynhans et al., 2005). Both study areas also fall within the Fynbos Biome of Southern Africa (Mucina and Rutherford, 2006). Mean annual precipitation across the entire Fynbos Biome is 480 mm. The majority of the biome either receives winter or even/bimodal rainfall with few exceptions of summer rainfall areas on the eastern and north eastern extent of the biome (Figure 3.1) (Mucina and Rutherford, 2006).

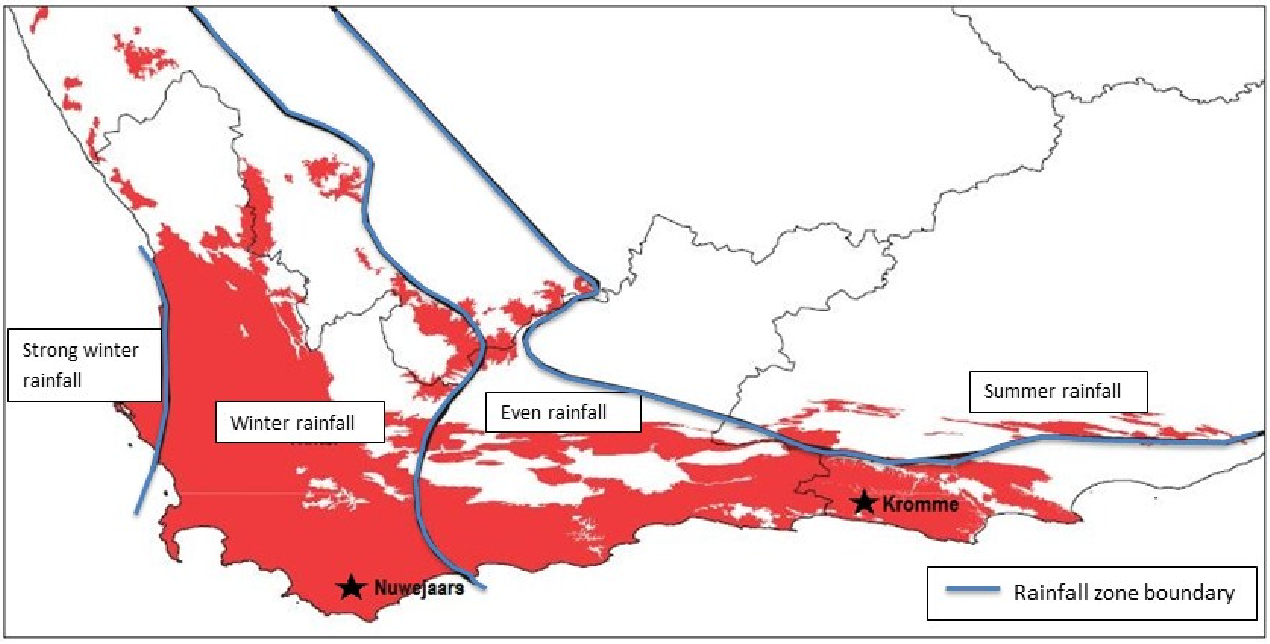

Figure 3.1: Rainfall season zones for the Fynbos Biome (shown in red) using mean winter rainfall (April to September) (Mucina and Rutherford, 2006). Study areas are marked with a star and labelled.

3.3) Dominant wetland vegetation: Palmiet

The indigenous vegetation that naturally inhabits the wetlands within this research project is Palmiet vegetation (Plate 3.1) and native restioids. Many of these vegetation types contribute to peat formation (Job, 2014). Palmiet is a robust, perennial, semi-aquatic, rhizomatous, flowering herbaceous plant, which is endemic to South Africa (Sieben, 2012). It dominates the lower banks and mid-stream of rivers and valley-bottom wetland systems in the Western Cape, Eastern Cape and KwaZulu-Natal. It occurs on substrates associated with very nutrient-poor sandstones and quartzites of the Table Mountain Group (TMG) and Natal Group (Munro and Peter Linder, 1997; Sieben et al., 2017b, 2017a). Palmiet belongs to the Prioniaceae family and is the only species that belongs to the genus Prionium (Sieben et al., 2017a; Melly, 2016). When mature it has the potential to reach a height of 3m and an average stem diameter of 8 cm (SANBI, 2018). Palmiet forms dense monospecific stands of woody stems which are covered with black fibrous reticulate remnants of its decomposing leaves (Zimmermann and Tomlinson, 1968). These flexible stems bend against stream banks during high flow events obstructing flow, thus decreasing the waters erosive power (Munro et al., 2001; Munro and Peter Linder, 1997). The top extremity of the plant forms a crown of rigid serrated lanceolate leaves growing up to 1 metre in length, making up a third of the plants height (Zimmermann and Tomlinson, 1968). It has a shallow horizontal taproot system and an extensive deep rooting system, which is hypothesised to leak oxygen into the otherwise completely anoxic root zone of peatlands (Sieben, 2012). The structure of the plant and habitat in which Palmiet occur, provide ecosystem services such as the amelioration of floods and the filtering of water. Floods are inhibited by flow diffusion and the frictional force of Palmiet vegetation. Water filtration is achieved by Palmiet's ability to bind soil, trap sediments and detritus thereby building up stream beds, forming a natural filter (Munro et al., 2001). These characteristics, together with the clonal structure and ability to persist through large flood events and in high stream power environments, form the basis of its classification as an ecosystem engineer (Sieben, 2012; Sieben et al., 2017b).

An ecosystem engineer is defined as an organism which has the ability to directly or indirectly modulate the availability of resources to other species, by causing physical changes in biotic and abiotic characteristics, thereby modifying, maintaining and/or creating habitats (Jones et al., 2010). Ecosystem engineers are split in two categories namely; autogenic engineers and allogenic engineers. When a species physical structure alters the environment it resides in, it is referred to as an autogenic engineer (e.g. trees, coral). Allogenic engineers (e.g. beavers, woodpecker) refers to species that change the environment by transforming living or non-living material from one physical state to another via mechanical or other means (Jones et al., 1994). Based on these definitions Palmiet vegetation can be categorized as an autogenic ecosystem engineer, ultimately controlling wetland development.

There has been a common misconception among farmers that Palmiet blocks river waterways and decreases flow, resulting in a poor relationship between farmers and Palmiet vegetation. This assumption has proven detrimental to many Palmiet wetlands occurring in agricultural areas, as farmers had actively removed the vegetation from waterways. It has been hypothesized that this misconception formed due to the tendency of Palmiet stems to bends over the decreasing water mass during the dry season, sheltering the water body from the effect of evaporation, giving the illusion of blocking and overcrowding waterways (Boucher and Withers, 2004).

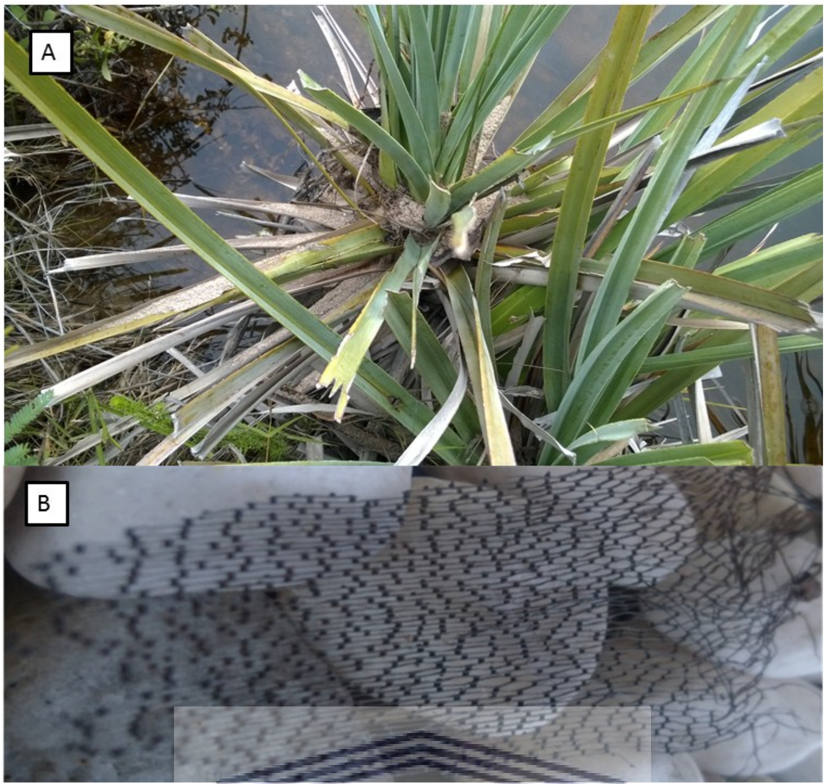

Plate 3.1: a) Indigenous Palmiet (*Prionium serratum*) vegetation and b) Remnant of decomposed Palmiet leaves.

3.4) The Kromme River catchment (K90A), Eastern Cape

3.4.1) Study area

The study area is located in the Eastern Cape, specifically the upper Kromme River catchment and peat basin. The Kromme River is part of the Fish to Tsitsikamma WMA and occurs in catchment K90. This catchment is divided into seven quaternary catchments with a combined area of 1558 km^2 (*Living Lands & PRESENCE LNet*, 2012). Water from these catchments feeds the Kromme dam, formally known as the Churchill dam, and Impofu dam respectively. These dams supply 40% of Nelson Mandela Metropole's total water demand (Rebelo et al., 2015). The Eastern Cape Province has a varied climate which is due to its location and its diverse topography. The region is more precisely referred to as the South Eastern Coastal Belt eco-region (Kleynhans et al., 2005). According to Marneweck et al. (2001) the peat deposits in the Kromme River catchment fall under the Cape Fold Mountains Peatland Eco-region which is the seventh largest eco-region in Southern Africa containing 4.49% of total peatland area.

The catchment is faced with many issues such as wetland loss, alien vegetation riparian invasion, and floodplain cultivation, which decrease both water quality and quantity (Rebelo, 2012). Indigenous Palmiet wetlands occur predominantly in the upper regions of the catchment above the dams. Erosional degradation of these wetlands forms the basis of this study. A more focused study area situated in the upper regions of quaternary catchment K90A, on the Krugersland farm has been highlighted due to the presence of multiple active headcut features (Kotze and Ellery, 2009). These headcuts are rapidly migrating upwards to the head of the wetland, thus eroding the stream bed of the wetland.

3.4.2) Climate

The Eastern Cape is positioned between Kwazulu-Natal which lies north of it and the Western Cape which lies south of the province. These neighbouring provinces have different climatic patterns. The Western Cape has a Mediterranean climate receiving the majority of its rain during the winter season, whereas KwaZulu-Natal has a subtropical climate receiving the majority of its rainfall during the summer season. Thus, climatic conditions in the Eastern Cape vary spatially from the Western to Eastern border of the province, categorizing it as a warm-temperate biogeographic zone (Ollis et al., 2009). The western area is relatively drier as precipitation and humidity increases in an east and northeast direction towards Kwazulu-Natal (Hamann and Tuinder, 2012). This leads to varied climatic conditions along the

Kromme River as it is situated in the western region of the province, resulting in bimodal rainfall patterns. The Kromme River catchment (K90) receives between 500-800 mm of rainfall per annum, with the annual appearance of snow in higher altitudes in northern ranges and occasional flooding (Nsor and Gambiza, 2013).

3.4.3) Geology

The Langkloof valley stretches from beyond the Western Cape border eastward into the Eastern Cape. The Krugersland farm is located in the middle section of the valley and is bounded by the Suuranys and Tsitsikamma Mountain Range (Haigh et al., 2004; Rebelo et al., 2015). The mountain ranges in the surrounding area are more or less homogenous, following the same east-west orientation, drainage pattern and geologic structure (Figure 3.2).

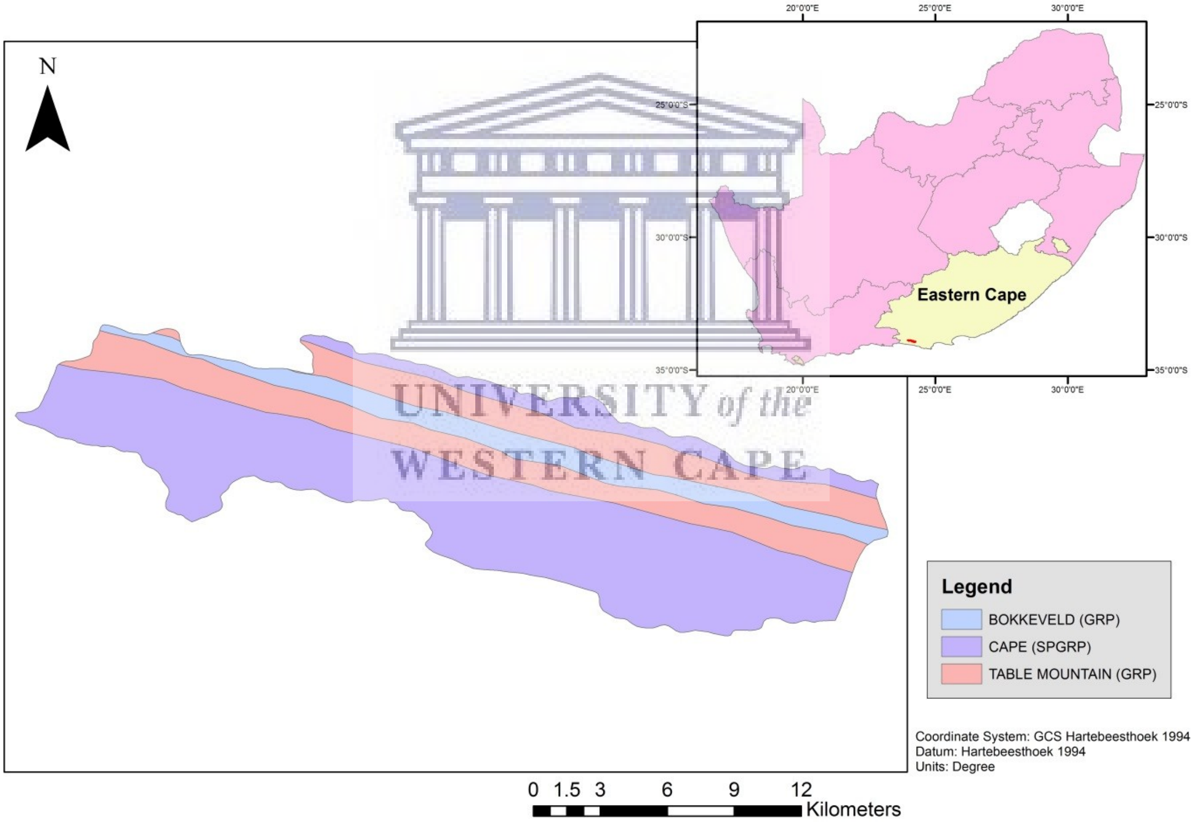

Figure 3.2: Geology of the Kromme River catchment and a reference map showing its location within South Africa.

The Suuranys and Tsitsikamma mountain ranges comprise highly fractured metasediments from the Cape Supergroup (Spgrp). The fractured nature of these geologic units is a result of the deformation of the Cape Fold Belt through extensive thrusting and folding that began

278Ma (Shone and Booth, 2005). The Cape Spgrp is divided into the TMG (lower Cape Spgrp), Bokkeveld Group (middle Cape Spgrp) and Witteberg group (upper Cape Spgrp); these are the present and identifiable geologic units in the Langkloof valley (Figure 3.2). The Bokkeveld Group (Grp) has an argillaceous nature whereas the Witteberg group is more arenaceous (Booth et al., 2004). The older TMG is highly arenaceous with dominating quartzitic sandstone formations (Shone and Booth, 2005). The sedimentary composition of these groups varies due to the difference in setting wherein sediments of each unit were deposited and solidified (Shone and Booth, 2005).

The Langkloof valley was initiated by the formation of a Bokkeveld group synform during the Cape Fold Mountain-building event. The Kromme River has been eroding naturally and more recently unnaturally, through LULC changes, into the soils and rock formation that the valley comprises of. This exponentially increasing phenomenon has resulted in the appearance of the Bokkeveld group along the Kromme River stream bed (Figure 3.3). Dominating shale occurring in the Bokkeveld group leads to a higher erodibility rate compared to the adjacent mountain ranges. These mountain ranges are dominated by the quartzitic rich sandstone of the TMG (Ayine, 2007). This results in a more or less horizontal banded configuration of the TMG and Bokkeveld group across the quaternary catchment K90A (Rebelo, 2012).

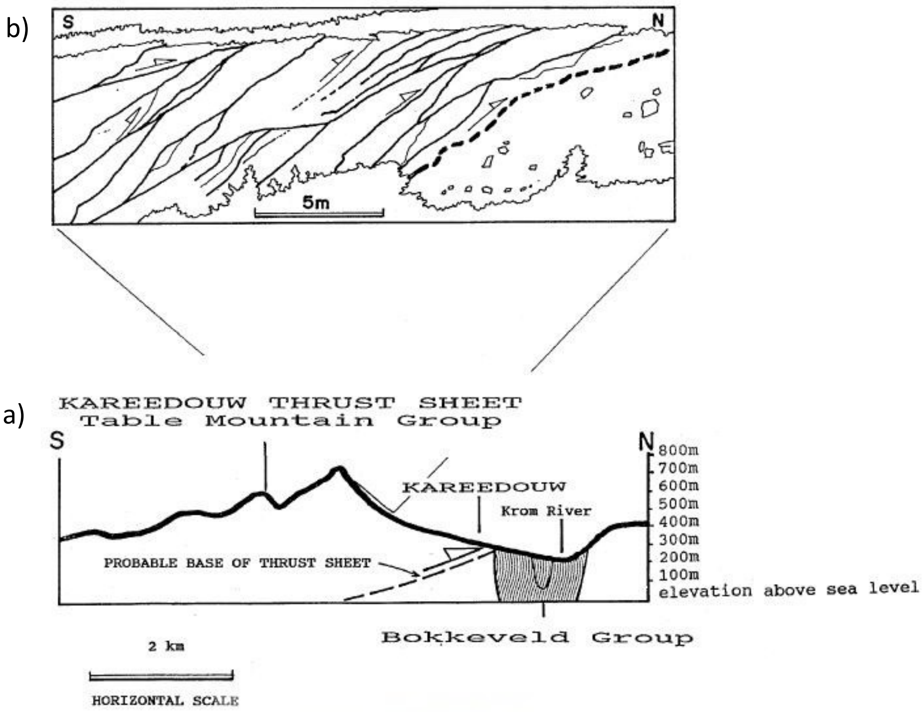

Figure 3.3: a) Cross-section through the Kareedouw area showing a thrust sheet (the Kareedouw thrust sheet) and its relationship to a synform in Bokkeveld strata. Here the quartzite's (Table Mountain Group) appear to have been thrust over folded TMG and Bokkeveld strata. b) The inset diagram shows closely spaced thrusts in the Kareedouw Pass (Booth and Shone, 2002).

3.4.4) Topography

The origin of the Kromme River is in the Tsitsikamma Mountains which is located on the south flank of the valley in which the river occurs (Figure 3.4). The north side of the valley is bordered by the Suuranys Mountain ranges (Rebelo et al., 2015). These respective mountains form part of the Cape Fold Mountain belt. The upper reach of the river follows a long intermontane valley, known as the Langkloof, through the town of Kareedouw, and eastwards into the Indian Ocean at St. Francis Bay (Nsor and Gambiza, 2013). The Langkloof is well known for boosting agricultural activity (fruit, apples) commonly located along the foothills of the mountain ranges and within the nutrient rich floodplains. The Langkloof valley is one of the many transverse valleys created by the folded geologic units of the south eastern region of the Cape Fold Belt. The majority of alternating mountain ranges and valleys run parallel to the coast. The headwaters of the river occur at an elevation of approximately 950-600 m.a.s.l with the study site situated at ±380 m.a.s.l.

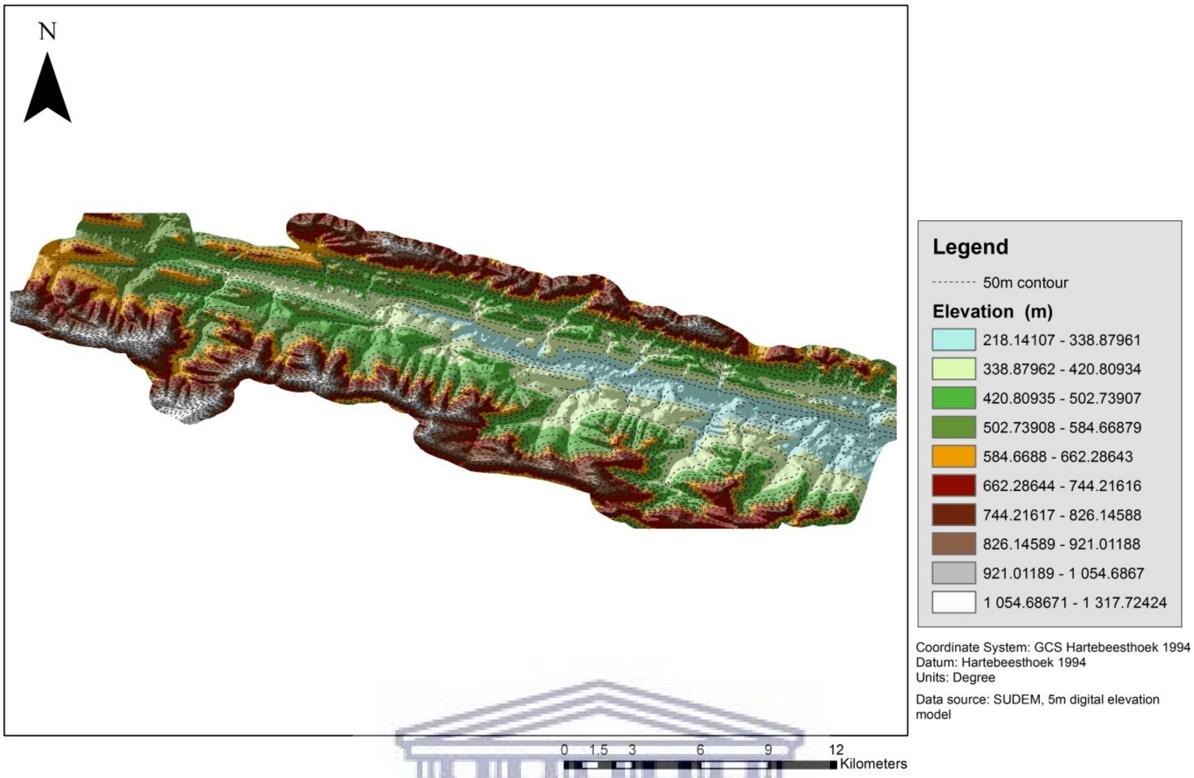

Figure 3.4: Map showing the topography of the Kromme River catchment K90A.

3.4.5) Hydrology

The Kromme River supplies Port Elizabeth Metropole with 40% of its water supply, 24% of which is drawn from the Churchill dam which is solely fed by the upper Kromme River (Rebelo et al., 2015). The drainage network forms a trellis drainage pattern which occurs throughout the majority of the quaternary catchments (Haigh et al., 2004; Kotze and Ellery, 2009) (Figure 3.5). Dendritic drainage patterns along the slopes of the bordering mountain ranges also give rise to noticeable alluvial fans on the margins of the valley floor. The region generally experiences low rainfall with short high rainfall events in between. This climatic behaviour is highly associated with flooding (Rebelo et al., 2015). The Kromme River is also a high-energy river. Mean annual runoff for quaternary Catchment K90A is approximated as 30.12 million m^3 (Xu et al., 2009).

The TMG, which makes up a majority of the mountain ranges of the CFB (including the Suuranys and Tsitsikamma ranges) are dominated by fissures, faults, folds and fractures. These geologic features generate springs and secondary aquifers. Secondary aquifers are geologic layers that have undergone mechanical erosion (Rebelo et al., 2015; Xu et al., 2009).

These planes of weakness, formed by the orogenic event which created the CFB, make up the connective system of the secondary aquifer. Aquifers store groundwater and regulate stream flow during the dry seasons and is crucial to the sustenance of ecological systems of the area (Xu et al., 2009). Groundwater recharge is fairly high due to the shallow soils in mountain slopes (Wilson and Guan, 2004), minimal water use of indigenous vegetation and fractured nature of sandstone. The Kromme River develops into an estuarine system at the river outlet along the coast of Indian Ocean.

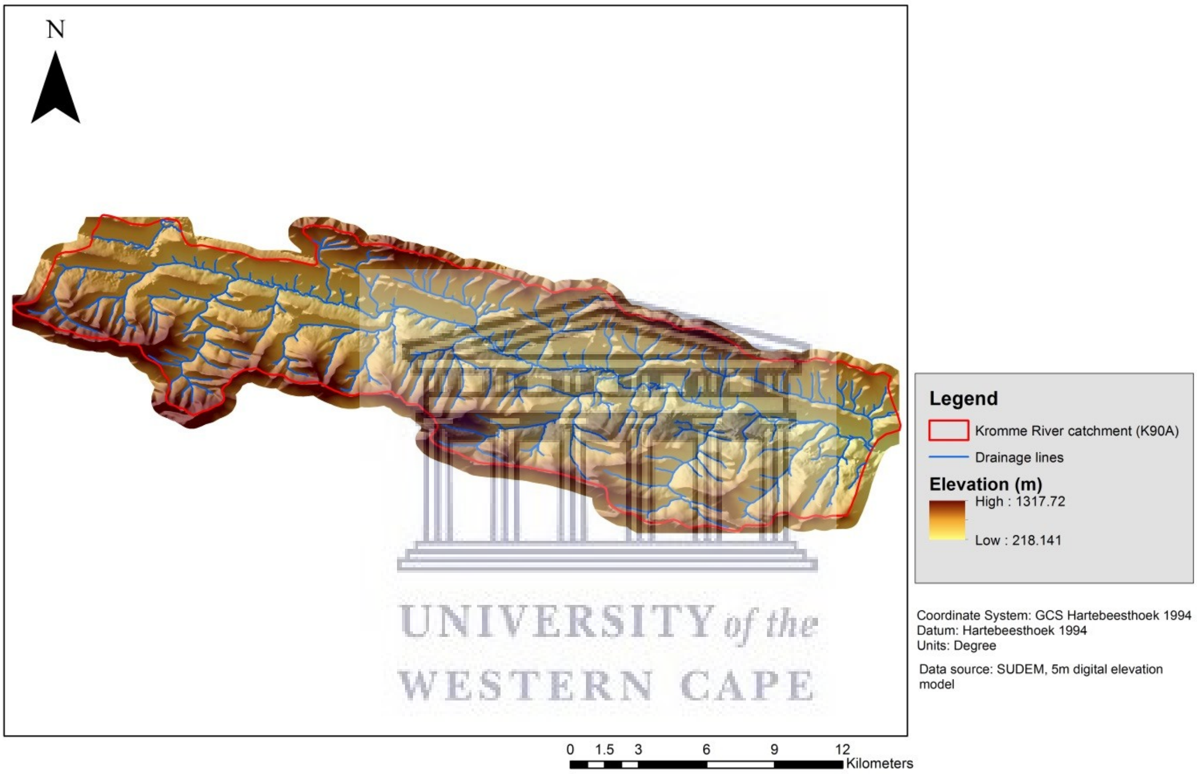

Figure 3.5: Drainage lines of the Kromme River catchment K90A.

3.4.6) Land use

The Kromme Catchment has significantly changed from its natural form over the past few decades. Landscape transformation of the Kromme catchment has been predominantly due to agricultural clearing and alien vegetation invasion (Rebelo et al., 2013). There has been approximately an 84% decline in the Kromme River valley-bottom wetland are due to agricultural activity (Rebelo et al., 2015). The banks of the upper-Kromme River are dominated by irrigated pastures for the sustenance of livestock. These pastures are a key anthropogenic threat to the wetland's survival as the grazing area extends onto the fertile floodplains of the wetland. Deciduous fruit orchards (mainly apples and pears) and dryland agriculture are also located on the Kromme Rivers floodplain and floodplain margins (Rebelo et al., 2015). The land cover changes associated with agricultural activities are partially controlled by farmers restricting the growth of their produce to farms, whereas alien plant invasion is uncontrolled resulting in erratic and boundless land cover changes.

3.4.7) Vegetation

The Upper Kromme catchment is home to natural fynbos shrubland, which is characteristic of the Cape Floristic Region (CFR) (Rebelo et al., 2015). Wetlands are dominated by Palmiet vegetation with other shrub type vegetation (Rebelo, 2015). Other wetland vegetation includes *Typha capensis, Phragmites australis, Nymphaea nouchali, Cyperus denudatus, Paspalum dilatatum* and *Juncus lomotophylus*. Among these wetland plants an array of terrestrial plants also occur. These include; *Pteridium aquilinum, Persicaria lapathifolia, Bidens pilosa, Zantedeschia albomaculata* and *Arundinella nepalensis* (Ayine, 2007). Wetland and wetland floodplain are frequently cultivated by deciduous orchards and pastures. The encroachment of the alien invading tree black wattle, *Acacia mearnsii,* into wetland's has been identified as a key factor in Palmiet wetland degradation (Rebelo, 2012). The invasion of black wattle has detrimental effects on the sustainability of the wetland, decreasing flow due to its high intake of water and its shallow root system exacerbates erosion. The water intake of *A. mearnsii* is estimated at approximately ±200 mm per annum more than the indigenous *P. serratum* (Rebelo et al., 2015).

3.5) The Nuwejaars River catchment (G50B, G50C), Western Cape

3.5.1) Study area

The Nuwejaars quaternary catchment falls within the Breede WMA and is one of the six quaternary catchments associated with the Heuningnes River. The Heuningnes catchment has an approximate area of 1401 km^2 (Bickerton, 1984) located in Cape Agulhas and receives a mean annual precipitation of 400-500 mm. The Heuningnes River and De Mond estuary fall within quaternary drainage area G50F and G50E, the Kars River System in G50D and G50E, the Nuwejaars River System in G50B and G50C (Cleaver and Brown, 2005). The Heuningnes River catchment comprises all of the quaternary drainage areas except the Ratel River system (G50A) as it drains into the Indian Ocean at a separate river outlet and does not form a tributary of the Heuningnes River. Peak rainfall occurs during the months of June to August during the winter season. The Bredasdorp Mountains are the source of water feeding the southern low lying coastal plains. The rest of the catchment is characterised by low-gradient topography resulting in significant areas of wetland development within this area (Noble and Hemens, 1978). The catchment is thus home to a number of temporary wetlands and lakes, the most notable being fed by the Nuwejaars River is the Soetendalsvlei Lake which is the largest freshwater lake in South Africa (Gordon et al., 2011). The magnitude and multitude of wetlands in the Nuwejaars makes it an area of great ecological importance. The ability of wetlands to support aquatic, terrestrial and avian species provides an oasis for fauna and flora amongst an agriculturally dominated landscape. The catchment thrives economically on large scale agricultural activity but is plagued by invasive alien infestation.

This study will focus on the Nuwejaars River catchments only. The headcuts analysed in this study falls within Palmiet wetlands in the upper reaches of the Nuwejaars River and its associated tributaries. These tributaries in the upper catchment originate from the south-facing Bredasdorp Mountains and the west-facing Koueberg Mountains. These gullies have been causing extensive damage to both agricultural farm land and indigenous Palmiet wetlands since their inception during a high rainfall event in 2005.

3.5.2) Climate

The Western Cape has a Mediterranean climate with hot dry summers and receiving 60-75% of precipitation during the winter (May to October) (Lubke and Hertling, 2001). Mean annual rainfall varies within the catchment, based on location, with rainfall between 445 mm to 540 mm along the coastal region increasing in a westerly direction and rises to 650 mm in the northern higher elevation areas which are characterised by mountains and hills (Kraaij et al., 2009; Spies et al., 1963). The area reaches its highest temperature during January and the lowest during August. The rainfall type is mainly cyclonic with some orographic rainfall in the northern regions (Bickerton, 1984). Prevailing winds are westerly in winter and easterly in summer. With 4% recorded calms the Cape Agulhas is the windiest area along the South African coast (Kraaij et al., 2009). Rain bearing winds originate from the west or south-west resulting in higher rainfall on south-facing slopes (Bickerton, 1984).

3.5.3) Geology

The mountain ranges within the Heuningnes catchment are part of the CFB, which consists of a parallel band of quartzitic sandstone often separated by undulating shale valleys (Bickerton, 1984) (Figure 3.6). These low mountain ranges and valleys are the result of an orogenic event during which the Cape Fold Mountain belt was formed approximately 200 million years ago (Herdien et al., 2005). The higher elevation areas dominated by the erosion resistant TMG sandstone and the valleys being dominated by the older less erosion resistant Bokkeveld shale geologic group, both of which form part of the Cape Super-group (Kraaij et al., 2009). The upper catchment of the Nuwejaars River is dominated by variable sandstone, shale and quartzitic geologic units. However, there is also a presence of the Malmesbury group, characterised by sheared shale and fine-grained greywacke, and post Malmesbury, pre-Cape granite outcrops on the south-facing slopes of the Bredasdorpberg Mountain (Bickerton, 1984; Cleaver and Brown, 2005; Spies et al., 1963). Further downstream the Nuwejaars River is underlain by the Bokkeveld group all the way east to its outlet into the Soetendalsvlei (Spies et al., 1963).

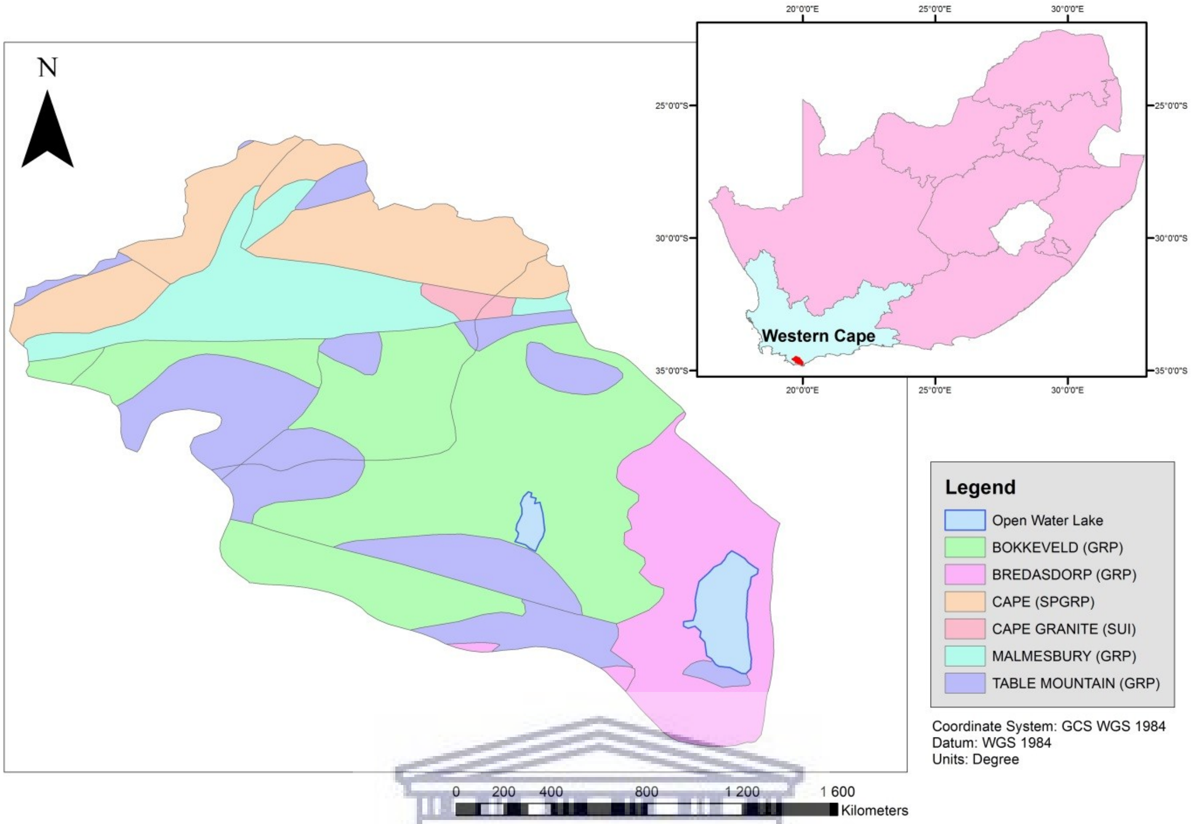

Figure 3.6: Geology of the Nuwejaars River catchment and a reference map showing its location within South Africa.

3.5.4) Topography

The origin of the Nuwejaars River is on the south-facing slopes of the Bredasdorpberg mountain ranges which are located along the northern border of the quaternary catchment (Figure 3.7). Other areas that contribute flow to the Nuwejaars River include the south-facing slopes of Koueberg, north-facing slopes of the Soetanysberg and the hills south of Elim (Bickerton, 1984). The area beyond the foot of these mountains and hills are low-gradient hence the name "Cape Agulhas Plain" (Gordon et al., 2011). These undulating plains within the catchment are relatively fertile, compared to the catchments sandstone-derived soils, resulting in agricultural activity (Kraaij et al., 2009).

The north-west to south-east orientation of the Bredasdorp and Soetmuisberg Mountains serves as the controlling factor of flow direction in the upper catchment (Russell and Impson, 2006). With few confining or restricting geological features the drainage pattern of the Nuwejaars River is dendritic; this is also true for the rest of the Heuningnes catchment. The headwaters of the catchment occur at an approximate elevation of 450-550 m.a.s.l with the study site situated between 175-60 m.a.s.l.

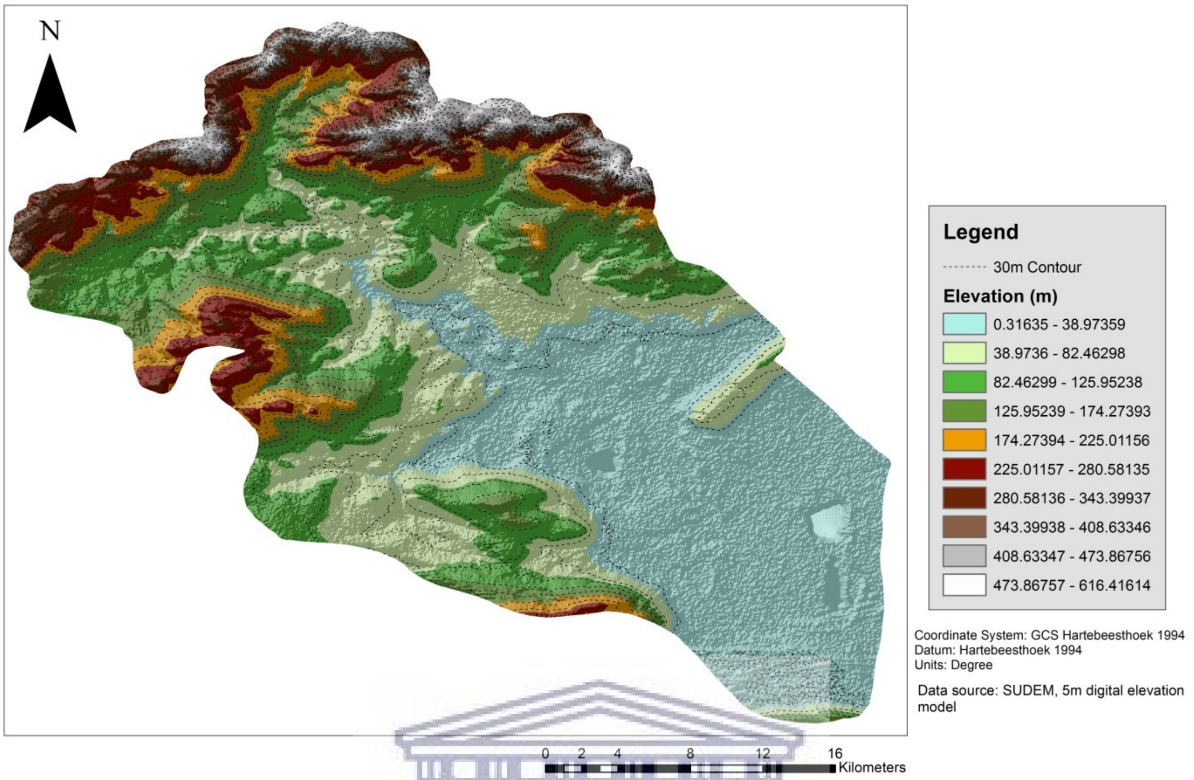

Figure 3.7: Map showing the topography of the Nuwejaars River catchment G50B&C.

3.5.5) Hydrology

The Heuningnes catchment produces a mean annual runoff of 37.6 million m^3 (Pitman et al 1982; Bickerton 1984) with the Nuwejaars contributing a simulated mean annual run-off of 27.57 million m^3 (Toens et al., 1998). The Nuwejaars River and Kars River are the main tributaries of the Heuningnes Catchment and drains the upper catchment in a general south-east direction. The water drains from the Soetendalsvlei into the Heuningnes River onto which the Kars River converges. The Heuningnes River drains the entire catchment into the Indian Ocean at the De Mond estuary (Figure 3.8). Of the many tributaries that contribute flow to the Nuwejaars River five have been named and recorded by Bickerton (1984); namely the Koue, Wolwegatskloof, Jan Swartskraal, Boskloof and Uintjieskuil tributary. The perennial Nuwejaars flows through two quaternary drainage areas of G50B and G50C with an estimated length of 55km from the western most source, through the Soetendalsvlei to the confluence of the Kars River forming the Heuningnes river (Bickerton, 1984). The trending flow direction remains relatively constant in a general south-east direction. However, at certain times in the year when there are flood flows in the Nuwejaars there have been reports of flow in the opposite direction in the vicinity of the Soetendalsvlei and its outlet (Gordon et al., 2011).

Various types of wetlands occurs throughout the catchments including both floodplains, which are hydrologically dependent on the river, and also endorheic wetlands, not hydrologically connected to the river (Kraaij et al., 2009). These endorheic wetlands are largely ephemeral with winter inundation (Russell and Impson, 2006). When the Nuwejaars flows through areas of high relief (i.e. upper catchment/mountainous regions) the river has a steep gradient and narrow sided valleys whereas in low-lying areas the river meanders and is bound by broad marshy vleis (Spies et al., 1963). The water itself has a relatively high natural salinity owing to the underlying geology (Van Der Ende, 2015).

Following a devastating flood in 2005 the upper reaches of the Nuwejaars River has since been undergoing river rejuvenation resulting in large scale vertical and headcut erosion, degrading and destroying various Palmiet wetlands.

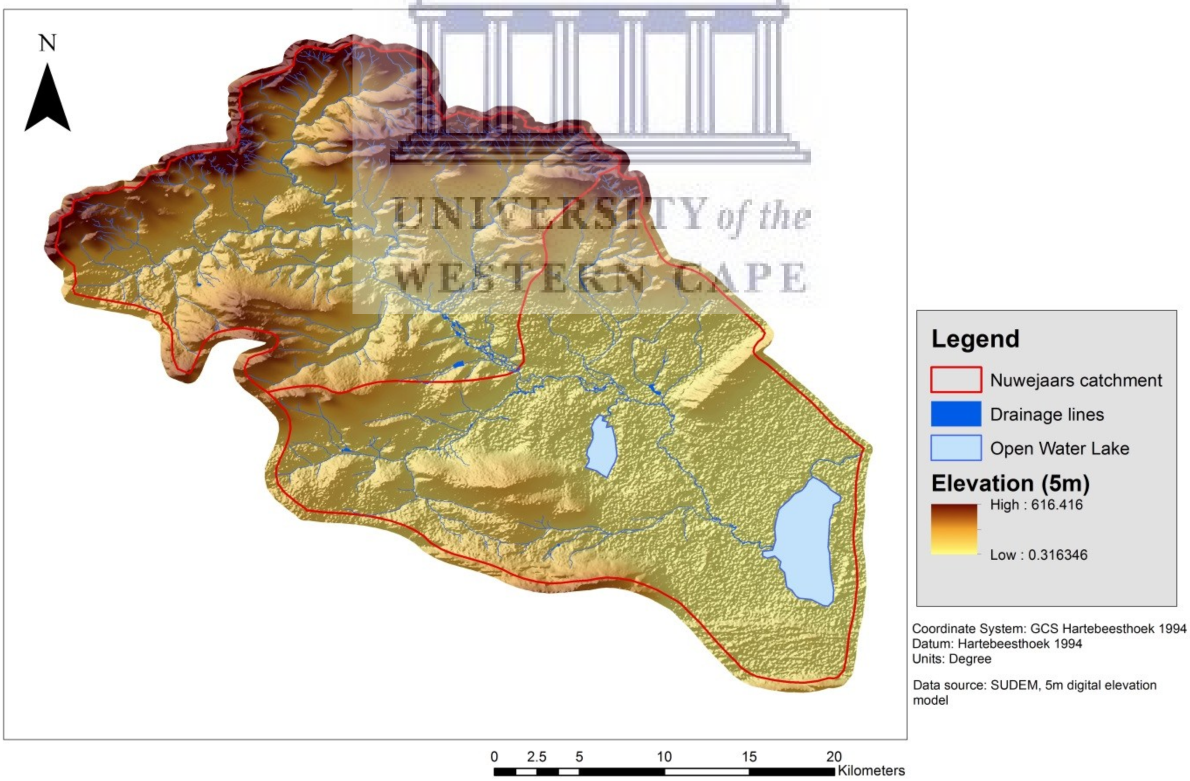

Figure 3.8: Drainage lines and open water bodies of the Nuwejaars River catchment (G50B & G50C).

3.5.6) Land use

The undulating hills underlain by Bokkeveld shale produce fertile soil in contrast to the infertile soil produced by the Table Mountain Group (Cowling et al., 1986). These moderately fertile inland hills support agriculture. The farming includes livestock, dairy, wheat, barley, canola, dry land pastures and small-scale grape farming along the Nuwejaars River (Cleaver and Brown, 2005; Gordon et al., 2011; Van Der Ende, 2015). In the higher elevation areas wildflower cultivation and harvesting is also a major industry, with the acid sand fynbos being the most lucratively harvested flora (Kraaij et al., 2009). Freshwater abstraction from the Nuwejaars and its tributaries supply adjacent farms with an unrestricted source of water for irrigation (Gordon et al., 2011).

3.5.7) Vegetation

The Nuwejaars terrestrial catchment vegetation is classified as sclerophyllous vegetation in higher altitude areas whereas the lower lying areas are classified as temperate and transitional forest and scrub type vegetation. Study sites fall with in laterite and mountain fynbos vegetation types (Herdien et al., 2005). Along Bokkeveld shale patches the Elim asteraceous fynbos dominates (Cleaver and Brown, 2005; Cowling et al., 1986; Herdien et al., 2005). Wetland areas comprise of a diverse vegetation species sedge-beds, reed-beds, grasses, restios and Palmiet, which is a dominant perennial wetland species (Cleaver and Brown, 2005). Alien invasive vegetation has become exceedingly problematic, establishing along waterways competing with indigenous vegetation for water and also shading them out (Gordon et al., 2011; Herdien et al., 2005), thus compromising river bank stability, water availability, indigenous species and habitat type. The most common threating species are *Acacia saligna* and *Acacia longifolia* (Cleaver and Brown, 2005). The eradication of the invaders is essential to the long-term health of indigenous vegetation and natural riverbank stability.

Chapter 4: Methodology

4.1) Introduction

This chapter of the study will describe the methods used to collect, generate and analyse data. It will also be used to discuss limitations of this study. The chapter outline is as follows; research design, data collection methods, data generation methods, data analysis methods and limitations. Of the factors identified to affect headcut migration rate in the literature review and illustrated in Figure 2.5 rock fragments, tailwater depth, jet entry angle, roughness, precipitation, LULC, groundwater seepage and piping were not included in this study due to either their absence infield or difficulties surrounding their retrieval. Variables measured and analysed include headcut dimensions, soil characteristics and regional controls.

4.2) Research design

The data analysed in this study was both primary and secondary data. Primary data included headcut dimensions, characteristics and soil samples, all of which were collected in the field. Secondary data included 5 m digital elevation model's (DEM), orthophotos and satellite imagery, which were used to determine headcut migration rates, drainage area and average drainage area slopes. The development of a conceptual model of factors that influence headcut migration rate, Objective 1, was achieved by reviewing past literature on headcut migration rates. Thereafter headcut migration rates were determined, as Objective 2, for each site through image analysis of secondary data. Migration rates were determined over different time spans based on the availability of high resolution imagery and expressed as the average annual migration rates. Objective 3 was completed by running both correlation and regression analysis on headcut dimensions, characteristics and migration rate. Figure 4.1 illustrates the process followed to achieve objectives 2 and 3. These statistical analyses were performed in order to determine whether or not some of these parameters influence one another and how they relate to erosion rates. The fourth objective brought all results and research findings together through the refinement of a conceptual model of headcut migration rates specific to Palmiet wetlands.

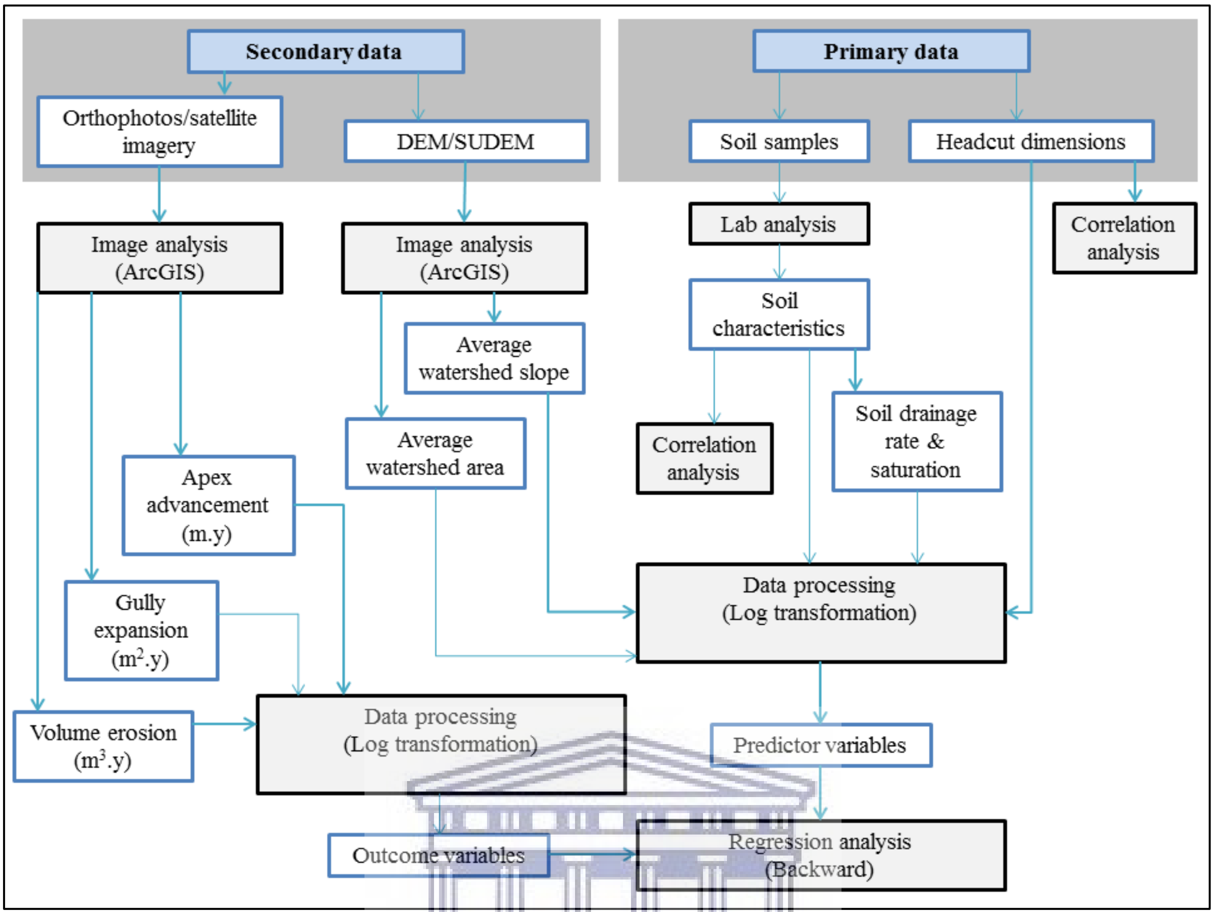

Figure 4.1: Flow diagram illustrating the process followed to generate results and achieve objective 2 and 3.

4.3) Data collection methods

Data collected for analysis was selected based on its known influence on headcut migration rates established in the literature review. Due to infield time limitation and the dispersed study sites, data collection for analysis was limited to measurable headcut characteristics, soil characteristics derived from soil samples collected infield and regional characteristics that would be extracted from satellite imagery.

4.3.1) Infield data collection

4.3.1.1) Elevation data

This data collection was limited to the Kromme River wetlands as sample sites were clustered within a radius of 50 m from the central most sample site. This makes the delineation of headcut drainage basins a challenging task when using a DEM with a 5 m resolution. Thus, the generation of higher resolution DEM was necessary for the extraction of regional control data (drainage basin area and slope). A topographic survey was done in order to collect point elevation data of the wetland study site. These data were required to construct a DEM of the wetland for the purpose of delineating headcut drainage area and determining drainage area slope. Elevation data were recorded at cross-sections of the wetland. The cross-sectional data were collected from the edge of the cultivated farm pasture to the road (R62) that passes through the valley on the slope of the Suuranys Mountains. Five cross-sections were marked off and surveyed at an angle perpendicular to the valley axis. Of these cross-sections, three were situated above the headcut features, one passing through the headcut features and the last one downstream of the erosional features. The headcut configuration and elevation were later surveyed assessing the current position and extent of headcut migration in the wetland. Headcut configuration was surveyed along the apex of the erosional feature. The longitudinal profile of each headcut was also surveyed to establish the slope and produce a more detailed DEM.

4.3.1.2) Headcut setting and gully dimensions

The headcut setting data for each site was collected and recorded with the use of a custom field assessment. The collection of this data was for the purposes of understanding the various factors that might be affecting the migration rate of each headcut. The headcut setting data were aimed at collecting dimension data of the headcut feature and providing an overview of the environment of each feature. The co-ordinates of each site were also recorded. The dimension data collected for each headcut was measured using both a staff gage and measuring tape. These dimensions include drop height, average plunge pool depth, apex width and gully width. The width of the gully was measured at a distance three times that of the apex width to achieve a standardized measurement of gully width for each site (Figure 4.2). An overview of each feature's environment was also observed and recorded. These factors include active slumping, presence of active groundwater seepage and vegetation at the headcut, bed roughness both above and below the headcut.

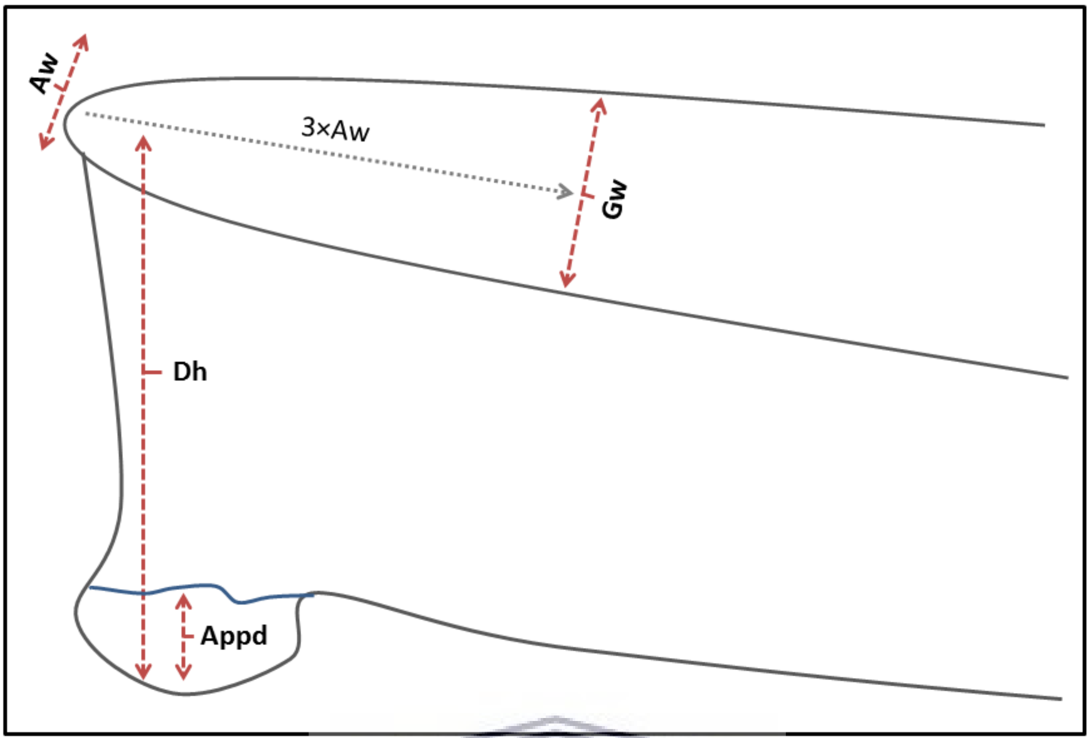

Figure 4.2: Schematic diagram of a gully head and the various dimensions recorded at each headcut. Where Aw is apex width, 3×Aw is the apex width multiplied by 3, Gw is gully width, Dh is drop height and Appd is average plunge pool depth.

4.3.1.3) Soil profile of headcuts

The soil profile data were collected and recorded by measuring the depth from the headcut apex at which changes in soil composition were noticed. Substratum was sampled according to the occurrence of change in soil composition vertically along the face of the headcut; therefore, increased homogeneity along a headcut face decreased the number of samples taken at each feature. This was done for the entire drop height of each headcut. The soil sample was extracted at the centre of each homogeneous soil layer and stored in a soil ring for lab analysis.

4.3.2) Desktop data collection

This includes the acquisition of data from external bodies, namely The Department of Rural Development and Land Reform: National Geo-spatial Information (DRDLR: NGI), South African National Space Agency (SANSA) and Stellenbosch University Digital elevation model (SUDEM). These datasets include; Digital Elevation Models (DEM), point elevation data, orthophotos and satellite imagery.

4.4) Data generation methods

4.4.1) Soil analysis

This subsection describes the method used and process followed to generate the appropriate soil data that were used to understand the relationship between soil characteristics and headcut migration. For the purpose of soil analysis all samples, subsamples and lab equipment were weighed on an Ohrus pioneer scale to an accuracy of 0.001g throughout lab analysis experiments. Soil analysis experiments done were bulk density, soil moisture content, loss on ignition (LoI) and particle size analysis.

4.4.1.1) Bulk density and soil moisture content

Determining Bulk Density (BD) of soil sample is important as it provides the density of an undisturbed soil sample with a known volume, taking into account both pore spaces and organic matter. These characteristics are known to influence soil structure and therefore, they can be related to soil erosion. Bulk density is expressed as the mass of dry soil per unit bulk volume and is specified as grams per cubic centimetre (Grossman and Reinsch, 2002). Gravimetric and volumetric moisture contents were calculated for each sample. Gravimetric Moisture Content (GMC) of a specific soil sample is expressed as the gravimetric moisture content and is given by the mass of water in the sample per mass of oven-dry sample. It can be expressed in grams of water per grams of oven-dry soil sample or as a percentage. Volumetric Moisture Content (VMC) is calculated using bulk density and gravimetric moisture content and is given as a ratio of the volume of water in the soil per volume of the bulk soil. This means it would be measured as cubic centimetres of water per cubic centimetre of bulk soil. Both bulk density and soil moisture contents were determined using standard laboratory procedures and were determined through the calculation of soil samples weight difference after drying samples of a known weight and volume at 105˚C for 24 hours (McKenzie et al., 2002).

4.4.1.2) Organic matter content

The organic matter content in soils can be determined by measuring the weight loss that occurs when organic material oxidizes at high temperatures. This method is referred to as LoI. It is particularly useful for the determination of organic matter content of well-aerated soil samples with low clay content (i.e. sand and peat) (Salehi et al., 2011).

Most of the organic material is burnt off at temperatures above 325˚C, but some losses may occur at higher temperatures. This is why the standardized ignition temperature is set at

550˚C to account for further losses that may occur. With ignition the “structural” water, which is part of the crystal lattice of particular clay minerals, is removed. LoI is therefore, an approximate measure of organic matter content in sandy soils and can be up to twice the amount of organic matter in heavy textured soils. This means that in using this method on soils with high clay content there is a high probability of over-estimating the organic matter content. Therefore, LoI for soils containing more than 5% clay needs to be corrected to account for the effect of loss of structural water. LoI_{550} was used to determine the organic matter of all soil samples and ignition was limited to 3-4 hours depending on soil texture and colour (Salehi et al., 2011; Wright et al., 2008).

4.4.1.3) Particle size analysis

Particle size distribution was achieved with the combined use of the settling tube method and the principle of sedimentation. This principle is based on the effect of the weight of different soil particles, where the largest particles will settle first and the silt and clay fractions will settle after a longer period. The settling speed of particles was derived from Stoke’s law and is influenced by the size of particle, its density and the properties of the fluid. The method that follows involves the settling of particles through 10 cm of liquid at 20˚C. To accurately determine particle size the organic matter binding clay sized particles needs to be removed. This is necessary to ensure that clay particles do not behave as larger particles, settling first and thereby giving a skew representation of the grain size distribution. Thus, all samples require pre-treatment prior to particle size analysis. Soil pre-treatment follows chemistry based principles whereas the grain size distribution determination follows physics based principles (Flemming and Thum, 1978).

The organic material was destroyed through a chemical reaction by adding hydrogen peroxide (H_2O_2) and hydrochloric acid (HCl) and heating the soil solution. The reaction between the organic matter, hydrogen peroxide and the hydrochloric acid produces a pure soil sample and by product solution of hydrogen peroxide and sulfuric acid. The pure soil sample was then extracted from the solution through filtration. The soil sample was now ready for particle size analysis. The sample was placed in a settling tube with water and a dispersion agent (sodium hexametaphosphate and anhydrous sodium carbonate) to facilitate the dispersion of the clay-sized fractions.

The soil particle size was determined using the settling tube method where 25 ml suspension samples were extracted from the 1000 ml settling tube, after agitation, at a depth of 10 cm below the meniscus. Samples were extracted at both 32 seconds and 8 hours after equal dispersion of soil was achieved by shaking the settling tube. The first 25 ml suspension sample that was extracted contained both clay and silt as it takes 32 seconds for sand particles larger than 60 µm initially at the surface to have settled beyond 10 cm. The second suspension sample extracted after shaking contained only clay size sediments as it take 8 hours for silt particles to settle beyond the 10 cm depth in the settling tube. After the second sample was taken the supernatant liquid was gently poured away and the soil material was transferred into a weighed 600 ml beaker. A mark was made 10 cm above the base of the 600 ml beaker and was filled with water up until this mark. The soil material and water solution was gently stirred with a glass rod to mobilize the sediments; 32 seconds after stirring has stopped the supernatant liquid containing silt and clay fractions was decanted. This process was repeated until all the silt and clay sediments were removed, when this is achieved the water in the beaker will be absent of suspended sediments at the 32 second mark. Thus, only the sand sized sediments that have settled to the base of the beaker were left in the beaker of known weight.

These three samples were then placed in the drying-oven at 105˚C to evaporate the excess water. Thereafter, the beakers containing soil fractions were reweighed and the recorded weight of the empty beaker was subtracted from this weight. Through this process the mass of the soil fractions of each suspension sample was calculated.

The mass of sand fractions is the mass of the whole cylinder whereas the mass of the silt and clay are calculated by multiplying the mass of each sediment type by 40. This was done because there is 40 times more silt and clay in the sample of 1000 cm^3 than that of a 25 cm^3 sample. The clay content can now be calculated for the whole cylinder and by subtracting the mass of the clay fractions (8 hour sample) from the mass of silt and clay fractions sample (32 second sample) the mass of the silt fractions was obtained.

4.4.1.4) Soil properties

The data generated during particle size analysis was used to determine the saturation and drainage rate of the lowest soil horizon of each headcut. These parameters were calculated online using the USD NRC soil properties calculator. Saturation is defined as the potential volume of water the soil sample can hold per volume of soil and appropriately is measured as cm^3 water/ cm^3 soil. Drainage rate refers to the speed at which water flows through saturated soil sample and is measured in cm/hour

4.4.2) Headcut erosions

During the field survey, time constraints and difficult terrain limited the observation of gully morphology change. Field observation also only provides a limited understanding of historical gully growth trends. Therefore, various studies made use of time-series remote sensing products to track and facilitate research on gully erosion (Frankl et al., 2013). The use of aerial photography for measuring gully head retreat is a well-known method to determine gully retreat rates (Burkard and Kostaschuk, 1997; Vandekerckhove et al., 2003). This method was used to track the movement and morphology of gullies in this study, therefore, allowing the calculation of various headcut migration rates. Data collected through this process include apex advancement, gully extension/enlargement and volume rate of headcut erosion.

These gully migration rates were calculated using remote sensing techniques within ArcGIS and a combination of field assessment data collected during site visits and orthophotos. Thereafter, headcuts were identified on each imagery product and the shape of the headcut digitized as a polyline which was then labelled by site and year (e.g. UWC1_2006). Once this was completed for each imagery product the area between polylines was digitized with the use of a polygon. The area of the polygon was then calculated for each polygon indicating the area lost or eroded between subsequent imagery products. The years between subsequent imagery products were also recorded as it was a key parameter necessary for calculating the average headcut erosion rate. By virtually tracking changes in shape and position of a gully head through a series of orthophotos the rate of apex advancement and gully extension is established. Orthophotos combined with headcut characteristics observed during a field assessment provides the necessary information to approximate the rate of headcut erosion. Figure 4.3 illustrates how various headcut migration rates were determined and extracted.

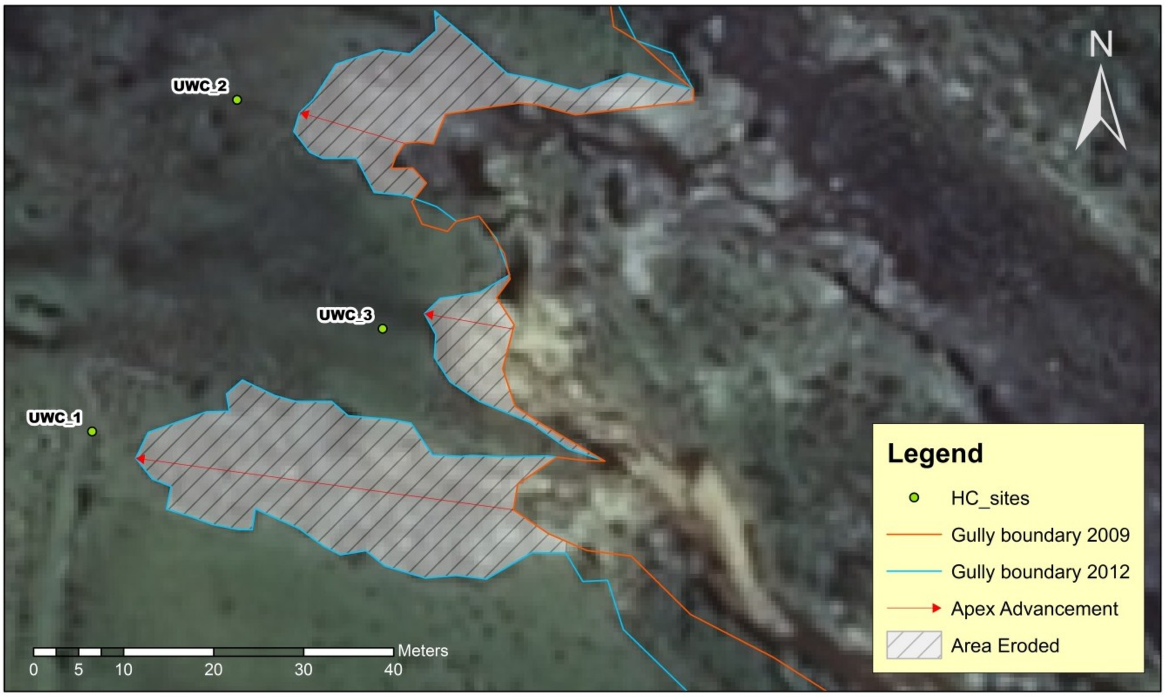

Figure 4.3: Illustration of how gully extension and apex advancement was extracted at the Kromme River sites within ArcGIS.

4.4.2.1) Apex advancement

Apex advancement was measured linearly by establishing the change in the upstream position of headcut apex across the available orthophotos, thus it is exclusively a measure of a headcut movement in the upstream direction. The distance between apex locations from image to image was measured in metres within ArcGIS using the measure tool (Figure 4.3). This measurement for a specific headcut illustrates the apex migration for the time interval between which the orthophotos were taken. By dividing the 'distance' measurement by the number of 'years' between two subsequent orthophotos the mean annual apex advancement is determined and measured in meters per annum (m/a). Two mean annual apex advancement measures were calculated for each headcut. The first is the annual migration rate between the two most recent orthophotos and the second is the mean annual migration rate across all available imagery for each headcut.

4.4.2.2) Gully head extension

Gully head extension rate was measured as the area of eroded stream bed above the gully head between orthophotos, providing an estimation of the amount of natural wetland habitat destroyed during the erosion process (Figure 4.3). This too was divided by the number of years between subsequent orthophotos to achieve the mean annual gully head enlargement rate. This two dimensional measure of erosion combines upstream and lateral extension of the gully head and was recorded in meters squared per annum (m^2/a). As with apex advancement two measures of gully extension rate were calculated; the first was the mean annual expansion rate that occurred during the latest imagery and secondly the mean annual gully expansion rate over all the available imagery for each headcut.

4.4.2.3) Headcut erosion

The headcut erosion rate is an approximation of the volume of soil eroded due to headcut migration and was thus measured in meters cubed of soil per annum (m^3/a). Headcut erosion rate is calculated using data from the above-mentioned gully head extension rate and gully dimension data collected during the field assessment, namely the headcut drop height. The product of these two variables is an estimation of the volume of soil eroded at the gully head and transported downstream. The volume of soil lost is divided by the number of years between the two image products to produce a mean annual volume of soil lost. Unlike apex advancement and gully extension, only the most recent headcut erosion is calculated. This is done as it would be incorrect to assume that headcut height stayed constant from the moment of the headcut's initiation throughout their entire existence (Rengers and Tucker, 2014).

4.4.3) Headcut drainage area and slope

A combination of both primary and secondary data collected from external sources was used to generate data for these parameters. These datasets were displayed, compared and analysed within ArcGIS in order to appropriately and adequately delineate the drainage area for each headcut and determine the slope of these drainage areas. Slope values include minimum, maximum, range and standard deviation slope. Primary data includes point elevation data and secondary data includes data extracted from a 5 m contour DEM provided by SUDEM. Using a combination of the DEM generated from the field survey and the 5 m SUDEM, contour lines were generated. These contour lines were used to identify high points and valleys. The high points were then connected through digitization at a perpendicular angle to contour lines, the output being mountain ridges. These mountain ridges encompass the valley lines (flow accumulation paths) this method used for extraction is commonly referred to as 'The New Hampshire method' (Ammann and Stone, 1991).

A polygon was then created by connecting the headcut point with mountain ridges and high points delineating the drainage basin. Once these drainage basins were delineated and digitized the area and slope was then calculated. An 'area' field was added to the attribute table of the drainage basin shapefile and was calculated in metres squared using the calculate field geometry function. For the determination of slope for each drainage basin feeding headcuts, a slope raster of each catchment was produced using the slope tool in ArcGIS. The Slope raster was produced in degrees. Thereafter, the slope raster and drainage basin polygons were used as inputs in the Zonal statistics as table tool to determine the maximum and mean slope for each drainage basin.

4.5) Data analysis methods

The migration of each headcut was measured over two timespans. The first being the average headcut migration rate observed between the two most recent aerial imagery/orthophotos because it is the most suitable dataset for correlation with the headcut characteristics, as they were collected during the same time period. The secondly the average headcut migration between each available aerial image/orthophoto for each headcut was determined to establish gully growth rate trends and also to determine the overall mean migration rate.

4.5.1) Soil particle size distribution

Soil type was classified using the results obtained from the particle size distribution experiment plotting the percentage sand, silt and clay, of each soil sample, on a soil textural diagram (Figure 4.4). Based on the principle of plunge pool erosion in stratified soils, the soil particle size distribution of the lowest soil horizon of each headcut was used for analysis. The percentage clay and silt content were selected for correlation analysis over percentage sand, as the percentage clay/silt was more distinguishable for each soil horizon. Clay sized sediments are known to control the erodibility of soil, and thus give an indication of the soil's resistance to erosion (Panagiotopoulos et al., 1997).

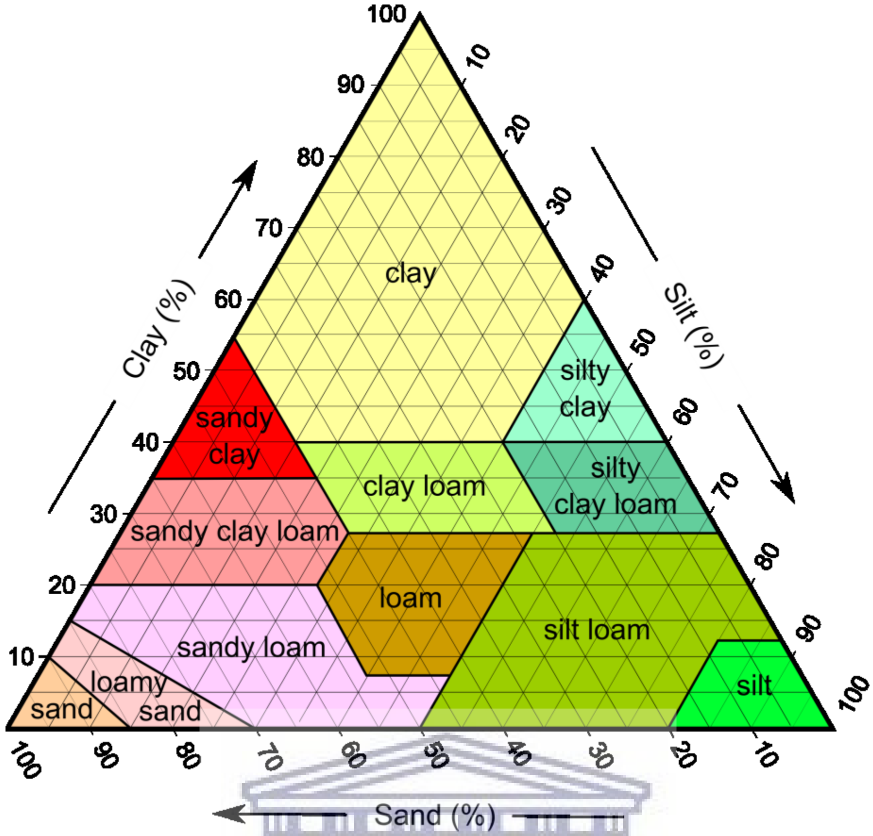

Figure 4.4: Soil textural diagram used to classify soils (García-Gaines and Frankenstein, 2015).

4.5.2) Statistical analysis

Correlation analysis was the main statistical approach used when analysing the relationships amongst all variables (both predictor and outcome variables) in the entire dataset. Once the relationships between variables had been calculated and analysed, multiple regression analysis was used to understand the relationship between headcut characteristics and other factors.

Throughout the literature reviewed for this research project the most common method used when trying to establish the relationship between gully characteristics and gully migration is multiple regression analysis, the most favoured being stepwise multiple regression (Bennett and Casali, 2001; Bocco, 1991; Gordon et al., 2011; Radoane et al., 1995; Stein and LaTray, 2002; Vandekerckhove et al., 2000; Vanmaercke et al., 2016). This statistical analysis method allows one to calculate the amount of variance each headcut characteristic contributes to gully erosion, thus allowing one to identify the factors that most influence headcut migration.

Multiple regression is defined as a family of techniques that can be used as to explore the relationship between one continuous dependant variable (outcome) and a number of usually continuous independent variables (predictor). It is an extension of simple linear regression and is used when you want to predict the value of a specific variable based on the value of two or more further variables (Pallant, 2013). The variables used in multiple regression were headcut erosion types which served as outcome variables and headcut characteristics which were used as predictor variables. Headcut erosion types included variables apex advancement, gully extension and headcut erosion rate and the respective long term averages for each (Table 4.1). Headcut characteristics included headcut morphology measures, soil characteristics and regional catchment measures (Table 4.2). Step-wise multiple linear regression analysis, in IBM SPSS Statistics, was utilized to evaluate the relationship between headcut and gully erosion and the headcut characteristics recorded for each site. Multiple regression analysis was run five times each time with a different outcome variable (Field, 2009).

Prior to running the regression analysis, the dataset was transformed and tested for normality, linearity, singularity and multicollinearity. Data transformation of the entire dataset is necessary in order to make the data more comparable. This transformation decreases errors that might have occurred due to differences in measurement units between variables. The data transformation, natural logarithm was applied to the entire dataset, achieving the required normal distribution. Thereafter, the data were tested for normality and linearity.

Pearson product-moment bivariate correlation coefficient (PPMCC) was used to test for multicollinearity and singularity among variables (Eq.1). The correlation coefficient between variables provides an idea on the measure of the relationship between two variables. This coefficient lies between the range of -1 and +1. The intensity and direction between every pair of variables was determined and also whether or not the variables are directly (+ PPMCC) or indirectly proportional (-PPMCC). Multicollinearity occurs when there is a very high correlation between predictor variables (0.8 to 1) and singularity occurs when one of the variables is calculated using the values of other variables in the dataset, thus it is important to understand how each variable was calculated.

Pearson product-moment correlation coefficient (PPMCC):

$$r = \frac{N\sum xy - (\sum x)(\sum y)}{\sqrt{\left[N\sum x^2 - (\sum x)^2\right]\left[N\sum y^2 - (\sum y)^2\right]}}$$

Where:

r= PPMCC

N= Number of pairs of variables

x= Variable 1

y= Variable 2

Other values that provide information of multicollinearity are tolerance and variance inflation factor (VIF). The commonly used cut-off points for determining the presence of multicollinearity is a tolerance value less than 0.1 or a VIF value above 10. If the results fall within these cut-off values it is assumed that the assumption of multicollinearity has not been violated. However, when multicollinearity was observed between predictors it can be remedied by removing one of the predictors or combining them linearly to produce a single predictor (adding them).

Table 4.1: List of dependent (outcome) variables in multiple regression analysis.

Apex Advancement	**Gully extension**	**Volume erosion**
Apex advancement (recent)	Gully extension (recent)	Volume erosion (recent)
Apex advancement (overall average)	Gully extension (overall average)	

Table 4.2: List of independent (predictor) variables used to predict the outcome variables

Headcut Characteristics	**Soil Characteristics (Lowest soil horizon)**	**Regional Controls**
Apex width	%Clay	Headcut drainage basin slope
Gully width	%Silt	Headcut drainage area
Drop height	%Sand	
	%Organic matter	
	Bulk density	
	Saturation	
	Drainage Rate	

4.6) Limitations

Secondary data in the form of satellite imagery and/or orthophotos is produced every three to four years, prohibiting the retrieval of specific headcut migration for each year. Another limitation in terms of secondary data was the lack of high resolution and frequent production of a DEM data, thus limiting remote sensing techniques to horizontal erosion and not the vertical loss of soil through headcut erosion. Furthermore, this also limited the accuracy to which specific headcut drainage basins are delineated.

Data collection limitations are mainly centred on the fact that measurements of gullies were taken during different seasons, thus measures such as average plunge pool depth and moisture content would be largely affected by the time of data collection and the amount of precipitation that fell prior to the day of field survey. Because average plunge pool depth and moisture content are susceptible to a large range of variability they were excluded from analysis. Another potential limitation to this study is the fact that headcut characteristics and soil characteristics were measured after the headcut migration had taken place. Furthermore, due to time constraints and distance between study areas actual flow data across each headcut was not measured.

In terms of statistical analysis, the key limitations identified in this research project was the fact that; 1) flow data was not measured for headcut migration rate and 2) the sample size was relatively small limiting large scale generalization. Without flow data statistical analysis would assume that headcut migration rate was a direct consequence of drainage area and slope (among other factors), neglecting the influence of rainfall variability and subsequent overland flow on erosion rate. This would then introduce a margin of error when analysing different headcut migration rates under varying climatic conditions. The sample size was limited by the fact that 6 of the headcuts identified infield were not included in analysis due to dense vegetation canopy cover, restricting the determination of headcut retreat rate through image analysis. Because Palmiet wetlands in South Africa are few and far between, the results of this analysis would require a bigger dataset to make more conclusive prediction of headcut erosion. However, this study attempts to understand which characteristics most affect the rate of headcut migration in Palmiet wetlands as an attempt to identify wetlands most vulnerable to degradation and allow for timeous intervention. Based on the limited number of Palmiet wetlands in South Africa, it is assumed that though the sample size included in this study is small, it probably represents quite a large portion of the overall statistical population of headcuts in Palmiet wetlands. The present state of headcuts was compared to headcut migration rates that occurred prior to the current headcut characteristics.

Chapter 5: Results

5.1) Introduction

In this chapter the results of data collected, generated and analysed are presented. Headcut characteristics collected in the field are presented first followed by soil analysis results and data produced from image analysis (headcut erosion rates and regional controls). Thereafter, the results of vertical stratification of headcut particle size and finally the results of statistical analysis are presented.

5.2) Headcut dimensions and infield characteristics

Table 5.1 summarises the headcut of all headcuts identified in the field. Headcut drop height ranged from 0.6 m to 10.23 m, averaging 2 m. Apex width ranged from 0.06 m to 31.19 m, with an average of 5.38 m. Gully width ranged from 0.6m to 32.77 m, with an average of 12.26 m. A distinct plunge pool was discernible at twelve of the fifteen headcuts, and plunge pool depths ranged from 0 m to 2.21 m and averaged 0.51 m. Based on an overview of the presence or absence of a plunge pool in relation to other headcut characteristics, headcut drop height seemed to be the most defining characteristic, as the presence of a plunge pool was limited to headcuts with a drop height ≥0.84 m.

Vegetation re-establishment on a gully bed seemed to be largely dependent on the width of the gully, occurring within gullies having an apex width and gully width of ≥1 m (Table 5.1). This can be explained by the indirect relationship that exists between gully width and flow, increased width results in increased contact with the stream bed area and therefore friction leading to decreased flow velocity. Vegetation was absent in both UWC6 and UWC7 which had apex and gully widths below this threshold and the highest flow conditions occurring over these headcuts. High flow conditions and low friction associated to narrow gully widths are thus key factors inhibiting vegetation re-establishment.

The headcuts were observed to migrate through plunge pool erosion a combination of two processes, namely fluvial processes and mass wasting. Headcuts located in the main line of flow were largely controlled by fluvial processes. This can be deduced due to the lack of slumping, producing a gradual transition in shape. It contrasts headcuts that were located further from the main flow path which showed an increasing occurrence of active slumping indicating evidence of migration through mass-wasting producing a more abrupt headcut shape.

Table 5.1: Headcut dimensions and characteristics.

Sites	Drop height (m)*	Apex width (m)*	Gully width (m)*	Average plunge pool depth (m)	Slumping	Groundwater seepage	Gully vegetation	Quat.
UWC1*	1.05	2.06	8.50	0.08	Yes	Yes	Yes	K90A
UWC2*	1.55	6.46	17.80	0.30	Yes	Yes	Yes	
UWC3*	2.05	2.40	11.40	0.15	Yes	No	Yes	
UWC4*	1.35	1.00	3.20	0.23	No	Yes	Yes	
UWC5*	1.14	2.73	10.00	0.10	Yes	No	Yes	
UWC6	1.00	0.90	0.90	0.26	No	No	No	
UWC7	1.80	0.60	0.60	0.77	No	No	No	
UWC8	1.84	1.07	10.45	0.61	No	No	Yes	
ENV1	0.79	1.60	3.58	0	Yes	No	Yes	G50B
ENV2*	0.80	4.18	11.66	0	No	No	Yes	
PSK1	0.84	8.50	11.77	0.48	Yes	No	Yes	
PSK2*	3.05	10.30	23.40	2.21	No	Yes	Yes	
JSK*	10.23	31.19	32.77	1.16	Yes	Yes	Yes	
KTK6*	2.00	3.70	19.30	1.25	Yes	Yes	Yes	G50C
KTK6.1	0.60	4.00	18.60	0	Yes	No	Yes	

* *Sites and characteristic marked with an asterisk were included in final regression analysis*

5.2.1) Relationships between gully dimensions

The relationships between headcut and gully dimensions measured infield were explored through statistical analysis. This was done in order to understand whether co-variation exists between variables and therefore, establish if headcut dimensions co-vary during erosion. Plunge pool depth was measured as depth of water in the pool, which was measured at various times of the year under a range of flow conditions. This meant that measurements were not comparable and these data were not included in further analyses. Table 5.2 provides the correlation coefficients and significance between the three headcut dimensions measured in field (apex width, gully width and drop height). Based on simple correlation analysis between dimension variables displayed in Table 5.2 the strongest and most significant correlation was 0.924 between apex width and drop height. The second strongest and most significant relationship existed between apex width and gully width at 0.809. An intermediate relationship of 0.699 was observed between gully width and drop height. These relationships were all significant at a 0.01 level highlighting the presence of relationships between these variables. These results do not necessarily signify cause and effect and more likely imply that the driving forces behind erosion affect headcut dimensions in a similar way leading to the concurrent evolution of dimensions.

Table 5.2: Correlation analysis between headcut dimension characteristics

Correlations

		dh	gw	Aw
dh	Pearson Correlation	1	.699**	.924**
	Sig. (2-tailed)		.004	<0.001
	N	15	15	15
gw	Pearson Correlation	.699**	1	.809**
	Sig. (2-tailed)	.004		<0.001
	N	15	15	15
aw	Pearson Correlation	.924**	.809**	1
	Sig. (2-tailed)	<0.001	<0.001	
	N	15	15	15

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Where; dh is drop height, gw is gully width and aw is apex width.

5.3) Soil analysis

The results of the laboratory soil analysis are presented in this sub-section. The data are presented in the form of various graphs and include the results for all headcuts identified in the Kromme and Nuwejaars catchments. Firstly, the result of organic matter content and bulk density are presented and described. Thereafter, the results of particle size analysis and soil classification are presented followed by a description of headcut soil stratigraphy. Finally, the relationship between soil type and soil characteristics is discussed. The data analysed here include all headcut sites except KTK6.1 because no soil data were collected at this site due to lack of resources.

5.3.1) Loss on ignition results

Figure 5.1 presents the percentage of organic matter observed in soil horizons along the headcut face at each sample site. The data are labelled according to the soil sample from which the organic matter content was determined and are presented from the top to the base of each headcut face, thus showing variation in organic matter with depth. Based on the results depicted in Figure 5.1 it is clear that the organic matter content generally decreases from the top soil horizon to the base horizon. However, the lowest organic matter was not exclusively found in the lowest soil horizon. The same can be said of the exclusivity of the highest organic matter content in the top soil horizon. However, the highest organic matter content was found in the top soil horizon in 11 out of the 14 headcut sites. The organic matter content for the top soil horizon of all sites averaged at 7.38% whereas the organic matter content of the headcut base soil horizon had an average of 2.82%. Based on a statistical t-test soil organic matter content of the topsoil horizons were significantly different to the soil organic matter content of the base soil horizons at the 0.05 level.

The reduction of organic matter with depth is an expected phenomenon within Palmiet wetlands as they are naturally aggrading bodies and Palmiet vegetation itself is a peat forming plant that grows on quartzitic sandstone and quartz-rich sediments. After Palmiet vegetation establishes on this substrate it slowly begins the production and accumulation of organic matter. In time the vegetation grows denser increasing their organic matter accumulation ability and organic matter production. Seasonal variations in stream flow and also flood/drought cycles also affect the sediment regime of a hydrological system often leading to cyclical deposition of sediment types. Based on flood/drought cycles various sediment types are deposited to the stream bed during certain seasonal flow conditions, thus providing justification for the highest soil organic matter occurring in the middle horizons of some headcut profiles. Seasonality influences organic matter content with depth in soil horizon as infiltration mobilizes soil organic matter facilitating translocation to greater depths.

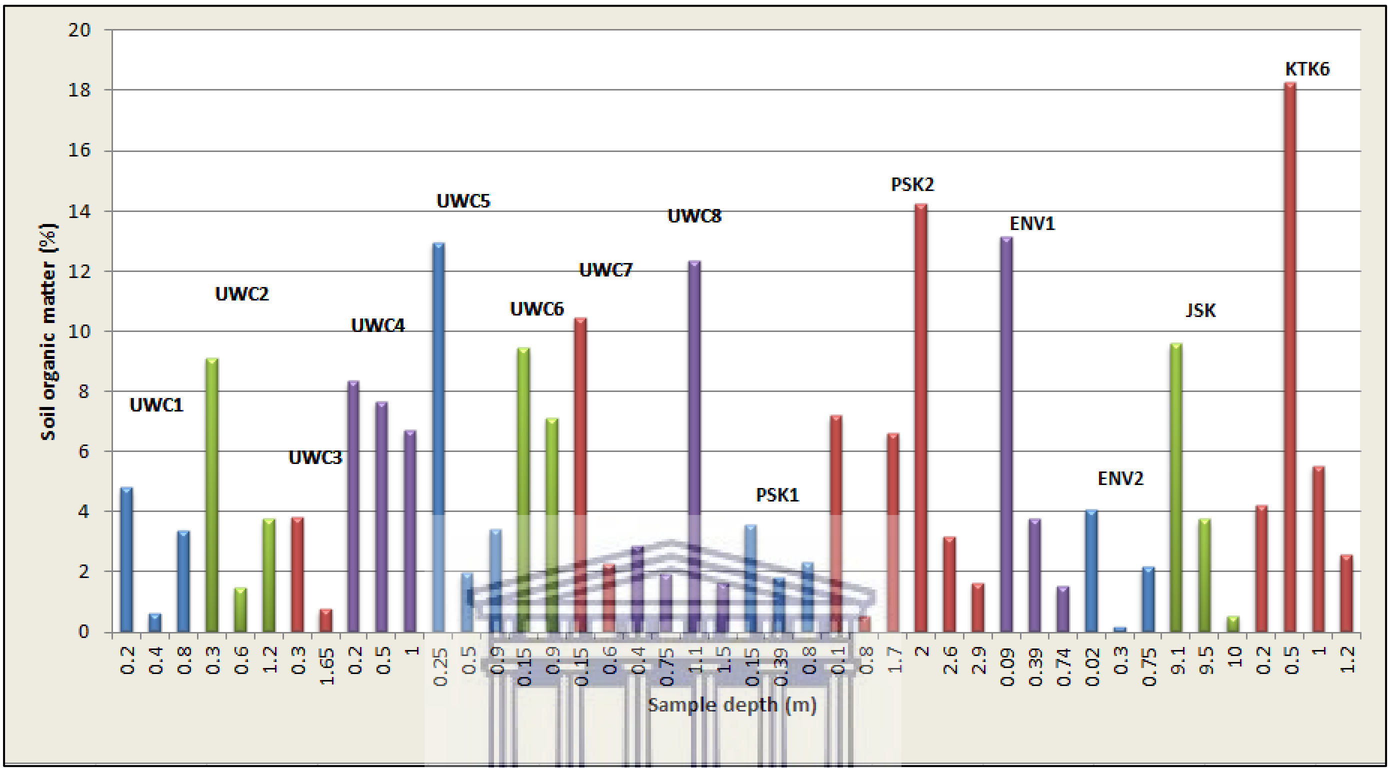

Figure 5.1: Organic matter results for soil samples retrieved from the headcut face of each gully.

5.3.2) Bulk density

Figure 5.2 shows the bulk density results for soil samples extracted along each headcut face. The dataset does not follow any strict identifieable trend however, the highest bulk density tended to occur in the at intermediate depths for the majority of the headcut faces. There are multiple ways to explain this trend but the main reason is the association between particle size and the associated ability of sediment to be compacted. Fine-textured sediments are easily compacted, whereas coarse material is not. Hence the lower bulk densities in some of the base soil horizons (containing coarser grain sediments) and higher bulk densities in the top soil horizons (containing finer grain sediments). The frequent occurrence of high bulk densities in the middle soil horizons could also be substantiated by the fact that the top soil layer is under the least amount of pressure (lack of overlying soil layers compacting it) and the lowest soil horizons are naturally sandy soils or other coarse textured soils.Whereas the middle soil horizons are comprised of sandy soils whose pore spaces have been filled with fine grained sediments through the process of translocation via percolation, resulting in higher bulk density. The bulk density of a mid-soil horizon is also impacted by the pressure of overlying soil horizons compacting the soil horizon. Another potential factor that could partly be responsible for lower bulk densities observed in some of the base soil horizon is the increased pore water pressure due to the presence of groundwater acting as a dispersive force on sandy sediments in the lower soil horizons. However, the soil horizon with the highest bulk density in the Kromme was situated at the base of headcut UWC3 and at the base soil horizon of headcut JSK in the Nuwejaars. These headcuts also had the highest drop height for each respective catchment, highlighting the effect of pressure on the base soil horizon's bulk density, from overlying soil horizons.

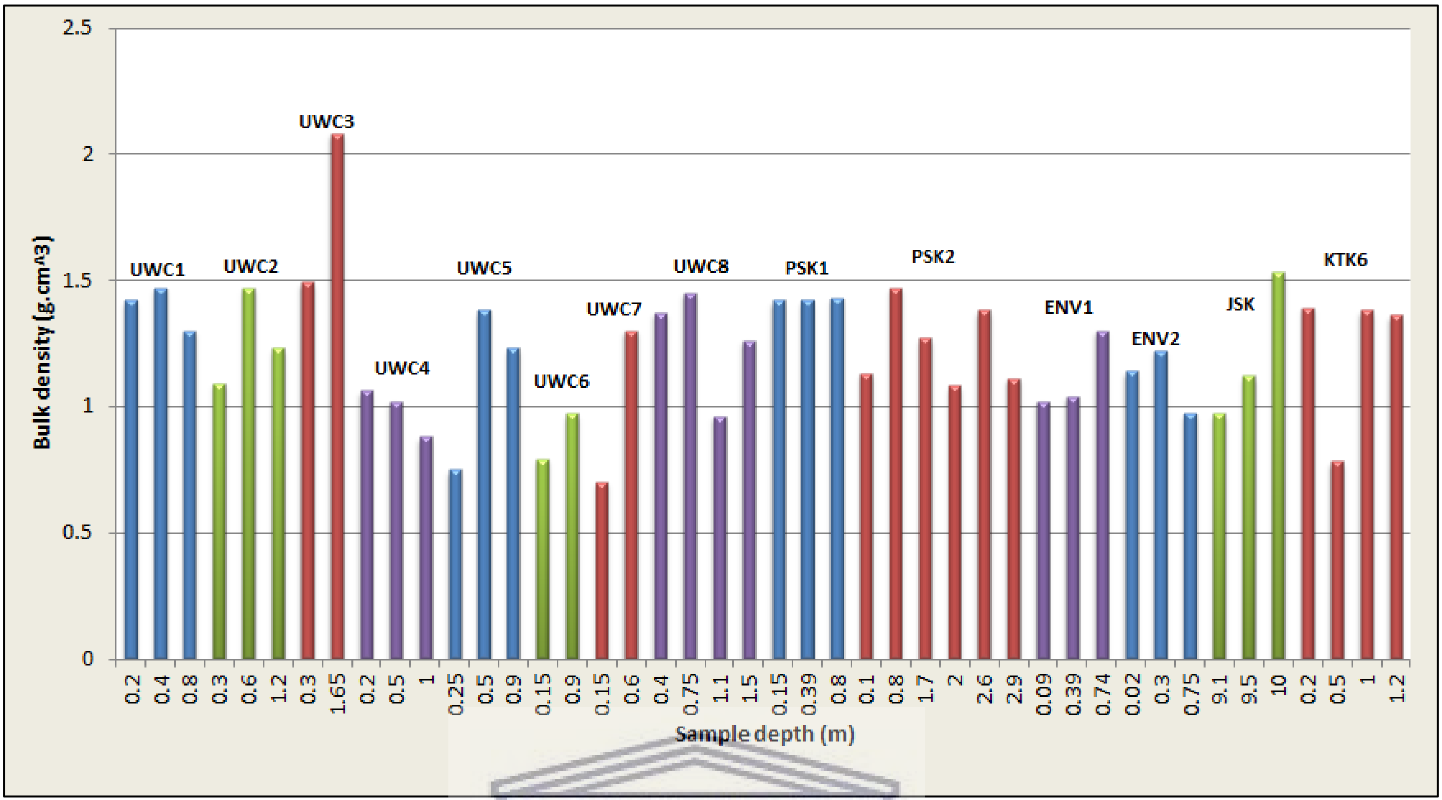

Figure 5.2: Bulk density of soil samples extracted along the headcut face at each sample site.

5.3.3) Bulk density and soil organic matter content

When analysing the LOI and bulk density results together, it is evident that an inversely proportional relationship exists between these two soil parameters. The result of this relationship is displayed in Figure 5.3. When looking at Figure 5.3 an inverse trend is noticeable such that low organic matter content is associated with a high bulk density and vice versa. The Pearson's correlation coefficient for LoI and bulk density for the headcut soil data was -0.72 for the entire dataset including headcut soil data initially excluded from further analysis.

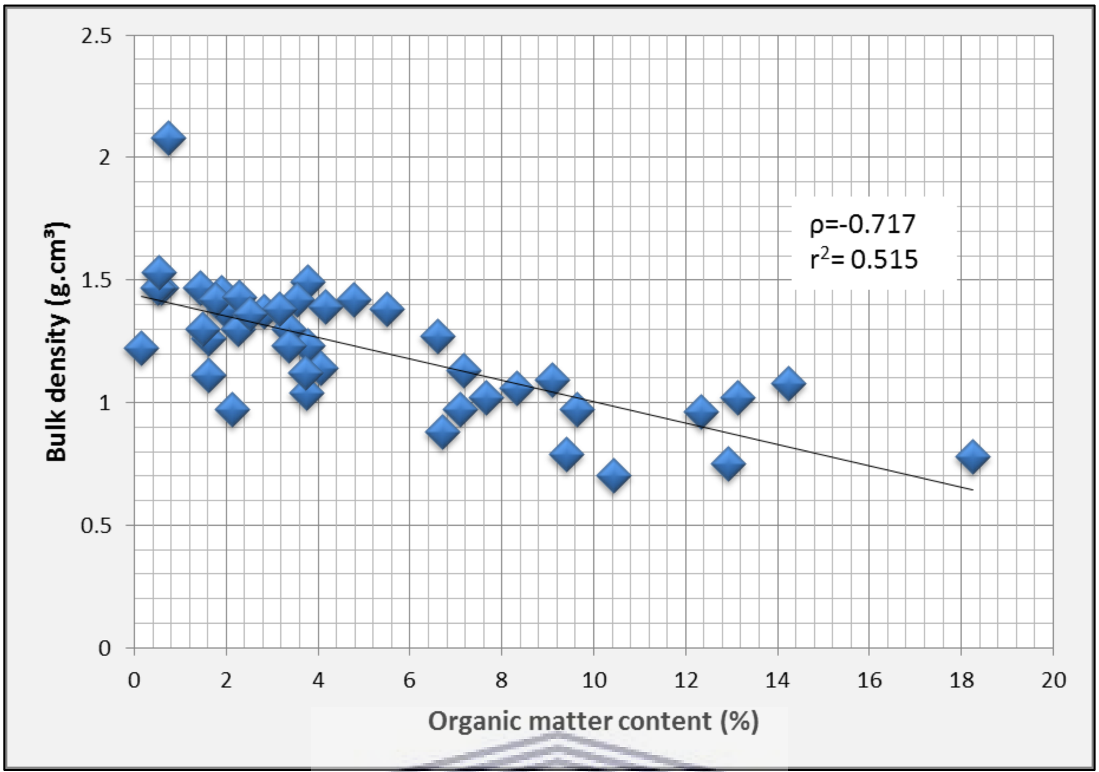

Figure 5.3: The relationship between bulk density and organic matter content of soil samples collected in the field.

5.3.4) Particle size results

The particle size analysis is presented in Figure 5.4 in the form of a stacked column graph with soil fractions adding up to 100 %. The graph displays the percentage of each sediment size that makes up the composition of each soil sample. The percentage clay and sand are labelled for each sample while the remaining percentage makes up the silt content of each soil sample. The 100% displayed here does not include the organic matter percentage determined using LOI. LOI is excluded from this graph because the organic matter was removed from the soil samples prior to particle size analysis. This data was used to calculate soil type properties on the USD NRCS site, namely saturation and drainage. Both drainage and saturation is a product of soil composition, particle shape and size affecting soil permeability and porosity. Increased particle size results in increase pore spaces and therefore increased permeability and drainage rate, whereas smaller particle size results in pore infilling restricting flow pathways between soil sediments and therefore resulting in decreased drainage rate of soil stratum. The data in this graph were used to determine the soil texture of these soil samples.

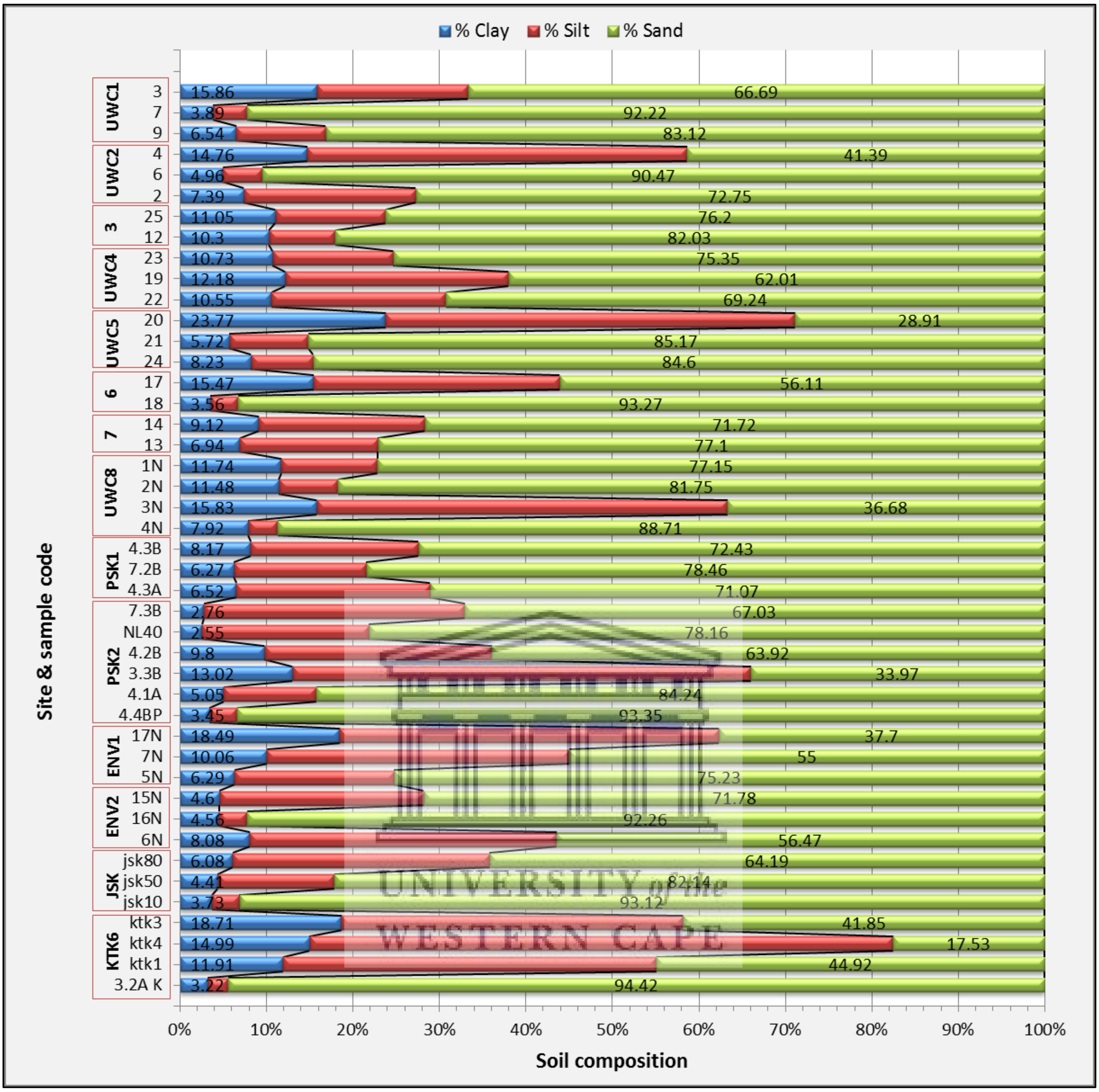

Figure 5.4: Soil sample composition; clay, silt and sand percentage of each soil sample. Vertical boxed labels on the y-axis are the names of each sampling site whereas the horizontal labels are the soil sample codes.

The soil texture of each sample was determined using the above-mentioned data and a textural diagram. The USDA NRCS soil texture calculator was used to determine soil type of each sample to ensure accuracy. The result of soil texture analysis is presented in Figure 5.5 illustrating the soil stratigraphy of each headcut. Headcut sites labelled UWC1 through to UWC8 are Kromme sites and headcut sites ENV1 through to KTK6 are Nuwejaars sites. Based on the results from Figure 5.5 soil textures in the Kromme were classified as sandy loam, loam, sand and loamy sand. These soil types are very sandy containing ≥40% sand contents mainly a result of the sandstone geology on which wetlands occur. Soil types between the two catchments remained relatively consistent. However, the only differentiation in soil types between the two catchments is the presence of silt loam in the Nuwejaars catchment containing <40% sand content (Figure 5.5).

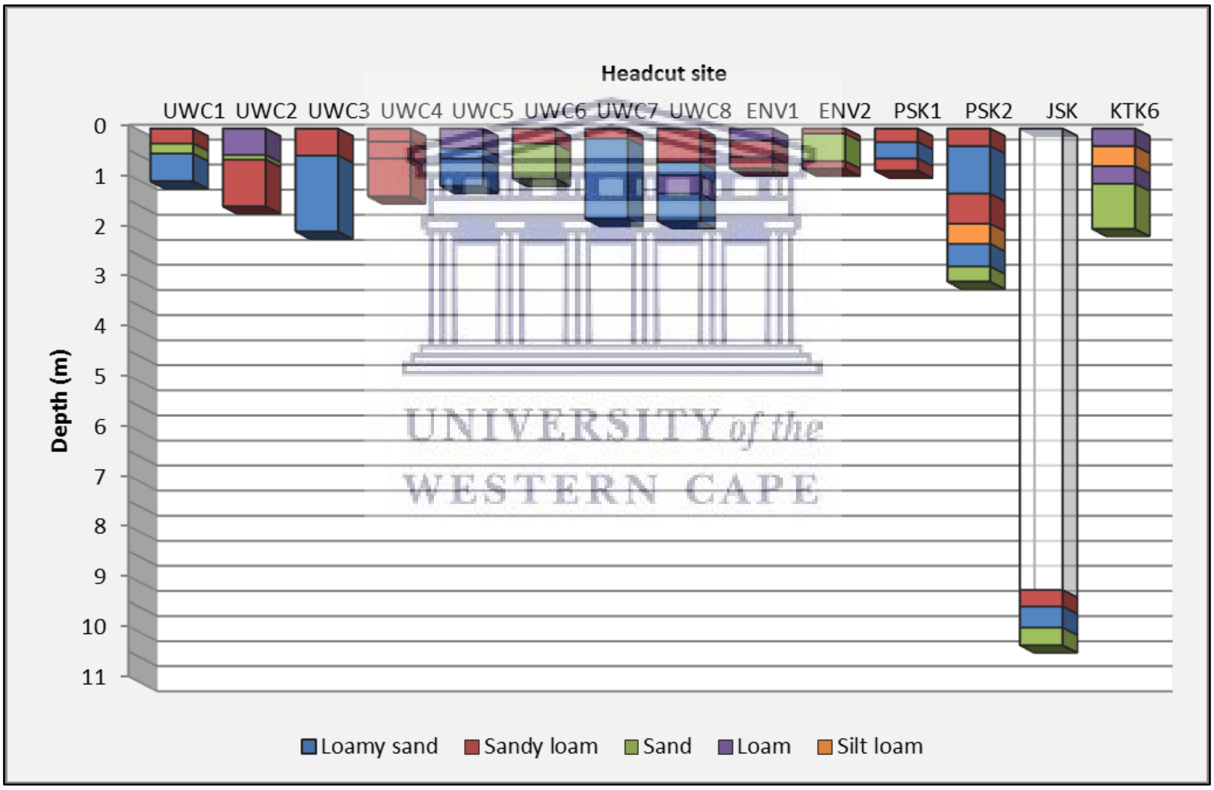

Figure 5.5: Headcut soil type and soil stratigraphy.

5.3.5) Soil composition, bulk density and drainage rate

The change in headcut soil type with depth for each headcut is displayed in Figure 5.5. The sand content remained in a relatively similar range for soil horizons. The soil types identified in the horizon ranged between sand, loamy sand, sandy loam, loam and silt loam texture. However, soil types dominating the lowest soil horizon included loamy sand, sandy loam and sand. Because headcut migration rate in Palmiet wetlands has been identified as progressing through the mechanism of plunge pool erosion the soil properties of base soil horizons were highlighted and used for statistical analysis. The results of headcut stratigraphy illustrated in Figure 5.5 indicate that headcut base soil type was limited to sandy loam, loamy sand and sand. Further analysis of the relationship between soil type and bulk density illustrated the influence of soil composition on bulk density. The average bulk density of each soil class was calculated and displayed in Table 5.3.

Table 5.3: Soil type and average bulk density

Soil type	Frequency	Average bulk density ($g.cm^3$)	Standard deviation
Silt loam	2	0.93	0.21
Loam	6	1.1	0.26
Sandy loam	18	1.15	0.23
Loamy sand	11	1.4	0.24
Sand	7	1.3	0.23

The average bulk density of various soil types shows the average bulk density generally increased with an increase in the contribution of sandy material to the sample however, soil composition cannot be used as the sole contributor to a soil horizon's bulk density as various factors such as compaction and organic matter are also contributing factors. An analysis of the trends between bulk density and percentage sediment fraction, displayed in Figure 5.6, revealed a similar relationship between bulk density and silt content as was observed between bulk density and organic matter content. Increased silt content resulted in decreased bulk density.

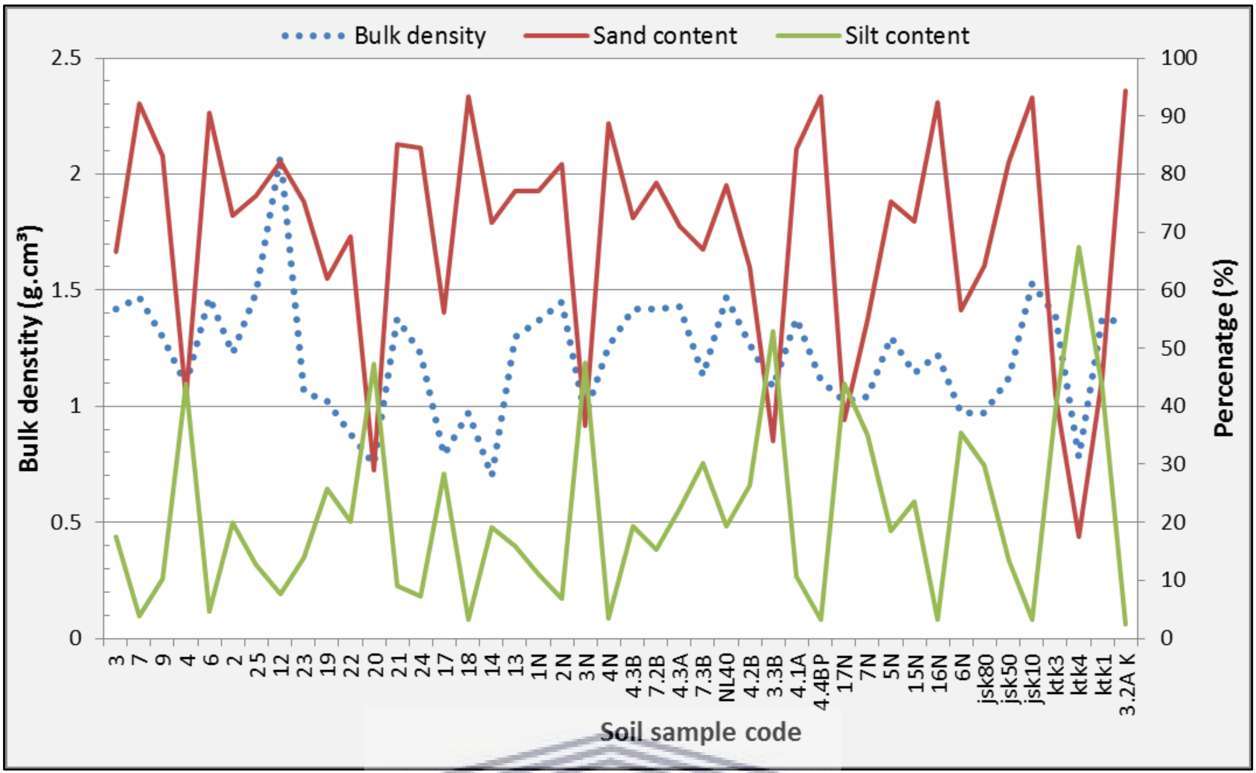

Figure 5.6: Bulk density and soil composition trends.

An analysis of the relationship between drainage rate and soil type validated the relationship between soil composition and soil permeability. With the use of correlation analysis sand content was found to have the most significant effect on soil drainage rate followed by sand and then silt. An analysis of the trends between drainage rate and percentage sand and clay fraction, displayed in Figure 5.7, revealed an inverse relationship between clay and drainage rate and a direct relationship between sand and drainage rate. Increased silt content resulted in decreased bulk density. Increased sand content resulted in increased drainage rate and increased clay content resulted in a decreased drainage rate.

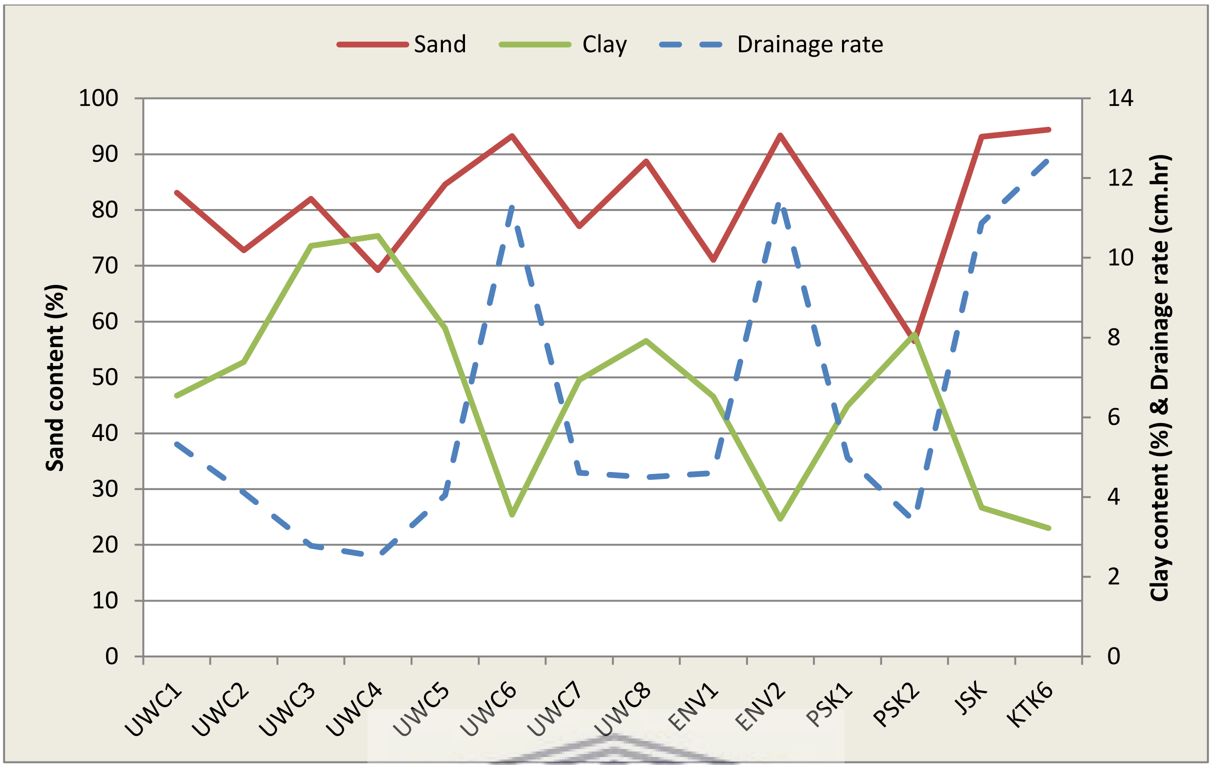

Figure 5.7: Drainage rate and soil composition trends.

5.4) Image analysis results

Data presented in this section were derived using spatial analysis techniques of orthophotos within ArcGIS. The data include headcut migration rates, headcut drainage area and average drainage basin slope. Table 5.4 depicts the results of the spatial analysis, showing the average headcut migration rates for each site and time span (listed below average values in Table 5.4) for which it was calculated. The data in this section excludes 6 sample sites identified in the field due to lack of aerial imagery or presence of vegetation canopy preventing the tracking of the erosional feature.

Headcut site UWC1 showed the highest apex advancement in a 3 year period, migrating at an average distance of 14.12 m/a during this time span. In terms of gully extension PSK2 had the highest erosion rate at 159.44 m^2/a during a4 year time period. The highest volume of erosion occurred at headcut site JSK eroding a total volume of 1031.83 m^3/a during a two year period. Drainage basin area was found to be largest at UWC2 as it occurred along the main flow path in the Kromme wetland and the drainage area slope of UWC1 was the steepest as the drainage area extended upwards along the foothill of the adjacent mountain.

Table 5.4: Image analysis results (headcut migration rates, drainage basin area and slope). Apex advancement, gully extension and volume erosion rates listed show the most recent average erosion rates, whereas their respective averages depicts erosion rates determined from a more extensive historical data.

Site	Apex Advancement (m/a)	Average Apex Advancement (m/a)	Gully Extension (m^2/a)	Average Gully Extension (m^2/a)	Volume Erosion (m^3/a)	Drainage basin area (ha)	Average Drainage basin slope (°)
UWC1	14.12 (2012-2015)	7.75 (2009-2015)	15.03 (2012-2015)	105.00 (2009-2015)	15.78 (2012-2015)	11.97 (2015)	21.87 (2015)
UWC2	3.98 (2012-2015)	2.97 (2009-2015)	35.22 (2012-2015)	66.96 (2009-2015)	54.59 (2012-2015)	4192.94 (2015)	16.94 (2015)
UWC3	3.54 (2012-2015)	2.32 (2009-2015)	24.40 (2012-2015)	28.94 (2009-2015)	50.02 (2012-2015)	18.06 (2015)	17.62 (2015)
UWC4	1.74 (2012-2015)	1.45 (2009-2015)	13.24 (2012-2015)	15.06 (2009-2015)	17.87 (2012-2015)	18.88 (2015)	15.64 (2015)
UWC5	1.12 (2012-2015)	0.94 (2009-2015)	11.54 (2012-2015)	7.52 (2009-2015)	13.16 (2012-2015)	21.46 (2015)	20.31 (2015)
ENV2	1.75 (2014-2016)	45.53 (2012-2016)	27.27 (2014-2016)	534.01 (2012-2016)	21.82 (2014-2016)	65.20 (2016)	13.84 (2016)
PSK2	6.91 (2010-2014)	6.91 (2010-2014)	159.44 (2010-2014)	159.44 (2010-2014)	486.29 (2010-2014)	58.34 (2014)	8.82 (2014)
JSK	5.56 (2014-2016)	10.80 (2010-2016)	100.86 (2014-2016)	374.10 (2010-2016)	1031.83 (2014-2016)	28.88 (2016)	12.38 (2016)
KTK6	1.69 (2014-2016)	19.01 (2012-2016)	70.82 (2014-2016)	319.16 (2010-2016)	141.64 (2014-2016)	14.91 (2016)	6.90 (2016)

5.5) Factors affecting headcut migration rate

The results of statistical analysis presented in this section include correlation and regression analysis between the various headcut migration rates and headcut characteristics. Stepwise backward linear regression analysis was used to determine which variables have an influence on headcut migration rate. The data used includes all the migration data for traceable headcuts and headcut characteristics excluding average plunge pool depth due to the parameter's variability with rainfall and time. Regression analysis in this section does not attempt to predict headcut migration rate but is mainly aimed at identifying headcut characteristics that significantly affect the rate of headcut erosion in Palmiet wetlands. Multiple regression analysis was carried out five times, once for every outcome variable (headcut migration rate type). Though multicollinearity was present between some headcut characteristics factors were not combined linearly due to the fact that headcut characteristics investigated in this study are known to co-evolve thus, resulting in multicollinearity.

The results in Table 5.5 are colour coordinated based on significance and also the direction of the apparent relationship between headcut migration rates and characteristics. For the description of the direction of apparent relationships 'direct' implies a directly proportional relationship and 'inverse' implies inversely proportional relationships. Direct relationships imply both the predictor and outcome variable follows the same trend direction whereas indirect means the outcome and predictor variables follow different trend directions. Data coded in blue indicates a significant indirect relationship and data coded in orange indicates a significant direct relationship whereas white represents an insignificant relationship. Significant relationships were observed and limited to regression analysis models of volume erosion; gully expansion and average gully expansion whereas no significant relationships were observed in apex advancement and average apex advancement models.

Factors found to have a direct significant relationship with volume erosion rate include drop height, apex width, gully width, sand content and drainage rate. In contrast, indirect significant relationships with volume erosion rate existed with average drainage basin slope, clay content, silt content, soil organic matter and saturation. Gully expansion rate showed direct significant relationships with drop height, apex width, gully width and drainage rate and indirect significant relationships with average drainage basin slope, clay content, silt content and saturation. Characteristics resulting in direct significant relationships with average gully expansion include apex width, gully width and drainage rate whereas indirect significant relationships existed with average drainage basin slope and clay content characteristics.

Table 5.5: Statistical analysis of headcut characteristics and headcut migration rates. Variables shaded in blue show a significant negative relationship and variables shaded in orange show significant positive relationships.

Volume erosion (m^3/a)				***Gully expansion (m^2/a)***				***Average gully expansion (m^2/a)***				***Apex advancement (m/a)***				***Average apex advancement (m/a)***			
	R	***Sig.***			***R***	***Sig.***			***R***	***Sig.***			***R***	***Sig.***			***R***	***Sig.***	
Drainage basin area	.073	.426	**X**	Drainage basin area	.162	.338	**X**	Drainage basin area	.076	.423	**X**	Drainage basin area	.057	.442	**X**	Drainage basin area	-.045	.454	**X**
Average Drainage basin slope	-.679	.022	←	Average Drainage basin slope	-.806	.004	←	Average Drainage basin slope	-.596	.045	←	Average Drainage basin slope	.121	.378	**X**	Average Drainage basin slope	-.535	.069	**X**
Drop height	.913	.000	←	Drop height	.727	.013	←	Drop height	.325	.196	**X**	Drop height	.325	.197	**X**	Drop height	.091	.408	**X**
Apex width	.859	.001	←	Apex Width	.808	.004	←	Apex Width	.602	.043	←	Apex Width	.330	.193	**X**	Apex Width	.399	.144	**X**
Gully width	.815	.004	←	Gully width	.833	.003	←	Gully width	.628	.035	←	Gully width	.297	.219	**X**	Gully width	.457	.108	**X**
Clay content	-.807	.004	←	Clay content	-.859	.001	←	Clay content	-.658	.027	←	Clay content	-.300	.217	**X**	Clay content	-.523	.074	**X**
Silt content	-.716	.015	←	Silt content	-.647	.030	←	Silt content	-.203	.300	**X**	Silt content	-.197	.306	**X**	Silt content	-.072	.427	**X**
Sand content	.605	.042	←	Sand content	.500	.085	X	Sand content	.010	.490	**X**	Sand content	.336	.189	**X**	Sand content	-.146	.354	**X**
Soil organic matter content	-.682	.022	←	Soil organic matter content	-.559	.059	X	Soil organic matter content	-.412	.135	**X**	Soil organic matter content	-.297	.219	**X**	Soil organic matter content	-.294	.221	**X**
Bulk density	.300	.216	**X**	Bulk density	.158	.342	X	Bulk density	-.014	.486	X	Bulk density	.268	.243	**X**	Bulk density	-.102	.397	**X**
Saturation	-.812	.004	←	Saturation	-.828	.003	←	Saturation	-.538	.068	**X**	Saturation	-.312	.207	**X**	Saturation	-.392	.148	**X**
Drainage Rate	.797	.005	←	Drainage Rate	.831	.003	←	Drainage Rate	.607	.041	←	Drainage Rate	.324	.197	**X**	Drainage Rate	.468	.102	**X**

Chapter 6: Discussion

6.1) Introduction

In this chapter the results will be discussed and associations made with previous research provided in the literature review in an attempt to achieve the objectives set out for this research project. A conceptual model of factors affecting headcut migration rate adapted from literature is presented and discussed. Factors found to influence headcut migration rate in Palmiet wetlands are discussed with reference to literature. Based on the findings of statistical analysis combined with the conceptual model a refined conceptual model of factors influencing headcut migration rate in Palmiet wetlands is presented. Thereafter, the predictive capability of results is discussed and a potential standardized method of measuring gully dimensions is suggested. Furthermore, these findings are discussed in terms of their contribution to wetland management tools such as WET-Health, WET-RehabPlan and WET-Prioritize.

6.2) Conceptual model of headcut migration rate

The conceptual model presented below (Figure 6.1) was created based on the factors found to have a significant statistical relationship with headcut migration rates in Palmiet wetlands within this research project. The factors that were analysed for their potential effects on headcut migration rate and gully erosion are subdivided into three categories, namely topographic, gully structural and land-use / land cover controls and will be discussed in that order. These controls were simplified from the six groups of factors affecting gully erosion according to Vanmaercke et al. (2016) for the purpose of this study.

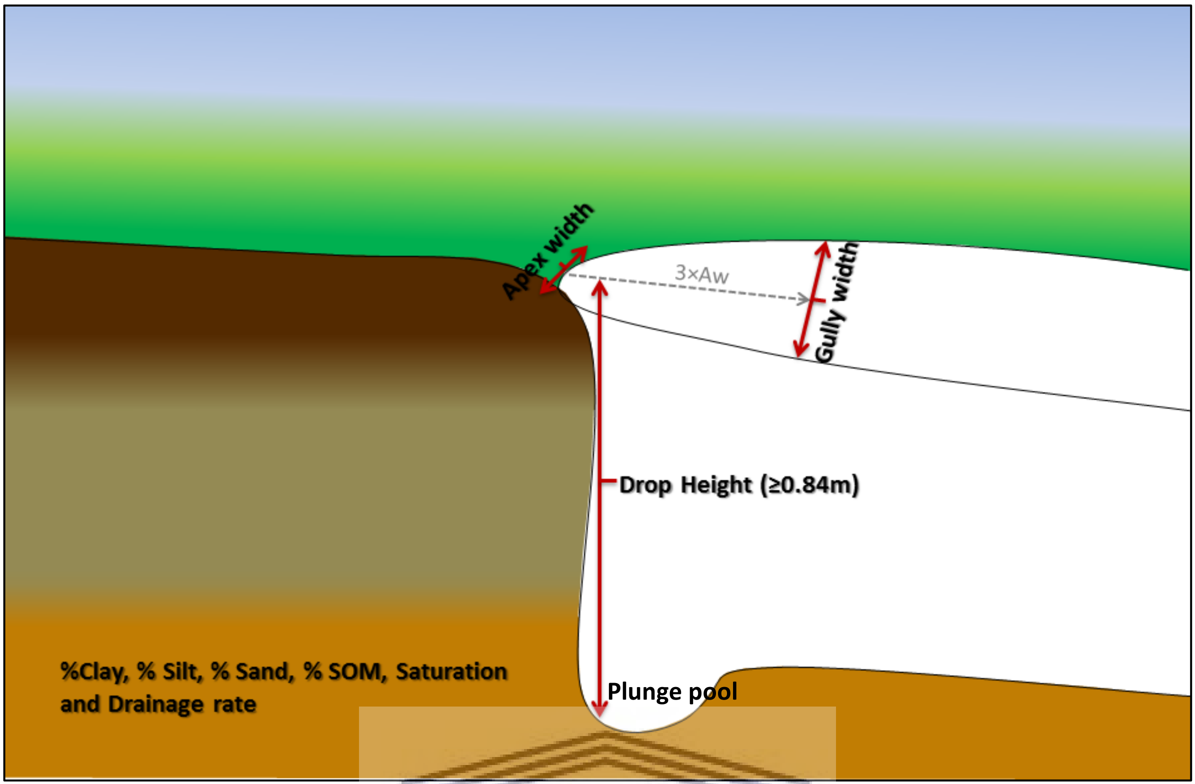

Figure 6.1: Factors; apex width (Aw), gully width, drop height, percentage clay (%Clay), percentage silt (%Silt), percentage sand (%Sand), percentage soil organic matter (%SOM), saturation and drainage rate, affecting headcut migration and gully erosion rates in Palmiet wetlands. Presence of a plunge pool was limited to drop heights ≥0.84m.

6.2.1) Topographic controls

For the purpose of this study, factors assessed under this category include drainage basin area and drainage basin slope as continuous flow monitoring was not possible due to time constraints and the fact that the study area included two catchments which stretched across two provinces. The relationships between these parameters and headcut erosion rates are discussed below in respective order.

i) Drainage basin area

The most widely known and direct factor influencing headcut and gully erosion is overland flow due to the resulting erosive force of water on a soil mass, not overlooking the influence of precipitation on this factor. An extension of this key factor was measured by means of a proxy (in this case drainage basin area) explained by the direct relationship between discharge and area draining into a given headcut or gully. Even though the literature provides strong evidence of the relationship between drainage basin area and gully erosion rate the results of regression analysis presented in the Table 5.5 above show weak and insignificant relationships between all headcut migration types with drainage basin area (Bennett et al., 2000; Burkard and Kostaschuk, 1997; Macfarlane et al., 2009; Sidorchuk et al., 2003; Vandekerckhove et al., 2003; Vanmaercke et al., 2016).

The lack of relationship between these parameters may be attributed to a number of factors. A key factor is the difference in timescale under which this study was investigated as opposed to previous studies. Vandekerckhove et al. (2001b) found that spatial rainfall variation may be responsible for important variation in headcut retreat rate within semi-arid environments. Over longer timescales, spatial variation in rainfall averages out, resulting in a significant relationship between drainage basin area and migration rates. This is not true for shorter timescales as seen in this study. The timescale for this study is relatively short, introducing irregularities of spatial variation in rainfall, resulting in insignificant and possibly false interpretation of the relationships between drainage basin area and migration rates (Vandekerckhove et al., 2001b). Vandekerckhove et al. (2001b) also noted that if gully drainage basins received different amounts of rainfall, the present headcut drainage basin area parameter will not reflect relative differences in runoff volume between sites and the variations in headcut retreat rate cannot be attributed to this parameter (Vandekerckhove et al., 2001b). The fact that average headcut migration rates were measured at varying short time scales (2-6 years) and that study sites investigated in this research project occurred in different provinces and climatic regions further supports the lack of significant relationships between drainage basin area and migration rates.

ii) Drainage basin slope

The results of statistical analysis between measures of erosion rate and watershed slope in this study raise concern as shows a significant negative relationship of slope with volume erosion, gully expansion and average gully expansion (r=-0.679, r=-0.806 and r=-0.596 respectively). This implies that as slope increases a decrease in the rate of the above mentioned headcut migration types will be observed within Palmiet wetlands. This relationship contradicts the literature as an increasing slope is known to result in increased stream power and therefore, increased erosion rate (Macfarlane et al., 2009; Vandekerckhove et al., 2001b). Both Vandekerckhove et al. (2001b) and Vandekerckhove et al. (2000) included the present average slope of drainage basin in linear retreat headcut erosion models as positive significant relationship existed between these parameters (Vandekerckhove et al., 2001b, 2000). The erroneous relationship between headcut erosion rate and slope in this study could be due to the problem of spatial variation in rainfall for different catchments over short timescales. It should also be noted that the relationship between average drainage basin slope and migration rate supported by literature is described in terms of bank gullies whereas this study primarily focuses on headcuts migrating through the valley floor of Palmiet wetlands.

The multitudes of factors that influences flow in a drainage basin and the interrelationships within a drainage basin makes drainage basin slope a poor predictor of erosion rate. Furthermore, the multitude of factors within a drainage basin known to influence flow velocity, such as vegetation cover, surface roughness, channel modification, rainfall amount and intensity, makes drainage basin slope on its own a poor proxy for flow velocity and therefore, a poor predictor of erosion rates. Thus average drainage basin slope cannot be solely relied on to represent the runoff rates and stream power within a given drainage basin.

6.2.2) Gully structural controls

The second category of controls evaluated in this study was structural. This category refers to gully features such as drop height, gully width-depth ratios, tension cracks, groundwater seepage and piping. Furthermore, this category also encompasses finer structural detail such as soil characteristics and stratigraphy. This category of variables displayed the most influence on headcut migration rates measured in this study.

i) Headcut dimensions

Headcut shapes and the process through which they migrate shows similarities with results found by Oostwoud Wijdenes et al. (1999). Headcuts located in the main line of flow were largely controlled by fluvial processes. This can be deduced due to the lack of slumping, producing a gradual transition in shape. It contrasts headcuts that were located further from the main flow path which showed an increasing occurrence of active slumping indicating evidence of migration through mass-wasting producing a more abrupt headcut shape.

Drop height was one of the most important structural factors measured and analysed in this study due to its evident implications for erosion. Drop height showed a significant strong relationship of r=0.913 and r=0.727 with both volume erosion and gully expansion respectively. The significant strong relationship between these erosion types and drop height is an expected phenomenon due to the influence of gravity on water as it flows across the headcut face increasing the velocity of water and therefore, its erosive force (Bennett and Casali, 2001; Stein and Julien, 1993; Stein and LaTray, 2002; Vandekerckhove et al., 2001b). Headcut height can also influence migration rate as increased drop height could allow for deeper tension cracks that destabilize headcuts, increasing the volume of soil lost to erosion (Rengers and Tucker, 2014). Because drop height was used to calculate volume erosion rate, the relationship between these parameters cannot be completely relied upon as the principle of singularity was violated. The significance value of <0.001 indicates a highly significant relationship between volume erosion and drop height. Although some co-linearity exists between variables, it is reasonable to suggest drop height would influence volume erosion rates from a geometric perspective. The significant 0.727 relationship between headcut drop height and gully expansion further supports the notion that headcut drop height does play a physical role in both volume erosion and gully expansion rates. The relationship between drop height and gully expansion was also recognised by Vandekerckhove et al. (2001b), who explained the correlation as a demonstration of the role of energy transfers and undercutting at the headcut (Vandekerckhove et al., 2001b).

Apex width was also found to have a significant positive relationship of r=0.859, r=0.808 and r=0.652 with volume erosion, gully expansion and average gully expansion respectively. This implies an increased apex width results in the increase of the above mentioned headcut erosion rates. This can be understood as an increased apex width would result in an increased area of headcut face being exposed to the erosive forces of flow. This relationship would more significantly affect erosion rates when flow comes into contact with a larger surface area of the less erosion resistant base soil horizon resulting in the undermining of a larger area of erosion resistant top soil horizons, ultimately leading to cantilever failure. The increased loss of stream bed area therefore, leads to an increased loss of volume of soil.

Gully widening is a natural process of channel stabilisation whereby increasing the cross-sectional area is likely to decrease depth, flow velocity and therefore, erosion (Schumm, 1994). Statistical analysis showed a significant positive relationship between gully width and volume erosion (r=0.815), gully expansion rates (r=0.833) and average gully erosion rate (r=0.628). This is due to the fact that gully widening is a product of headcut migration and gully incision (Bennett, 1999a). Gully widening increases with time as gully banks are exposed to natural forces such as gravity, flow, drying (Rengers and Tucker, 2014). Increased gully width also increases the spreading of flow and the area of soil horizons saturated by flow. This results in gully sidewalls slumping leading to gully widening (Kotze and Ellery, 2009; McCloskey et al., 2016). Gully widening consequently increases the area and volume of soil lost to erosion. The relationship between gully width and gully expansion is directly proportional as increasing gully width increases the eroded area. The positive relationship between gully width and volume erosion is indirect due to the fact that eroded area was used when calculating volume erosion during data analysis.

Though apex and gully width showed significant relationships with headcut and gully erosion rates, it should be established that gully widening is a consequence of headcut erosion and thus could explain the significant relationship achieved during analysis (Ellery et al., 2009; Kotze and Ellery, 2009; Schumm, 1994). Through cross-correlation of headcut dimensions, it was found that these parameters co-evolve during erosion, providing justification for significant relationships between these parameters and migration rate. However, gully widening could potentially have an effect on gully erosion as increased gully width increases the amount of flow captured from the surrounding wetland area. This could also be explained by increased discharge observed with increased channel width (Hawley et al., 2013; Nachtergaele et al., 2002; Torri et al., 2006). This two-way interplay therefore, limits the definitive determination of cause and effect, making the classification of apex and gully width as factors affecting gully erosion complex. Based on literature, gully width and depth has been observed to increase with discharge, and therefore, its potential to incise (Nachtergaele et al., 2002; Torri et al., 2006), supporting the observed positive relationship between headcut migration rate and headcut dimensions in this project.

ii) Headcut characteristics

Tension cracks contribute to large erosion volumes through increased slumping and episodic soil fall as they create a preferential vertical flow pathway through the topsoil strata, forcing soil masses away from one another (Bennett, 1999a; Vandekerckhove et al., 2003, 2001b, 2001a). Tension cracks also results in the removal of the soil surface seal, exacerbating erosion rates (Bennett, 1999a, 1999b; Bennett et al., 2000). The effects of this factor were observed in the field at some headcut sites but data was not collected for this parameter in this study. The presence and rate of groundwater seepage and piping both directly increase the rate of erosion as removal or increased saturation of the lower soil horizons increases erosion susceptibility. This leads to the undermining of the overlying soil strata resulting in mass wasting. The qualitative data recorded for groundwater seepage, due to time constraints and lack of appropriate equipment, proved insufficient for identifying trends and relationships between it and other variables measured or calculated. Piping was not prevalent at any of the sites and the collection of jet entry angle data was hindered by no or low flow conditions prevalent during field visits.

iii) Soil composition

Soil characteristics and properties that were identified as having a strong relationship to gully erosion in this project and in literature were soil texture/grain size concentration, organic matter content, soil saturation and drainage rate. A well-known relationship exists between soil characteristics and all forms of erosion based on the cohesive and non-cohesive nature that exists between various soil fractions (Panagiotopoulos et al., 1997; Radoane et al., 1995; Vandekerckhove et al., 2000; Vanmaercke et al., 2016; Zhao et al., 2013). These relationships are confirmed in the results regarding their influence on headcut migration rate. Clay content seemed to be the most impactful soil attribute in erosion as significant negative correlations of r=-0.807, r=-0.859 and r=-0.685 were observed with volume erosion, gully expansion and average gully expansion respectively. This is a result of the cohesive forces that exists between clay sediments controlling a soil horizon's resistance to erosion. A similar relationship occurs between silt content and these erosion rates, with the exception of average gully expansion, as a result of the cementing properties of fine grained sediments. A significant positive correlation was observed between sand content and volume erosion (r=0.605) and negative equivalent relationship between SOM content and volume erosion (r=-0.682). This relationship highlights the influence of the non-cohesive nature and high permeability of sand, which leads to soil fall and headcut retreat (Vandekerckhove et al., 2001b). The evident relationship between SOM and migration rate is explained by increased soil structural stability provided by the organic matter serving as a binding agent between sediments, reducing headcut retreat (Valentin et al., 2005; Vandekerckhove et al., 2001b). The lack of correlation between soil characteristics and average apex advancement was also observed by Vandekerckhove et al. (2003).

Since Palmiet wetlands occur exclusively on lithologies associated with quartzites and sandstones, which, when weathered, produce large volumes of sand, it can be said that Palmiet wetlands are inherently vulnerable to rapid headcut migration from a sedimentary perspective. The subsequent organic matter accumulation after wetland establishment results in the inherent decrease of organic matter along soil profiles with depth, increasing the likelihood of rapid headcut migration through the development of plunge pool erosion undermining basal sand soil horizons.

iv) Soil characteristics

Soil characteristics calculated from soil composition, namely saturation and drainage rate both had significant relationships with headcut migration rates. Soil saturation showed significant negative correlations with both volume erosion and gully erosion (r=-0.812 and r=-0.828 respectively). This indicates an increase in saturation of a soil horizon will decrease the rate of headcut migration. This relationship is supported by the assumption that a higher saturation will require longer exposure to water for the soil horizon to reach a saturated state, after which large scale erosion takes place. Increased pore-water pressure decreasing the effective stress of the soil, which in turn decreases the shear strength and apparent cohesion of soil horizon, is likely to accelerate soil erosion (Chu-Agor et al., 2008; Rengers and Tucker, 2014). Drainage rate was found to have a positive correlation with volume erosion, gully expansion and average gully expansion (r=0.797, r=0.831 and r=0.607 respectively), suggesting that increases in the lowest soil horizon's drainage rate will lead to an increase in erosion rate. This relationship exists due to the fact that drainage rate influences the amount of flow that passes through a soil horizon with time therefore, influencing erosion rate.

Bulk density on the other hand, highlighted in literature for the influence it plays in increasing soil strength and therefore decreasing erosion rate, did not show a significant relationship with erosion rate in this study (Chu-Agor et al., 2009). This could be a result of various factors continuously changing the bulk density of the soil horizon such as flow and groundwater seepage (Chu-Agor et al., 2008; Rengers and Tucker, 2014). These factors alter the soil horizon's original bulk density with time (such as; seasonality, climate variability) resulting in a poor relationship with headcut migration rates. Bulk density did however show an inverse relationship with soil organic matter content. This is an indicator that organic matter content has a direct impact on the bulk density of a soil horizon. This is an expected relationship as it is well known that organic matter increases the porosity and permeability of soil, thus decreasing the resulting bulk density (Arvidsson, 1998).

The identified direct relationship sand content and bulk density and indirect relationship between silt content and bulk density could be explained by the porosity and permeability of a given soil mixture. The porosity of soil influences the potential filling, through translocation, of pore space of a given soil mixture hence influencing bulk density. As increased grain size and increased angularity results in increase pore spaces, sandy soil mixtures more readily allow for the filling of pore spaces, by smaller sediments, as opposed to silt and clay soil mixtures which have less pore space (Bennett and Casali, 2001). The percentage sediment fractions also influence the permeability of a soil mixture, thus having an influence on the rate of translocation of sediments through a soil column. Because porosity and permeability decrease with decreasing soil grain size it also limits the infilling of pore spaces with smaller sediments therefore, leading to decreasing bulk density.

This process may be used to explain the highest bulk density along the headcut face occurring at the middle soil horizons. Due to the occurrence of Palmiet wetlands on sandstone and quartz rich geology, sandy sediments are deposited on the bed as the wetlands establishes. This is followed by the deposition of progressively finer material due to decreased flow velocity associated with the diffuse flow of naturally vegetated wetland flow paths increasing friction. These finer particles percolate and translocate down into the pores of sand sediments eventually filling pore spaces restricting further percolation into lower soil horizons (Figure 6.2). The process therefore, results in sandy soils at the base soil horizon followed by a mixture of sandy and silty sediments with a higher bulk density in the middle soil horizon and more silty soils near the top of the soil profile.

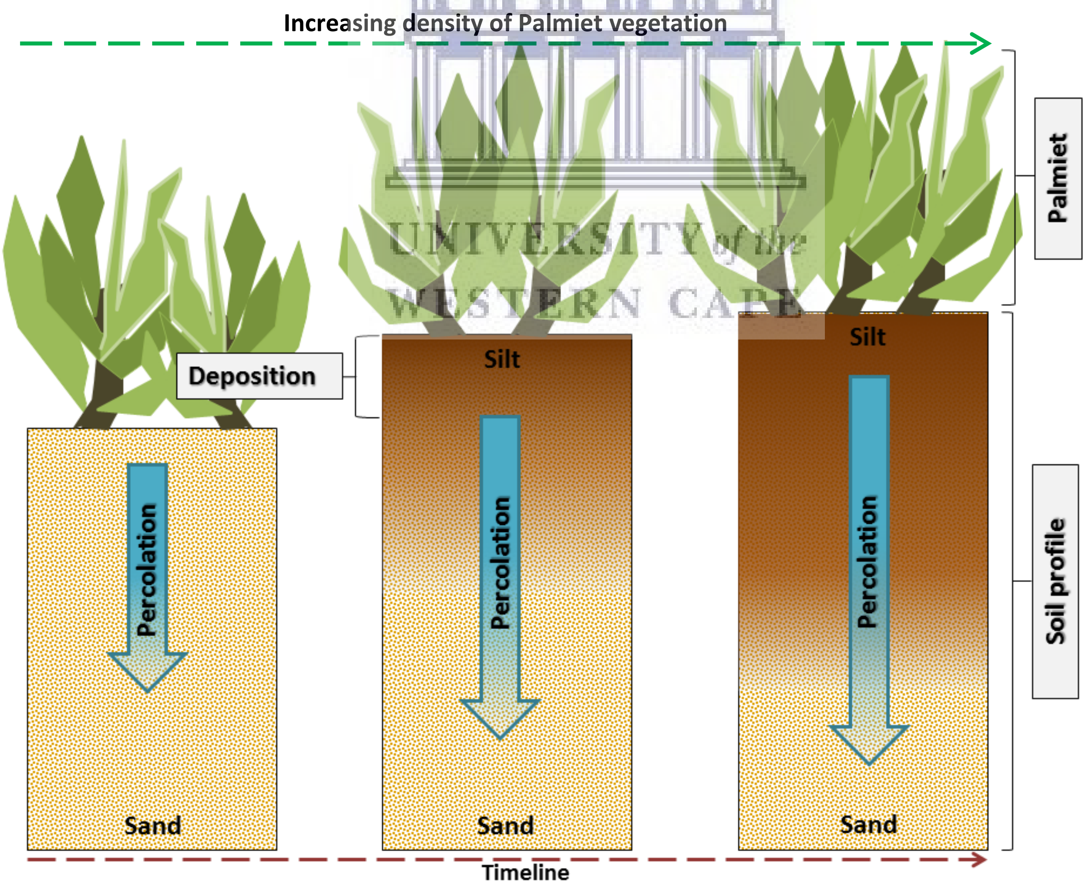

Figure 6.2: Process of Palmiet wetland formation and subsequent percolation and sediment translocation subsequently affecting soil profile bulk density.

6.2.3) Land-use and land-cover controls

Lastly, land-use is known to have a considerable influence on erosion rate due to its direct effect on infiltration rate, runoff and flow. Land-cover also affects soil's vulnerability to erosion. Crucial land-cover factors include vegetation density, root depth and flexibility. The presence of vegetation along a gully bed affects erosion rates but is also an indicator of the stage of gully erosion. This was the only land-use and land-cover factor measured in the field and was limited to the presence or absence of vegetation resulting in the exclusion of this factor in statistical analysis.

The qualitative data collected displayed identifiable trends with gully widths. The presence of vegetation was limited to gully beds with an apex width and gully width of ≥1 m. This is an expected phenomenon due to the stages of gully evolution where in gullies only begin stabilizing and therefore, allowing vegetation re-establishment, after gully widening has taken place (Ellery et al., 2009). Gullies below this threshold, namely UWC6 and UWC7, also showed little to no change in width from the apex to the point where gully width was measured, indicating that the gully was still in the early stages of evolution; namely incision. The re-establishment of vegetation in a gully is the final stage of gully evolution, occurring after the aggradation of sediments on the gully bed, as depicted in Figure 2.2 (Ellery et al., 2009; Schumm, 1994), thus explaining the lack of vegetation in UWC6 and UWC7. The evident relationship between gully width and the presence of gully vegetation could also be affected by increased flow concentration in narrower gullies, preventing vegetation or seeds from settling and anchoring in the gully bed.

6.3) Predictive capability and threshold determination

The data gathered and produced in the research project shows potential for predictive capability and some (although limited) promise for drainage basin area threshold determination. However, the biggest constraint is an insufficient sample size, limiting the generalization of its predictive capabilities. However, based on the limited number of Palmiet wetlands in South Africa, it is assumed that though the sample size included in this study is small, it probably represents quite a large portion of the overall statistical population. Based on the significant results of multiple regression analysis between gully retreat rate and morphodynamic characteristics, the formulation of a predictive equation is possible but additional characteristics are necessary in order to account for changes in the environmental setting. Additional characteristics such as hydrologic setting, roughness, vegetation type and root depth, could broaden the potential predictive capabilities to account for variation in environmental settings beyond just Palmiet wetlands. For the purpose of expansion and generalization it would be necessary to establish standardised measuring methods of characteristics, including plunge pool metrics that are independent of hydrology, to ensure that data collected from various sites are homogenous, thus limiting the influence of human error.

Threshold drainage area determination conducted by Crosby and Whipple (2006) provides a basis for improvement of the current study. Establishing gully threshold drainage area will allow geomorphologists to determine the maximum extent of a headcut's retreat and from that it may be possible to estimate the time it would take to reach that point. This would allow for informed and timely wetland restoration. The drainage areas of headcuts observed in this study largely fell in between a range of 1.19×10^5 m^2 and 6.52×10^5 m^2 with the exception of the UWC2, which had a contributing drainage area of 4.19×10^7 m^2. This drainage area outlier is attributed to the fact that UWC2 was located along the main flow path, extending the drainage area all the way up to the headwaters of the Kromme River drainage basin. These drainage area results, apart from UWC2, fall within the drainage area range established by Crosby and Whipple (2006) who found that approximately 70% of headcut site drainage areas fell between a range of 1×10^5 m^2 and 1×10^6 m^2 (Crosby and Whipple, 2006). Though the studies vary in geologic setting (i.e. bedrock retreat and alluvial retreat), a noticeable trend exists, indicating the potential to explore in greater detail the concept of a threshold drainage area. As with the predictive capability, threshold determination would require an increased sample size and also require the incorporation of spatial rainfall pattern products, such as Climate Hazards Group Infra-Red Precipitation with Stations data (CHIRPS), in order to make more conclusive arguments.

6.4) Standardised method for measuring gully-head characteristics

The formulation of a standardised method for measuring headcut characteristics will ensure that further research into the topic and expansion of the study sample size will be aligned. This is an important step in investigating any earth system process as it provides an initial guideline for use by researchers in the field and an improved method can be devised from it. The standardised measuring method recommended is largely the one used in this research project with a few improvements that were recognized in hindsight. Drop height being a common and straight forward characteristic measured in field requires minimal explanation. This characteristic is measured at the point of the headcut apex where active flow seems prevalent. This is necessary as the erosive force of water results in scouring of the headcut base/plunge pool, increasing the headcut height. Apex width on the other hand is less well-defined than drop height; generally apex width refers to the width of the drainage accumulation outlet measured along the apex of the gully head from gully side wall to gully side wall. Apex width was in this case a linear measurement of the gully head apex that received active flow. However, due to the variability of active flows with seasonality, the apex width was retrieved by measuring the length of the gully head that stretched perpendicular to flow. Gully width, which is generally measured as an average of total gully width, was in this study measured at a point 3 times the length of the apex width. This provides a more site specific measurement of a gully width, and also provides insight on the progression of gully widening. Plunge pool depth measurement was largely excluded in the analysis of this study due to the lack of an appropriate standardised measuring method. The key discrepancy highlighted in this study was the fact that plunge pool depth was recorded as the depth of water in the plunge pool. Given the influence of seasonality on this measurement, it is recommended that plunge pool depth should be measured from a detailed longitudinal profile through the gully thalweg, starting from above the gully head to well beyond the headcut base. This will allow for a detailed analysis of longitudinal change in elevation, allowing for a clear representation of the plunge pool depth with reference to elevation in the gully bed not based simply on water depth.

6.5) Contribution to wetland management tools

The results of this study are of scientific importance as they broaden the knowledge base of the process of headcut retreat in general, and more specifically, aid in understanding and identifying controls that influence the process in a wetland setting. Additionally, the results can inform various wetland management tools such as WET-Health, WET-Prioritise and

WET-RehabPlan. WET-management tools were designed specifically for the use and evaluation of wetlands in South Africa. WET-Health is a management tool used to examine the overall health of an entire wetland using indicators based on geomorphology, hydrology and vegetation (Macfarlane et al., 2009). WET-Prioritise is a tool that was developed to identify where rehabilitation should occur once the objectives of rehabilitation are identified. It works at a national and provincial level. An interactive GIS modelling tool assists in identifying priority catchments by evaluating a range of scenarios, based on combinations of socio-economic and bio-physical criteria (Rountree et al., 2009). WET-RehabPlan on the other hand is a tool designed to assist in undertaking well-planned and well-informed wetland rehabilitation that is integrated into the broader management of the wetland and catchment, and which produces sustainable outcomes (Kotze et al., 2009).

6.5.1) WET-Health

The data generated in this study allows for an evaluation of the extent to which WET-Health captures geomorphologic controls. For the purpose of evaluation, the data collected at each site were used to complete the "Intensity and magnitude of impact of erosional features" tool, within WET-Health, producing a "scaled intensity of impact score" for each headcut (Table 6.1). This data coupled with the headcut migration rate dataset was then statistically analysed through the use of correlation analysis. Results showed significant positive relationships between the scaled intensity of impact score and gully expansion rate (ρ=0.034), significant positive relationship with volume erosion rate (ρ= 0.045) and a positive correlation with apex advancement (ρ=0.406) however, insignificant (Table 6.2). The identifiable significant positive correlation that exists between these parameters provides a validation to the adequacy of the WET-Health tool for capturing geomorphic controls. It also provides insight into which headcut migration rate type is most adequately captured by the 'Scaled intensity of impact score tool', represented in WET-Health, which has been identified as gully expansion with an r=0.7 and a significance of 0.034. The correlation coefficients can also substantiate the use of scaled intensity impact score as an indicator for the erosion rate of a specific gully head, providing a rapid infield assessment identifying which headcuts have been migrating at the fastest rate.

Table 6.1: Intensity and magnitude of impact of erosional features. The scores for rows 2 and 3 are unscaled for any natural recovery that may have taken place. Factors to use to scale the intensity of impact of erosional features for natural recovery are presented in rows 7 and 8 (Macfarlane et al., 2009).

Factor	2	4	6	8	10	Unscaled Score
Mean depth of gullies[F]	<0.50 m	0.50-1.00 m	1.01-2.00 m	2.00-3.00 m	>3.00 m	
Mean width of gullies[F]	<2 m	2-5 m	5.1-8 m	8.1-16 m	>16 m	
Number of headcuts present[F]	1	2	3	4	>4	
Unscaled intensity of impact score: mean score of above 3 rows						
Scaling factor	**0.4**	**0.5**	**0.7**	**0.9**	**1.0**	**Factor**
Extent to which sediment from the gully is deposited within the HGM or wetland downstream of the HGM unit (as opposed to being exported)[F]	Entirely deposited	Mainly deposited	Intermediate	Mainly exported	Entirely exported	
Extent to which the bed and sides of the gully have been colonized by vegetation and/or show signs of natural recovery[F]	Complete	High	Moderate	Low	None	
Scaling factor score: mean of above 2 rows (value is between 0 and 1)						
Scaled intensity of impact score = unscaled intensity of impact score x scaling factor score						

Table 6.2: Correlation analysis between WET-Health scaled intensity of impact score and headcut migration rates

	Scaled intensity of impact score	Significance
Volume erosion (m^3/a)	0.68	0.045
Gully expansion (m^2/a)	0.70	0.034
Apex advancement (m/a)	0.32	0.406

6.5.2) WET-Prioritise and WET-RehabPlan

When wetland rehabilitation is required, practitioners take into account aspects of hydrology, geomorphology and vegetation. Wetland degradation can take effect on one or more of these controls, often followed by degradation of the other components as they are all interlinked. Through the establishment of factors that influence headcut migration rate and the relationship between these factors and headcut migration rate, the results of this research project provides insight into wetland rehabilitation planning and can therefore, expand wetland management tools such as WET-RehabPlan and WET-Prioritise. WET-Prioritise provide an understanding of which wetlands should undergo rehabilitation based on wetland rarity and biodiversity. This is an important tool used in limiting wetland degradation a tertiary catchment level, than a quaternary catchment level and lastly at a wetland cluster level. A key limitation to this tool is the lack of resources for the collection of large quantities of data required to make wetland rehabilitation prioritisation decisions at a quaternary sub-catchment scale. This has led to prioritisation of wetlands based on existing knowledge and priorities of stakeholders (Rountree et al., 2009). This research project can potentially address the scale issue of wetland prioritisation in terms of a geomorphology aspect as headcut characteristics identified to influence migration rate (i.e. average drainage basin slope, drop height, apex width, gully width, sand, silt, clay and organic matter content) can be used by wetland conservation practitioners to identify which headcuts are most likely to migrate at a faster rate. By identifying headcuts that are most susceptible to rapid erosion rates practitioners will have insight into the urgency of wetland restoration interventions based on potential headcut migration within the wetland. This will decrease the rate of net wetland degradation and improve the management and efficiency of wetland restoration. Ultimately this provides guidance on the prioritisation of each wetland rehabilitation intervention addressing the issue of wetland prioritisation at a finer scale.

Furthermore, the regression analysis results allow one to improve rehabilitation planning. The characteristics of headcuts identified to influence headcut migration rate most in Palmiet wetlands adds to WET-RehabPlan when deciding which rehabilitation intervention is most appropriate for a given site. In understanding the influencing factors of headcut erosion, wetland rehabilitation practitioners would have a better background when deciding which restoration structures are most suitable. This has the potential to improve intervention structures, their success and therefore, their sustainability. In the end successful and sustainable intervention limits resource expenditure, allowing for the implementation of more restoration intervention, improving wetland conservation efforts.

Chapter 7: Conclusion

The study showed that morphodynamic characteristics of gully-heads and catchment characteristics do have an influence on headcut migration rates in Palmiet wetlands. Gully characteristics identified to influence headcut migration rates were drop height, apex width, gully width, clay content, silt content, sand content, SOM, saturation and drainage rate. Each of these characteristics were found to influence volume erosion, gully expansion rate and/or average gully expansion rate. However, none of the evaluated characteristics showed a significant relationship with apex advancement rates. The study further showed an association between gully dimensions, indicating that gully head dimensions co-evolve during the process of erosion, not necessarily proving a cause and effect. These relationships support the process of gully evolution established by Ellery et al. (2009) and Schumm (1994). The occurrence of increased grain size with depth in Palmiet peat forming wetlands was found to have a strong influence on the formation and further development of headcuts. The characteristics of the lowest soil horizon largely influenced migration rate as the process of plunge pool erosion resulted in undermining and subsequent slumping of overlying soil horizons, leading to rapid headcut migration rates.

The confined occurrence of Palmiet wetlands on TMG quartzitic sandstone and the natural process of Palmiet wetlands establishment, which leads to grain size sorting vertically in the soil profile, make it evident that these wetlands are inherently susceptible to headcut erosion from a structural perspective. Moreover the fact that Palmiet wetlands commonly occur in upper catchment agricultural areas characterized by high flow concentration and land-use/land-cover change makes wetland restoration and rehabilitation interventions almost unavoidable. Together these factors make Palmiet wetland conservation a formidable task. The findings of the current study aid this dilemma as they provide a means for the assessment of the efficacy of wetlands management tools such as WET-Health, and they furthermore, provide guidance on gully characteristic quantification and wetland management that may aid tools such as WET-RehabPlan and WET-Prioritize.

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Appendix

Appendices 1.1: Headcut site locations

Site code	Farm name	GPS co-ordinates
UWC1	Krugersland	33°52'10.02"S 24°1'17.616"E
UWC2	Krugersland	33°52'8.832"S 24°1'18.264"E
UWC3	Krugersland	33°52'9.66"S 24°1'18.876"E
UWC4	Krugersland	33°52'8.22"S 24°1'19.344"E
UWC5	Krugersland	33°52'8.04"S 24°1'19.668"E
UWC6	Krugersland	33°52'7.536"S 24°1'18.048"E
UWC7	Krugersland	33°52'7.392"S 24°1'18.084"E
UWC8	Krugersland	33°52'9.624"S 24°1'25.32"E
ENV1	Eenvoud	34°29'13.34"S 19°45'0.07"E
ENV2	Eenvoud	34°29'16.87"S 19°45'4.03"E
PSK1	Kersgat	34°33'32.50"S 19°48'33.60"E
PSK2	Kersgat	34°33'28.73"S 19°48'33.60"E
KTK6	Haze Vlakte	34˚34'30.6"S 019˚52'17.4"E
KTK6.1	Haze Vlakte	34˚34'30.8"S 019˚52'17.6"E
JSK	Akkerdrift	34˚30'53.9"S 019˚43'41.6"E

Appendices 1.2: Infield tools and equipment

- Differential Geographic Positioning System (DGPS)
- Garmin GPS
- Marker pegs
- Measuring tape and rod
- Electromagnetic Flow Meter (EFM)
- Soil sampler (100cc)
- Custom field assessment