THE REGENERATION OF PALMIET (PRIONIUM SERRATUM) FOLLOWING HYDROGEOMORPHIC DISTURBANCE: A CASE STUDY OF THE KROMME RIVER WETLAND

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PREFACE

The research within this thesis was carried out at the Department of Geography of Rhodes University, Makhanda, under the supervision of Professor W. N. Ellery. This research represents the original work by the author. Where use has been made of the work of others it is duly acknowledged in the text.

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ABSTRACT

The Kromme River wetland in the Eastern Cape of South Africa occupies a broad valley (up to 350 m wide) with a gentle longitudinal slope of less than 2 % that has been formed by cut-and-fill cycles that are initiated by trunk-tributary interactions. These hydrogeomorphic disturbance events trigger gully erosion and generate sediments, the coarse fraction of which is deposited less than 2 km downstream, leading to depositional floodout features that fill gullies headwards. This process has been occurring at intervals for at least 10 000 years, and as such pre-dates the introduction of European farming practices in the area. Plants that regenerate by colonising these features are thought to have evolved adaptions necessary to colonise intermittently produced bare sandy sediments.

This study aimed to examine the regeneration ecology of palmiet (*Prionium serratum)*, the dominant vegetation community within these cut-and-fill wetlands, by relating its regeneration characteristics to environmental factors in a reach of the Kromme River wetland that has experienced a recent hydrogeomorphic disturbance event (approximately 10 years before the commencement of this study). Palmiet was found to be regenerating on sedimentary deposits on beds of gullies and on depositional bars on the margins of gully beds. The large depositional floodout downstream of a large gully also favoured palmiet regeneration, where it was found to be regenerating along not only the active channel, but also along old abandoned flow paths and sometimes areas well elevated above the channel. The geomorphic features that favoured palmiet regeneration were characterised by coarse-grained sediments (mean particle size approximately 310 µm) with low organic matter content (0.61 %), a low depth to the water table and low elevation above the thalweg (mean depth to water table is approximately 0.6 m), and a relatively close distance to the thalweg (< 10 m).

This understanding of palmiet's regeneration characteristics was viewed in relation to existing literature on undisturbed palmiet wetland plant communities and its reported contribution to conditions that favour wetland formation through gully filling, which allowed for the creation of a conceptual model of palmiet regeneration, colonisation and long-term persistence. This model was based on the Fluvial Biogeomorphic Succession concept. It suggests that palmiet's interaction with the hydrogeomorphic environment throughout the different stages of its life cycle results in self-organising biogeomorphic landforms. Over hundreds of years, the reciprocal interactions between palmiet, sediments and water, fills gullies and restores valley bottoms, ultimately leading to the formation of a wetland landform. It is further proposed that through continued accretion, the geomorphic wetland landscape becomes more and more disconnected from the hydrogeomorphic dynamics of the fluvial system, such that the prevailing conditions begin to favour fynbos establishment, which may outcompete palmiet.

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LIST OF ABBREVIATIONS

General

AES - African Erosion Surface
BP - Before present
FBS - Fluvial Biogeomorphic Succession
Masl - Metres above sea level
MRT - Multiple range test
Mya - Million years ago
PAES1 - Post-Africa Erosion Surface 1
PAES2 - Post-Africa Erosion Surface 2
RDA - Redundancy analysis
Vs - Versus

Palmiet life history classes and the non-palmiet class

Regen - Regenerating class of juvenile palmiet
Pers - Persisting class of adult palmiet rooted 1.5 m above water table
NPal - Non-palmiet class
Stable - Stable class of adult palmiet rooted less than 0.5 m above water table

Geomorphic disturbance classes

GBar - Gully bar
GBed - Gully bed
FOut - Floodout
RVBot - Remnant valley bottom
VBot - Valley bottom

Environmental variables

DTha - Distance from the thalweg
DWTa - Depth to the water table
FDep - Flood depth
OMat - Organic matter
REle - Relative elevation
SPwr - Stream power
PSiz - Particle size
Vel - Velocity

1. INTRODUCTION

Gosselink and Turner's (1978) model of wetland formation is the most widely accepted model describing wetland formation and factors that influence wetland structure and functioning. In the model, the hydrological regime is suggested to be the main driver of wetland formation, structure and function. Flooding of the soil results in anaerobic conditions that are stressful to organisms that are rooted or live in the soil, because in these conditions, only plants and animals that are tolerant of flooded soils and the accompanying anaerobic conditions can survive.

Given this, wetlands have three characteristics: 1) the water table is within 0.5 m of the wetland surface, or the water can be above the surface; 2) biogeochemical reactions that occur when soils are flooded results in dissolution of metals that are leached from the soil profile, giving wetland soils a distinctive morphology; and 3) wetlands can only support plants and animals suited to the saturated conditions (Gosselink and Turner, 1978; Mitsch and Gosselink, 2015).

The Gosselink and Turner (1978) model is the basis for wetland restoration initiatives in South Africa and around the world (Russell, 2009). Any event in a wetland that alters the hydrological regime is thus viewed as detrimental and the work of wetland restoration is to repair such perturbations. Gully erosion leads to local entrainment of flow and therefore the wetland adjacent to the gully dries out. Restoration efforts will therefore stabilise the gully by construction of a weir, and the design will typically attempt to control flow over the head of the gully, thereby halting its progression upstream (Russell, 2009).

While Gosselink and Turner's (1978) model is highly applicable to wetlands in the northern hemisphere, where the climatic conditions result in a positive water balance, southern Africa's negative water balance and highly elevated land surface results in most wetlands forming along fluvial systems (McCarthy and Rubidge, 2005; Ellery *et al*., 2009). Given this, fluvial geomorphology is seen as central to wetland formation and dynamics. This has led many wetland scientists to adopt a hydrogeomorphic approach to understanding wetland formation and change (Longmore, 2001).

Over the past 100 million years, the southern African subcontinent has been undergoing morphological changes associated with prolonged weathering and erosion to produce the African Erosion Surface (AES), which is an ancient land surface that formed following the breakup of Gondwanaland. By the end of the Cretaceous (about 60 million years ago), during which time the subcontinent was equatorial with a warm and wet climate associated with deep weathering and erosion, the average altitude of the subcontinent was approximately 300 to 400 m (Maud, 2012). Over the last 20 million years, two isostatic uplift events caused the continent to rise over 1000 m in the east and 300 m in the west. This resulted in the rejuvenation of rivers and the formation of the Post-

Africa Erosion Surface 1 (PAES1) and the Post-Africa Erosion Surface 2 (PAES2). This means that presently the subcontinent is dominated by erosion, which is gradually lowering the elevation of the subcontinent. However, there are areas above the AES, such as the Cape Fold Mountains and the Great Escarpment, which occur inland and sub-parallel with the coastline. Although situated in a valley at the foot of the Cape Fold Mountains, the Kromme River wetland occurs below the AES and is likely to be working to lower its bed over time through erosion.

Job (2014) and Rebelo (2017) suggest that anthropogenic factors are likely responsible for accelerated erosion in recent times through changes in land use related to agriculture and the construction of roads. However, in the Kromme wetland in South Africa, Lagesse (2017), McNamara (2018) and Pulley *et al.* (2018) found that natural cycles of erosion and deposition resulted in the formation of a broad valley-bottom wetland dominated by palmiet. Given the steep-sided catchment slopes and the very low-sloping trunk valley floor, delivery of sediments by tributaries results in depositional alluvial fans that impinge the trunk valley. The effects of tributary alluvial fans encroaching on the trunk stream alters the local hydrodynamics to such an extent that cut-and-fill cycles are initiated, whereby gullies are thought to be initiated and erode headward up the trunk valley (Pulley *et al.,* 2018). Such erosion is natural and has been happening repeatedly in the Kromme River wetland over thousands of years. The sediment generated from these disturbance events is deposited at the toe of the gully, creating coarse-grained depositional fan-like features that spread out across the valley and gradually fill the gully headwards. These repeated cycles of cutting and filling have lowered the longitudinal slope of the valley to less than 2% and planed the valley to form a broad near-horizontal valley floor across the trunk valley (Langer*,* 2018; Pulley *et al.,* 2018).

These disturbance events, whether due to natural or anthropogenic factors, result in the removal of biomass and the exposure of bare sediment by erosion and deposition, creating niches suited to regeneration by ruderal species (the regeneration niche; Grubb, 1977). Following the dispersal of propagules, plants vary in their ability to colonise bare sediment that is exposed by erosion and deposition because of natural variation in regeneration strategies such as vegetative versus sexual reproduction, seed number, seed size and dispersal mechanism (MacDonald, 2003).

MacArthur and Wilson (1967) suggested that organisms such as plants have characteristics of being r- or K-strategists. Plants that rapidly colonise recently exposed sediments typically produce a large number of very small seeds such that when suitable conditions appear, a small number are likely to establish. Such plant traits are considered typical of r-strategists that are well suited to rapidly colonise recently disturbed areas (MacArthur and Wilson, 1967; Begon *et al.,* 2006). Such species have fast growth rates and are usually the first to colonise and exploit opportunities created by disturbance events. In contrast, those species that inhabit sites that remain stable for long periods typically have slow growth rates, are strongly competitive, and produce a small number of large seeds that have a high chance of survival. Such species are considered K-strategists that have populations close to the carrying capacity (MacArthur and Wilson, 1967; Begon *et al.,* 2006). Such species are well suited to environments that are infrequently disturbed.

The establishment of a single propagule can result in the re-establishment of a reproducing population via vegetative growth (MacDonald, 2003). Vegetative growth is an important characteristic that allows for the maintenance of species in areas that are frequently disturbed (Bellingham and Sparrow, 2000; Bornette *et al*., 2008). Clonal growth after disturbances is typically associated with deeply anchored roots or rhizomes growing outwards from refuges, or even resprouting from vegetative propagules (Prach and Pysek, 1994; Bornette *et al*., 2008). Given this, it is clear that traits from both sexual reproduction as well as vegetative growth vary in their suitability in the recolonisation of patches created by disturbance events (Bornette *et al*., 2008).

Plants that colonise areas prone to disturbance have evolved the necessary adaptive traits to persist in these environments (Corenblit *et al.*, 2007; 2015). These traits are thought to have biomechanical effects which affect the hydrogeomorphic functioning of the fluvial system in which they grow (Corenblit *et al.*, 2007; 2015). These morphological adaptations alter the hydrological setting by increasing the overall roughness and by offering mechanical and flow resistance to riverbeds and banks as well as floodplain surfaces (Hupp, 1992). As a result, plants growing along river corridors often trap sediment along channels and on the floodplain, as well as initiating and stabilising islands or depositional bars with their below- and above-ground adaptations (Page and Nanson, 1982; Gurnell *et al.,* 2001; Gurnell, 2014). These plants are known as ecosystem engineers due to the way in which they are able to modulate the flow of resources in an ecosystem (Jones *et al.,* 1994).

Corenblit *et al.* (2007; 2015) observed how self-organising biogeomorphic landforms along fluvial corridors in the northern hemisphere developed as a result of the reciprocal interactions between engineering vegetation, sediment and water. In order to describe co-evolutionary processes between fluvial landforms and the vegetation communities, Corenblit *et al.* (2007) developed the Fluvial Biogeomorphic Succession (FBS) concept. Following disturbance, a “geomorphic phase” is initiated that is characterised by depositional features that provide bare patches suited to vegetation regeneration. The “pioneer phase” sees pioneer plant recruitment occurring in areas that are still prone to hydrogeomorphic disturbance. Following this, the “biogeomorphic phase” occurs where vegetation begins to interact with the hydrogeomorphic environment such that vegetation, sediment and water build up a landform and a later stage of vegetation succession begins. As this happens, the landform becomes more and more disconnected from the hydrological disturbance regime, and an “ecological phase” occurs where autogenic processes drive succession.

Palmiet (*Prionium serratum*) is a robust hydrophyte that grows in saturated environments such as wetlands. It is somewhat enigmatic as it is found to grow in areas of recent disturbance (Barclay, 2016; Jarvis, 2020) but also dominates areas that have not been disturbed for decades. It flowers during spring and summer, with fruit being produced from November to March (Boucher and Withers, 2004; Rebelo *et al.,* 2020). It forms dense stands with a dense root, rhizome and stem system, and is found to grow from islands and banks into flowing waters (Barclay, 2017). Boucher and Withers (2004), Barclay (2016), Gull (2012), and Job (2014) note that palmiet is able to tolerate large floods as its robust stem (10 cm diameter) is encased by old leaf bases, protecting tissue in the stem from flow and abrasion related to rapidly flowing water and moving sediment, and also because of the high flexibility of its stems that bend in the direction of the prevailing flow. The flexibility of stems means that banks and stream beds covered by palmiet withstand flows that would otherwise be erosional (Barclay, 2016). Palmiet is viewed as an ecosystem engineer due to the way in which it alters the hydrogeomorphic dynamics of the rivers in which it grows. It is viewed as a nuisance plant by landowners as it blocks rivers and it is thought to deplete water resources through its high use of water (Rebelo, 2012). Palmiet is often removed in order to use the cleared floodplain as agricultural land (Rebelo, 2012).

The aim of this study is to identify palmiet regeneration characteristics, along with the conditions that favour its regeneration. While it seems to favour areas of recent disturbances, which suggests that it is a pioneer species (Barclay, 2016; Jarvis, 2020), not much else is known about the environmental conditions that best favour regeneration. Evidence suggests that palmiet colonises large valley-bottom areas covered with a depositional feature, the beds of gullies recently filled with coarse clastic sediment, as well as the banks of open bodies of water (Barclay, 2016). However, there is little understanding of the local environmental conditions that favour its establishment following disturbance events. Further investigation would stimulate understanding of palmiet's requirements for regeneration, thereby promoting restoration that mimics natural processes.

In addition, palmiet is thought to be an ecosystem engineer that directly contributes to wetland formation through the way in which it interacts with the hydrogeomorphic dynamics of the fluvial systems wherein it grows (Job, 2014; Barclay, 2016). Since most wetlands form through fluvial geomorphic processes in the southern African region, this study provides an opportunity to examine palmiet's regeneration characteristics through the lens of the FBS framework of Corenblit *et al.* (2007). While the concept largely applies to rivers that are dominated by deposition, such as those in the northern hemisphere, it will be applied and examined with the southern African context in mind, where rivers are generally erosional, with the Kromme River wetland being used as a case study.

1.1. Aim and objectives

1.1.1. Aim

This study aims to develop an understanding of the environmental characteristics that favour palmiet regeneration throughout the Kromme River wetland and to explore its regeneration within the context of the Fluvial Biogeomorphic Succession (FBS) model.

1.1.2. Objectives

1) To map the distribution of palmiet in areas of recent disturbance.
2) To determine environmental conditions in areas of palmiet establishment, including factors such as elevation and depth to the water table, as well as substrate characteristics.
3) To relate sites of palmiet regeneration to hydraulic factors, including stream velocity, unit valley stream power, and flood depth.
4) To create a unifying conceptual model of palmiet regeneration within the Kromme River wetland based on the environmental conditions that favour its establishment and regeneration characteristics.

2. LITERATURE REVIEW

2.1. Introduction

Southern Africa's landscape is one that is characterised by a higher than usual elevation as a result of uplift events over the last 20 to 30 million years. These uplift events rejuvenated rivers, meaning that most rivers are actively incising as they work towards an appropriate slope to accommodate discharge. Erosion such as this (at a subcontinental scale) is a mixed blessing for wetlands, given that where valleys rapidly degrade (the surface of the valley floor is rapidly lowered), wetlands degrade (Ellery *et al.*, 2009). However, where highly erosion-resistant lithologies occur across eroding watercourses, valley degradation is very slow and valleys widen as lateral erosion becomes a dominant process. As a result of the country's low rainfall and high evapotranspiration rates, most of South Africa's wetlands occur along fluvial systems (Ellery *et al.,* 2009).

The Kromme River wetland is one such wetland that has formed through fluvial geomorphic processes, making it prone to episodic geomorphic disturbances through erosion and deposition. It is one of many palmiet wetlands that are found across an erosional landscape within the southern Cape and southern Kwazulu-Natal regions, where they occupy mountainous landscapes within valleys incised into the African Erosion Surface. These landscapes mean that only plants with appropriate adaptations to infrequent geomorphic disturbances (hundreds of years; Pulley *et al.*, 2018) will be able to regenerate and survive in these environments. These adaptations can have important implications for wetland formation processes through their interaction with water and sediment.

2.2. Plant regeneration and growth in fluvial wetland environments

Plants linked to fluvial wetland systems vary in their ability to colonise newly created patches through disturbance. For plants to establish and colonise bare sediment, they need to be adapted in their regeneration phase to grow in these environmental conditions. Some plants have evolved adaptations to exploit opportunities created by hydrogeomorphic disturbance.

2.2.1. The regeneration niche

The regeneration niche can be defined as a plant species' biotic and abiotic requirements to replace individuals that are in the mature phase of their life cycle or to colonise newly exposed surfaces where adult populations have been destroyed by a disturbance event (Grubb, 1977). It is considered to describe the environmental conditions most suited to the establishment of plant communities in their early life stages. Disturbance events result in gap formation, which are areas free of competition, allowing for the successful exploitation by opportunistic plants (Bullock, 2000). Any given plant species' 1) seed production, 2) dispersal abilities, 3) requirements for germination, 4) requirements for successful seedling establishment, and 5) requirements for further development, requires that all factors that determine the degree of success to which plants will be able to colonise gaps are satisfied (Grubb, 1977; Bullock, 2000). Plants have developed a variety of strategies to exploit the regeneration niches that are created as a result of disturbance, thus ensuring their own persistence.

2.2.2. Life history characteristics of fluvial wetland plants in relation to disturbance

During events that threaten the survival of animals and plants, animals are able to migrate, while plants are unable to do so other than through propagule dispersal (Walbot, 1985). Given this, plants need to make the necessary adaptations in order to survive stressful situations such as those created by large disturbance events (Walbot, 1985). While changes in the short term (seconds to days) allow the population to cope with immediate threats, the survival of at least one generation until the next disturbance event can lead to plants making the necessary adaptations that allow them to better withstand hostile environments created by large disturbance events (Walbot, 1985).

In any fluvial ecosystem, duration, magnitude, timing, frequency and the rate of change of flow events are recognised as being key hydrological components that can result in the alteration of the structure and overall functioning of the ecosystem (Poff *et al.*, 1997). The physical, abiotic habitat, is considered a template whereupon the dynamics of any given ecosystem and its accompanying ecological organisations can be observed (Townsend and Hildrew, 1994; Harper and Everard, 1998; Maddock, 1999). Disturbances in lotic systems have been recognised as constraining both ecological processes and patterns, such that long-term disturbances act as a habitat template that determines the types of species that are able to establish and persist within the disturbed environments (Southwood, 1977, 1988; Resh *et al.*, 1988; Poff and Ward, 1990).

2.2.2.1. The r- and K-selection theory: a general overview in relation to plants

MacArthur and Wilson's (1967) proposed idea of r- and K- selection suggested that the growth rate of any population (such as plants) is inversely related to the density of individuals in the community, such that there are high population growth rates when the population density is low, while there is a low population growth when the population density is high and nearing carrying capacity (MacArthur and Wilson, 1967; Pianka, 1970; Begon *et al.,* 2006). Species that typically colonise areas that are subjected to episodic disturbances that expose bare soil are seen as being more opportunistic in nature (r-selected; Table 1). Population growth is rapid during times of favourable conditions (bare soil) as there is little competition from a population approaching the carrying capacity (MacArthur and Wilson, 1967; Pianka, 1970; Begon *et al.,* 2006). The species that rapidly colonise an area following episodic disturbance typically have small, long-lived seeds that are dispersed by wind. Seedlings exhibit rapid growth rates after germinating and plants typically mature and reproduce rapidly in order to exploit the next disturbance event (Begon *et al.,* 2006).

K-selected populations are those that live in stable habitats with very few environmental fluctuations. This results in a fairly crowded and constant population density (MacArthur and Wilson, 1967; Pianka, 1970; Begon *et al.,* 2006). Competition amongst individual adults is high, with competition being the main determinant of an adult's survival rate, with fewer opportunities afforded to young individuals to reach maturity (MacArthur and Wilson, 1967; Pianka, 1970; Begon *et al.,* 2006). Begon *et al*. (2006) point out that trees in terrestrial woodland habitats exhibit long lifespans, they produce large seeds, the size of individuals is large, and their age to maturity is high. Additionally, although seeds are large, their reproductive allocation per reproductive cycle is low. However, they are likely to have multiple reproductive cycles per lifetime.

Table 1: Expected life history characteristics identified by Pianka (1970).

	r-selected	**K-selected**
Climatic conditions	Variable and unpredictable	Consistent and generally predictable
Mortality	Catastrophic and density-independent	Slow, continuous, density dependent
Survivorship	High mortality rate in juveniles	Generally low and constant mortality rate throughout lifespan until old age
Population size	Below carrying capacity and variable	At or near carrying capacity and fairly constant
Competition	Low	High
Selection favours	Early reproduction, small propagule and body size, single reproductive cycles before death	Delayed and prolonged reproduction, large body size, multiple reproductive cycles before death
Lifespan	Short lifespan	Long lifespan

2.2.2.2. Dispersal of propagules and initial establishment in suitable niches

Generally, pioneer (r-selected) species are able to take advantage of areas that experience episodic disturbances through erosion and deposition (Bornette *et al.,* 2008). When disturbance occurs, allogenic processes dominate as bare depositional or erosional features are formed. These are suited to the regeneration of opportunistic plant species adapted to rapidly colonise bare, exposed sediments. As colonisation takes place, there is an increase in biological interactions and competitive species begin to dominate as the system moves towards a climax state that is usually dominated by

K-selected species (Bornette *et al.,* 2008; Russel, 2009). Autogenic processes become the dominant process here (Bornette *et al.,* 2008).

For plants to successfully establish in areas where the abiotic conditions are appropriate, parent material or seed dispersal needs to coincide with the disturbance event, such that it acts as a mechanism for dispersal (Corenblit *et al.*, 2015). Should they not overlap, plant seeds will simply fall to the ground immediately surrounding the plant (Cronk and Fennessy, 2001). Additionally, there should be a window period between disturbance events that provides an opportunity for seedlings to germinate and establish (Bornette *et al*., 2008; Balke *et al.,* 2014). The alternative mechanism for dispersal is via wind or animals, or even through humans (Cronk and Fennessy, 2001).

The requirements for germination of seeds versus vegetative regeneration differ. Seeds germinate best under shallow water or when the soil is damp, having a higher resource requirement compared to asexually produced propagules, which come with reserves to support establishment (Silvertown, 2008; Mitsch and Gosselink, 2015). Plant material separated from adult plants that is able to propagate following disturbance is associated with vegetative growth through adventitious root and shoot production and establishment (Grace, 1993; MacDonald, 2003; Begon *et al.,* 2006).

Once seedlings or propagules of opportunistic plants reach sediments exposed by recent disturbance, they germinate and anchor rapidly, with the plants that establish first usually having traits that favour high net productivity, reproduction, dispersal and survival rates (Cronk and Fennessy, 2001; Corenblit *et al*., 2015). Seedlings will be resistant to hydrodynamic forces and burial by sediment, and they will also be able to tolerate stress from water table fluctuations (Corenblit *et al.,* 2015).

2.2.2.3 Clonal growth and colonisation

Once seedlings have germinated, certain traits allow them to colonise environments that are prone to disturbance. Plants have developed traits such as clonal growth, which allow them to propagate very successfully via vegetative means, often offering resistance to erosion and accretion (Sculthorpe, 1967; Grace, 1993; Bornette *et al.,* 2008). Vegetative growth is considered a dominant form of propagation when compared to sexual reproduction in environments that are flooded and/or a product of disturbance by erosion or deposition (Sculthorpe, 1967; Grace, 1993). A large number of fluvially-linked wetlands have been found to be dominated by vegetation types that are largely made of monospecific clonal species (Sosnová *et al.*, 2010; Sieben *et al.,* 2018).

Vegetative or clonal growth is the process whereby an individual plant is able to asexually spread and branch out, either following seed germination or via plant fragment establishment (Begon *et al.,* 2006). This effectively allows organisms to rapidly colonise patches such as bare sediment. The offspring formed by clonal growth are called ramets, which are horizontal stems originating from the same parent (Harper, 1977). An individual that comprises many ramets that originate from the same parent is called a genet. Some of the morphological specialisations include creeping stems, which include above-ground horizontal stems (stolons) that adventitiously root when they make contact with soil from the original parent plant and thus form a new plant (Grace, 1993). In addition, stem tubers and rhizomes (below-ground stems) also produce adventitious roots to form a new and completely independent plant, even if separated from the original genet (Grace, 1993; Hutching and Wijesinghe, 1997).

Additionally, aquatic plants are thought to have adapted traits that allow for the survival in areas where water table fluctuations are high and disturbance is regular, including a high allocation to root biomass, stems that are flexible, and narrow and hard leaves (sclerophylly; Mitsch and Gosselink, 2015; Moor *et al.*, 2017). Being required to survive oxygen-deprived environments such as those where the soil is saturated also leads to the development of aerenchyma with large spaces between cells that promote oxygen diffusion rates in the tissue (Mitsch and Gosselink, 2015; Moor *et al.*, 2017). Sosnová *et al*. (2010) found that habitats with waterlogged soils were populated by a high portion of species with rhizomes, making them well adapted to withstand floods (Grace, 1993; Kotschy and Rogers, 2008). A study by McNaughton (1975) on *Typha* (Cattail) found that in *Typha* marshes, seedlings were unlikely to establish due to competition, so the plants invested in rhizome production as a fecundity measure.

There are two types of clonal plants commonly found in fluvial wetlands prone to disturbance, namely the guerrilla and phalanx types. The phalanx form has ramets that are closely spaced (mm to cm apart; Sieben and Le Roux*,* 2017; Xue *et al.*, 2018). The guerrilla plants have ramets from the same genet that are spaced widely apart (1 to many dm; Xue *et al.*, 2018). The guerrilla strategy allows plants to escape patches with low resource availability or high stress through competition, while the phalanx strategy allows plants to competitively maintain patches that are more favourable in resource provision (de Kroons and Hutchings, 1995; Chen *et al.*, 2011). Some species have been shown to be able to change from closely spaced ramets to ramets that are more spread out along elongated rhizomes. This means it is able to change from a phalanx strategy to a guerrilla strategy, suggesting a high level of plasticity (Chen *et al.,* 2011).

2.2.3. From pioneer to climax: plant succession

Russel (2009) notes that plant establishment following disturbance and the subsequent modification of the environment that leads to colonisation by individuals of other species is known as succession. The change of the composition and structure of the vegetation slows down over time, such that given enough time, species composition will be stable as individuals that die are replaced (on average) by individuals of the same species (Russel, 2009). This stable community is known as the climax community (Russel, 2009).

Allogenic succession is where plants respond to the abiotic environment, which drives community composition. Examples of allogenic factors include disturbance. Alternatively, autogenic processes such as biotic interactions (e.g., competition or peat accumulation which reduces water depth) are primarily responsible for driving composition of communities (Mitsch and Gosselink, 2015). Corenblit *et al.* (2007) and Bornette *et al.* (2008) suggest that in fluvial systems, allogenic succession dominates initially, where resilient pioneer species with the appropriate adaptations are able to establish following disturbance. Biological diversity increases with decreasing disturbance frequency, such that autogenic succession begins to dominate, driving the system towards a climax state (Bornette *et al.,* 2008).

2.3. Ecosystem engineers

Jones *et al.* (1994) coined the term “ecosystem engineer”, which refers to the role played by organisms in the way in which they are able to modulate the flow of resources in ecosystems. Plants in fluvial wetland systems are becoming more and more recognised as playing a role in the way in which they alter hydrogeomorphic dynamics in rivers. Gibling *et al.* (2014) have examined variation in river landforms over geological time and have shown the response of river planform in relation to the evolution of land plants. Over geological time, plants have increasingly modified rivers from braided with unstable islands with limited presence of emergent aquatic plants, to braided with stable islands with the evolution of small herbaceous land plants, to anastomosing with the presence of robust macrophytes. This led these authors to suggest that rivers and plants have “co-evolved” over geological time, although the use of the term “co-evolution” in this case is rather problematic. In this instance, the term “ecosystem engineering” will be used in the discussion of the modification of fluvial system processes and consequent planform geometry.

Due to plants having to endure episodic disturbance associated with fluvial systems, the traits that they have evolved have biomechanical effects on the hydrogeomorphic functioning of the fluvial system they inhabit (Corenblit *et al.*, 2007, 2015). They are able to increase roughness, and they offer mechanical and flow resistance to riverbeds and banks and floodplain surfaces (Hupp, 1992). As a result, they assist in trapping sediment along river channels and floodplains and initiate and stabilise islands or depositional bars with their roots and morphological above-ground adaptations (Page and Nanson, 1982; Gurnell *et al.,* 2001; Gurnell, 2014).

Gurnell *et al.* (2012) noted that channel bed and bank colonisation by riparian and aquatic plants leads to bank stabilisation, accelerated sediment trapping and stabilisation, thereby creating unique biogeomorphic landforms which they term “pioneer landforms”. Corenblit *et al.* (2010) suggested that interactions between landform pioneer species and disturbances such as large floods are able to result in fluvial landscapes that are highly resilient. The development of these resilient biogeomorphic landforms is determined by accretion, the succession of vegetation and an increased hydrogeomorphic stability.

In the southern African region, Tooth *et al.* (2014) found that *Phragmites australis* can control fluvial form through the way in which it slowly invades streams with slow flows. As it invades from channel margins, it traps sediment and causes channel filling and abandonment. In Botswana’s Okavango Delta, the function and structure of fluvial systems is modified by the growth of *Cyperus papyrus* (papyrus) on channel banks (Ellery *et al.,* 2003). This confines bedload sediments to in-channel areas. As papyrus increasingly dominates the bank, hydraulic conductivity along the channel margin increases, increasing water loss from the channel. This combination of factors increases bedload deposition and channel aggradation, eventually leading to channel abandonment.

2.4. The concept of biogeomorphic succession

Corenblit *et al.* (2007, 2009, 2014, 2015, 2020) proposed the Fluvial Biogeomorphic Succession (FBS) model, which expands on the interactions between the abiotic and biotic environments in river systems. The model (Figure 1) summarises the co-evolutionary, bi-directional interactions between fluvial landforms and vegetation along riparian corridors, where the end result is a stable vegetated riparian area that once was influenced by the hydrodynamic regime of a stream but increasingly becomes completely disconnected from it, and which Balke *et al.* (2014) term a biogeomorphic ecosystem. Based on studies by Corenblit *et al.* (2007) of mostly temperate rivers in the northern hemisphere, synchronised changes that were observed to take place along fluvial corridors are a result of 1) vegetation responding to hydrogeomorphic conditions, 2) the subsequent effects of engineering by vegetation, and 3) the way in which vegetation responds to the changes induced by the biological feedback. The fluvial corridor consists of river channels, the margins alongside them, and the zone of flooding occupied by riparian vegetation (Corenblit *et al.,* 2010).

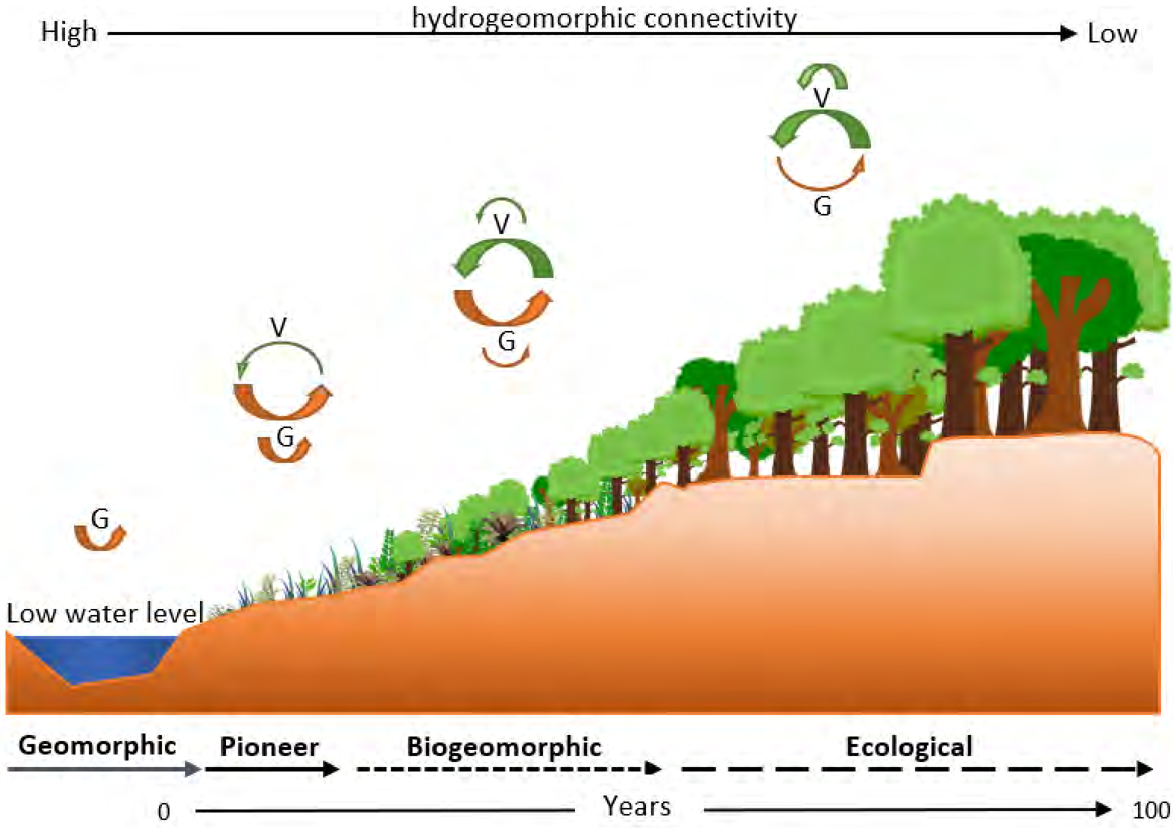


Figure 1: A conceptual diagram depicting the FBS model (adapted from Corenblit *et al.,* 2007).

The FBS concept consists of four main phases of geomorphic and biological organisation in space and time, and these include the geomorphic phase, the pioneer phase, the biogeomorphic phase and the ecological phase (Corenblit *et al*., 2007, 2015). Each phase presents as a space- and time-limited ecosystem with its own structure and function characterised by unique interactions and subsequent feedback between plants and hydrogeomorphic processes (Corenblit *et al*., 2007, 2015). The entire system is seen as shifting from a state of high resilience, where extrinsic hydrogeomorphic processes and r-strategists prevail, to a state of high resistance, where biological processes and K-strategists dominate (Corenblit *et al.,* 2009).

The “geomorphic phase” is described as the rejuvenation phase, occurring in the watercourse. It is subject to hydrologic disturbances such as floods. In this phase, hydrodynamics, the sediment’s intrinsic cohesiveness and transport properties define landform properties and stability. During the geomorphic phase, the fate and dynamics of plant diaspores are controlled by the hydrogeomorphic environment.

The “pioneer phase” is where vegetation recruitment occurs. In this phase, diaspores of the more opportunistic (r-selected) species establish, initiating the early primary or secondary successional process. Here, vegetation with strategies such as quickly reaching reproductive maturity, production of seeds that are small and easily dispersed via wind or water, and the ability to resprout vegetatively from plant fragments and reproduce via vegetative means are the first to establish (Pianka, 1970; Begon *et al.,* 2006; Gurnell *et al.,* 2012). This happens on the bare, newly formed sediment patches created by hydrogeomorphic disturbance events. Here, the hydrogeomorphic environment has an allogenic control on seed germination and establishment. Plants need to survive erosional and depositional threats, with traits such as deep anchoring roots and flexible stems allowing for this (Gurnell *et al.*, 2012). Spatially, this phase is typically observed close to the watercourse in areas that are regularly flooded.

The “biogeomorphic phase” is where strong feedback between hydrogeomorphic dynamics and vegetation occurs. The effects of plants’ biomechanical and morphological adaptations result in changes in the cohesiveness of the substrate, as well as exerting control on the hydrogeomorphic flows of energy and matter. Plant roles have shifted from biostabilisation to bioconstruction. Because pioneer species trap and stabilise sediment and accumulate organic matter as well as plant diaspores, new regeneration niches are generated, facilitating the establishment of new species. Plants with more competitive strategies appear in this stage, as both allogenic and autogenic processes control community composition, and vegetation succession progresses towards a climax state (Russel, 2009). The above- and below-ground biomass of engineering vegetation exerts control by either building up the landforms through accretion, or through affecting the hydrodynamics of water, such that scouring results in either lateral erosion or incision in areas surrounding the landform.

The final stage is known as the “ecological phase”. In this phase, islands, banks, or floodplains are stabilised by vegetation, hydrogeomorphic disturbance is absent, and individual landforms become independent of fluvial processes. Vegetation with K-selected traits begins to dominate and these riparian ecosystems become largely autogenic. Disconnection from the hydrogeomorphic drivers occurs either from deposition accelerated by pioneer vegetation communities, or by incision or lateral migration of the channel. Succession to the climax stage and the associated reduction in hydrogeomorphic connectivity can be reinitiated should a large enough flood or other disturbance event occur such as erosion.

Having reviewed regeneration strategies, succession and the FBS model, it is necessary to consider southern African wetlands that are most widely integrated within fluvial systems and therefore lend themselves to examination in the context of FBS models. However, fluvial systems in southern Africa are also largely erosional and therefore operate in ways that may differ from those in other parts of the world not overwhelmingly dominated by net erosion over lengthy periods (thousands to tens of thousands of years). This is the basis of the review that follows from here.

2.5. Wetland formation and the role of geomorphology in southern Africa

2.5.1. The conventional model of wetland formation: hydrology as the driver

The current model of wetland formation is largely based on hydrology as the primary driver of wetland formation and structure, as proposed by Gosselink and Turner (1978; Figure 2). The hydrological regime (depth, frequency and duration of inundation), that may be seasonally variable but has a measure of long-term cyclicity, leads to flooding of soil that transforms it from a generally oxidising state to being dominated by reduction reactions (Mitsch and Gosselink, 2015). These physiochemical conditions are unfavourable for life below the soil surface, such that only those plants and animals adapted to tolerate life without oxygen are able to prevail. Hydrology is seen as being the most important factor since it drives the structure and overall functioning of wetlands globally. Climate and geomorphology are seen as extrinsic factors that passively shape the wetland by affecting the volume and timing of water inputs (climate) and how it flows in the landscape (geomorphology; Tooth *et al*., 2015).

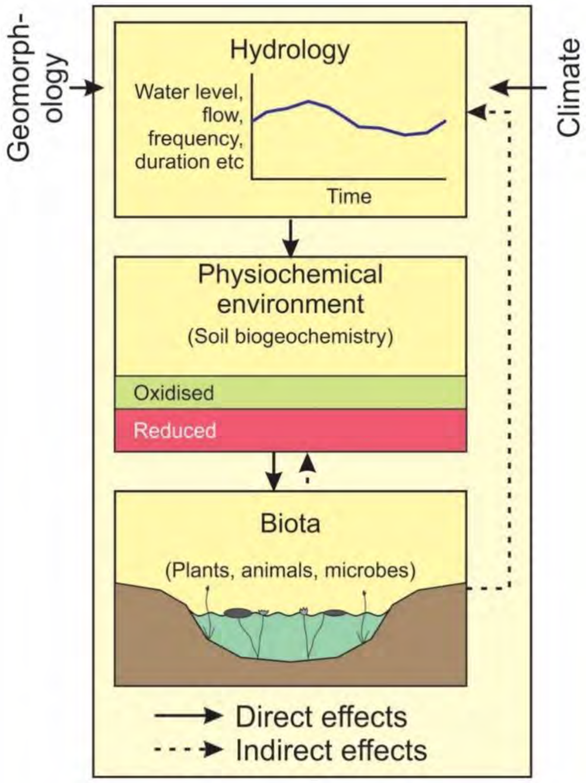


Figure 2: Gosselink and Turner’s (1978) model of wetland formation.

2.5.2 The emerging model of wetland formation that recognises the importance of geomorphology

For those wetlands that are integrated with the fluvial system, several characteristics illustrate the important underlying role of geomorphic processes. Irrespective of the terrain and underlying geology on which wetlands occur, they have a low longitudinal slope and a broad cross-section. These conditions promote slow flow and shallow flooding such that the shallow inundation conditions described in the Gosselink and Turner (1978) model of wetland formation can be satisfied.

The role of geomorphology in wetland formation, structure and function is captured in a model proposed by Ellery *et al.* (in prep), which is shown in Figure 3. Rainfall in the catchment influences the properties of the hydrological regime in fundamental ways, leading to runoff that interacts with the catchment and local landscapes to erode and deposit sediment and create a landform suited to the creation of a wetland landform, where water flows slowly and at a shallow depth over the land surface. These conditions combine to alter soil biogeochemistry and ultimately biotic composition, structure and dynamics.

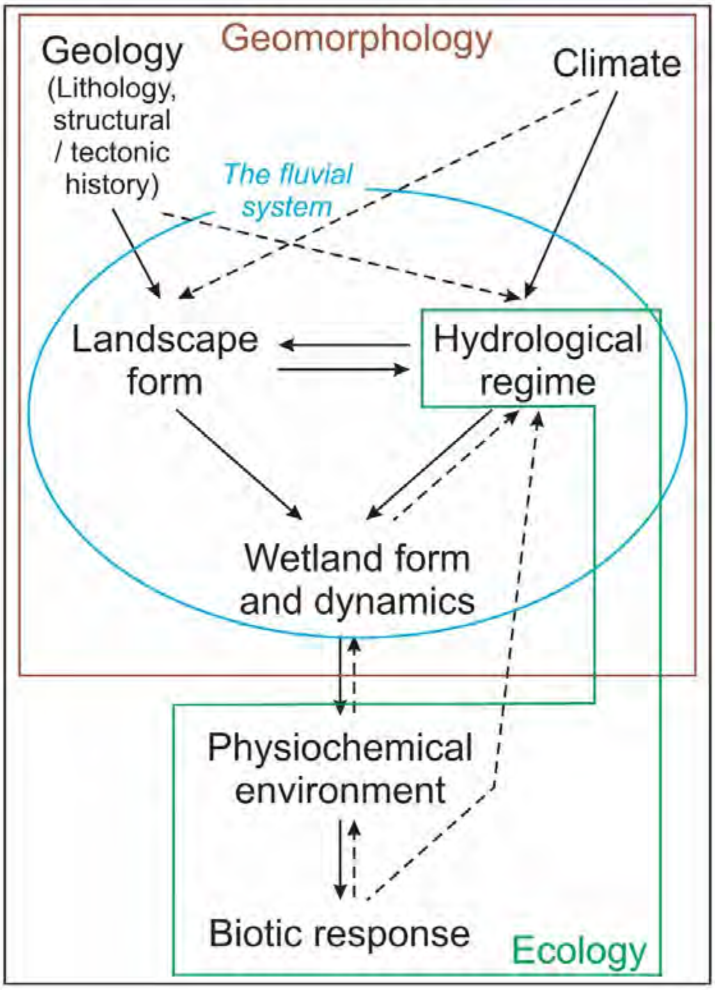


Figure 3: Conceptual model of factors that control wetland formation, structure and function within fluvial settings (Ellery *et al*., in prep).

Spatial heterogeneity is determined by the hydrological regime as well as the local-scale elevation, with these factors determining niche availability and therefore species richness (Mitsch and Gosselink, 2015). Low spatial diversity results in low species richness (Gosselink and Turner, 1978). The interactions between hydrology and land surface morphology are said to contribute to local differences in elevation and substrate characteristics, which in turn are related to species and habitat diversity (Gosselink and Turner, 1978).

2.5.3. Southern African geomorphology: a history of continental uplift and subcontinental scale erosion

The breakup of Gondwanaland that started about 180 Mya was followed by a period of warm temperatures during the Cretaceous, where rainfall was high. This resulted in a period of weathering that gradually lowered the subcontinent's average altitude to approximately 400 metres above sea level (masl; McCarthy and Rubidge, 2005; Holmes and Meadows, 2012; Maud, 2012). The ancient surface that was a product of these weathering processes is known as the African Erosion Surface (AES; Partridge, 1988; Figure 4). An isostatic uplift event occurred around 20 Mya as a result of a hot mantle plume heating the crust, lowering its density, such that the eastern part of southern Africa was elevated by about 250 m, while the west rose around 150 m (McCarthy and Rubidge, 2005). The proximity of the eastern half of the subcontinent to the mantle plume saw the development of an east-to-west downward tilt, which became more pronounced as a second uplift event, 5 Mya, further elevated the east by 900 m, while the west was lifted by an additional 100 m (McCarthy and Rubidge, 2005).

As a result of the first uplift event, rivers that flowed inland off the escarpment, as well as the shorter rivers that drained the escarpment to the coast began eroding headward, which gradually saw the formation of the Post-Africa Erosion Surface 1 as valleys widened (PAES1; Partridge, 1998). The second cycle of erosion that was initiated by the second uplift event created the Post-Africa Erosion Surface 2 (PAES2; Partridge, 1988). These uplift events forced rivers to adjust their base level, leading to downcutting and subsequent lateral erosion of valleys that were incised (Anderson and Anderson, 2010). As a result of these uplift events, the southern African landscape is at an unusually high elevation (average altitude is greater than 1 000 masl) compared to that of other continents that have not undergone mountain building through plate tectonics for over 200 million years (McCarthy and Rubidge, 2005). There are areas above the AES that remained in place, and these include the ancient mountain ranges of the Cape Fold Mountains and the Great Escarpment (Partridge, 1988).

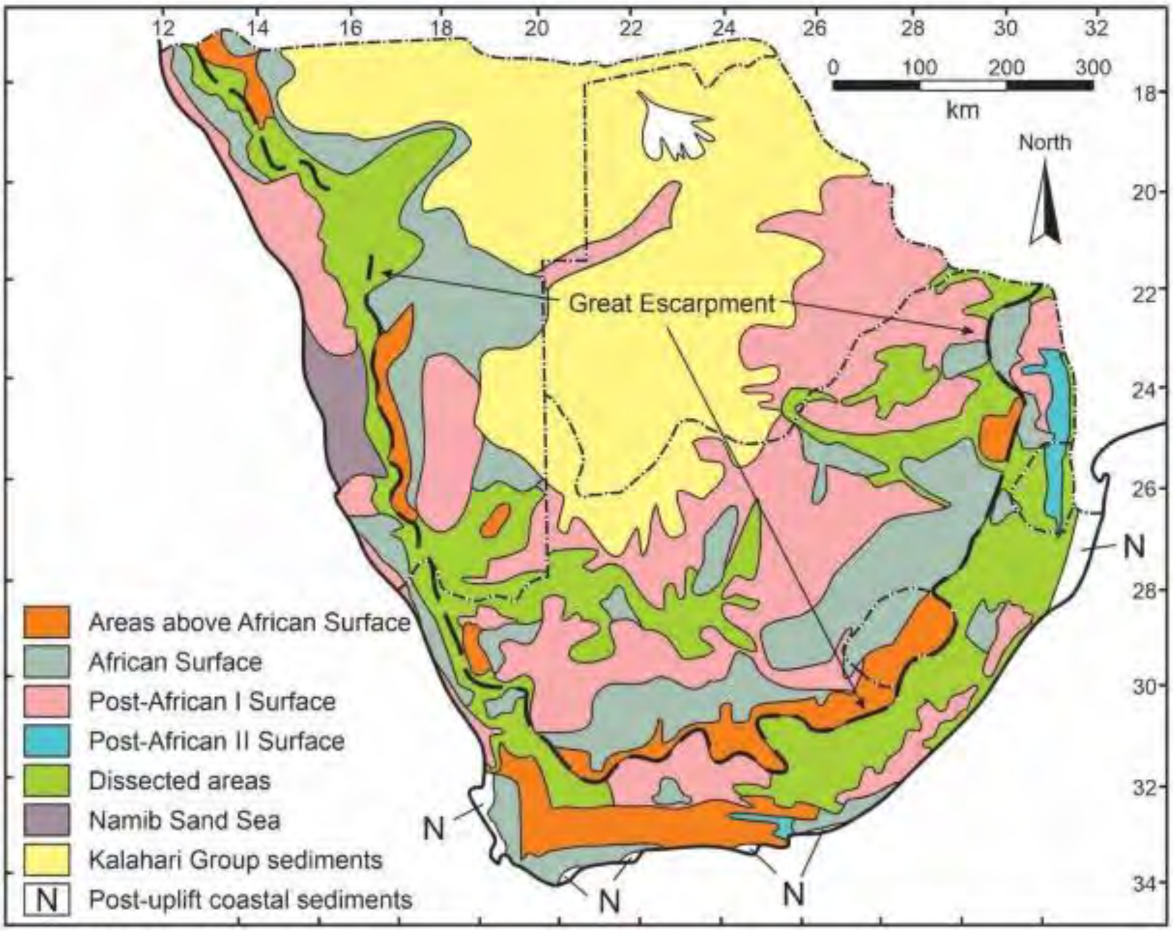


Figure 4: A map showing the various land surfaces of southern Africa (modified from Partridge, 1988).

Following the uplift events described above, the crust of the southern African subcontinent warped on either side of two south-west – north-east trending axes: the Kalahari-Zimbabwe axis and the Griqualand-Transvaal axis (Maud, 2012). These slightly elevated areas separated the upper Zambezi and Okavango rivers from the Limpopo River and led to the connection of the upper Orange / Vaal catchments with the lower Orange River to form the Orange River basin as we know it today. This warping also led to the formation of a large internal basin that is largely coincident with the "Kalahari Basin", as mapped in Figure 4. It includes the Okavango, Makgadikgadi and Etosha basins, although the eastern margin of the basin has been incised and captured by the Zambezi River. Apart from this basin and the eastern seaboard of northern Kwazulu-Natal ("Maputaland"), which are areas dominated by deposition, the rest of the southern African landscape is erosional and being degraded (there is a net lowering of the land surface).

2.5.4. Fluvial processes in an erosive setting

The southern African subcontinent's elevated land surface means that it is dominated by erosion (Partridge and Maud, 1987). With an average elevation of roughly 1000 masl, it is significantly higher than countries that share a similar geology, such as Western Australia, eastern South America, northern Canada or northern Asia (McCarthy *et al.,* 2007). These countries have an average elevation of a few hundred metres above sea level (McCarthy *et al*., 2007). Given the largely semi-arid conditions and the fact that the region's evapotranspiration rates exceed precipitation (Ellery *et al.,* 2009), most wetlands exist where water inputs are dominated by fluvial inflows (Tooth and McCarthy, 2007). Therefore, understanding rivers and fluvial dynamics in a landscape that is gradually being lowered is vital if one is to understand the distribution of most wetlands in the region, including palmiet wetlands.

Rivers generally incise quite rapidly following uplift as they work to achieve an appropriate longitudinal slope along their length in response to the change in base level. The achievement of such a slope is a result of erosional and depositional processes interacting along their length to reduce and increase slope respectively (Ellery *et al.,* 2009). Once the river has developed the appropriate slope, the longitudinal profile is logarithmic such that headwaters, where discharge is low, are characterised by a steep slope, with the gradient decreasing as the stream approaches the sea as discharge increases due to continual addition of water from tributaries. This leads to an increase in a stream's capacity to erode and transport sediment (Knighton, 1998; Ellery *et al.*, 2009). Although degradational in the long term, depositional areas that temporarily store sediment along river profiles seemingly coincide with wetland formation (Schlegel, 2017). This is especially true for the formation of floodplain wetlands (e.g., Tooth *et al.,* 2002a, 2002b, 2004), and valley-bottom wetlands such as the Kompanjiesdrif Palmiet wetland in the upper Kromme River (Lagesse, 2017; McNamara, 2018; Pulley *et al*., 2018). The patterns of erosion and deposition within wetlands will occur as a result of rivers that work to distribute energy uniformly along their courses by slope adjustment (Ellery *et al.,* 2009).

2.5.5. The formation of the Kromme River wetland

The Kromme River valley in its contemporary form occupies a position believed to be on either the relatively young PAES1 or the older PAES2 surface, which is the result of the two uplift events 20 Mya and 5 Mya that rejuvenated rivers and initiated incision through the AES and PAES1 (Partridge and Maud, 2000; McCarthy and Rubidge, 2005; Lagesse, 2017). The controls on the geomorphic structure and dynamics of the wide Kompanjiesdrif valley in the upper Kromme were investigated by Lagesse (2017), McNamara (2018) and Pulley *et al.* (2018) to gain insight into the formation of the wide, longitudinally gently sloping, laterally planed (up to 300 m wide) valley in which it lies. It was found that trunk-tributary interactions were largely responsible for initiating cut-and-fill cycles that lowered the river's longitudinal slope and widened the valley over time.

The Kromme River has various tributaries flowing in from both the Kouga/Suuranys and Tsitsikamma mountains, both of which host large tributary catchment areas. These tributaries deposit sediment into the trunk valley where they form tributary alluvial fans, constricting the trunk valley and altering its longitudinal slope (Figure 5; Schlegel, 2017; Langner, 2018; Pulley *et al.,* 2018). As shown in Figure 6, which shows the longitudinal slope of the Kromme River trunk valley, it is logarithmic in a general sense, but contains localised areas that are somewhat elevated relative to the ideal logarithmic profile, and there are areas below a locally steepened section that are lower than the idealised profile. A locally elevated area is shown that coincides with a tributary alluvial fan, which has altered the longitudinal slope of the trunk stream such that it is lowered in an upstream direction and increased in a downstream direction. During flood events, the reduction of the trunk valley width opposite the alluvial fan, and the increase in slope downstream of the alluvial fan, are thought to lead to the initiation of cut-and-fill cycles (Langner, 2018; Pulley *et al.,* 2018). Once a gully is initiated along the trunk valley downstream of a tributary alluvial fan, it propagates headward up the trunk valley, locally lowering the slope, and over many cycles contributing to valley widening (Langner, 2018; Pulley *et al.,* 2018).

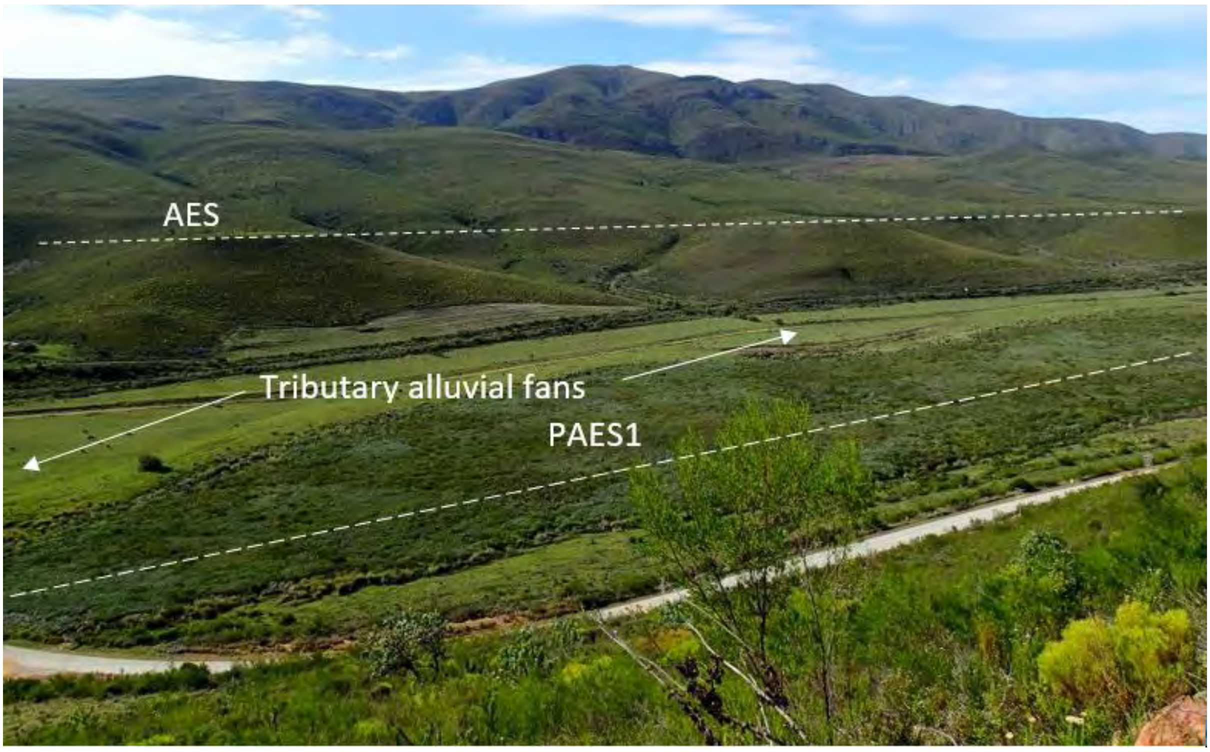


Figure 5: Photograph looking northwards across the Kromme River wetland in the Kompanjiesdrif basin showing the AES and PAES1, and two tributary alluvial fans that impinge the trunk valley. Photo: Philippa Schlegel.

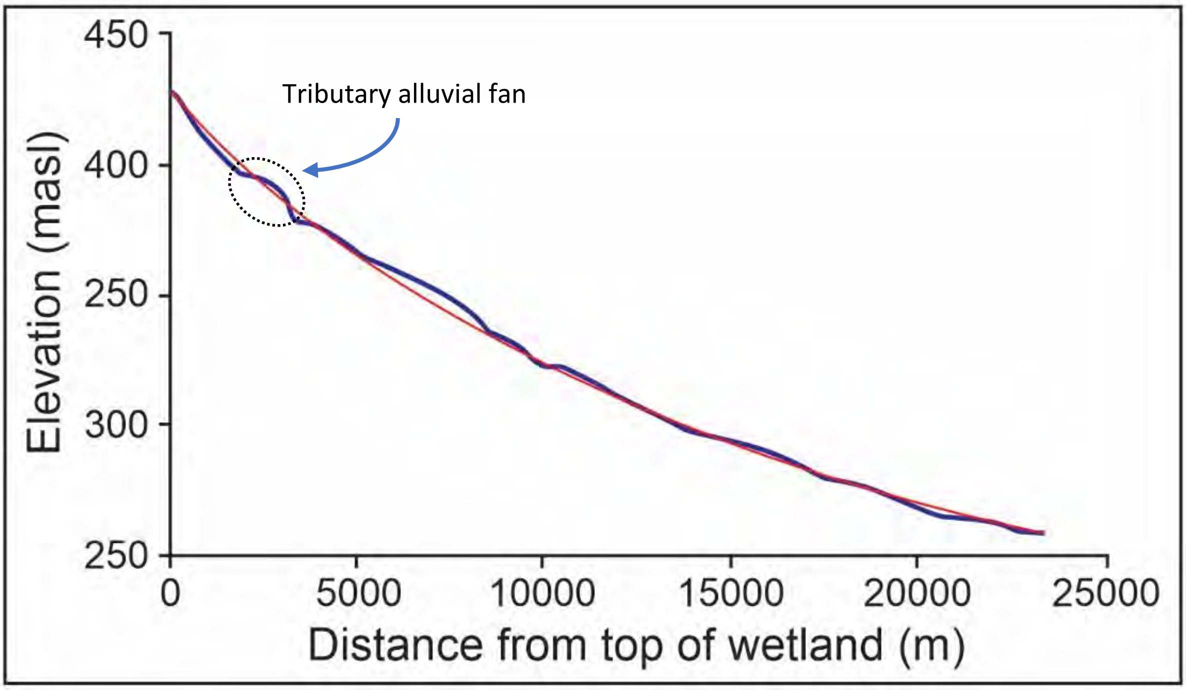


Figure 6: A comparison of the Kromme River wetland's longitudinal slope (blue) in relation to an idealised logarithmic profile (red line). Modified from Thulo (2021).

MacNamara (2018) looked at the Jagersbos floodout, which is located roughly 12 km downstream of the Kompanjiesdrif basin, and found that sediment from such an erosion gully is mobilised and deposited at the toe of the gully within less than 2 kilometres below the gully as a fan-shaped floodout feature (Figure 7). As gully erosion proceeds headward, filling of the gully is proposed to take place, slowly filling the gully over time.

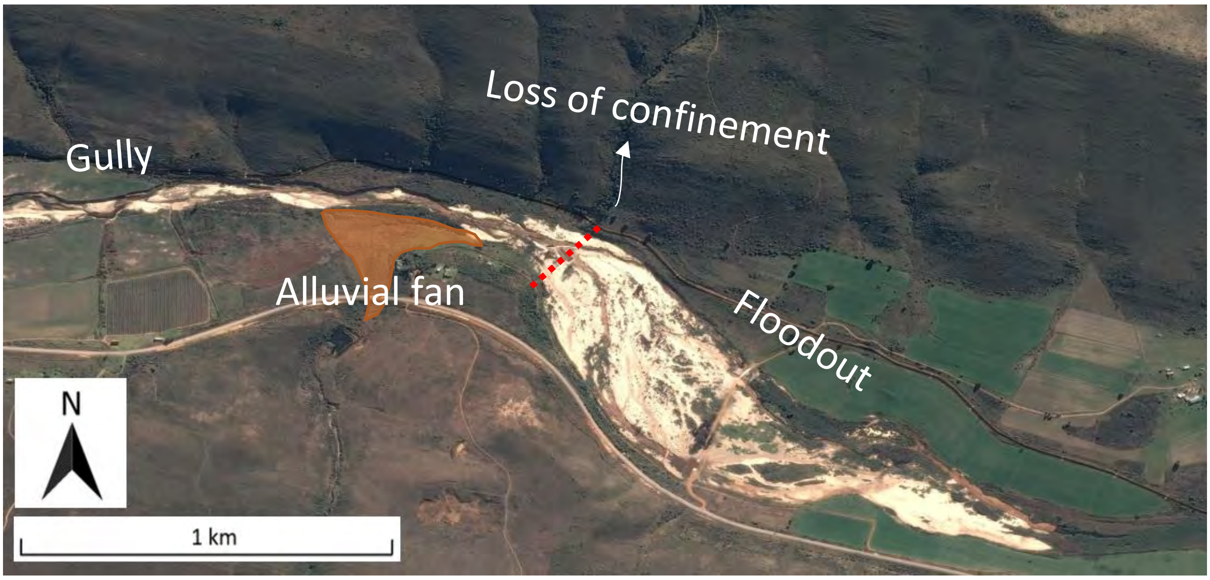


Figure 7: The depositional reach that resulted from sediment generation due to gully erosion upstream (Image from Google Earth Pro, 2013).

In summary, over long periods (thousands to tens of thousands of years), cut-and-fill cycles initiated by 1) interactions between the trunk stream and the tributary alluvial fans, and 2) the crossing of a geomorphic threshold during a flood event result in valley bottoms with a low longitudinal slope and planar cross-section, and therefore conditions that are suited to the formation of wetlands.

Having examined processes that have formed and that structure the Kromme River wetland, it should be clear that within the study site there are a range of geomorphic disturbance characteristics (basins that have been geomorphically stable for long periods, gullies, floodouts, steepened reaches downstream of tributary alluvial fans and reaches with a lower slope than might be expected upstream of them). Given that palmiet has been viewed as an ecosystem engineer in the Kromme River wetland, it is opportune to examine its morphology and life history characteristics in order to understand its possible adaptations to persistence and dominance in the Kromme River wetland.

2.6. Palmiet: the plant

2.6.1. Plant characteristics

Prionium serratum, or palmiet as it is commonly known, is described in detail by Boucher and Withers (2004). It is the only member of the Prioniaceae family, and it has strap-shaped, greyish to green leaves, which are able to reach lengths of up to 1.2 m long, while reaching widths of up to 30 – 40 mm (Boucher and Withers, 2004). It is a robust plant that reaches a height of up to 3 – 4 m, with aerial, occasionally branching stems that are woody. They are well adapted to floods through the way they encase their stems with old leaf bases, protecting them from abrasion by boulders and stones during high flow episodes (Boucher and Withers, 2004). Their flexible stems allow them to be bent but not broken during flood events (Gull, 2012). Coincidentally, due to their ability to bend during floods, banks and the beds of rivers are protected from erosion, and sediment is trapped (Gull, 2012). Sieben (2012) has also found that it has a much greater rooting depth and higher root-to-shoot ratio than other wetland plants. Additionally, palmiet is thought to be fire resistant (Boucher and Withers, 2004).

2.6.2. An ecosystem engineer with peat-forming properties

For soil to be described as peat, it needs to contain at least 30 % organic matter (Joosten and Clarke, 2002; Ollis *et al*., 2013). However, some scientists consider peatland as an area that is either vegetated or unvegetated that accumulates as a layer that is at least 300 mm thick with organic content greater than 20 % (Rebelo, 2019). Palmiet wetlands, such as the Goukou in the Western Cape Province, have been found to contain peat deposits of up to 8 m deep (Job, 2014).

The role of vegetation on hydrological and geomorphological processes has been studied quite extensively (Ellery, 1988; Ellery *et al.,* 1990, 1993, 1995, 2003). Much like Ellery's (1988) study on papyrus in the Okavango Delta, palmiet has similarly been described as being an ecosystem engineer due to the way in which it alters its environment, slowing flows and trapping sediment, thereby altering valley morphology (Sieben, 2012; Job, 2014; Barclay, 2016). During periods of low flow, patches of palmiet are thought to be able to vegetatively expand on sediment that has been deposited, and this is aided by its clonal growth habit (Job, 2014; Barclay, 2016). This allows it to extend into river channels, which results in channel width reduction (Job, 2014). Barclay (2016) found that palmiet in the Kromme wetland was able to colonise the beds of gullies through expansion from small islands. As palmiet colonises the edges of gully beds, it expands and traps clastic sediment, leading to aggradation. It increasingly traps sediment and may accumulate organic sediment, eventually colonising the whole gully bed. As sediment accumulates, the gully fills and the valley cross-section eventually becomes near-horizontal across the entire valley floor (Barclay, 2016).

2.6.3. Is palmiet adapted to being a pioneer or a climax species?

An important question that Rebelo (2017) and Rebelo *et al.* (2022) attempt to answer relates to whether palmiet has traits that make it adapted as a pioneer (r-selected) or a climax (K-selected) species. This is based on the fact that many palmiet wetlands are found to be patchy with the occurrence of fynbos communities. Rebelo *et al.* (2022) proposed three hypotheses of succession in palmiet wetlands that attempt to answer the question of whether it has traits that make it r- or K-selected.

The first hypothesis suggests that palmiet is a climax species and that fynbos communities are at an earlier stage of succession than the climax species. Over time, autogenic succession will result in a community that is dominated by palmiet. Given this, fynbos can be thought of as comprising opportunistic pioneer species that are better suited to early colonisation, while palmiet is a better competitor given its competitive traits.

The second hypothesis suggests that fynbos comprises species that are adapted to competition and palmiet is a pioneer species. This is based on the fact that palmiet is usually the first to colonise newly created depositional patches (Barclay, 2016). Following its arrival and establishment on sedimentary patches in gullies, the gully fills due to sedimentation induced by palmiet, resulting in wetland conditions that are suited to the colonisation of other species, such as fynbos plants (Barclay, 2016). At this stage, fynbos is thought to outcompete palmiet, making fynbos the climax community following earlier colonisation and growth of palmiet.

The final hypothesis is that both palmiet and fynbos species are good competitors adapted to conditions that prevail late during succession, with palmiet and fynbos having similar colonisation abilities as juveniles and that are good competitors for the rest of their life cycle. As such, succession may well be non-directional, such that there is no climax palmiet community.

2.7. Conclusion

This study has emerged from the contention that the Kromme River wetland has formed as a result of repeated cycles of erosion and deposition. By extension, it is possible that all valley bottom palmiet wetlands are subject to similar cycles of cutting and filling. This proposal that episodic erosion and deposition disturbance events are natural raises questions about plant adaptations to regenerate and colonise habitats that are subject to these sorts of geomorphic processes.

As observed by Corenblit *et al.* (2007), colonisation of river margins by plants leads to the creation of conditions that favour succession along river corridors, which, over time, leads to progressive isolation of the community from the hydrogeomorphic dynamics of fluvial systems. By examining palmiet's regeneration characteristics within the Kromme wetland in relation to the FBS concept, it may be possible to better understand the processes that lead to the development of landforms that favour palmiet wetland formation.

3. STUDY AREA

3.1. Location and topography

The Kromme River wetland (33°S, 24°E) is situated in the Cape Fold Mountains in South Africa's Eastern Cape province (Figure 8). Its headwaters are located in the Formosa Nature Reserve in the Tsitsikamma Mountains to the south of the mainstem Kromme River, which flows in a west to east direction, with its upper reaches flowing past the town of Kareedouw, and into an estuary in the Indian Ocean at St Francis Bay (Rebelo *et al.*, 2013). In its upper reaches, it is bordered by the Tsitsikamma Mountain range to the south, which has an approximate elevation of 1250 masl, and the Suuranys Mountain range to the north, elevated roughly 1050 masl (Rebelo *et al.,* 2013). Both ranges have very steep slopes with exposed rocks and very shallow soils (Haigh *et al.,* 2009). The Kromme River drains an area of approximately 1125 km^2, namely the K90 catchment, which consists of K90A, K90B, K90C, K90D and K90E quaternary catchments, with the total length of the Kromme River being around 95 km from its headwaters to where it enters the ocean (Dennis and Wentzel, 2007).

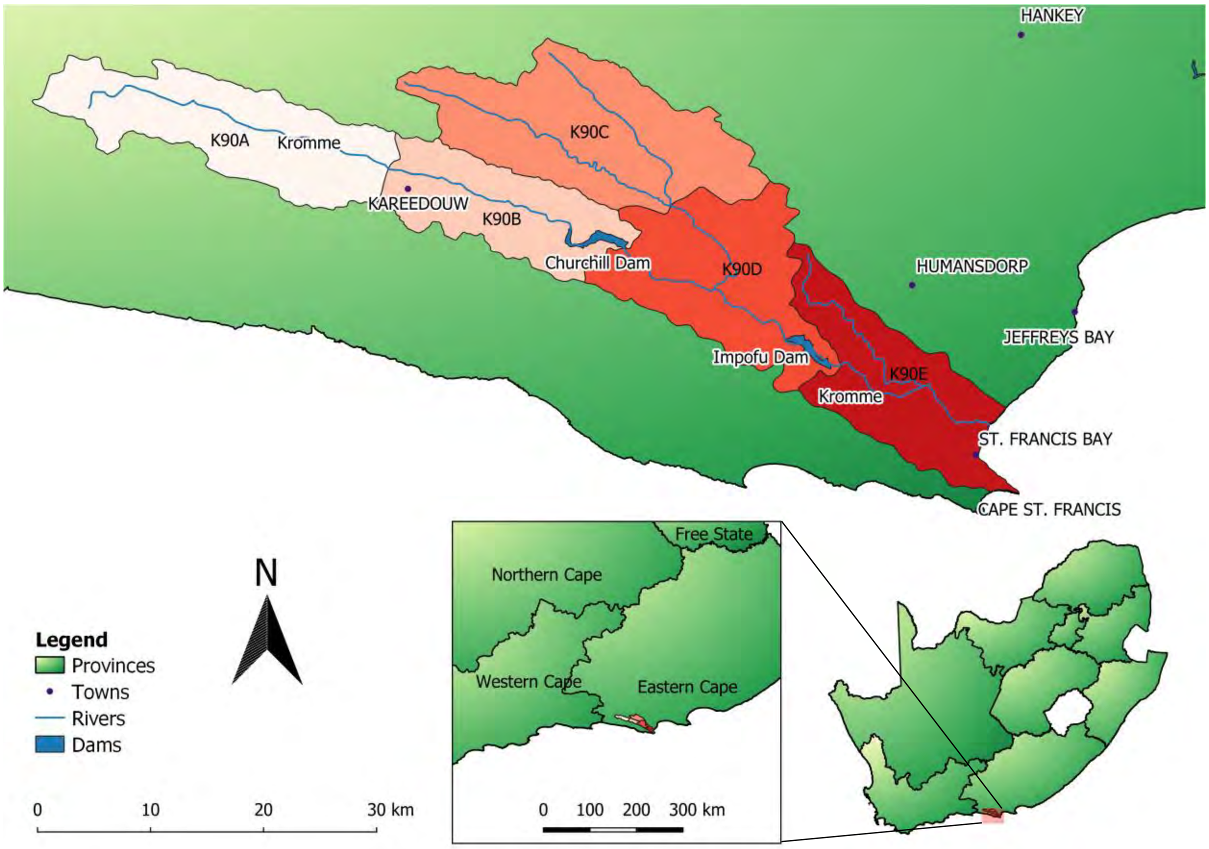


Figure 8: The K90 catchment in which the Kromme River wetland is situated.

The Kromme River wetland, which is in the upper Kromme catchment, consists of four basins: Krugersland, Kompanjiesdrif, Hendrikskraal, as well as the Jagersbos basins (west to east; Figure 9).

The Krugersland and Kompanjiesdrif basins are currently stable and have been so for decades to centuries (Lagesse, 2017), and they host extensive palmiet wetlands. The Hendrikskraal and Jagersbos basins have gullies present, and the lower Jagersbos basin has a large depositional floodout feature (McNamara, 2018). Of particular interest in this study are the Hendrikskraal and Jagersbos basins that have experienced recent erosional and depositional events.

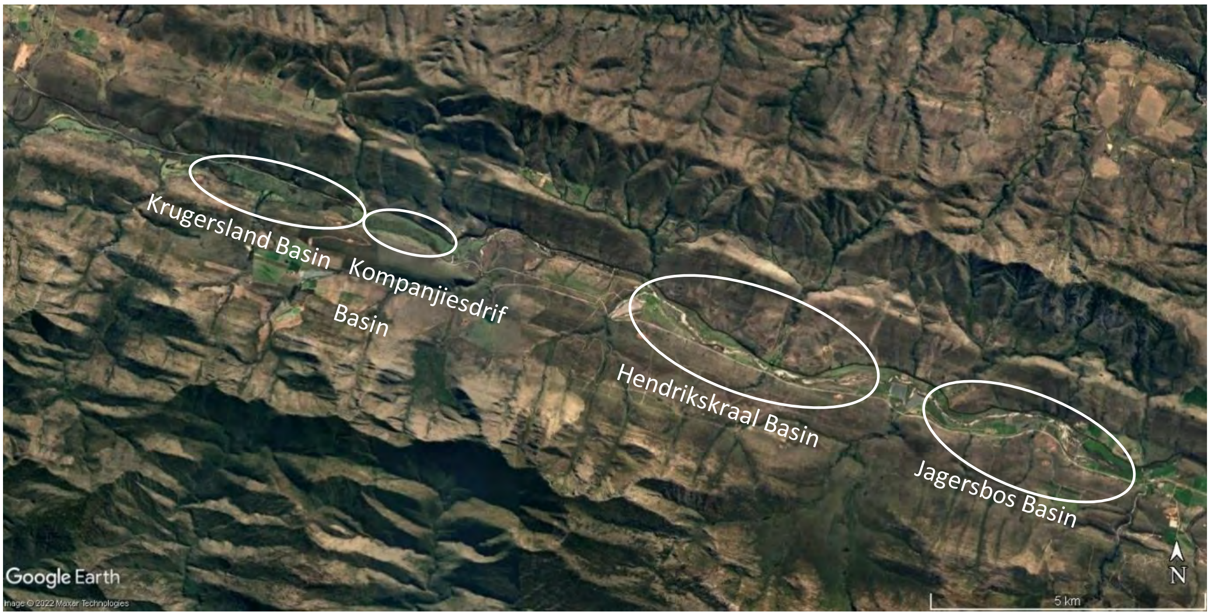


Figure 9: The location of the four basins along the Kromme River Wetland (Google Earth Pro, 2020).

3.2. Climate, hydrology and flood events

Ellery and Langner (2021) state that the Kareedouw weather station in quaternary catchment K90B, which is near enough to the study site to be considered reliable, recorded a mean annual rainfall value of 688 mm for the years 1978 to 2019, with a standard deviation of 200.5 mm (Figure 10). The Kromme's rainfall seasonality index is 0.47 according to Ellery *et al.* (in prep), which suggests that it has non-seasonal rainfall and a short dry period. The rainfall across the catchment declines from south to north, with an average rainfall as high as 800 mm in the Tsitsikamma Mountains, while an average of 400 mm was recorded in parts of the Kouga Mountains in the north (Rebelo *et al.*, 2013).

Middleton and Baily (2008) note that the upper Kromme River catchment has an average water loss of 1300 – 1500 mm as a result of annual runoff. Furthermore, the K90A and K90B quaternary catchments have a mean annual runoff of 100 – 200 mm (Middleton and Baily, 2008). The upper Kromme valley floor has a mean annual potential evaporation of roughly 1980 mm, and this exceeds the mean annual rainfall recorded at the Kareedouw weather station by a factor of 3.

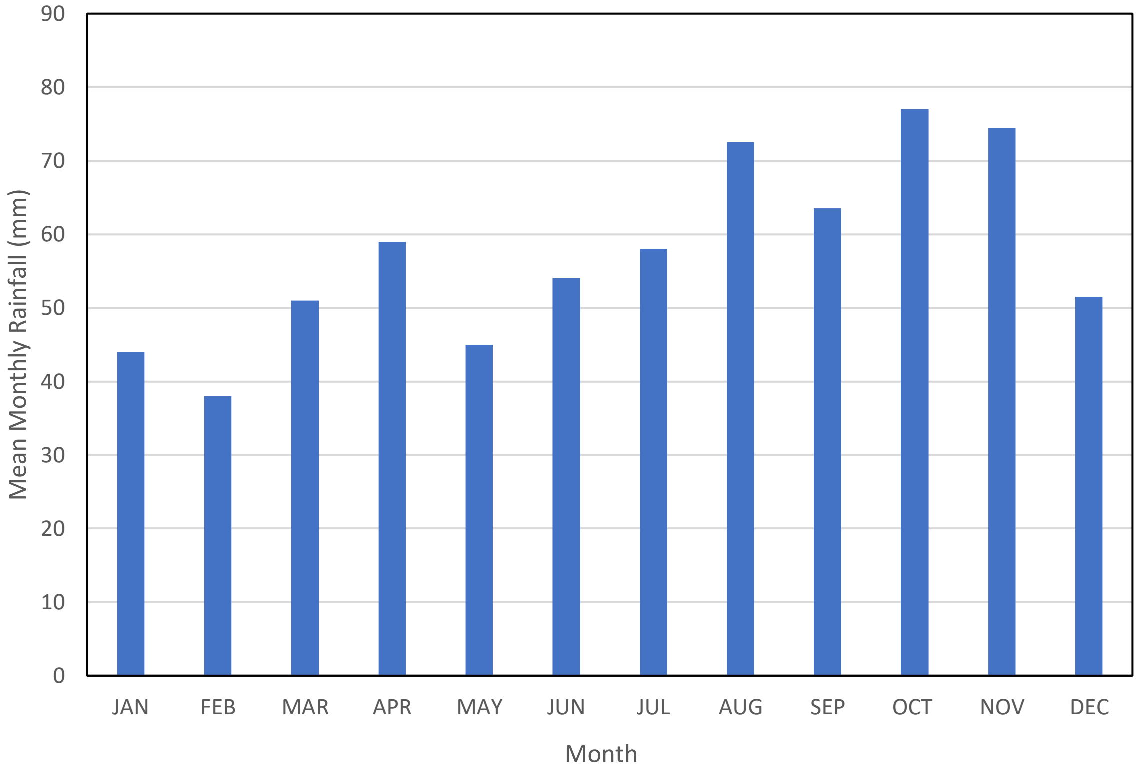


Figure 10: Mean monthly rainfall from the years 1978 – 2019 at the Kareedouw weather station.

The K90A catchment is characterised by a trellis drainage network made up of six large and semi-permanent tributaries and many small ones that enter the trunk stream at right angles, with the wetter southern side being drained by five semi-permanent tributaries, while the dryer northern slopes are drained by seven mostly seasonal tributaries (Haigh *et al.,* 2009). A number of tributaries have alluvial fans that encroach onto the palmiet wetlands, constricting the width of the trunk valley palmiet wetlands. These are the same alluvial fans that trigger gully erosion and the formation of depositional lobes identified by Lagesse (2017), Pulley *et al.* (2018) and McNamara (2018) through the way in which they alter the hydrodynamics of the trunk stream (Langner, 2018). They are also a significant source of groundwater believed to be feeding the palmiet wetlands in the upper Kromme (Smith, 2019).

The Kromme River wetland has experienced numerous floods throughout its recent history, with the most recent one taking place in 2012 (McNamara, 2018). Haigh *et al.* (2009) have detailed the flood return intervals, with records from 1955 to 2006 (Table 2). A gauging weir that is located downstream of the Churchill Dam (quaternary catchment K90B) was used to obtain the data. The more recent floods (most notably 2001 and 2006) were powerful enough to damage some of the erosional control structures (Haigh *et al.,* 2009).

Table 2: Kromme River's flood return intervals at Churchill Dam based on data from 1955 – 2006 (modified from Haigh *et al.,* 2009).

Return intervals (Years)	**Discharge (cumecs)**
2	2.26
5	25.17
10	91.18
25	389.73
50	999.06
100	2366.00
200	5264.15

3.3. Geology

The Tsitsikamma (to the south) and the Suuranys (to the north) mountain ranges consist of resistant quartzite lithologies of the Peninsula and Skurweberg Formations, which are at the base of the Table Mountain Group (Schlegel, 2017). The more easily weathered shale and sandstone lithologies of the Cape Supergroup are (from oldest to youngest) Pakhuis, Cedarberg, Goudini, Baviaanskloof, Gydo and Ceres Formations (Figure 11; Haigh *et al.,* 2009). The mountains and valleys are largely related to synclines and anticlines that were formed when Antarctica collided with Africa, such that the Kromme River occupies a syncline, as can be seen by the lithologies that repeat themselves in reverse order from south to north across the valley.

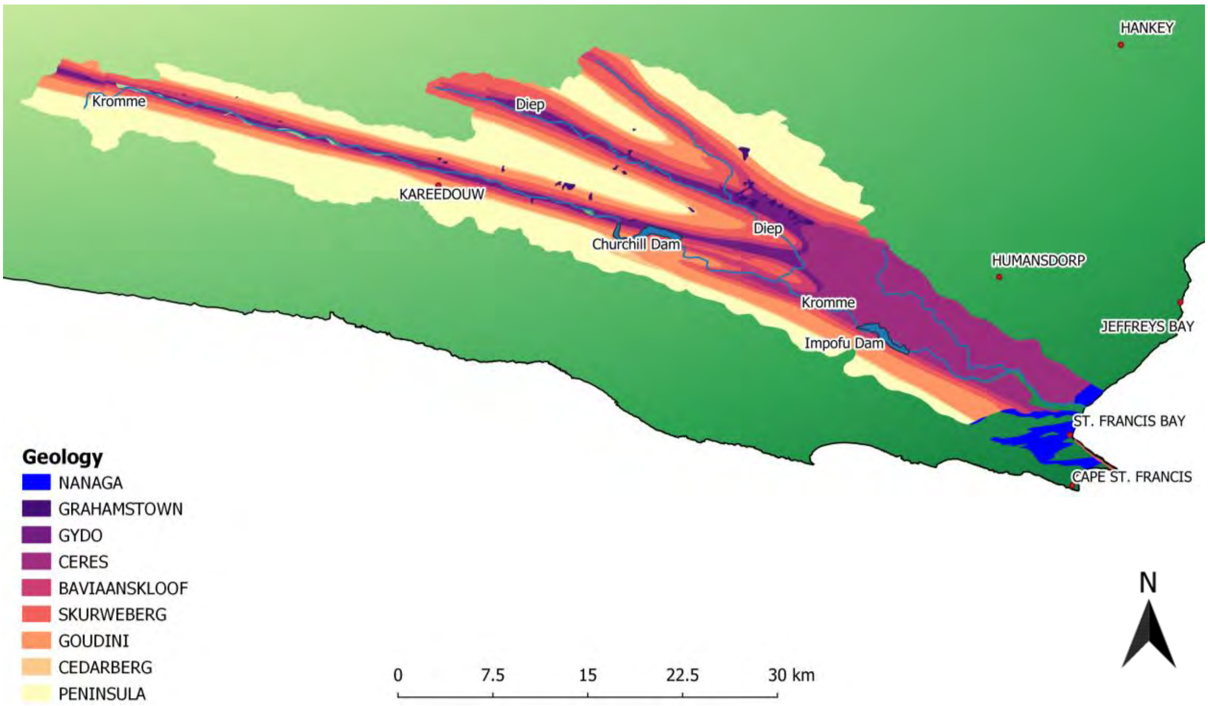


Figure 11: Geology of the Kromme catchment.

3.4. Vegetation

Fynbos is the dominant vegetation in the Kromme River catchment, and it forms a part of the Cape Floristic Region (Schlegel, 2017). The fynbos is said to be heavily degraded due to overgrazing along the wetland and lower slopes of the mountains (Barclay, 2016). There are various classes of fynbos cover found throughout the Kromme River catchment, making up an area of 46% of the K90A catchment (Mucina and Rutherford, 2006; Mander *et al.,* 2010). Grassland, thicket, Renosterveld, as well as forest cover make up 12.5 %, 9.8 %, 9.2 %, and 2.2 % respectively (Mucina and Rutherford, 2006; Mander *et al.,* 2010).

Barclay (2016) examined the plant communities and their distribution within the Kompanjiesdrif wetland basin. The palmiet community (the dominant community) was found to be growing throughout the entire core of the Kompanjiesdrif valley-bottom wetland, in addition to the occurrence of palmiet seedlings in erosion gullies below the wetland. The *Miscanthus capensis* community was found along the wetland fringe regions, along with the *Juncus kraussii* community. This *Juncus kraussii* community is uncommon in the Kompanjiesdrift basin when compared to other reaches of the Kromme River wetland. Along the riverbanks, the *Metalasia densa* community occurs, while the *Pennisetum clandestinum* community occurs along the terrestrial margins of the wetland.

Acacia mearnsii (black wattle) occurs throughout the catchment and within parts of the wetland. The plant is invasive and is known to use large quantities of water, so much so that it is viewed as being responsible for the destruction of areas of wetland in which palmiet occurs (Rebelo, 2012). Rebelo (2012) notes that wattle has been present in the catchment since the 1930s, contributing to the deterioration of the wetland's health, while by 2007, upwards of 11 % of the Kromme River wetland had been invaded.

3.5. Land use

3.5.1. Historical land use

Earliest records of the Langkloof show the arrival of European farmers in 1775, with what was the first recorded application for grazing rights (Rebelo *et al.,* 2013). The 1800s saw land use comprising mainly sheep and cattle, with extensive livestock grazing practices (Gull, 2012). Additionally, farmers would burn the veld in the Langkloof as it allowed for greater livestock production (Gull, 2012). The fertile soils of the palmiet wetlands floodplains prompted landowners to clear these areas of vegetation for orchard cultivation (Rebelo *et al.,* 2013). A large flood in 1931 destroyed large portions of the planted orchards as the removal of the vegetation affected the wetlands such that their ability to attenuate floods had decreased (Rebelo *et al.,* 2013). Additionally, the large floods also resulted in wattle trees appearing in greater numbers. From the start of the 20th century to the 1940s there was increased fruit production on the fertile floodplains of the Kromme River wetland, which complimented livestock grazing (Haigh *et al.,* 2009). From about 1940, vegetables and intensive dairy and sheep farming were introduced to stimulate the regional economy (Haigh *et al.,* 2009; McNamara, 2018).

3.5.2. Current land use

The catchment area is largely still being used for farming, with orchards and livestock farming still dominating land use. Timber harvesting also contributes to the local economy. Haigh *et al.* (2009) note that the palmiet wetlands located in the upper reaches of the Kromme River play a relatively large role in the purification of water, much of which is fed to the Nelson Mandela Metropole. The water is stored in two large dams, which are located along the Kromme River. The Churchill Dam is found southeast of Kareedouw in quaternary catchment K90B (Haigh *et al.,* 2009). It has a capacity of 35 710 000 m^3 (Haigh *et al.,* 2009). The second dam is the Mpofu Dam, which is in quaternary catchment K90D, and it has a capacity of 10 706 000 m^3 (Haigh *et al*., 2009). Forty percent of Port Elizabeth's water comes from these dams, while the upper Kromme River alone feeds 24% of the Churchill Dam's water (Haigh *et al.,* 2009; Rebelo *et al.*, 2015).

3.6. Current conservation efforts within the Kromme wetland

Current conservation efforts are being carried out by Working for Wetlands. Since 2000, eleven large gabion weirs have been installed below gully headcuts within the upper Kromme River to prevent gullies from propagating headwards into the unchannelled valley bottom basin of the Kompanjiesdrif palmiet wetlands, with an example of one of the weirs being shown in Figure 12. Gully erosion diminishes benefits derived from water flowing through an unchannelled section, such as sediment trapping and water quality enhancement (Kotze *et al.,* 2009). These gabion structures trap sediment that is mobilised during floods and assists with soil and bank stabilisation, reducing erosion and slowing the flow of water (Haigh *et al.,* 2009). Additionally, Working for Wetlands and Working for Water have been working to remove alien vegetation along wetlands and in the catchment (Barclay, 2016). The project also benefits the local community in that it employs labourers to build and maintain structures in the area.

Figure 12: An example of one of the weirs located in the Kromme River wetland upstream of the reach where this study was conducted.

3.7. Study site location and characteristics

For this study, a reach of the upper Kromme River that covered roughly 8 km was selected due to having incurred recent geomorphic disturbance (Figure 13). This spanned from just above the gabion weir at Kammiesbos in the Hendrikskraal basin to above the gabion weir in Jagersbos. From the Kammiesbos weir, the landscape is punctuated by a deep (> 5 m deep) series of gullies that extend a distance of approximately 6.6 km long with a near-horizontal remnant valley bottom area (the previous valley bottom) occupying the gully margins on either side. The bottom-most gully in the study site terminates in a floodout at Jagersbos, where the valley widens and confinement is lost. Below the floodout feature, above the lowermost gabion structure in the study area, is a largely preserved wetland that has not been affected by any disturbance.

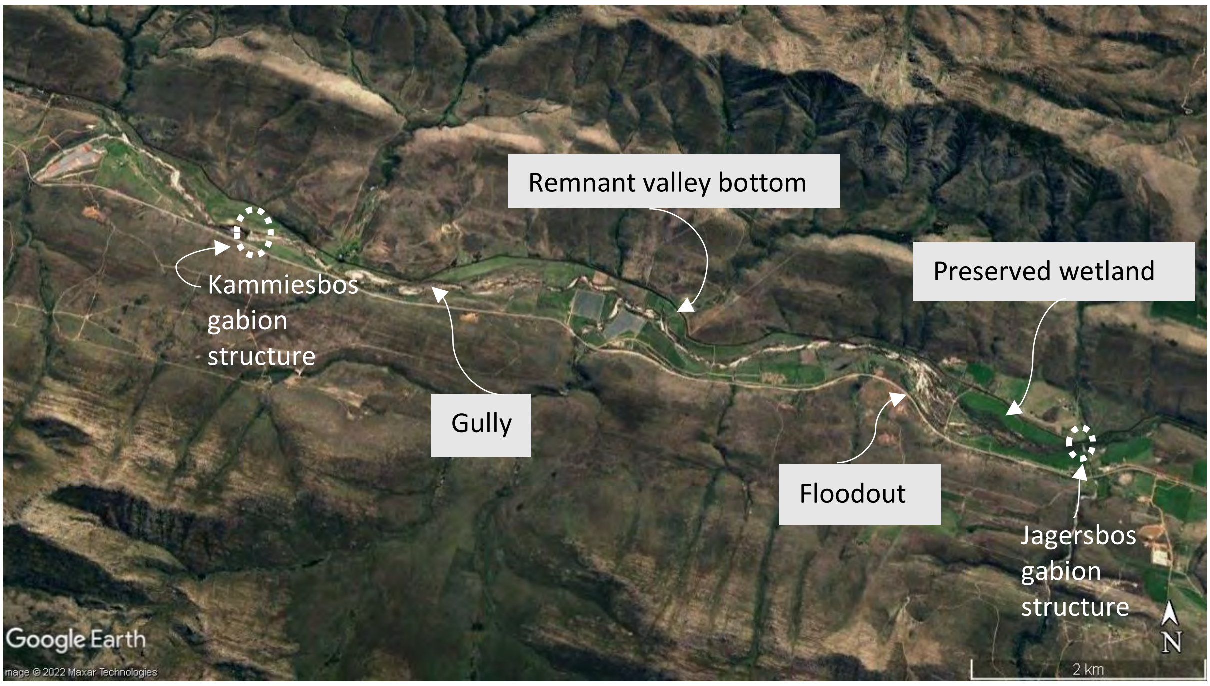


Figure 13: A map showing the major physiographic features of the study area wetland (Google Earth Pro, 2020).

4. METHODS

4.1 Introduction

The study was designed to map the distribution of palmiet in various stages of its life history as they relate to its establishment and persistence. In the case of juveniles, they were viewed as being in the regeneration phase of establishment. In the case of adults, individuals were either in habitats that were ideally suited to palmiet growth, where they were rooted in shallow water or with a shallow depth (< 0.5 m) to the water table (Stable), or as growing in environments that formed subsequent to disturbance through localised erosion, where they were usually elevated more than 1.5 m above the water table and were therefore viewed as persisting in an environment no longer suited to palmiet growth (Pers; Table 3). Environmental factors considered to be related to palmiet establishment and growth were substrate characteristics, including particle size (PSiz) and soil organic matter content (OMat), as well as depth to the water table (DWTa), distance from the thalweg (DThal), relative elevation (REle), and geomorphic disturbance history. A number of characteristics of palmiet that are likely to be indicators of its establishment and growth were also measured, such as plant height and canopy aerial cover in the case of multi-stemmed clumps. Plant and local environmental characteristics were continuous variables while the life history stage and geomorphic disturbance type were in one of a small number of distinct classes.

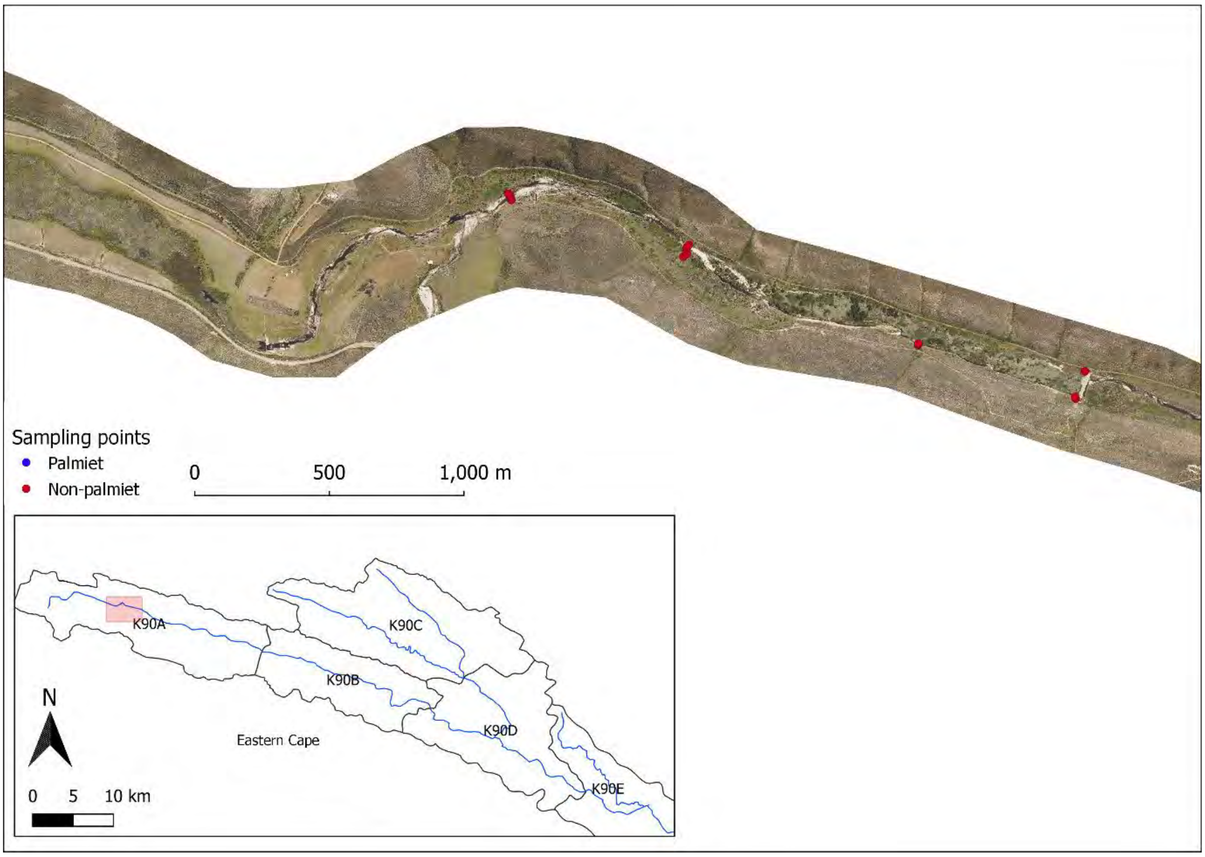
Table 3: A table providing the details of the data collected, including life history stages, plant characteristics, local environmental characteristics and the geomorphic disturbance types.

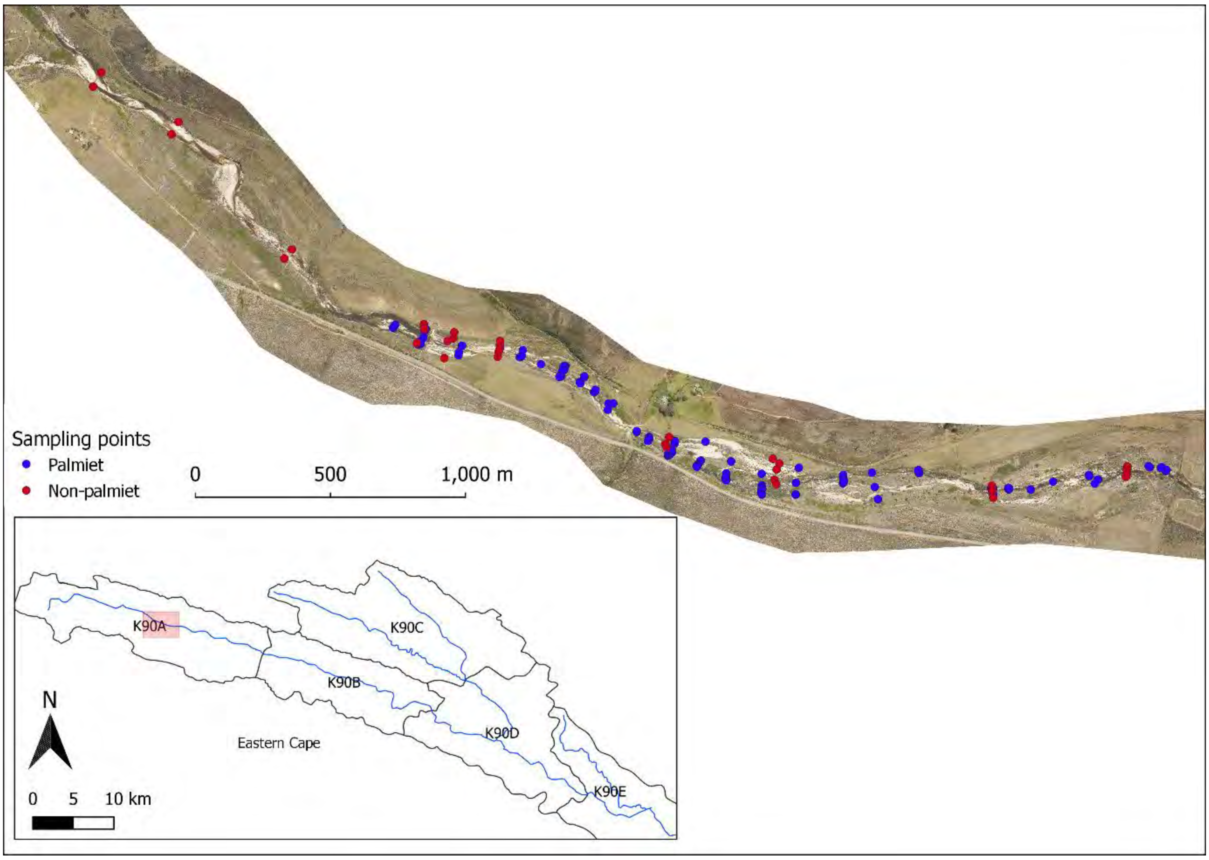
Life history stage		**Plant characteristics**		**Local environmental characteristics**		**Geomorphic disturbance type**	
L h class	**Abbrev**	**Characteristic**	**Abbrev**	**Characteristic**	**Abbrev**	**Characteristic**	**Abbrev**
Juvenile	Regen	Height	n/a	Soil particle size distribution	PSiz	Gully bed	GBed
Adult, rooted in water or < 0.5 m above water table	Stable	Canopy cover	n/a	Organic matter content	OMat	Gully bar	GBar
Adult, rooted > 1.5 m above water table	Pers			Depth to water table	DWTa	Incised, remnant valley bottom	RVBot
				Distance from thalweg	DThal	Valley bottom	VBot
				Elevation relative to local thalweg	REle	Floodout	FOut

4.2 Field data collection

The field data collection required sampling of every palmiet individual in a transect 15 m wide oriented at varying lengths across the valley floor. The intention was to relate palmiet distribution at a number of life history stages to environmental characteristics, with a particular emphasis on regenerating (Regen) populations. In addition to palmiet individuals, some samples that did not contain palmiet (NPal) were included. These samples were provided by Mr S Jarvis, a contemporary MSc student, who is similarly relating environmental factors to vegetation community distribution throughout selected reaches of the Kromme River wetland where hydrogeomorphic disturbance has occurred (Jarvis, in prep). Mr Jarvis's transects occurred at intervals of roughly 600 m apart, where sampling took place in 2 m x 2 m quadrats across the valley at various point. As such, the region of the Kromme wetland examined in this study was the lower half including Hendrikskraal and Jagersbos.

A handheld Garmin GPSMap 60CSx GPS was used to capture the geographic coordinates of the samples and ArcMap 10.8.1 and QGIS 3.12 București were used for the mapping. The classes were colour-coded and spatially plotted on a high-resolution hillshade model obtained from an airborne LiDAR survey with a spatial resolution of less than 1 m x 1 m, which was obtained from the Rhodes University Geography Department (Appendix A). The location of all samples in this study is shown in Figure 14.





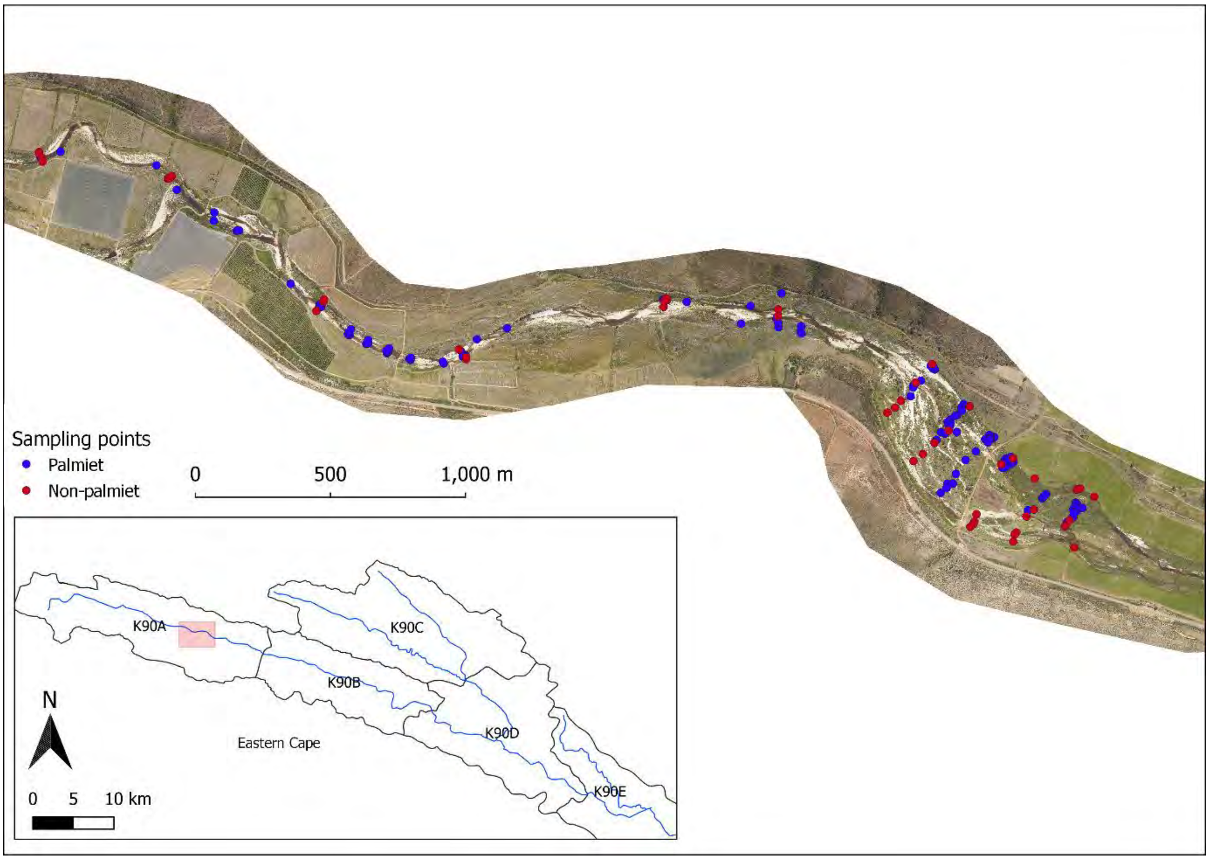


Figure 14: Maps showing the distribution of palmiet and non-palmiet samples throughout the study area reaches.

4.2.1 Biological data

The height of every individual or clump of palmiet was measured to the nearest 0.1 m using a ranging rod calibrated to intervals of 0.1 m. In the case of clumps of juvenile plants, the height of the tallest plant was measured to the height of the tip of the tallest leaf. Canopy cover was measured by measuring the longest axis across the individual or clump and the longest dimension across the canopy perpendicular to the first measurement. These measurements were to the nearest 0.1 m and canopy cover was calculated based on the formula used to calculate the area of an ellipse.

In the case of mature stands of palmiet (Stable), the height of the canopy was measured and the aerial cover of individuals as a percentage of ground cover on a scale as follows: 0 - 2 %, 3 - 5 %, 6 – 10 %, 11 – 25 %, 26 – 50 % and > 50 %.

4.2.2 Environmental data and sampling

Soil samples were collected in the field for determination of PSiz and OMat content. Samples were composite samples of 5 soil samples within a radius of 3 m of the rooting point of individuals. Subsamples were collected to a maximum depth of 30 cm using a hand trowel. These were well mixed before taking a single subsample of the composite sample.

DWTa was determined to the nearest 0.01 m by measuring the depth to water where it was above the soil surface (a negative value for DWTa was assigned in such cases), or where the DWTa was below the soil surface, the depth was measured in a hole augered into the soil. Where groundwater was below the soil surface by greater than 1.2 m, it was recorded as such, and the DWTa was estimated based on landscape position, DThal and REle. In cases where the sample was close to a tributary alluvial fan where water is entering the wetland continuously, the DWTa is expected to be higher than the elevation of the water surface above the thalweg (Ellery *et al.,* in prep). In cases where the sample was between alluvial fans, the DWTa is likely to have been lower than the elevation of the water surface above the thalweg.

The REle and DThal were extracted from the high-resolution LiDAR image of the Kromme River wetland perpendicular to the valley and passing through the sample location. In the case of the floodout (FOut) and the unchannelled valley bottom (VBot), where a number of flow paths were present, the nearest low-lying feature where flow was present (at least during moderate discharges) was considered as the thalweg.

4.3. Laboratory analyses

The sediment samples that were collected in the field were dried at 50°C for 48 hours and crushed with a pestle and mortar. A portion of the sample was sieved through stacked sieves with an automatic shaker with mesh sizes of 2000 µm, 1000 µm, 500 µm, 250 µm, 125 µm, and 63 µm, with anything under 63 going into a pan. The mass of material remaining in each sieve (and the pan) was weighed to the nearest 0.001 g and expressed as a percentage of the total sample weight. PSiz distribution was arranged according to the Udden (1914) and Wentworth (1922) grain class size.

OMat content was measured using a muffle furnace to determine the loss of ignition. The furnace was preheated to 450°C, and no less than 10 grams of sediment was added to each crucible. The crucibles with the sediment samples were combusted for a period of 6 hours. Prior to combustion, each crucible was weighed without any sediment and then again after sediment was added to calculate the sediment mass. Following combustion, the crucibles with sediment were weighed again such that the mass of sediment could be calculated. The difference between the pre- and post-combustion masses was converted to a percentage of the mass of the sample prior to combustion.

The geometric mean particle size (Folk and Ward 1957) was used as the indicator of PSiz differences between samples and was calculated using Gradistat (Blott and Pye, 2001). Folk and Ward measures are thought to be a more robust method for measuring sediments that are compositionally variable. The formula to determine the geometric mean (M_G) is:

$$M_G = \exp\frac{\text{In } P_{16} \ + \ \ln P_{50} \ + \ln P_{84}}{3}$$

Where P_x is the particle diameter in µm at the cumulative percentile value of x (Bouffard and Amyot, 2009).

4.4 Modelled flood hydraulics as environmental variables for samples

Using HEC-RAS, Ms W Langner from the Rhodes University Geography Department created a hydraulic model of the study area to approximate a 1-in-50-year flood event, such that flood depth (FDep), velocity (Vel) and stream power (SPwr) could be plotted spatially (Figure 15). These data were used to determine the hydraulic conditions of each sample during such floods and were used to compare flow conditions for each sample plot. The hydraulic data did not cover all of the sampled plots, as some plots were out of the flooded zones.

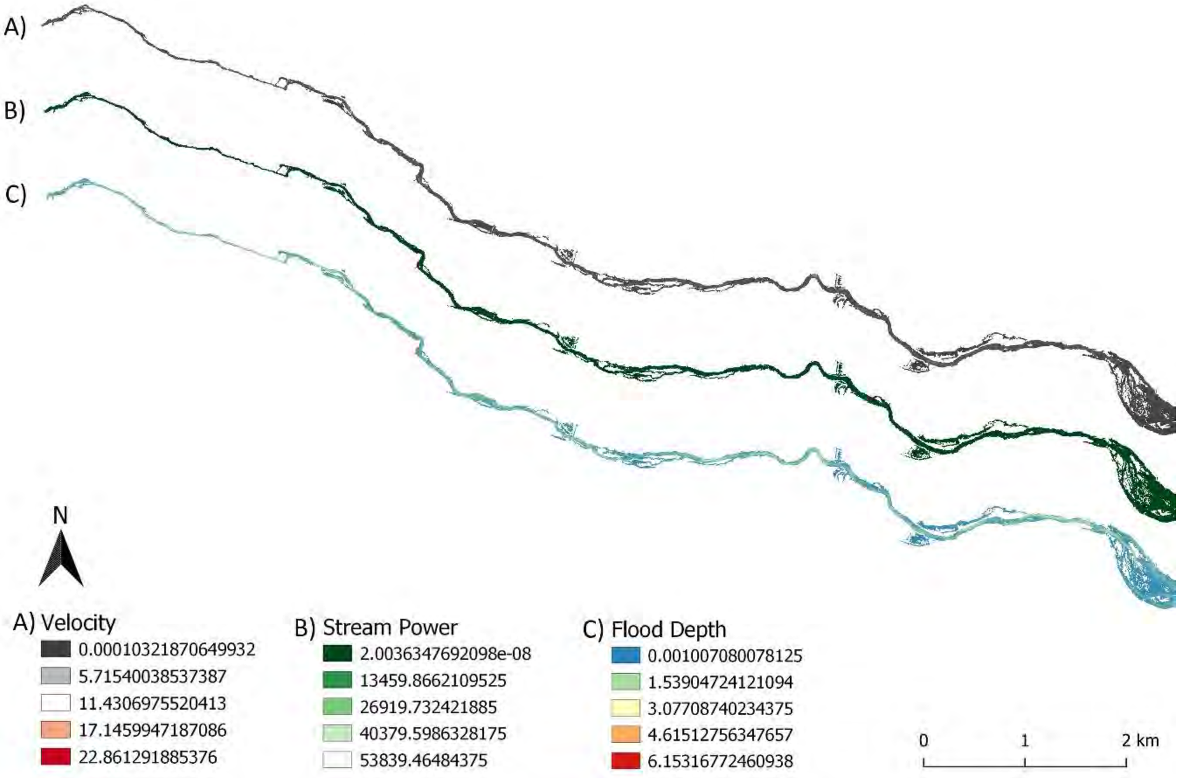


Figure 15: Hydraulic models of the Kromme river depicting **A**) Vel, **B**) SPwr, and **C**) FDep for a modelled 1:50 year flood of 47 cumecs at the lower end of the study reach.

4.5. Data analysis

All data analysis was carried out using Excel and Addinsoft's (2016) XLSTAT, which is a statistical analysis add-in for Excel. The aims were to see whether or not the environmental data collected were related to the distribution of the three palmiet classes (Regen, Stable, Persist) and the NPal class. The collective four classes will henceforth be referred to as "palmiet classes". Techniques that were appropriate for a large multivariate data set were selected, which was made up of both categorical and continuous data.

4.5.1. Exploring relationships between environmental variables and palmiet classes

Ordination is a popular tool in ecology given its ability to simplify complex sets of data, and it is particularly useful for the type of data collected in this study, where it can show relationships between dependent and independent variables in a limited number of dimensions (Capblancq, 2021). A redundancy analysis (RDA) was performed in order to explore the relationship between the environmental variables and the palmiet classes. About 30 % of all samples in each palmiet class were randomly selected through the use of XLSTAT's Data Sampling function and included in the redundancy analysis in order to provide some insight into the relationship between the classes and the environmental variables. These insights were further explored through more specific explanatory research methods, where all the data was used. The independent continuous variables consisted of PSiz, OMat, DThal, REle and DWTa, while the variables representing geomorphic setting were categorical.

An RDA was also completed for the hydraulic data, where again a subset of about 30 % of all samples in each class of palmiet were included. Here, only the Regen and Stable classes were explored, as many of the samples in the Pers class did not experience inundation under the modelled flood scenario.

4.5.2. Validating the relationship between the environmental variables and the palmiet classes

For the purpose of validating the relationships between the environmental variables and palmiet classes, a logistic regression was used. Logistic regression was found to be appropriate for the purpose of modelling the response of palmiet classes to the binomial response variables (Hosmer and Lemeshow, 2000). The purpose of the binary logistic regression was to see if the variables associated with the classes were in fact reliable predictors of palmiet being present in the class or absent from the class.

Similar to the RDA, the environmental predictor variables were a mixture of continuous and categorical variables, and therefore they were similarly coded. DWTa and REle were highly correlated, given which the DWTa was removed from the logistic regression analysis. The response variables, which were the four palmiet classes, were also coded with binary numbers, where 1 represented presence in the class of interest, while 0 represented absence from the class of interest. For the categorical variables related to geomorphic type, issues of separation occurred due to the mutually exclusive nature of these variables. A solution to this is the application of Firth's (1993) penalised regression function, which uses a penalised estimation method (Heinze and Schemper, 2002; Allison, 2008; Addinsoft, 2016). The Firth's Method function is included with the XLSTAT package, such that the overall contribution of the variables was determined without incurring estimation bias.

Four models were created due to there being four classes of palmiet. Each model produced a parametric table and a classification table. The parametric tables consisted of the variables' standardised coefficients, standard errors (S.E.), the Wald $\chi 2$, and the Pr > $\chi 2$. These were used to evaluate the overall contribution of the variables to the models, with significant variables ($P < 0.05$) being considered to best discriminate between the categorical classes. The categorisation table showed the outcomes of the prediction in the form of the number of samples that were correctly classified as either being present in the class, or absent from the class (true positives and true negatives) and was used as a test of model performance. Again, the hydraulic variables were not included in the logistic regression analysis as result of there being fewer samples due to many of the samples in the Pers class falling outside the areas of inundation under the modelled flood scenario. The relationships between the hydraulic variables were instead analysed through simple linear regression models.

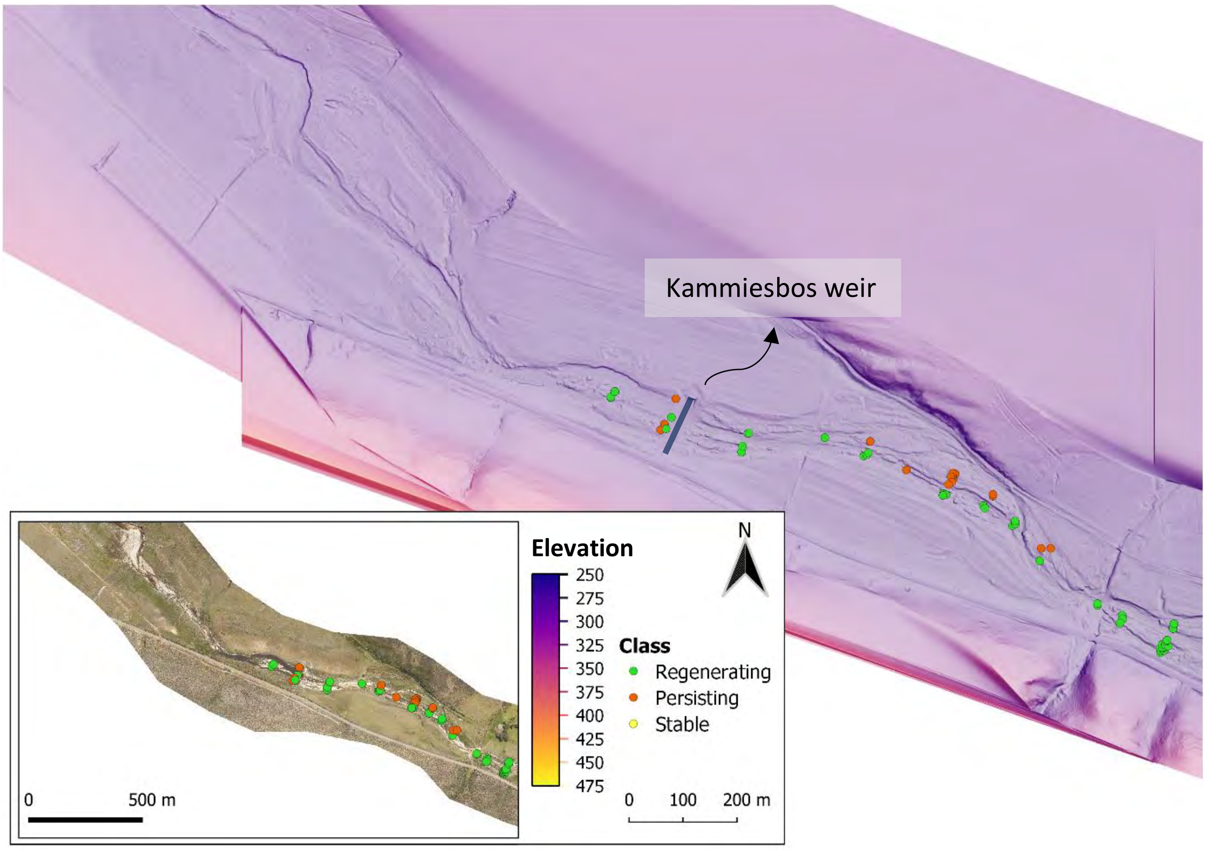
4.5.3. A further evaluation of the variation of variables across the palmiet classes

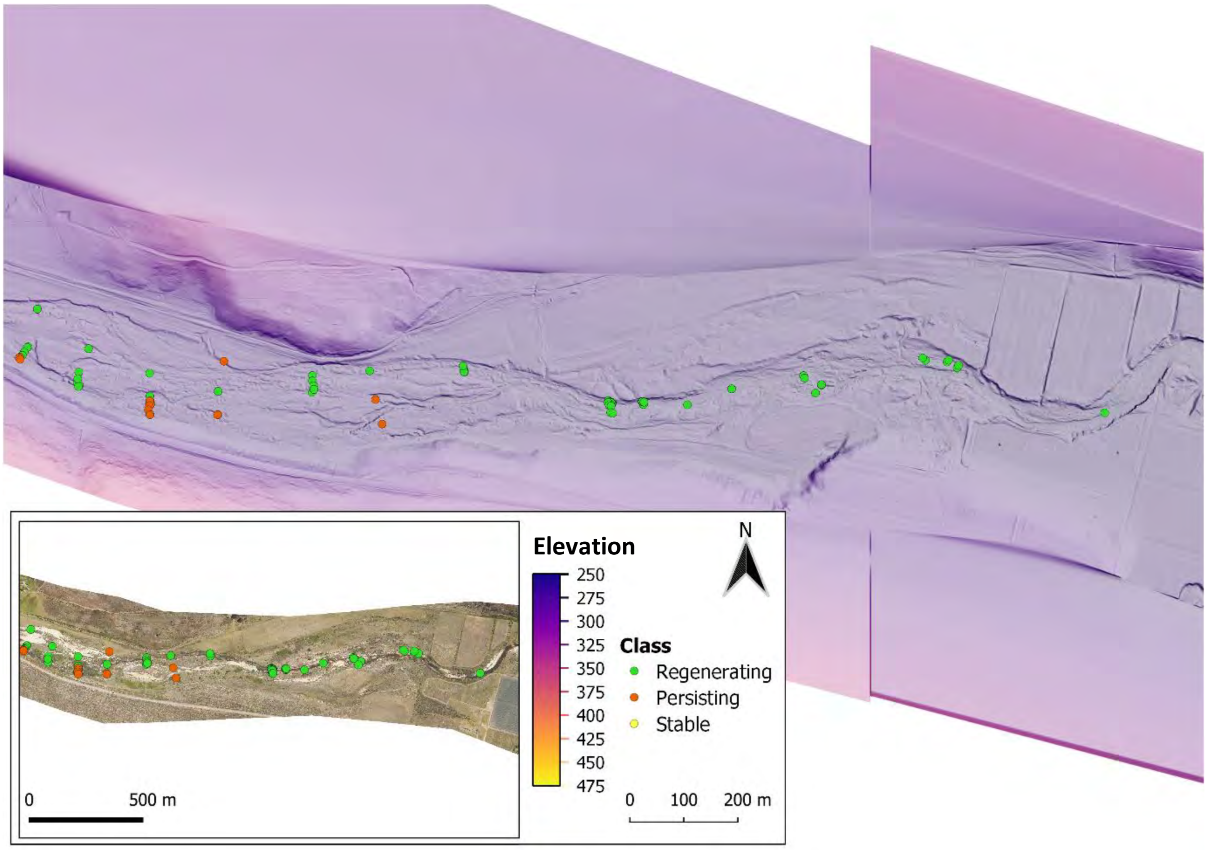
A one-way analysis of variance (ANOVA) was used to more closely examine variation of the continuous variables across the four classes. The ANOVA models confirmed whether there were significant differences ($P < 0.05$) between the variable means across classes. Tukey's multiple range test (MRT) separated means for significant ANOVA models. Classes were grouped based on the differences or similarities and represented by the letters A, B and C, which were superimposed over box and whisker plots for each environmental factor for each of the palmiet classes.

5. RESULTS

5.1 The distribution of palmiet throughout the wetland

The series of maps (Figure 16) show the distribution of the three classes of palmiet from the Kammiesbos weir to the Jagersbos weir at the lower end of the wetland. These include the persisting (Pers), regenerating (Regen) and stable (Stable) classes. The maps are organised from upstream to downstream (west to east). Palmiet occurs in a range of areas throughout the wetland, including areas where recent geomorphic disturbance occurred as erosion or deposition, as well as stable areas. These areas include gully beds (GBed), gully bars (GBar), floodout (FOut) deposits, the elevated remnant valley bottom adjacent to a gully (RVBot) and preserved areas of valley-bottom wetland (VBot) that have not experienced recent geomorphic change. The maps shown in Figure 16 do not include non-palmiet samples, but instead focus only on sites where palmiet has been sampled from the study site.

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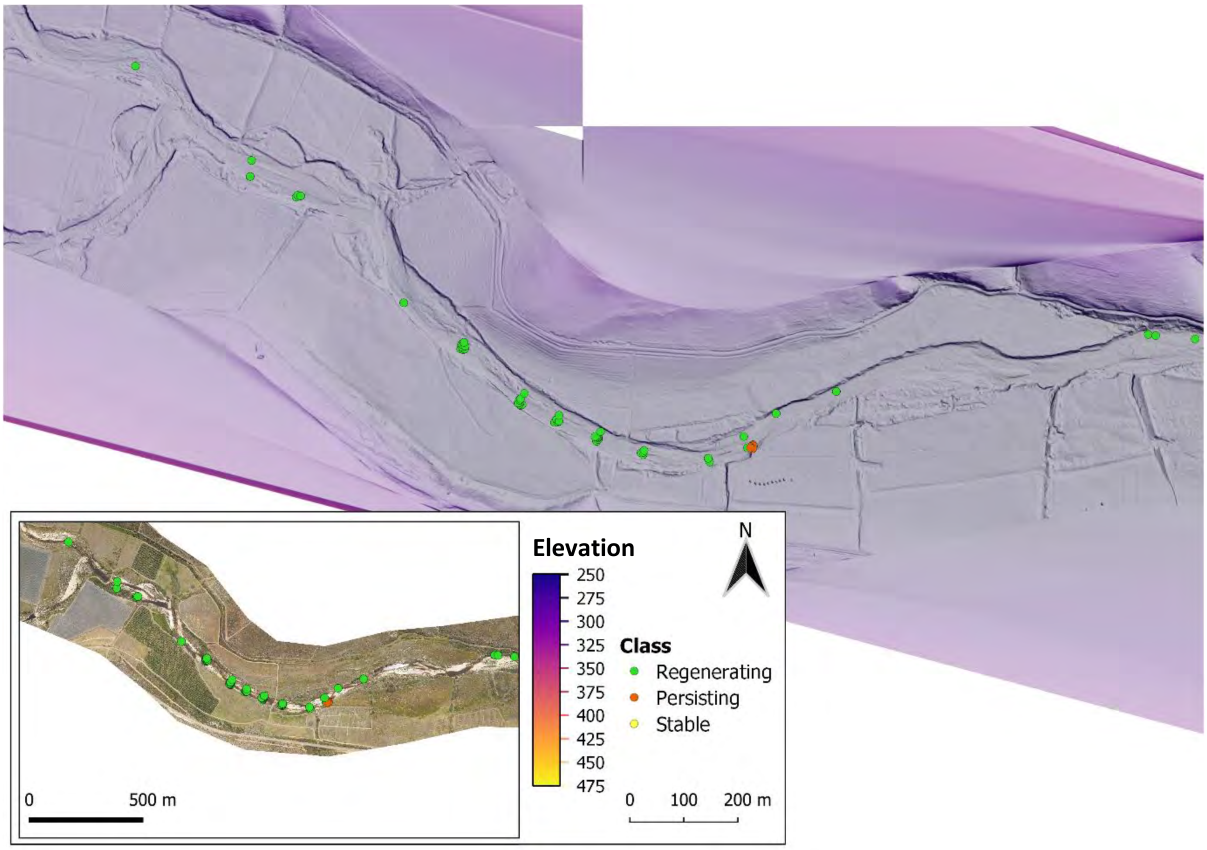
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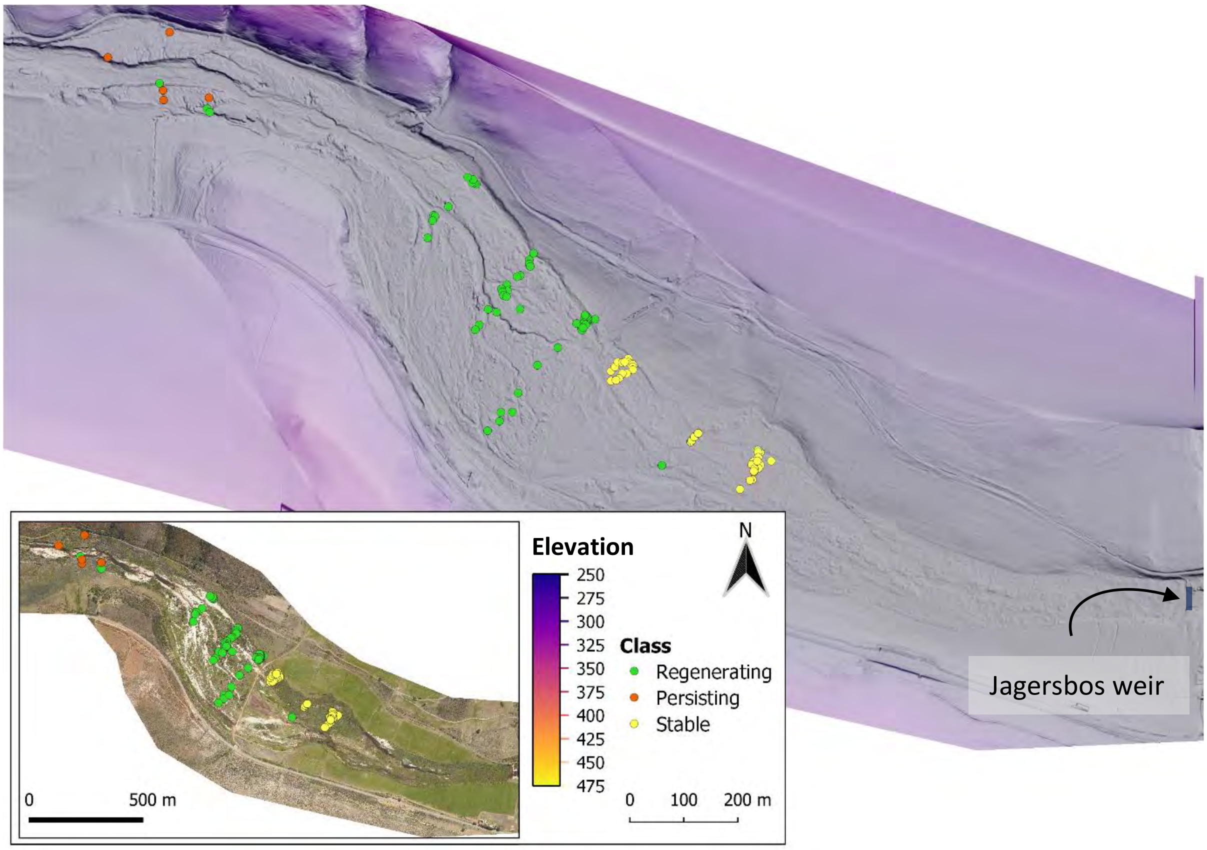


Figure 16: A series of hillshade models with an orthophotographic inset map showing the distribution of the three classes of palmiet. The maps are arranged from upstream to downstream.

5.1.1. Areas of young palmiet individuals or clumps (the regenerating class)

Deep gullies punctuate a large portion of the reach of the Kromme River that was sampled, with the toe of the gully ending in the FOut feature that occurs at the most downstream reach on the farm Jagersbos. Within the gullies, palmiet is most commonly found as individuals or as small clumps within two distinct geomorphic zones favouring its regeneration, namely the GBeds and GBars (Figure 17A, B and C). The GBed consists of coarse sediments, pebbles and small boulders, and in some areas, even bedrock. The GBars are made of mostly sandy sediments and they are slightly raised above the GBed, often occurring on the sides of gullies and sometimes making up transitional areas between the GBed and RVBot. Palmiet is found to occur as single palmiet seedlings, small monospecific stands (< 5 m diameter) or islands, or large palmiet plants growing clonally alongside stream channels and into active channels.

Across the large FOut at the most downstream reach of the sampled area on Jagersbos farm, palmiet is found to be growing as clumps of young plants across the entire width of the depositional feature (Figure 17D and E). Juvenile palmiet plants are found to be either growing near a local thalweg that represented the bed of an old abandoned flow path, or they grow as scattered clumps on the FOut. The palmiet on the FOut occurs more often as small to large clumps with diameters of 5 m or more.

The Regen class of palmiet with young individuals or clumps of individuals makes up 231 of the 330 palmiet samples (70 % of the total number of palmiet samples). It should be noted that the absence of palmiet in the Regen class in the first 700 m of the channel immediately upstream of the floodout was largely due to issues of accessibility and due to plants falling outside of the transects.

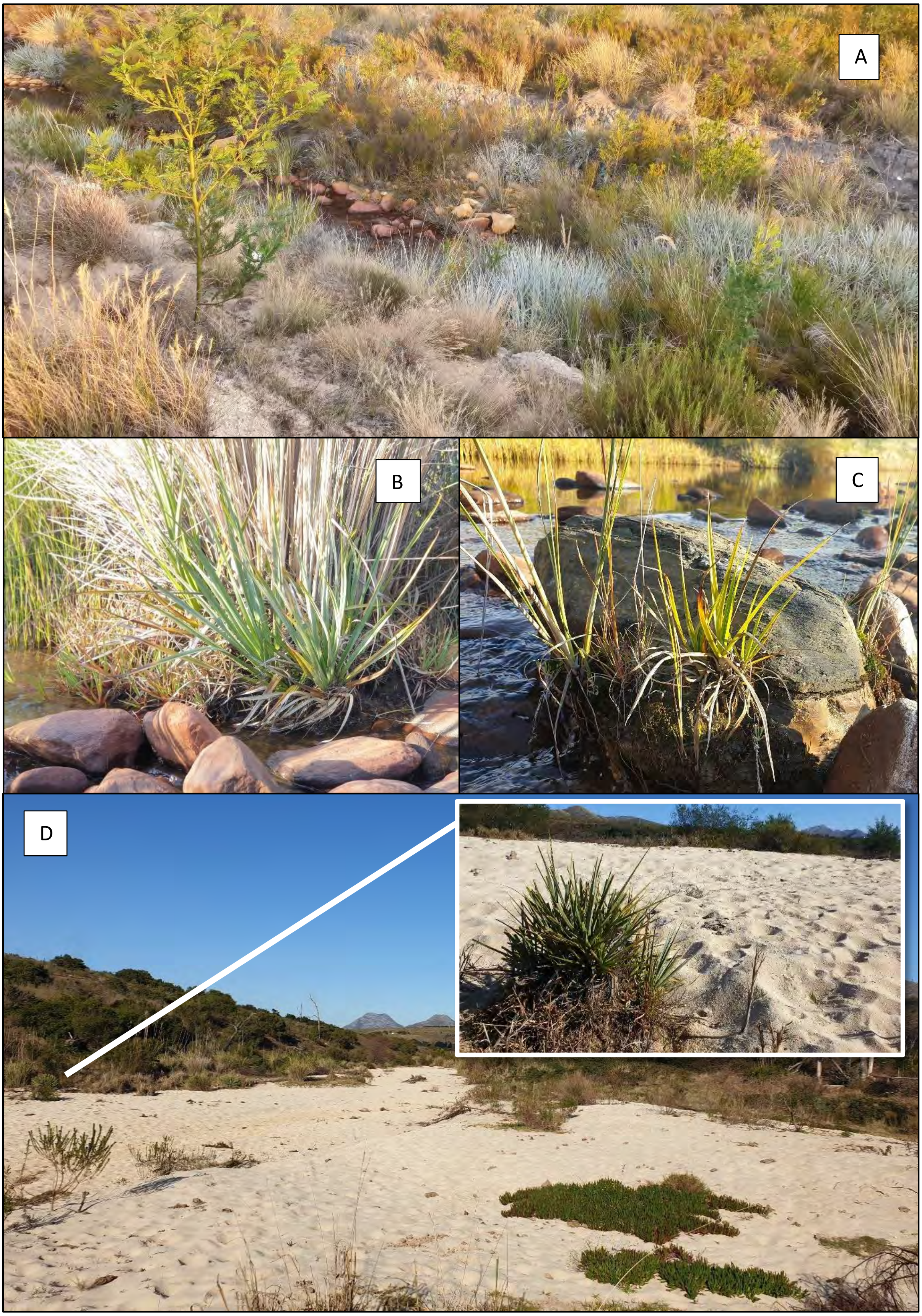
5.1.2. Areas of extensive mature stands of palmiet (stable palmiet class)

The palmiet in the Stable class is found at the most downstream reach surveyed across a band of preserved valley-bottom wetland on the northern side of the valley floor. Here palmiet occurs as a dense band that spans tens of metres, with plants generally taller than 2 m, sometimes reaching heights in excess of 3 m (Figure 17F, G and H). In some parts, dense clonal bands of palmiet are found to have interwoven their stems, such that they are found to be growing across what seems to be a channel. The VBot is broad and flat, and it is without any deep incised gullies such as those in the upper disturbed reaches.

Of the 330 samples, the palmiet in the Stable class comprises 49 samples, or 15 % of the total number of samples. This area seems unaffected by past erosional or depositional disturbance events (two or three decades based on flood history, local knowledge and past aerial photography).

5.1.3. Stands of mature palmiet elevated above the gully bed in eroded reaches (the persisting class).

Mature stands of palmiet were often found as small patches that were elevated more than 1.5 m (generally > 2 m) above the bed of a nearby gully. These stands were usually associated with the RVBot surface adjacent to the gullies (Figure 17I and J). Of the 330 total number of samples, 50 were of the Pers group, making up 15 % of the samples.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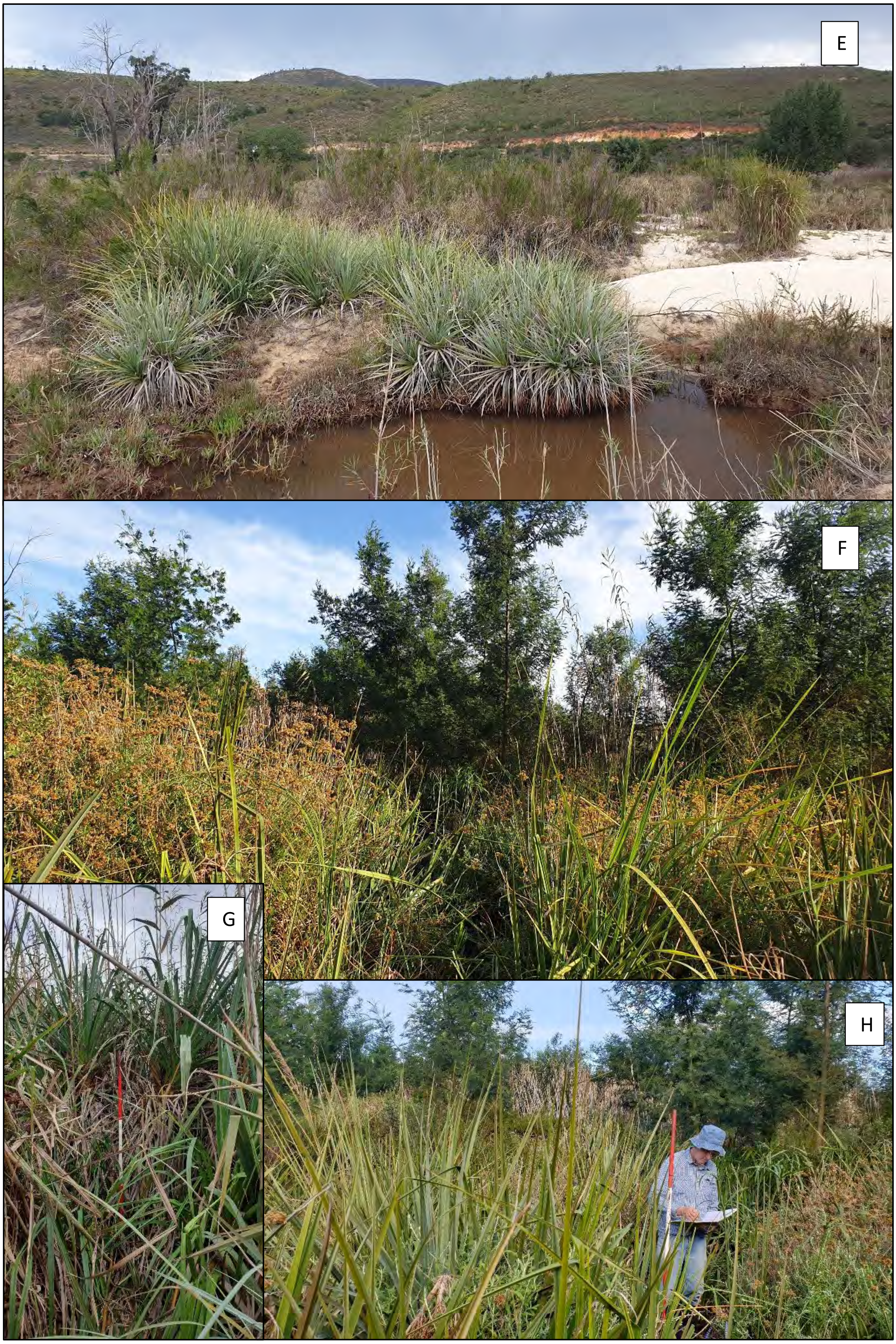
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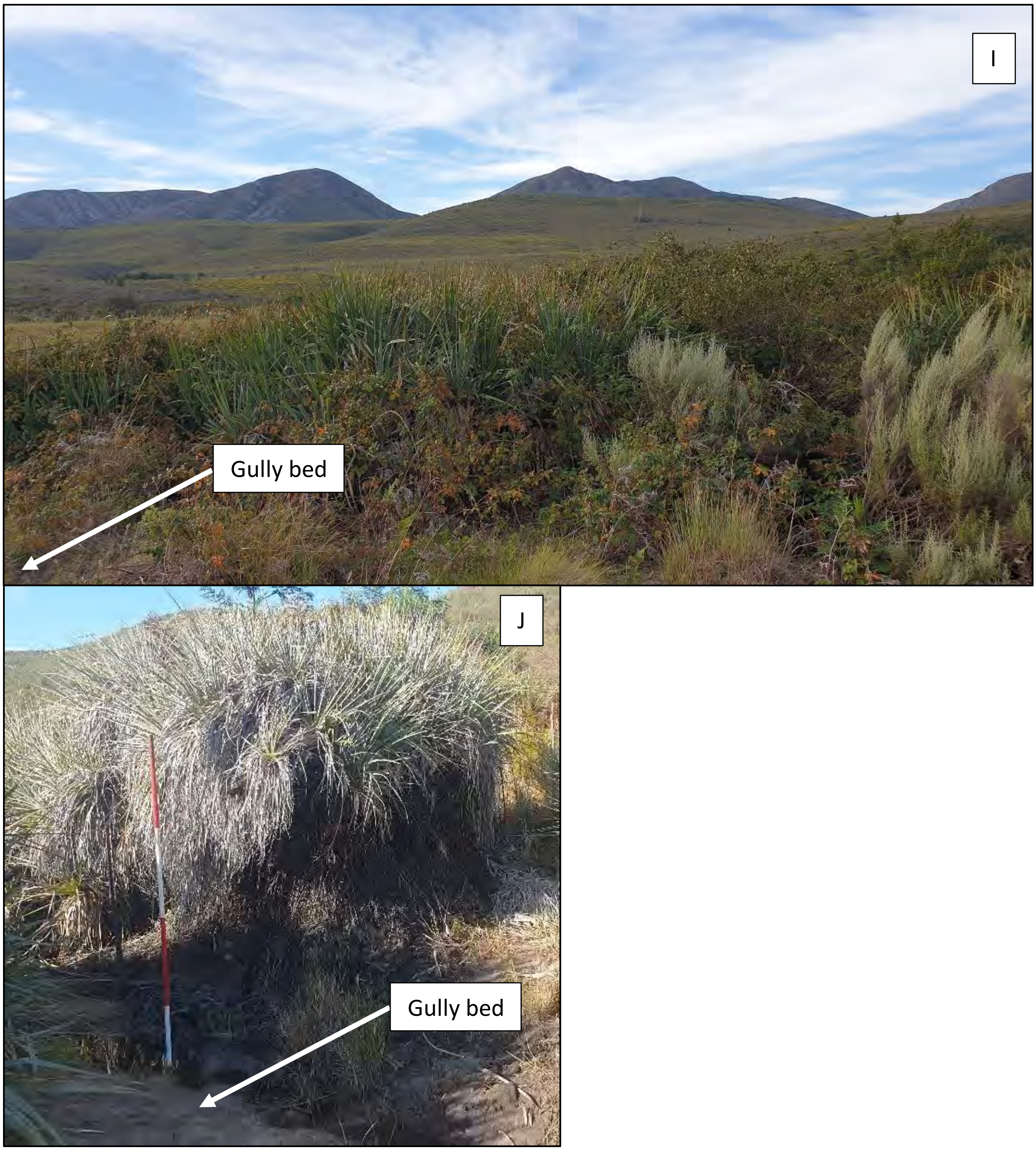


Figure 17: An illustration of palmiet in various stages of regeneration and in various classes as defined in this study and as observed throughout the wetland. **A**) Young palmiet plants occurring alongside a stream on the Jagersbos FOut as both clumps and longer bands along the active channel. **B**) Palmiet growing on a depositional bar adjacent to the stream in the upper study area. **C**) Palmiet growing on a partly-eroded sand deposit adjacent to a small boulder on the gully bed. **D**) A small clump of palmiet growing on the Jagersbos FOut deposit. **E**) Clumps of palmiet growing on the Jagersbos FOut adjacent to an active channel. **F**, **G** and **H**) Palmiet in the stable valley bottom reach downstream of the Jagersbos FOut. **I** and **J**) Clumps of palmiet on the RVBot elevated above the bed of an erosion gully (GBed), representing the Pers palmiet class.

5.2. The distribution of palmiet classes in relation to environmental variables

This section describes the broad relationship between the distribution of different classes of palmiet and measured environmental variables using redundancy analysis (RDA). It explores the relationship between the distribution of classes of palmiet and 1) continuous environmental variables particle size (PSiz), organic matter (OMat), depth to the water table (DWTa), distance from the thalweg (DTha) and relative elevation (REle) and 2) categorical geomorphic variables FOut, GBed, GBar, VBot and RVBot.

A number of hydraulic variables were also included, which include velocity (Vel), stream power (SPwr), and flood depth (FDep), but given that not all samples were inundated for the modelled flood scenario, they were analysed separately just for those samples that were inundated.

5.2.1. An exploration of the relationship between the distribution of palmiet classes and environmental (other than hydraulic) characteristics

Figure 18 shows the results of the RDA, including environmental variables other than hydraulic variables. The RDA biplot shows the relationship between the response variables (palmiet classes) and the measured environmental variables. The variation is explained by the first three factors (F1, F2, F3) where F1 explains 61.25 %, F2 explains 30.06 % and F3 explains 8.68 % (Table 4). Given that F3 explains such a small proportion of the variation, it has been excluded from further analysis. The centroids of the palmiet classes Regen, Stable, Pers and NPal are shown as green triangles for Factor 1 (F1) and Factor 2 (F2) of the RDA, while environmental factors are shown as red dots at the end of red lines that originate at the origin (Figure 18).

The variables GBed, GBar, FOut and PSiz are all correlated with each other and are positively related to F1 scores. This means that the geomorphic variables GBed, GBar, and FOut are associated with an increase in PSiz. These variables are positively related to the regenerating class of palmiet (Regen), the centroid of which is displayed with a high positive F1 and low F2 score. OMat is negatively related to F1 however, and therefore to GBed, GBar, FOut and PSiz. This indicates that an increase in the F1 score is associated with a decrease in OMat but with increased PSiz and with the geomorphic categories GBed, GBar, and FOut.

The palmiet class Pers occurs in areas with negative F1 and F2 scores and is associated with samples with a high DTha, high REle above the thalweg, a great DWTa and occurrence on the RVBot. DWTa and REle are highly correlated to each other with a correlation coefficient of 0.91 ($P < 0.0001$). This class of palmiet also has small a PSiz and higher OMat content.

Palmiet in the Stable class is related to both F1 and F2, as it scores a high positive score on F2 and a low negative score on F1. It is strongly associated with the VBot. Palmiet in this class has a low REle and DWTa, and is characterised by small PSiz and a high OMat content when compared to palmiet in the Regen class. The Stable class has also not been affected by recent geomorphic disturbances and remains as a largely intact class of palmiet wetland vegetation.

The NPal class has low F1 and F2 scores and is not clearly associated with any of the environmental variables measured in this study. This is likely because it is associated with a wide range of environmental characteristics as it covers a very wide range of vegetation types.

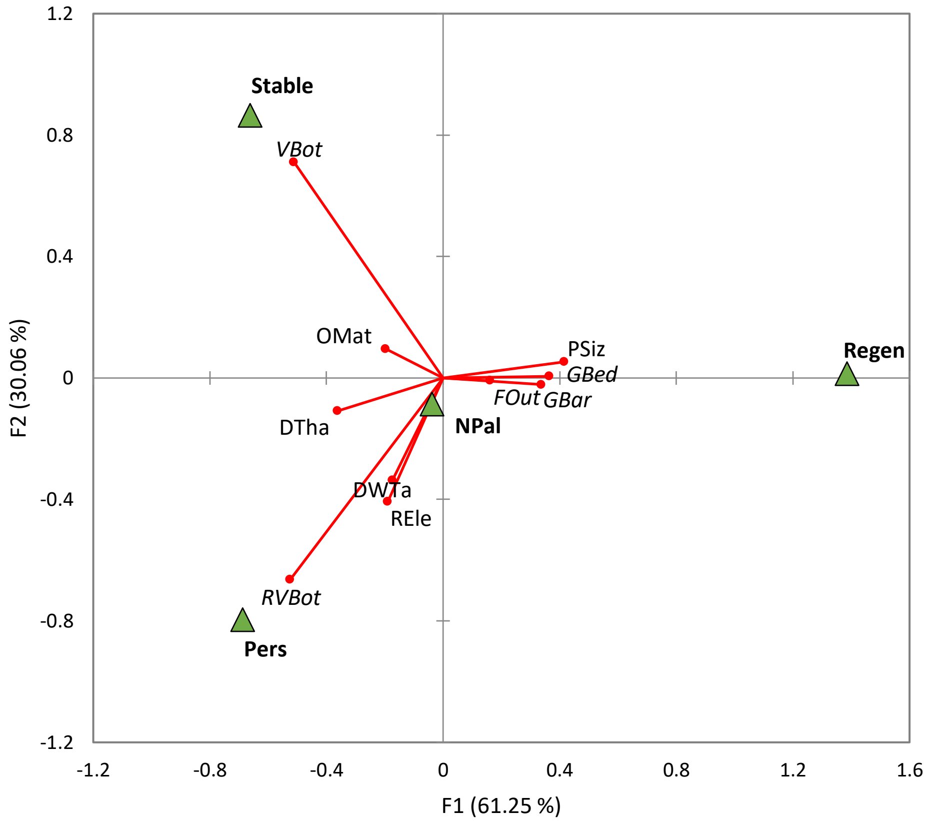


Figure 18: A biplot showing the relationship between classes of palmiet sampled in this study and environmental variables (including geomorphic setting).

Table 4: Eigenvalues and percentages of inertia for the RDA of palmiet classes in relation to non-hydraulic environmental variables

	F1	F2	F3
Eigenvalue	0.2027	0.0995	0.0287
Constrained inertia (%)	61.2536	30.0626	8.6838
Cumulative %	61.2536	91.3162	100.0000

5.2.2 The influence of the hydraulic variables

Figure 19 explores the relationship between palmiet classes in relation to hydraulic variables that are derived by modelling a limited number of flow characteristics following a simulation of a 1-in-50-year flood. These include Vel, SPwr and FDep. F1 explains 98.82 % of the variation in the distribution of the Stable and Regen classes (Table 5), while F2 explains 1.18 % of the variation. Only the Stable and Regen classes of palmiet are examined in this analysis, as many of the samples in the Pers class did not experience inundation under the modelled flood scenario.

Palmiet in the Regen class has low negative F1 scores and occurs in areas where the Vel is higher, and SPwr and FDep are greater than the Stable class (Figure 19). Vel, SPwr and FDep are quite closely related to each other with correlation coefficients shown in Table 6.

The location of the Stable class centroid in relation to the Regen class centroid suggests that the two classes of palmiet are highly dissimilar, with Stable scoring a high score on F1. It is associated with low Vel, SPwr and a low FDep. The palmiet here exists on the VBot where the impacts of erosion and deposition were absent.

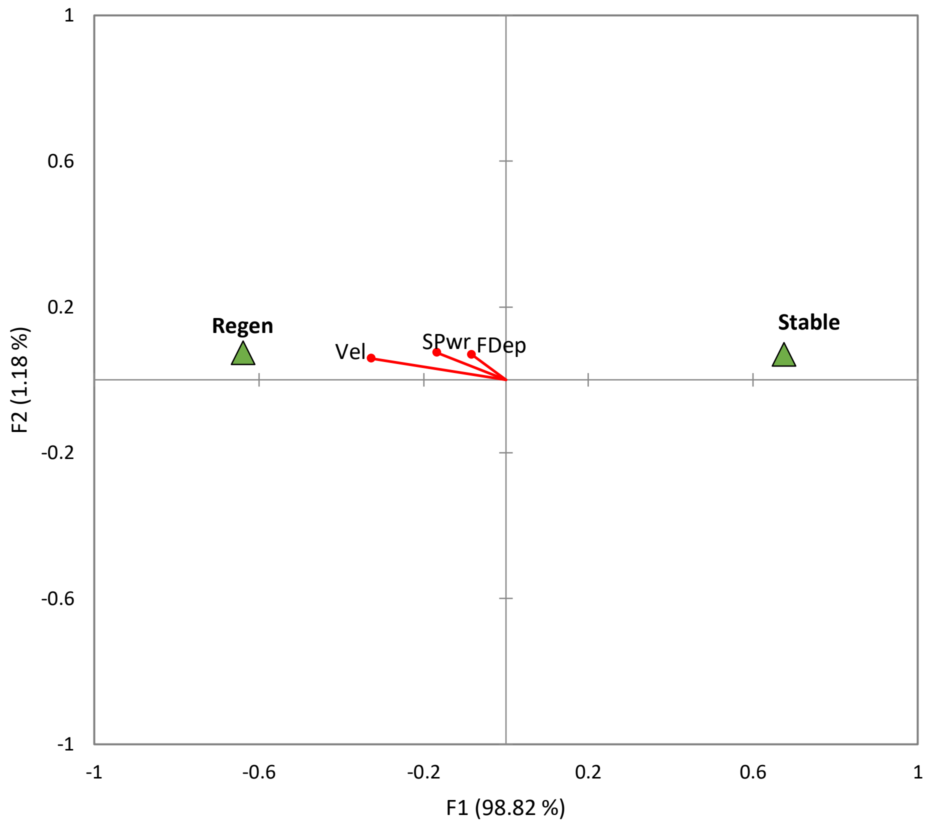


Figure 19: A biplot showing the relationship between the Stable and Regen classes of palmiet and the hydraulic variables Vel, SPwr and FDep.

Table 5: Eigenvalues and percentages inertia for the RDA of palmiet classes in relation to hydraulic variables.

	F1	F2
Eigenvalue	0.0539	0.0006
Constrained inertia (%)	98.8241	1.1759
Cumulative %	98.8241	100.0000

Table 6: A correlation matrix showing the relationship between SPwr, Vel and FDep. All comparisons scored a P-value of < 0.0001.

Variables	SPwr	Vel	FDep
SPwr	**1**		
Vel	0.8707	**1**	
FDep	0.5239	0.6287	**1**

5.3. Environmental variables as predictors of palmiet class distribution

The next section further investigates the relationship between the geomorphic categories and continuous environmental variables and how they might be used as predictors of palmiet class distribution. The correlation matrix below (Table 7) summarises the relationship between all the continuous variables excluding the hydraulic variables. Given the correlation between REle and DWTa ($R = 0.95$; $P < 0.0001$), DWTa has been omitted from the logistic regression modelling. Similarly, the relationship between the hydraulic variables has been analysed through linear regression.

Table 7: A correlation matrix examining relationships between continuous variables (excluding hydraulic data). All values scored a P-value of < 0.0001.

Variables	OMat	PSiz	DWTa	DTha	REle
OMat	**1**				
PSiz	-0.2621	**1**			
DWTa	0.2576	-0.3606	**1**		
DTha	0.2021	-0.2637	0.5586	**1**	
REle	0.2680	-0.3573	0.9532	0.5431	**1**

5.3.1. Predicting palmiet classes based on environmental characteristics

The logistic regression models act as a test of fidelity, confirming whether the palmiet classes can confidently be associated with the variables that are correlated with them. The $\chi 2$ (Wald) and P-values ($\alpha = 0.05$) of each variable that are seen on parameter tables produced by the models (Table 8) show the significance of the relationships between the independent variables of each model, allowing one to see whether or not they contribute to the model in a meaningful way. The models for the palmiet classes Regen, Stable and NPal automatically excluded the geomorphic variable RVBot as a result of multicollinearity, while the model for the Pers excluded GBed. The categorisation table (Table 9) shows the overall success of the model's ability to correctly predict the presence in the class of interest. For each model, the dichotomous dependent variables (the palmiet classes) have been coded as either a 1 or 0, where 1 = present in the class of interest and 0 = absent from the class of interest.

PSiz, DTha, FOut, GBar and GBed ($\chi^2 = 20.2894$, $P < 0.0001$; $\chi^2 = 13.9475$, $P = 0.0002$; $\chi^2 = 16.9000$, $P < 0.0001$; $\chi^2 = 17.3010$, $P < 0.0001$; $\chi^2 = 15.1058$, $P = 0.0001$) are significant contributors in their ability to predict palmiet in the regenerating class. VBot, REle and OMat are not considered significant in their contributions towards predicting the presence of palmiet in this class ($P > 0.05$). The classification table suggests that the model is able to correctly classify 224 of 231 of the Regen class of palmiet samples based on the accompanying environmental variables, which translates to a 96.97% success rate. Of the absent group, 146 out of 196 are correctly classified, making it 74.49 % accurate. The model's overall accuracy in terms of correctly predicting the presence and absence of palmiet in the Regen class is 86.65 %, which is highly accurate.

Five variables are found to contribute meaningfully towards explaining the presence of palmiet in the Pers class. These include OMat, PSiz, REle, along with the categorical geomorphic variables GBar and RVBot ($\chi^2 = 14.1653$, $P = 0.0002$; $\chi^2 = 7.0393$, $P = 0.0080$; $\chi^2 = 7.5708$, $P = 0.0036$; $\chi^2 = 14.0423$, $P = 0.0002$). VBot and FOut are considered insignificant in the context of the model, along with DTha. The classification plot predicts that of the 50 Pers samples, 47 are correctly predicted as being present in this group, while 3 are misclassified. This is a 94.00 % accuracy. Of the 377 other samples that make up the absent group, 371 are correctly predicted, and 6 are misclassified, giving it an accuracy of 98.41 %. Overall, the model accuracy in terms of correct prediction is 97.89 %, which suggests it is highly accurate.

The three explanatory variables OMat, PSiz and VBot ($\chi^2 = 8.1045$, $P = 0.0044$; $\chi^2 = 8.5095$, $P= 0.0035$, $\chi^2 = 10.8505$, $P= 0.0010$) all contribute significantly towards predicting the presence of palmiet in the Stable class. DTha and REle have not contributed significantly, along with the geomorphic variables FOut, GBar, and GBed ($P > 0.05$). Of the 49 Stable palmiet samples, only 2 are misclassified, suggesting that 95.92 % of the samples are correctly predicted as being present in this class. Of the absent group, 98.41 % are correctly predicted as being absent (371 out of 377). The model's overall accuracy in terms of correctly predicting the presence or absence of palmiet is 98.13 %, which is highly accurate.

OMat, PSiz, DTha and GBed ($\chi^2 = 21.0931$, $P < 0.0001$; $\chi^2 = 31.8644$ $P < 0.0001$; $\chi^2 = 11.4392$, $P = 0.0007$; $\chi^2 = 3.9073$, $P = 0.0481$) contribute significantly to explaining the non-palmiet class (NPal). Of the 97 samples in the NPal class, 31 are correctly classified (31.96 %). Of the 330 samples that make up the absent group, 5 are misclassified, meaning the absent group has been correctly predicted with 98.48

% accuracy. The overall ability of the model to correctly predict both the presence and absence groups is 83.37 %. This further suggests that NPal samples are difficult to predict based on their associated environmental variables, probably because they cover a very wide range of environmental variables.

Table 8: The standardised coefficients, standard error, and the χ^2 (Wald) and Pr > χ^2 (Wald) for each variable class generated by the penalised logistic regression models for each class.

VARIABLE	**Regen**				**Pers**			
	Value	S.E.	Wald χ^2	Pr > χ^2	Value	S.E	Wald χ^2	Pr > χ^2
OMat	0.1626	0.1147	2.0087	0.1564	2.2429	0.5959	14.1653	**0.0002**
PSiz	0.5250	0.1165	20.2894	**< 0.0001**	1.1960	0.4508	7.0393	**0.0080**
DTha	-0.4393	0.1176	13.9475	**0.0002**	-0.0655	0.2005	0.1066	0.7441
REle	0.0872	0.1524	0.3275	0.5671	-0.8836	0.3036	8.4686	**0.0036**
FOut	1.3106	0.3188	16.9000	**< 0.0001**	1.3282	0.6801	3.8135	0.0508
VBot	0.0157	0.3863	0.0017	0.9676	-0.4058	0.6701	0.3667	0.5448
GBar	1.5537	0.3735	17.3010	**< 0.0001**	-3.7809	1.3741	7.5708	**0.0059**
GBed	1.2416	0.3195	15.1058	**0.0001**	0.0000	0.0000		
RVBot	0.0000	0.0000			3.7904	1.0115	14.0423	**0.0002**
VARIABLE	**Stable**				**NPal**			
	Value	S.E	Wald χ^2	Pr > χ^2	Value	S.E	Wald χ^2	Pr > χ^2
OMat	0.9620	0.3379	8.1045	**0.0044**	-0.6665	0.1451	21.0931	**< 0.0001**
PSiz	0.6978	0.2392	8.5095	**0.0035**	-0.6283	0.1113	31.8644	**< 0.0001**
DTha	-0.0698	0.2306	0.0916	0.7621	0.2880	0.0852	11.4392	**0.0007**
REle	-0.7463	0.4088	3.3320	0.0679	0.1283	0.1106	1.3436	0.2464
FOut	0.2247	0.6100	0.1357	0.7126	0.1773	0.1113	2.5395	0.1110
VBot	1.5600	0.4736	10.8505	**0.0010**	0.1163	0.1163	1.0000	0.3173
GBar	-1.2869	0.7888	2.6617	0.1028	0.1993	0.1091	3.3402	0.0676
GBed	-0.2776	0.6299	0.1942	0.6595	0.2700	0.1366	3.9073	**0.0481**
RVBot	0.0000	0.0000			0.0000	0.0000		

Table 9: The classification table generated by the logistic regression models.

Class	Present in / Absent from class	Absent	Present	Total	% correct
Regen	Absent	146	50	196	74.49%
	Present	7	224	231	96.97%
	Total	153	274	427	86.65%
Pers	Absent	371	6	377	98.41%
	Present	3	47	50	94.00%
	Total	374	53	427	97.89%
Stable	Absent	372	6	378	98.41%
	Present	2	47	49	95.92%
	Total	374	53	427	98.13%
NPal	Absent	325	5	330	98.48%
	Present	66	31	97	31.96%
	Total	391	36	427	83.37%

5.3.2. The relationship between depth to the water table (DWTa) and relative elevation (REle)

The regression analysis summarises the relationship between DWTa and REle for all the samples. The significant result (Table 10; $R^2 = 0.91$; $P < 0.0001$) confirms that DWTa is positively related to REle, such that samples with a low REle in relation to the local thalweg will have a low DWTa, while samples with a high REle will have a high DWTa.

Table 10: The regression results for DWTa and REle.

Regression Statistics	
Multiple R^2	0.953182
R^2	0.908557
Adjusted R^2	0.908342
S.E.	0.341973
Obs.	427

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	1	493.824	493.824	4222.693	7.1E-223
Residual	425	49.70175	0.116945		
Total	426	543.5258			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.052428	0.022359	2.344885	0.019492	0.008481	0.096376	0.008481	0.096376
X Variable 1	1.136561	0.01749	64.98225	7.1E-223	1.102183	1.17094	1.102183	1.17094

5.3.3. The relationship between the hydraulic variables

The regression analysis looking at the relationship between SPwr and Vel has returned a significant result (Table 11; $R^2 = 0.7066$; $P < 0.0001$). This means that SPwr and Vel are positively related, such that an increase in Vel is associated with an increase in SPwr, and conversely, a decrease in Vel with a decrease in SPwr. Given this, palmiet that occurs where the Vel is relatively high is also associated with high SPwr.

Table 11: The results of the regression analysis examining the relationship between SPwr and Vel.

Regression Statistics								
Multiple R^2	0.840595							
R^2	0.7066							
Adjusted R^2	0.705724							
S.E.	28.78411							
Obs.	337							
ANOVA								
	Df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	668442.8	668442.8	806.7865	3.26E-91			
Residual	335	277555.9	828.525					
Total	336	945998.6						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-37.2559	2.846857	-13.0867	6.83E-32	-42.8559	-31.656	-42.8559	-31.656
X Variable 1	92.21109	3.246414	28.40399	3.26E-91	85.82517	98.59701	85.82517	98.59701

The regression analysis looking at the relationship between Vel and FDep for all samples has returned a highly significant result (Table 12; $R^2 = 0.39$; $P < 0.0001$), which suggests that there is a significant positive relationship between Vel and FDep.

Table 12: The results from the regression analysis of the relationship between Vel and FDep.

Regression Statistics								
Multiple R^2	0.623791							
R^2	0.389115							
Adjusted R^2	0.387292							
S.E.	0.378622							
Obs.	337							
ANOVA								
	Df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	30.58978	30.58978	213.385	9.78E-38			
Residual	335	48.02387	0.143355					
Total	336	78.61364						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.180076	0.043042	4.183767	3.67E-05	0.09541	0.264742	0.09541	0.264742
X Variable 1	0.672299	0.046024	14.6077	9.78E-38	0.581768	0.762831	0.581768	0.762831

5.4. Variation of environmental variables across palmiet classes

An analysis of variance (ANOVA) was completed in order to further examine variation in environmental characteristics across the four palmiet classes, the result of which is shown below in Table 13. All values returned significant P-values ($P < 0.05$), which suggests a significant difference between the variables across the classes. DWTa was again excluded due to its high correlation with REle.

Table 13: The results of the ANOVA comparing individual variables across the four palmiet classes.

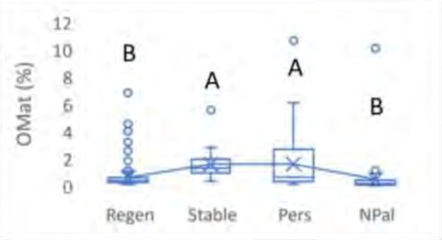
Variable	*Source*	*DF*	*Sum of squares*	*Mean squares*	*F*	*Pr > F*
OMat	Model	3	79.4971	26.4990	16.9717	**< 0.0001**
	Error	423	660.4577	1.5614		
	Total	426	739.9548			
PSiz	Model	3	780203.4106	260067.8035	29.9825	**< 0.0001**
	Error	423	3669097.9215	8673.9904		
	Total	426	4449301.3320			
DTHa	Model	3	13915.1724	4638.3908	32.1621	**< 0.0001**
	Error	423	61004.6136	144.2189		
	Total	426	74919.7860			
REle	Model	3	91.0598	30.3533	44.0200	**< 0.0001**
	Error	423	291.6726	0.6895		
	Total	426	382.7324			
SPwr	Model	3	34822.6276	11607.5425	4.2421	**0.0058**
	Error	333	911176.0004	2736.2643		
	Total	336	945998.6280			
Vel	Model	3	11.7738	3.9246	19.5527	**< 0.0001**
	Error	333	66.8398	0.2007		
	Total	336	78.6136			
FDep	Model	3	1.5993	0.5331	2.6865	**0.0465**
	Error	333	66.0793	0.1984		
	Total	336	67.6786			

Tukey's multiple range test (MRT; Table 14) further examines variation in individual variables across palmiet classes, with classes grouped based on similarities or differences between the distribution of values for environmental variables in each class. These classifications of palmiet groups based on Tukey's MRT has been superimposed onto the accompanying box and whisker plots showing the range (minimum, maximum and interquartile distributions) of variation for each environmental factor, as either an A, B, C or D. Where classes are grouped (assigned the same letter), the distribution of environmental variables is not different between classes, but classes with unique letters are different.

Table 14: Summary of the Tukey's (HSD) multiple range test (MRT). The box and whisker plots show the distribution of values for individual variables across the four palmiet classes. The letters represent the group into which each class has been classified as determined by Tukey's MRT.

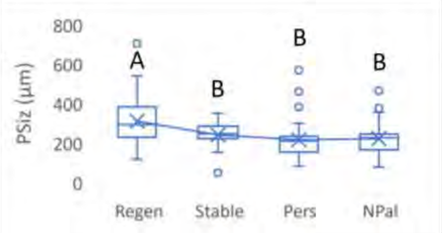
OMat

Contrast	Diff	Std diff	Crit val	Pr > Diff
Stable vs NPal	93.7183	6.4514	2.5793	**< 0.0001**
Stable vs Regen	88.3698	7.8424	2.5793	**< 0.0001**
Stable vs Pers	68.5289	4.6783	2.5793	**< 0.0001**
Pers vs NPal	25.1894	1.3455	2.5793	0.5345
Pers vs Regen	19.8409	1.2155	2.5793	0.6173
Regen vs NPal	5.3485	0.3299	2.5793	0.9876



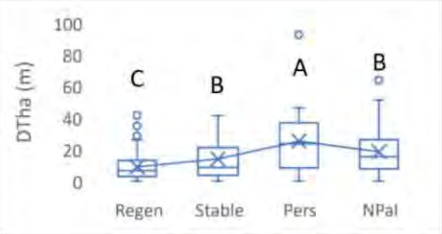
PSiz

Contrast	Diff.	Std diff	Crit val	Pr > Diff
Regen vs Persist	16.2132	8.6556	2.6507	**< 0.0001**
Regen vs NPal	11.2255	4.6501	2.6507	**< 0.0001**
Regen vs Stable	6.7686	3.2374	2.6507	**0.0013**
Stable vs Persist	9.4446	6.5002	2.6507	**< 0.0001**
Stable vs NPal	4.4569	2.1175	2.6507	**0.0348**
NPal vs Persist	4.9877	2.6407	2.6507	**0.0086**



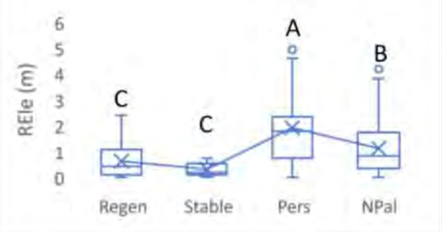
DTha

Contrast	Diff	Std diff	Crit val	Pr > Diff
Pers vs Regen	1.6110	9.6514	2.5793	**< 0.0001**
Pers vs Stable	1.3007	10.0423	2.5793	**< 0.0001**
Pers vs NPal	0.7980	5.5197	2.5793	**< 0.0001**
NPal vs Regen	0.8131	5.5867	2.5793	**< 0.0001**
NPal vs Stable	0.5027	5.0040	2.5793	**< 0.0001**
Stable vs Regen	0.3103	2.3762	2.5793	0.0833



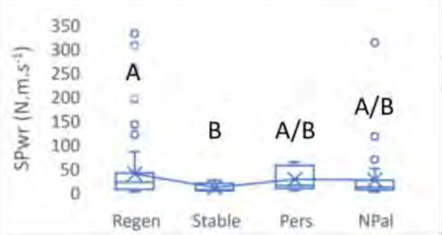
REle

Contrast	Diff	Std diff	Crit val	Pr > Diff
Pers vs Stable	1.6110	9.6514	2.5793	**< 0.0001**
Pers vs Regen	1.3007	10.0423	2.5793	**< 0.0001**
Pers vs NPal	0.7980	5.5197	2.5793	**< 0.0001**
NPal vs Stable	0.8131	5.5867	2.5793	**< 0.0001**
NPal vs Regen	0.5027	5.0040	2.5793	**< 0.0001**
Regen vs Stable	0.3103	2.3762	2.5793	0.0833



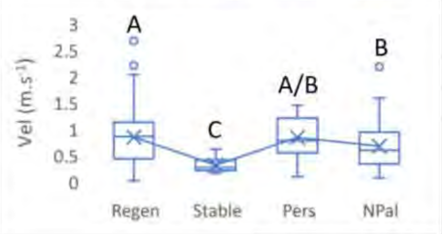
SPwr

Contrast	Diff	Std diff	Crit val	Pr > Diff
Regen vs Stable	28.5476	3.4288	2.5821	**0.0038**
Regen vs NPal	12.2589	1.6348	2.5821	0.3605
Regen vs Pers	11.1706	0.9316	2.5821	0.7879
Pers vs Stable	17.3770	1.2737	2.5821	0.5804
Pers vs NPal	1.0883	0.0827	2.5821	0.9998
NPal vs Stable	16.2887	1.6404	2.5821	0.3574



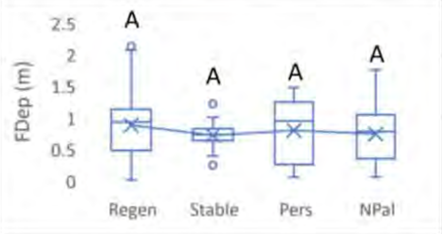
Vel

Contrast	Diff	Std diff	Crit val	Pr > Diff
Regen vs Stable	0.5346	7.4974	2.5821	**< 0.0001**
Regen vs NPal	0.1740	2.7097	2.5821	**0.0355**
Regen vs Pers	0.0076	0.0742	2.5821	0.9999
Pers vs Stable	0.5270	4.5101	2.5821	**< 0.0001**
Pers vs NPal	0.1664	1.4770	2.5821	0.4525
NPal vs Stable	0.3606	4.2402	2.5821	**0.0002**



FDep

Contrast	Diff	Std diff	Crit val	Pr > Diff
Regen vs Stable	0.1619	2.2830	2.5821	0.1041
Regen vs NPal	0.1353	2.1193	2.5821	0.1491
Regen vs Pers	0.0796	0.7791	2.5821	0.8639
Pers vs Stable	0.0823	0.7085	2.5821	0.8937
Pers vs NPal	0.0558	0.4980	2.5821	0.9595
NPal vs Stable	0.0265	0.3138	2.5821	0.9893



5.4.1. Organic matter (OMat)

The results of the ANOVA suggest that the mean OMat content across the four classes varies significantly ($P < 0.0001$). Based on the box and whisker plots, the Regen group has a mean OMat content of 0.61 %, the Stable group 1.60 %, the Pers group 1.59 %, and the NPal 0.50 %. The MRT shows significant differences ($P < 0.0001$) between the class means of Stable versus (vs) NPal, Stable vs Regen, Pers vs Stable and Pers vs NPal. Given this, the MRT has grouped palmiet in the Regen and NPal classes together (B), while palmiet in the Pers and Stable classes were found to be similar (A). This suggests that palmiet in the Stable and Pers class have the highest average OMat content in their soils, while the Regen class has the lowest.

5.4.2. Particle size (PSiz)

For PSiz, the results of the ANOVA suggests that there is a significant difference between the class means. Tukey's MRT suggests that palmiet in the Regen class have different PSiz to palmiet in the Pers, Stable and NPal classes ($P < 0.0001$). The box and whisker samples show that the average PSiz is 309.33 µm for the Regen class, which is the largest when compared to the other classes. Palmiet in the Stable and Pers class have an average PSiz of 240.80 µm and 215.61 µm respectively, while NPal samples have an average PSiz of 220.96 µm. Based on the class means, the Regen class has been grouped into a group of its own (A) by the MRT, while the Stable, NPal, and Pers classes have all been grouped together (B).

5.4.3. Distance from thalweg (DTha)

The ANOVA looking at DTha has returned significant results ($P < 0.0001$), with Tukey's MRT showing that all the classes are significantly different. However, the Stable vs NPal classes, while returning a P-value of 0.0348, have not been grouped separately by the MRT, and are instead grouped together as B. The Regen and Pers classes are grouped separately (C and A). The box and whisker test shows that palmiet in the Pers class have the furthest mean DTha at 25.35 m. Palmiet in the NPal class have a mean of 18.58 m. The Regen class has the lowest mean of 9.14 m, while the Stable class has a mean distance of 14.12 m.

5.4.4. Relative elevation (REle)

REle varied significantly amongst classes based on the ANOVA ($P < 0.0001$). Tukey's MRT shows that the Regen vs Stable classes are not significantly different ($P = 0.0833$), while the rest of the class means have highly significant differences ($P < 0.0001$). The box and whisker samples suggest that palmiet in the Stable class have the lowest mean REle at 0.32 m, followed by palmiet in the Regen class, which have a mean REle of 0.63 m. These have been grouped together by the MRT as C. The Pers class has the highest mean REle of 1.93 m, while NPal has a mean of 1.13 m, and they have therefore been grouped separately by the MRT as A and B.

5.4.5. Stream power (SPwr)

The ANOVA results returned a significant result for SPwr (P= 0.0058). The MRT only returned one significant result however, which was for Regen vs Stable (P = 0.0038). Regen has the highest mean SPwr unit of 37.41 $N.m.s^{-1}$ and was grouped as A. This was followed by the Pers group at 26.24 $N.m.s^{-1}$ (grouped as A/B), NPal at 25.15 $N.m.s^{-1}$ (A/B), and then lastly Stable at 8.86 $N.m.s^{-1}$ (B), which has the lowest value overall.

5.4.6. Velocity (Vel)

The ANOVA results for Vel shows a significant variation between the means of the four classes ($P < 0.0001$). Tukey's MRT shows that there are significant differences between the Regen vs Stable classes ($P < 0.0001$), Regen vs NPal classes (P = 0.0355), the Pers vs Stable classes ($P < 0.0001$) and the NPal vs Stable classes (P = 0.0002). Stable has the lowest mean Vel at 0.31 $m.s^{-1}$, with the Regen and Pers classes both sharing a mean Vel of 0.84 $m.s^{-1}$, which are the highest values of the classes. Samples in the NPal class have a mean Vel of 0.67 $m.s^{-1}$. Regen is grouped as A and Pers as A/B. The NPal class is grouped as B, while Stable, the group with the lowest mean Vel, has been grouped as C.

5.4.7. Flood depth (FDep)

The ANOVA results for samples with FDep are significant (P = 0.0465), however the MRT has not found any significant differences between the classes. Palmiet in the Regen class have a mean FDep of 0.88 m, followed by palmiet in the Pers class, where the mean FDep is 0.80 m. Stable has the lowest FDep at 0.71 m, while NPal has a mean depth of 0.74 m.

6. DISCUSSION

6.1. Hydrogeomorphic disturbance and palmiet regeneration

Palmiet is found to be widespread throughout the Kromme River, with presence in gullies, on the margins of gullies along the remnant valley bottom, and in areas that are unaffected by geomorphic disturbance. Where it occurs in undisturbed areas, it forms dense, expansive clonal stands that span tens of metres. While palmiet is found throughout the wetland in various stages of its life cycle, it is found to be actively regenerating in geomorphic settings that have been created by recent (< 10 years at the time of sampling) hydrogeomorphic disturbance. These include geomorphic features within gullies, such as on gully beds and gully bars, as well as immediately downstream of gullies on the large depositional floodout feature in Jagersbos.

For a wetland to form, the water table is usually found near or at the surface such that the land is flooded with shallow water periodically or permanently (Ollis, 2013; Mitsch and Gosselink, 2015). This leads to anaerobic soil conditions where only vegetation with the appropriate adaptations can survive (Mitsch and Gosselink, 2015). Additionally, an appropriate geomorphic setting needs to be present, such as having a low longitudinal slope and a broad cross-section, which further encourages shallow flooding and slow flow conditions (Gosselink and Turner, 1978; Ellery *et al.,* 2009; Mitsch and Gosselink, 2015).

The valley bottom in Jagersbos hosts a pristine wetland that is dominated by large clonal stands of adult palmiet plants that often exceed a height of 3 m (Figure 20). This area displays typical wetland characteristics, such as having a low depth to the water table and elevation relative to the thalweg (< 0.50 m, but generally flooded), diffuse flow, high organic matter content (1.60 %) when compared to what was measured in gullies (0.61 %), and an accumulation of fine sediments (mean geometric particle size = 215.61 µm) throughout the reach as a result of the tall, dense, robust and deep-rooted vegetation increasing the overall roughness, thereby altering the hydrological characteristics (Hupp, 1992). Flow modelling of 1-in-50-year floods has further revealed that this valley-bottom wetland plays an important role in erosion control and flood attenuation, where the velocity under flood conditions is approximately 0.31 $m.s^{-1}$, unit stream power is approximately 8.86 $N.m.s^{-1}$, and the flood depth is approximately 0.71 m. This reach has been largely undisturbed for decades and can be considered to represent stable palmiet wetland conditions that may represent the climax state, such that autogenic processes dominate (Russel, 2009).

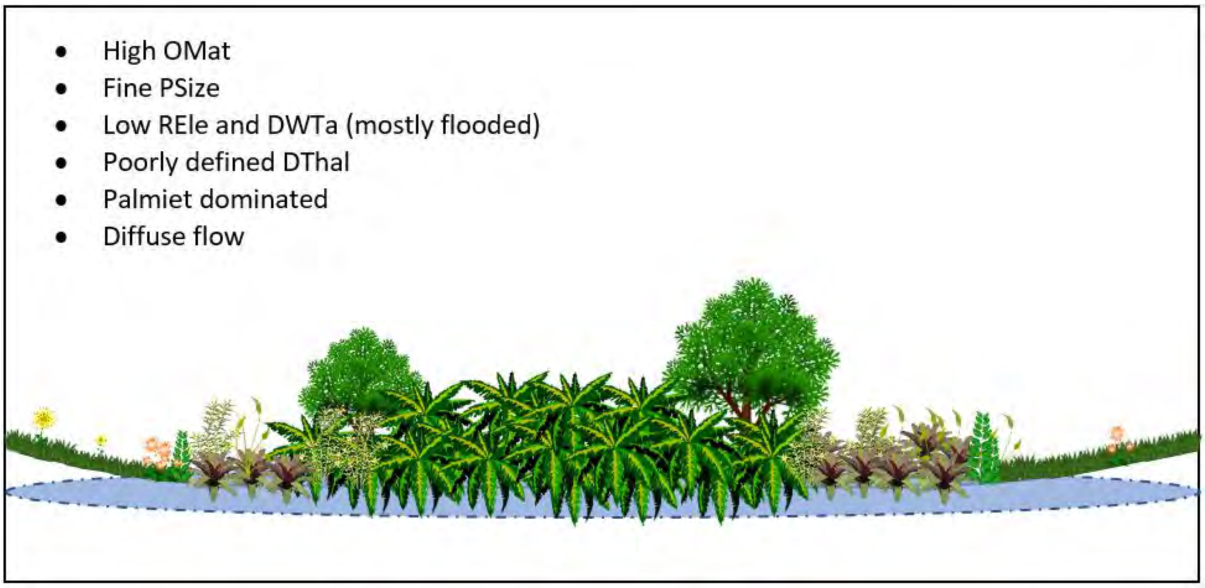


Figure 20: A diagram depicting characteristics of the undisturbed valley bottom palmiet wetland.

Much of the upper Kromme wetland occupies a broad valley with a gentle longitudinal slope. It is thought that much of the valley bottom in the study area was a wetland that shared many of the environmental characteristics that are associated with the undisturbed palmiet wetland in Jagersbos (Rebelo, 2012). Since the two uplift events 20 Mya however (Partridge and Maud, 2000; McCarthy and Rubidge, 2005), the upper Kromme River wetland has been undergoing morphological changes associated with river rejuvenation, where the river has incised through the African Erosion Surface (AES), and the valley now lies on the Post-Africa Erosion Surface 1 (PAES1) and the Post-Africa Erosion Surface 2 (PAES2). Additionally, cyclical cut-and-fill processes initiated by trunk-tributary interactions have strong controls over the Kromme valley's geomorphic structure and dynamics and therefore the functioning of the Kromme River wetland (Lagesse, 2017; McNamara, 2018; Pulley *et al.,* 2018).

A study into the structure of the upper Kompanjiesdrif basin revealed that tributary alluvial fans are responsible for altering the trunk stream's hydrodynamics, which have over time lowered the longitudinal slope of the valley through repeated and ongoing cut-and-fill cycles, forming the broad Kromme River wetland valley (Lagesse, 2017; McNamara, 2018; Langner, 2018; Pulley *et al.,* 2018). Alluvial fans are found throughout the Kromme River wetland valley, with one present at the toe of the gully at Jagersbos that terminates in the floodout feature. It is likely that during flood events, the tributary alluvial fan alters the hydrodynamics of the trunk stream, initiating erosion and the formation of a headward-eroding gully (Figure 21). Headward of the gully, a gabion structure has halted its progress. The coarse-grained sediment is mobilised and transported and deposited where confinement is lost, leading to the formation of the large floodout feature in Jagersbos (McNamara, 2018). The steepening of the slope downstream of the gully is likely to transgress the geomorphic threshold and initiate another cycle of erosion at a later stage, repeating the entire process (Lagesse, 2017; McNamara, 2018; Langner, in prep.).

Following cutting, the valley bottom becomes incised by a deep gully (often exceeding 5 m in depth). This incised remnant valley bottom area shares similar substrate characteristics to those of the valley-bottom wetland in Jagersbos, which includes fine sediment (mean geometric particle size = 240.80 µm) and a high organic matter content (1.59 %) when compared to what was measured in gullies. This is likely evidence of the remnants of the pre-existing valley-bottom wetland that is now incised. An example of recent incision through a previous valley-bottom wetland can be seen in Figure 21, which shows a large palmiet wetland where dryland fynbos communities are encroaching. The presence of other plants throughout the wetland does make up the basis for another study by Jarvis (in prep) of the plant communities in the Kromme River wetland.

Figure 21: An image depicting a typical gully and the marginal remnant valley bottom area with a palmiet wetland.

As a result of channel incision and the accompanying alterations in the relative elevation and depth to the water table, the previous valley bottom area is now less suited to hosting a wetland, as gully incision leads to the entrainment of flow, such that the saturated conditions of the valley-bottom wetland are no longer present (Mitsch and Gosselink, 2015).

The alteration of the valley morphology that is initiated by the cutting phase and the formation of deep gullies and the large floodout features immediately downstream thereof leads to environmental conditions that favour the regeneration of palmiet. One of the habitats that favours palmiet regeneration is gully beds and gully bars (Figure 22). Juvenile clumps of palmiet are actively regenerating within gullies, as shown in Figure 23. This geomorphic zone is created by hydrogeomorphic disturbances and is characterised by a substrate made of coarse sediments (mean geometric particle size = 309.33 µm) with low organic matter content (0.61 %) when compared to the substrate characteristics of the valley bottom in Jagersbos and the remnant valley bottom above the gully. Due to the proximity to the channel, the geomorphic features within gullies where palmiet is regenerating are mostly wet due to the low relative elevation and depth to the water table, and the plants are generally close to the thalweg (< 10 m). Under 1-in-50-year flood conditions, these habitats are subjected to an increase in stream velocity, stream power and flood depth, where velocity is approximately 0.84 $m.s^{-1}$, unit stream power is approximately 37.41 $N.m.s^{-1}$, and flood depth is approximately 0.88 m.

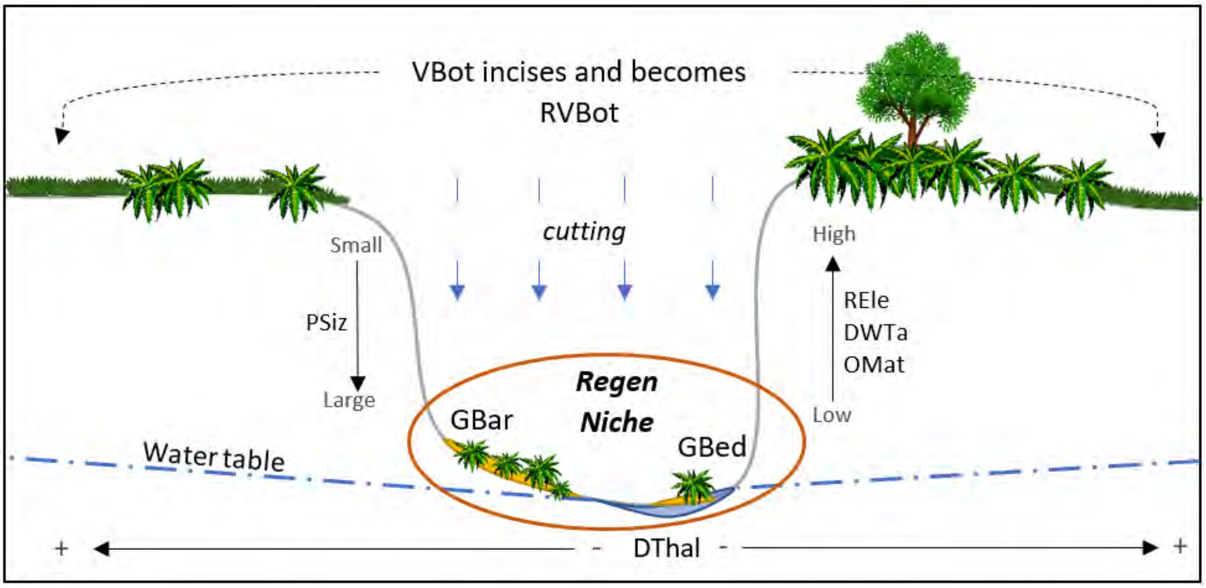


Figure 22: A conceptual diagram depicting a cross-section of the valley where incision has occurred and the associated environmental characteristics of the remnant valley bottom whereupon the persisting class of palmiet exists, and the gully where palmiet's regeneration niche occurs.

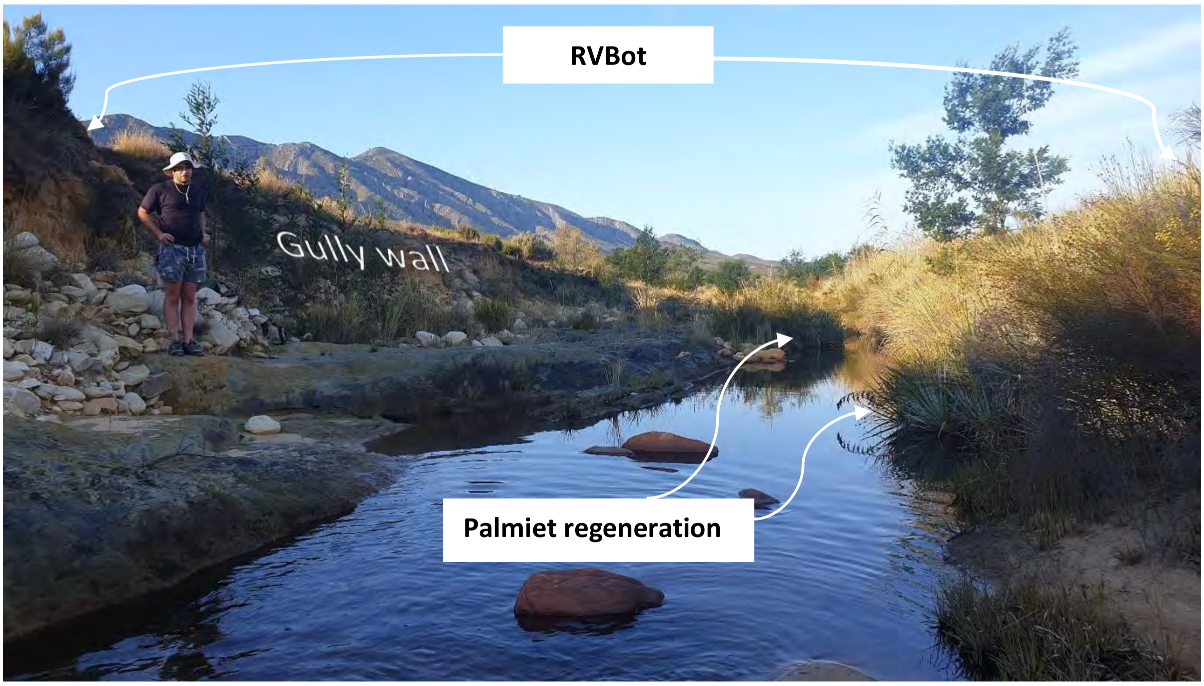


Figure 23: A photo from the bed of a gully in Jagersbos, wherein palmiet regeneration is evident. Samuel Jarvis, who is 178cm tall, is present for purposes of scale.

The generation of a large fan-like floodout across the valley bottom immediately downstream of where confinement is lost also favours palmiet regeneration (Figure 24). The water table remains fairly consistent across the valley, and the relative elevation and depth to the water table remain low, albeit somewhat variable. The substrate is characterised by similarly coarse sediments and organic matter content as the gullies. Palmiet was observed to be regenerating along abandoned flow paths, but most regeneration was taking place along the active channel. Palmiet was observed to also be growing in areas well elevated above abandoned flow paths. The floodout feature provides ideal conditions for wetland formation due to its broad cross-section and low longitudinal slope.

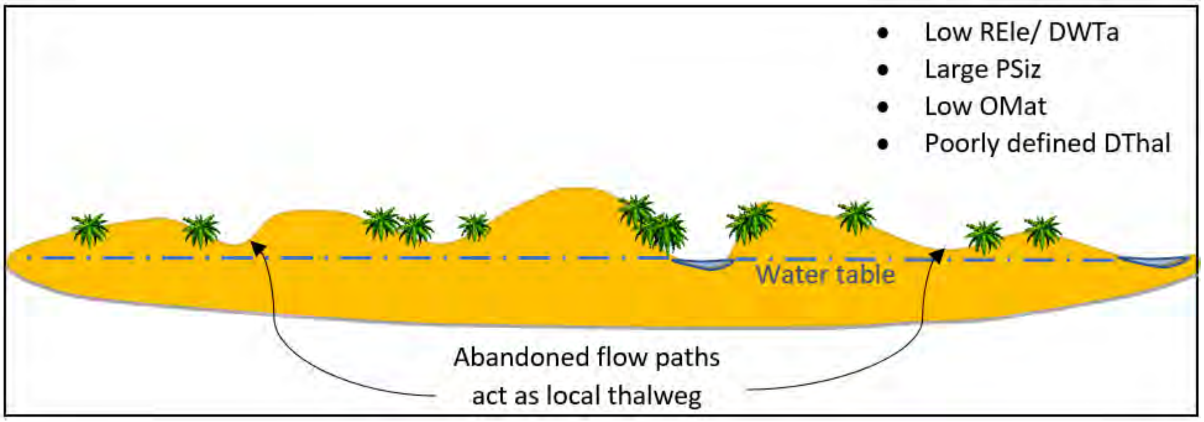


Figure 24: A cross-sectional diagram depicting the environmental characteristics of the floodout.

The Kromme's cut-and-fill cycles that widen the valley have been occurring for at least 10 000 years (Lagesse, 2017). Gullies exist in the upper Kromme that have been dated and were found to be around 8000 years old (Lagesse, 2017), which suggests that the gullies are not an uncommon occurrence in this area. They clearly pre-date European human settlement in the area, which introduced sophisticated farming methods and intense grazing practices within confined boundaries. Lagesse (2017) further suggests that these cutting cycles happen every 100 to 1000 years. Palmiet's presence in these gullies and on the floodout that are the product of the cutting events suggests that it has evolved appropriate traits to take advantage of the hydrogeomorphic disturbance events that occur in the Kromme. This will be explored further in the following section.

6.2. Palmiet growth and the effects of its colonisation

6.2.1. Palmiet's early life strategies

Hydrogeomorphic disturbances in lotic systems constrain ecological processes and patterns. Long-term disturbances act as a habitat template which is thought to determine the species types that can establish and persist within these unpredictable environments (Southwood, 1977, 1988; Resh *et al.*, 1988; Poff and Ward, 1990). Given this, plants have developed appropriate strategies to regenerate and persist in these environments.

Palmiet's regeneration on recently formed depositional areas following large hydrogeomorphic disturbance events suggests that it has r-selected traits (MacArthur and Wilson, 1967; Pianka, 1970; Begon *et al.,* 2006; Bornette *et al.,* 2008). Where it regenerates following a disturbance event, succession is primary and biological interactions are low as a result of very limited colonisation by other organisms (Bornette *et al.,* 2008; Corenblit *et al.,* 2007). Furthermore, palmiet produces very large numbers of very small seeds (personal observation suggests that each plant produces more than 10 000 seeds – estimated from the weight of seeds from 20 inflorescences and weighing several batches of 100 seeds at a time). Further to this, it is able to re-establish vegetatively from parent material (Job, 2014; Barclay, 2016), which further suggests that it possesses r-strategist life history traits. Palmiet does, however, also show characteristics of being a K-selected climax species given its dominance in basins that have not been disturbed for many decades, such as those identified in the stable valley bottom reach that has been undisturbed for tens of years, as well in the upper Kompanjiesdrif basin, which has been undisturbed for many decades to centuries (Lagesse, 2017).

For plants to be able to take advantage of bare patches created following disturbance, seed production or generation of vegetative fragments from parent plant material should ideally coincide with a disturbance event, thereby acting as a mechanism for dispersal (Corenblit *et al.*, 2015; Bornette *et al.,* 2008). Palmiet diaspores are likely reliant on floods for dispersal, particularly by vegetative means, due to the high energy associated with such events. Once flooding subsides, diaspores are likely to be deposited on marginal bars or depositional areas in the gully or on the floodout. The Kromme River's lengthy periods of low flow that likely follow a large disturbance event provide a window of opportunity for palmiet establishment (Balke *et al.,* 2014; McNamara, 2018). Following the establishment of a propagule, palmiet begins to colonise and stabilise depositional banks on the floors of gullies or on the floodout. Its high investment in root biomass (Sieben, 2012) allows it to anchor firmly into sediments in gullies or on the floodout, after which it starts to grow clonally and reproduce.

6.2.2. Palmiet colonisation and its effects on the hydrogeomorphic environment

Fluvial systems are widely dominated by vegetation types that are monospecific clonal species (Sosnová *et al.*, 2010; Sieben, 2018), and palmiet is one such plant. Plants that are able to grow via vegetative means are able to resist erosion and accretion that is associated with fluvial systems (Sculthorpe, 1967; Grace, 1993; Bornette *et al.,* 2008), and it is usually the dominant form of propagation compared to sexual reproduction in frequently disturbed environments (Sculthorpe, 1967; Grace, 1993; and Bornette *et al.,* 2008). Palmiet's robust form is able to exert a great deal of control over its hydrogeomorphic environment as a result of this (Job, 2014; Barclay, 2016).

Palmiet grows as large monospecific clonal stands with its above- and below-ground biomass influencing depositional and erosional patterns through the way in which it alters hydrological characteristics (Job, 2014). Along channels, palmiet spreads clonally from pockets of deposition along rivers, after which it begins to grow across the channel via a mat of entangled stems (Figure 25; Job, 2014; Barclay, 2016). The dense phalanx clonal form and its dense root, stem and rhizome system alters the in-channel hydrodynamics by increasing stream roughness, trapping sediment and stabilising banks during floods (Job, 2014; Barclay, 2016). This causes flow conditions to become diffuse, which slows flow, creating conditions that favour organic matter accumulation (Job, 2014; Barclay, 2016). Its net-like leaf bases that wrap around the stem contributes to sedimentation and the capturing of organic materials (Figure 26; Sieben, 2012; Job, 2014; Barclay, 2016). Its flexible stem allows it to bend over and lie flat along banks, which also stabilises the banks and reduces the likelihood of erosion, thereby exerting further control over the hydrogeomorphic dynamics of the system (Gull, 2012).

Figure 25: Palmiet growing into flowing waters in the Goukou River in the Western Cape. Photo: Nancy Job

Figure 26: The stem of a palmiet plant with sandy sediment trapped in the leaf bases. Photo: Philippa Schlegel

Control of the behaviour of a fluvial system's hydrogeomorphic dynamics is not unique to fluvial systems dominated by palmiet. *Cyperus papyrus* (Papyrus) and *Phragmites australis* colonisation of river channels have also been documented as having a biomechanical effect on the structure and function of fluvial systems (Ellery *et al.,* 1995, 2003; Tooth *et al.,* 2014). In the Okavango Delta, a 15 000 km^2 wetland in northern Botswana, papyrus was found to grow into the trunk channel from the banks. It grows on peat deposits 4 – 5 m thick, which continually allow water loss such that discharge and the capacity of the stream to transport sediment decline downstream (Ellery *et al.,* 1995, 2003). As such, deposition of bedload sediment occurs. The confinement of bedload sediment to channels, the maintenance of bank stability and the way that papyrus sustains bank aggradation to match that of bed aggradation (0.06 m.a^{-1}), illustrate the extent to which this plant controls channel form (Ellery *et al*., 1995). Ultimately these processes lead to major channel-switching events over timescales of centuries (McCarthy *et al*., 1986; Ellery *et al.*, 1995, 2003; Smith *et al*., 1997).

Similarly, *Phragmites australis* invades slow-flowing streams from channel margins and traps sediments, which also sees channels filling as a result of aggradation such that abandonment occurs (Tooth *et al.*, 2014). In the Cape, Holmes *et al.* (2005) further found that dense invasive alien trees that are found along the Huis River lowered the stream velocity and discharge. These dense alien trees increased flow resistance such that deposition occurs as a result of the decrease in turbulence.

Palmiet's life history characteristics are a product of its environment, and the morphological expressions of these products exert control over the hydrogeomorphic setting in which we see palmiet growing today. Therefore, palmiet is able to control erosional and depositional processes (Job, 2014; Barclay, 2016). It is for this reason that palmiet's ability to "engineer" its environment has been suggested to contribute towards the geomorphic evolution of the Kromme River valley, and it may play an important part in the filling phase of the cut-and-fill cycles that characterises the rivers of the Cape Fold Mountains (Job, 2014; Barclay, 2016; Lagesse, 2017; McNamara, 2018; Pulley *et al.*, 2018).

6.3. Palmiet as an agent of gully filling and wetland formation

The Kromme River's cut-and-fill cycles are thought to be initiated by tributary alluvial fans that impinge on the trunk stream, thereby altering the hydrodynamics during wetter periods (Lagesse, 2017; Langner, 2018; Pulley *et al.,* 2018). The filling phase is understood to be the result of the clastic sediment generated upstream and deposited at the toe of the gullies, such that it fills the gully in an upstream direction (Pulley et al., 2018; McNamara, 2018; Lagesse, 2018). This section will explore the development of a model of wetland dynamics given the understanding of palmiet recruitment and gully filling. This builds on Barclay's (2016) conceptual model of gully filling based on understanding developed by studying undisturbed palmiet wetland plant communities. The current model involves the bioengineering effects of palmiet's colonisation of the depositional features.

Following dispersal of palmiet diaspores after flood events, palmiet begins to establish on exposed bare sediments where it is free of competition. Its rapid colonisation of bare areas following geomorphic disturbance is consistent with the behaviour of r-strategist plants (MacArthur and Wilson, 1967; Pianka, 1970). This period of growth is responsible for the biostabilisation of depositional pockets of coarse-grained sediments found within gullies. Following early colonisation, it reproduces vegetatively, forming the initial stages of "pioneer landforms" (using the terminology of Gurnell *et al.,* 2012). It is believed that currently (as of 2021) palmiet is in this phase.

Across the floodout, palmiet growth favours areas close to the water table, such as along the active channel where the relative elevation and depth to the water table are lowest. It is of interest that extensive valley-wide sandy deposits such as that of the floodout were observed throughout the Kompanjiesdrif basin (Lagesse, 2017), but these were buried below about 1.5 m of organic-rich valley fill covered in palmiet-dominated vegetation. This suggests that the floodout is gradually colonised by palmiet and that aggradation takes place, which is probably largely related to the sediment trapping ability of palmiet. Therefore, it is likely that over time, the floodout is colonised by palmiet, such that in the future, the valley floor will be elevated above its present elevation and that the palmiet plant community will dominate.

Within the gully upstream of the floodout, gully filling takes place headward due to sediment generation by headward erosion at the head of the gully and erosion of gully banks (Figure 27). As the gully fills headward from the wetland at the toe of the gully, new opportunities for palmiet regeneration are created. Over time, the gully fills with clastic sediments (which may happen particularly fast during high flows) and localised peat accumulations. After the gully has filled, the incised remnant valley bottom is converted to unchannelled valley-bottom wetland such that flooding takes place across the valley floor, which is characterised by a gentle longitudinal slope and wide, near-horizontal cross-section.

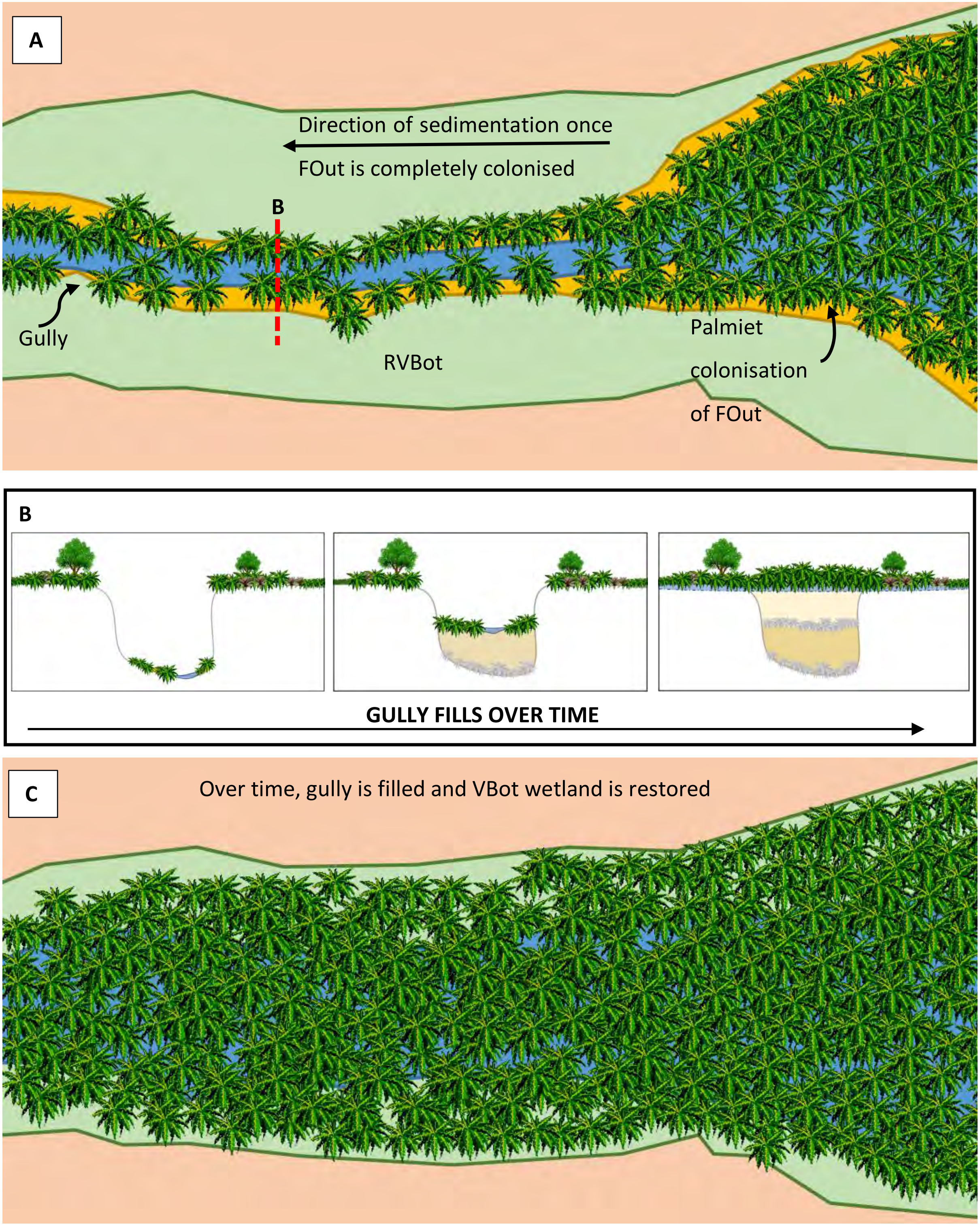


Figure 27: A conceptual diagram adapted from Barclay (2016) of gully filling processes and the formation of a valley-bottom wetland across the floodout and the incised remnant valley bottom. **A**) shows a plan view of palmiet regeneration and colonisation of the floodout and appropriate geomorphic zones within the gully, and the resulting sedimentation, **B**) shows cross-sections of the gully as it fills and **C**) shows the formation of a valley-bottom wetland as a result of palmiet's colonisation of the gully floor and floodout as sedimentation takes place.

6.4. Reconsidering the Fluvial Biogeomorphic Succession model in the light of this study

Corenblit *et al.'s* (2007) Fluvial Biogeomorphic Succession model explores the creation of landforms along fluvial corridors in temperate rivers in the northern hemisphere. It is thought that synchronised changes occur between vegetation and landform development due to the way in which 1) vegetation responds to the hydrogeomorphic conditions of the system, 2) vegetation traits affect the hydrogeomorphic conditions through environmental engineering, and 3) the response of vegetation to the changes induced by such biological feedback. Each phase forms what is said to be a space- and time-limited ecosystem that has its own structure and function.

Palmiet's regeneration in, and its environmental engineering of the Kromme River, lends itself to being examined in the context of the Fluvial Biogeomorphic Succession model. While this model is largely applicable to rivers in the northern hemisphere, it does not consider fluvial systems in a landscape where rivers have been rejuvenated by uplift events and are therefore actively adjusting their slope through predominantly erosional processes (Partridge and Maud, 2000; McCarthy and Rubidge, 2005). Be this as it may, the concept does provide a useful conceptual framework for better understanding wetland formation processes, given that most wetland landforms in the southern African context come about due to the interaction of hydrology, geomorphology and vegetation of fluvial systems. These three elements work together to create self-organising landform templates that are suited to wetland persistence.

In the context of the Kromme River wetland, erosion creates habitats that favour palmiet regeneration. Colonisation of these areas initiates a period of reciprocal longitudinal and lateral vegetation and fluvial landform development, where the outcome is a broad unchannelled valley bottom that hosts palmiet-dominated wetland. This section explores the Fluvial Biogeomorphic Succession model in the context of the Kromme River. The concept has been adapted to include wetland formation, and as such, will be called the Fluvial Biogeomorphic Wetland Succession model (Figure 28). The orange square represents the geomorphic drivers of environmental development, while the green circle represents vegetation (palmiet) processes. The thickness of these two elements approximates the relative contributions of these factors at any stage. The black arrows show interactions and the associated direction of the interaction of the geomorphic and vegetation components of the system, while their thickness indicates the strength of the interactions.

During the "geomorphic phase", hydrogeomorphic processes dominate and rejuvenation is initiated by large flood events that lead to gully erosion that propagate up the Kromme River valley (Lagesse, 2017; McNamara, 2018; Pulley *et al.,* 2018). These gullies propagate headwards through the previous valley-bottom wetland, which for the vegetation of the former valley bottom causes a significant drop in the water table and a rise in the elevation relative to the thalweg, such that the wetlands dry out and the incised remnant valley bottom landscape on the margins of gullies take on the characteristics of a terrestrial habitat. On the gully floor, depositional areas such as gully bars and gully beds form habitats that are suited to palmiet regeneration. The floodout feature that forms immediately downstream of the gully is another geomorphic feature that forms a habitat for palmiet regeneration. These areas are characterised by a generally low elevation relative to the thalweg and a low depth to the water table, and are made up of mostly coarse sediments with low organic matter. The 1-in-50-year flood data also suggests that gullies are subjected to higher velocities and stream power than other habitats. During this phase, palmiet diaspores are dispersed during the hydrogeomorphic disturbance event and arrive on these depositional features from upstream as the floods subside.

The second stage of the successional process, the “pioneer phase”, consists of palmiet recruitment from seeds or plant vegetative fragments that are deposited on bare sediment in gullies (gully bars or gully beds) or on the floodout following the hydrogeomorphic disturbance event, which initiates the early primary successional phase. The Kromme River’s long phases of low flow provide ample opportunity for palmiet to establish within gullies, where it begins to grow in areas close to water (McNamara, 2018). Along the floodout feature, palmiet recruitment occurs anywhere where the depth to the water table is low, such as along the active channel or old abandoned flow paths. Allogenic processes still control palmiet’s regeneration dynamics here, and as such palmiet’s influence on the geomorphic environment is minimal.

Following the pioneer phase, the “biogeomorphic phase” begins, which is the establishment phase of palmiet. At this stage, palmiet’s vegetative growth, form and structure begin to interact with the hydrogeomorphic environment, thereby creating a hydrological setting that promotes deposition, and palmiet thus starts to alter the geomorphic landscape. This is the engineering and bioconstruction phase. Within gullies, palmiet will begin to vegetatively grow across and impede the flow of the channel. Coupled with its sediment capturing ability, deposition will start to occur (Sieben, 2012). After decades, much of the floodout will be covered in palmiet, leading to the formation of wetland conditions, such as those seen in the undisturbed valley bottom reach in its current form immediately downstream of the floodout. As gully filling takes place, the wetland that has established on the floodout will begin to migrate in an upstream direction, such that over time the valley bottom is restored and palmiet colonises the valley floor. Due to the gentle longitudinal slope and the valley’s wide cross-section, the valley floods, thereby promoting saturated conditions that favour wetland formation dominated by palmiet.

The restoration of the valley bottom and the formation of a large wetland sees autogenic successional processes begin to dominate, with the influence of the geomorphic environment diminishing. This is the “wetland phase” of the Fluvial Biogeomorphic Wetland Succession model. Palmiet has reached adulthood at this stage, and while it still dominates much of the wetland vegetation, other competitive wetland plants that are K-strategists increasingly colonise and establish. It is likely that vegetation diversity is highest at this stage. The influence of the hydrogeomorphic environment interacting with vegetation still contributes towards building up the geomorphic landscape through accretion of fine sediments and peat formation, which leads to the wetland landform becoming more and more disconnected from the hydrodynamics of the fluvial system. The final biogeomorphic wetland landform is likely to have environmental characteristics consistent with those measured in the undisturbed Jagersbos wetland, where the substrate consisted of fine sediments, a higher organic matter content than what was measured in gullies, and the water was at or near the surface. Additionally, the modelled hydraulic data showed that these areas have low velocity and stream power during 1-in-50-year flood flows as a result of the roughness of vegetation.

Palmiet’s persistence throughout most of the successional stages suggests that it shares some life history characteristics consistent with K-strategists, such as its long lifespan and its general dominance over other plants for decades after early establishment. This is similar to the *Populus nigra* in Rivers of Europe, which shows both r and K strategies due to the way in which it establishes and persists throughout all four successional stages of the original Fluvial Biogeomorphic Succession model (Corenblit *et al.,* 2014). It is suggested to be a keystone engineering species that has played a vital role in the shaping of European fluvial systems (Gurnell and Petts, 2006).

Over time (centuries), the reciprocal interactions between vegetation, hydrology and sediment can result in landforms that self-organise into biogeomorphic ecosystems (Coreblit *et al.,* 2007; Balke *et al.,* 2014). In the Fluvial Biogeomorphic Wetland Succession model, the wetland phase comes before the “ecological phase” of the original Fluvial Biogeomorphic Succession model, where the geomorphic landform is largely disconnected from hydrogeomorphic influence. The implications of the wetland gradually becoming more and more disconnected from the hydrogeomorphic dynamics of the fluvial system such that it becomes a truly ecological landform will be discussed in the section that follows.

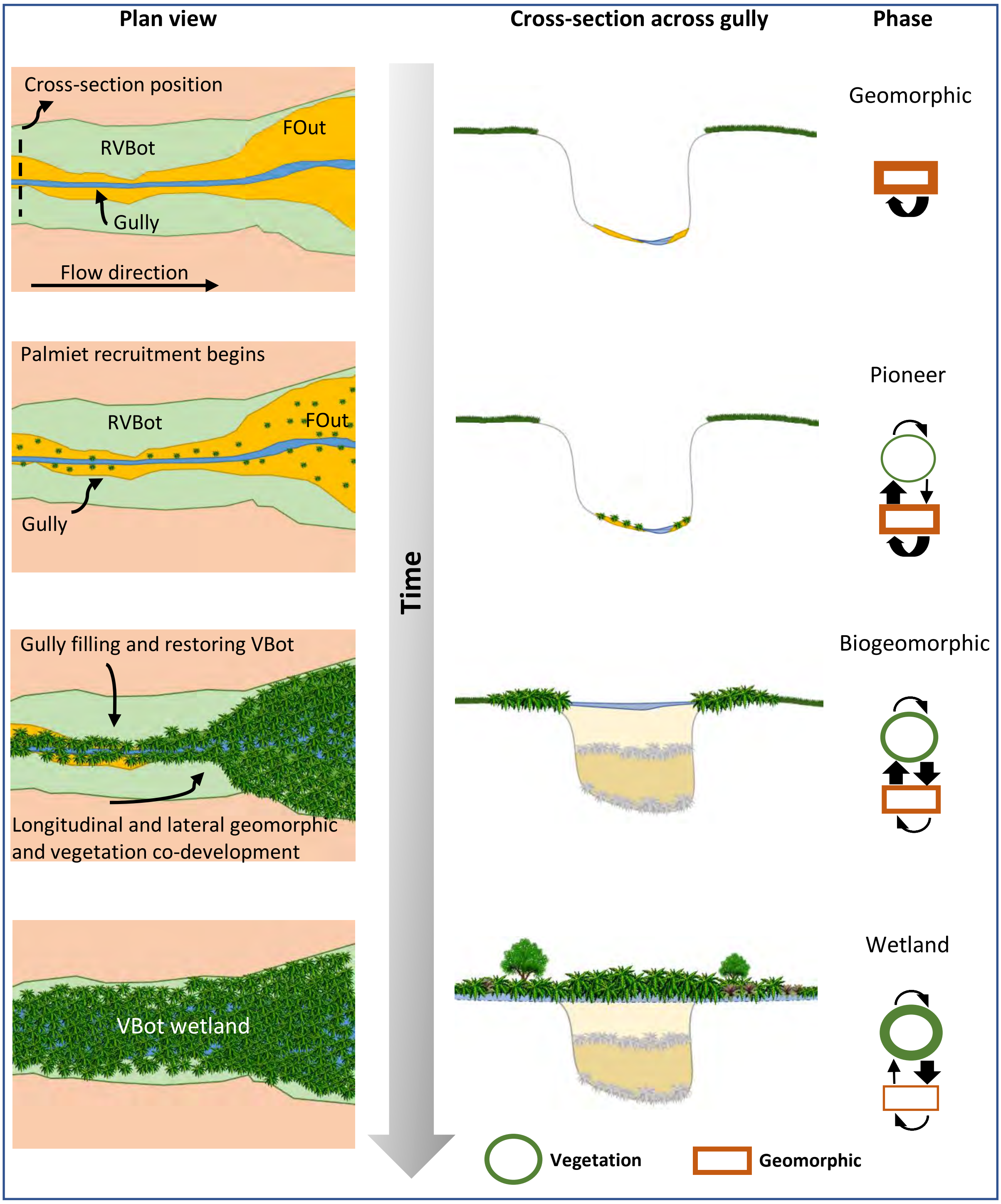


Figure 28: A conceptual model depicting various stages of the Fluvial Biogeomorphic Wetland Succession model.

6.5. Implications for vegetation succession in palmiet wetlands

Much of the regeneration that has been documented in this study has only been happening over the past decade, as this is when the last catastrophic flood event occurred that gave rise to the gully and floodout at Jagersbos. In terms of the Fluvial Biogeomorphic Wetland Succession model, it can be thought of as being at the beginning of the "pioneer phase". Should conditions remain such that the valley-bottom wetland remains undisturbed for long periods (hundreds to thousands of years), it is predicted that a true “ecological phase” will begin following wetland formation where a climax community will come to dominate. Figure 29 shows the hypothesised palmiet and fynbos abundance (Y-axis) in relation to the four phases of hydrogeomorphic connectivity described by Corenblit *et al.* (2007). The study of Barclay (2016) in the Kompanjiesdrift basin was of palmiet wetland that had not been disturbed for a very lengthy period, which is probably in the "wetland phase" and moving to the “ecological phase” as described in the original Corenblit *et al.* (2007) model.

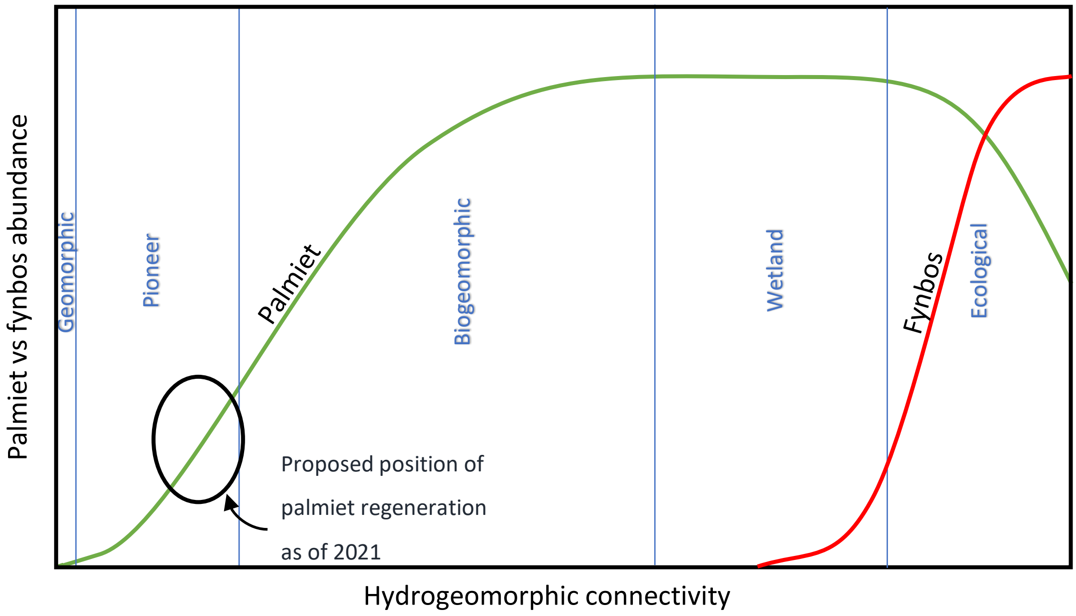


Figure 29: A diagram showing palmiet versus fynbos abundance in relation to hydrogeomorphic connectivity.

After hundreds to thousands of years, through continued accretion and peat formation, the wetland will likely become more and more disconnected from the hydrogeomorphic environment. Its complete disconnection from the hydrogeomorphic dynamics of the fluvial system is unlikely, however it is hypothesised that at this stage, more competitive K-strategist plants such as fynbos plants take advantage of the conditions created by palmiet, outcompeting it. This is consistent with Rebelo’s (2022) second hypothesis on succession within palmiet wetlands. Fynbos is thought to be a better long-term competitor and palmiet is better adapted at early colonisation of areas created by disturbance as seen in this study. Palmiet’s shade intolerance (Boucher and Withers, 2004) is likely to further contribute to its decline should dryland species or alien vegetation be introduced, driving the wetland towards becoming a terrestrial landform.

6.6. Generation time in relation to disturbance

Plant's adaptive traits are passed down through many generations as a result of natural selection and can be thought of as a reflection of their ancestors' successes or failures to respond to the constraints imposed by an environment (Begon *et al.,* 2006). The expressions of these adaptive traits can be used to identify the likely environmental conditions that a plant needed to adapt to in order to ensure the success of future offspring (Begon *et al.*, 2006). Palmiet's adaptations reflect a plant that is adapted to environments that are prone to disturbance events that are more frequent than the generation time of individual plants. However, where they occur in this study, catastrophic disturbance events are infrequent. This is based on the assertion by Lagesse (2017) that the cycles of erosion that characterise this study area happen centuries apart. The frequency of these erosional events is likely to increase headward in the Kromme valley, however. As such, it is unlikely that the origins of palmiet's inherited characteristics that favour establishment following geomorphic disturbance are a product of the disturbance regime present in this study area.

Munyai (2013) investigated the genetic diversity of palmiet populations found throughout its distribution range, including both mountainous and coastal areas in the Cape Floristic Region in the Eastern and Western Cape and KwaZulu-Natal. It was found that palmiet populations along the Agulhas Plain in the Western Cape shared genetic similarities to palmiet populations in Kwazulu-Natal, but interestingly, the same populations along the Agulhas Plain are genetically dissimilar to populations in mountainous regions of the Eastern Cape. Gene flow appears to be absent between palmiet populations that do not share drainage networks or where mountains act as a barrier. It is thought that palmiet along the Agulhas Plain and KwaZulu-Natal coastal areas are genetically similar as recruitment in this area is more recent than the mountainous regions of the Western Cape and Eastern Cape, given that much of this area was covered by ocean during the Pliocene, prior to the second uplift event 5 million years BP (Cowling *et al*., 2009).

The implication of Munyai's (2013) findings is that palmiet's origins can be traced back to mountainous regions, which are those areas of the Cape Fold Mountains above the African Erosion Surface. These are areas that are prone to more frequent geomorphic disturbances of varying intensity when compared to lower-lying areas such as lower-lying coastal areas. Headwater streams are generally characterised by higher flood velocities as a result of the steeper slopes (Ellery *et al.,* 2009) and are subjected to more frequent geomorphic disturbances than the Kromme. These environmental constraints are likely what resulted in the morphological and reproductive traits that we see in palmiet today, such as its deep rooting depth, its high root-to-shoot ratio, its ability to bend but not break during floods, and its ability to reproduce vegetatively and produce large numbers of very small seeds (Boucher and Withers, 2004; Gull, 2012; Sieben, 2012). These are the same traits that allow palmiet to exert biomechanical control over the hydrogeomorphic environment, thereby initiating reciprocal vegetation and landscape succession processes (Corenblit *et al.,* 2007).

7. CONCLUSION

Before this study, palmiet’s regeneration characteristics were generally poorly understood. The aim of this research project was to understand palmiet’s regeneration niche in the Kromme River wetland, which has recently experienced geomorphic disturbance. It is believed that this aim was met. Palmiet was found to be regenerating on depositional areas that were created by hydrogeomorphic disturbance events, such as on depositional areas on the beds of gullies, on marginal bars next to gully beds, and on the large depositional floodout feature immediately downstream of a gully. Its regeneration characteristics and its control over the hydrogeomorphic environment were explored and related to existing literature on the Kromme River’s cut-and-fill cycles (Lagesse, 2017; McNamara, 2018; Pulley *et al.,* 2018), and a biogeomorphic approach was used to shed light on the filling phase.

By examining the reciprocal processes between palmiet and the hydrogeomorphic landscape through the Fluvial Biogeomorphic Succession framework of Corenblit *et al.* (2007), a new conceptual model was developed to explain how the regeneration of palmiet within gullies and on large depositional features immediately downstream thereof contributes towards the creation of wetland landforms through its ability to promote the filling of gullies and restore unchannelled valley bottom conditions. The four-phased process suggests a longitudinal and lateral landscape development process through the way in which palmiet colonisation interacts with the hydrogeomorphic environment, and how it forms a wetland landform over time. Given that many of the wetlands within southern Africa are undergoing similar cut-and-fill cycles, this model could contribute towards understanding the geomorphic evolution of these landforms over time.

By gaining an understanding into why wetlands form where they do, insight can be gained into the processes that drive their natural dynamics. Hydrogeomorphic disturbances that lead to the formation of gullies within wetlands may in fact be part of the natural dynamic of a system, and are therefore not necessarily degradational, despite the associated desiccation of the existing wetland. These processes are likely contributing towards the long-term evolution of the landscape and of wetlands more generally (Ellery *et al.,* in prep; Ellery *et al.,* 2009; Lagesse, 2017; McNamara, 2018; Pulley *et al.,* 2018). These disturbance events present an opportunity for palmiet dispersal and regeneration, which has not been observed in undisturbed wetland settings. This study further suggests that palmiet is not adapted to survival in stable wetland environments that are becoming increasingly disconnected from the hydrogeomorphic dynamics of the fluvial system and colonised by fynbos plants that, under drying conditions, may outcompete palmiet. As such, restoration activities that stabilise wetland basins may be a threat to palmiet's long-term persistence. Further to this, palmiet’s ability to colonise and restore incised valley bottoms makes it a useful instrument for wetland practitioners who may be looking towards restoration techniques that are more sympathetic with natural processes.

In order to better understand the extent of palmiet alterations of the geomorphic environment, a study that quantifies its contribution to sedimentation may be beneficial. This could be done by coring in areas where previous gullies are believed to be. In addition, hydraulic models of reaches of rivers exhibiting different levels of colonisation by palmiet could provide better insights relating to its contribution to altering the hydrological setting and initiating deposition. Further studies could also look at the incorporation of an “ecological phase” into the Fluvial Biogeomorphic Wetland Succession model based on wetlands that are at a later stage of succession. The studies by Rebelo (2017) and Rebelo *et al.* (2022) on the Goukou wetland suggests that there may be reaches at a later stage of succession that are heading towards an “ecological phase”. This is based on the observations that fynbos is encroaching into the wetland and outcompeting palmiet. Due to the Goukou being at a later stage of succession, it is possible that the wetland is becoming more disconnected from the hydrogeomorphic drivers of the fluvial system and therefore creating conditions more suited to superior competitors such as fynbos and potentially even dryland species.

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APPENDIX A

GEOsense

Palmiet Wetland near Kareedouw
Lidar survey

Document No:	1
Revision:	0
Author:	HC de Wet (S0472)
Effective Date:	04/11/2019

Notice

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CONTENTS

1. Introduction

Geosense was appointed to perform an aerial LiDAR survey of the Palmiet wetlands near Kareedouw. The project was flown on the 4th Nov 2019, between 9:50 am and 10:45 am.

1.1 Survey Area

Figure 1.1 below shows the area of interest (study area – 1 282ha).

Figure 1.1 Study areas for LiDAR survey

1.2 Flight Specifications

The following flight specifications were applied during the survey:

- ✈ Survey took place with a fixed wing aircraft
- ✈ Flying height – 700 meters over study areas
- ✈ Flying speed – 110 knots
- ✈ Scan Rate – 300 KHz
- ✈ Point density p/m² - approximately 5.5 points per sqm

2. Survey control

The projection for the whole survey area was Hartebeesthoek Transverse Mercator, Central Meridian 25. Ellipsoidal heights were converted to orthometric heights using the SAG2010 geoid model.

Geosense was asked to survey the control for the survey. See 2.1.1 below. These were used to check the position of the survey. Three points were placed along the route and pre-marked.

T120 (ME-AL) Melkhoutkraal was held as a fixed point in the network and T194 (Joubertina) as a check point. See the network report in the appendix.

2.1 Coordinates Used During Post Processing

Base-Station Coordinates on the day of flying:

Hartebeesthoek Geographical			
Name	**Lat**	**Long**	**Ellipsoidal height**
KAR3	-33 53 52.01987	24 07 09.18216	332.613

Table 2.1.1 Control point coordinates surveyed by Promap

Name	Easting	Northing	Ellipsoidal height	Orthometric height SAG2010
JOUBERTINA T194	104 459.085	3 744 353.692	779.817	749.861
KAR1	92 644.881	3 748 754.548	470.364	440.614
KAR3	81 469.482	3 752 672.671	332.613	303.031
KAR4	72 810.013	3 755 155.526	303.721	274.370
ME-AL T120	70 172.763	3 756 020.828	349.513	320.200

3. Equipment used

3.1 Aerial lidar systems

Promap uses the advanced Riegl systems:
Harrier 68i & Rollei/PhaseOne 60 MegaPixel Camera.

3.2 GPS receivers

GPS base station is deployed on day of flight, and can be any of the following: Trimble R4/5800, Trimble 5700 and Geomax zenith 10.

4. Overview and Workflows

4.1 Team Responsible for the Aerial Survey (Expertise & Qualifications)

Mnr. Willie de Winnaar

- Pilot/CPL rating,
- 1 year with ProMap

Mnr. Armand Swanepoel

- System Operator in Aircraft
- 5 years with ProMap

Mnr. Hennie de Wet

- Surveyor/LiDAR Processing,
- SAGC #S0472, Nat. Dip. Surveying – CPUT,
- 32 years of experience, 1 year with ProMap

Mnr. Janco vd Merwe

- Technical Director/Project Manager/QC,
- SAGC# PGP0186,
- Nat. Dip. Cartography - TUT,
- B.Sc. Honors Geo-Informatics -UP,
- Project Management Principals (PMP) – UP
- 10 years at ProMap/Geosense

5. Processes and Workflow of Project/Program

5.1 Workflow followed during Aerial Survey project/program

5.1.1 Flight planning:
The flight is planned according to the project requirements and the system to be used.
GCP positions will be determined. Managers will do the quality control.

5.1.2 Mission/data capture:
If required, GCP's will be established.
Base station is setup in advance and operator also serves as weather observer.
The mission is flown; quality control is done in the air using the lidar capture software.

5.1.3 Post processing:
The raw field data is downloaded.
IMU/GPS processing is done to obtain trajectory, QC done on trajectory (RMS X, Y and Z).
Raw lidar data is processed using system specific software that combines the trajectory and field lidar data.
Manager does a quality control check on the trajectory and raw lidar.

5.1.4 Production:
Lidar point cloud is imported into a project and filtered into ground and non-ground.
From the ground a DTM is extracted for the processing of the images in TerraPhoto.
Tie points are run to determine inter image orientation as well as tie points with known points to check the position of the survey. The ortho rectification of the images is done and image tiles created.
Quality control is done on the lidar point cloud using the control.
The classification of the ground points are manually checked to ensure that there are no holes in the data set.
Quality control then done by manager.

DTM is extracted from the ground points using algorithms to ensure accurate surfaces.

6. Accuracies

Accuracies obtained are dependent on the GPS data logged in the air and ground and can vary on a day to day basis.

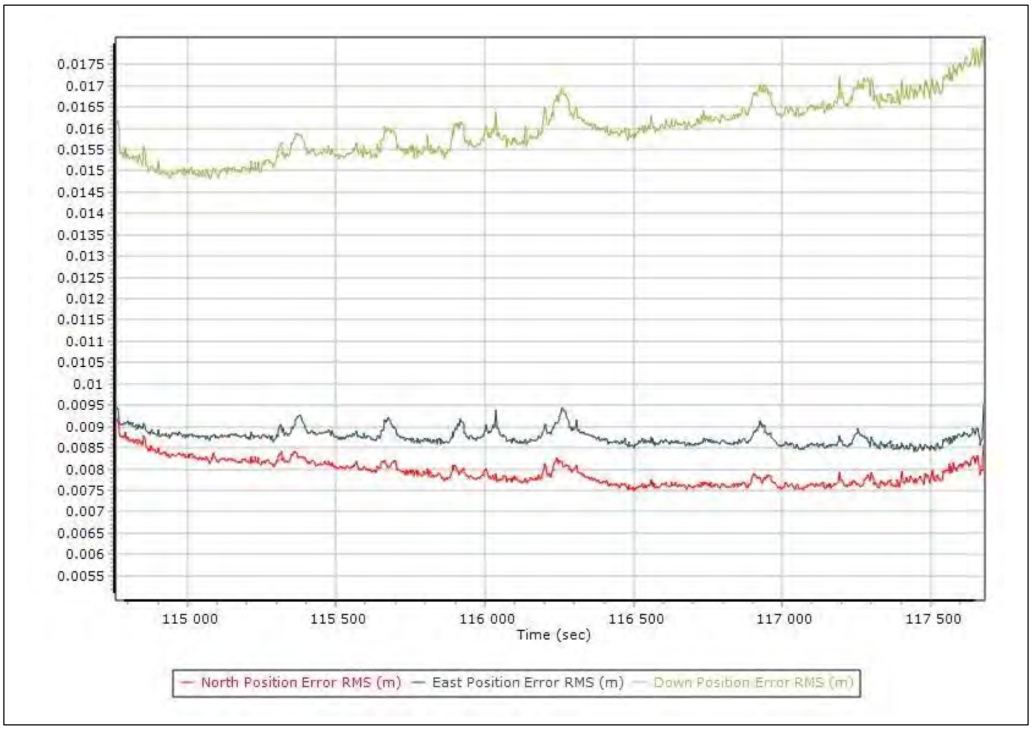
The accuracy of the trajectory is stated as North position Error RMS, east position Error RMS and down position Error RMS.

Accuracy of the lidar point cloud over bare ground is: XY <10cm and Z<5cm.

7. Quality Control

7.1 Combined solution result from post processing (IMU/GPS accuracies)

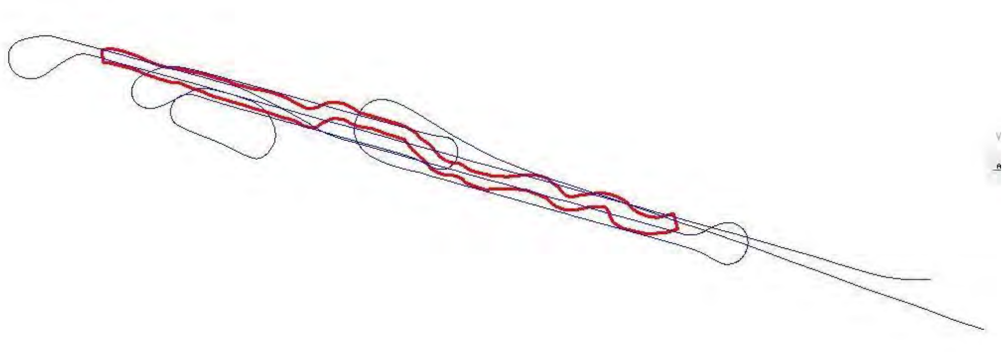
Figure 4.1 IMU/GPS solution (trajectory)



From the graph above it is apparent that the RMS values for the X, Y and Z respectively were below 20mm. This RMS values can be seen as a direct correlation to the accuracy of the aerial survey data.

7.2 Trajectory Plot

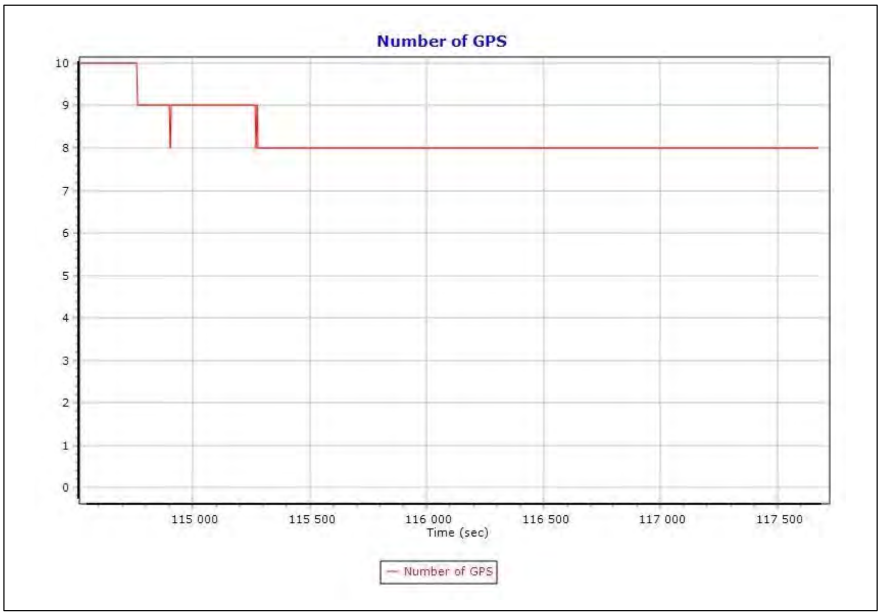
Figure 7.2 Trajectory/Flight plan of the aerial survey that took place on the 4th of November 2019.



In total 6 lines were flown in clear weather conditions

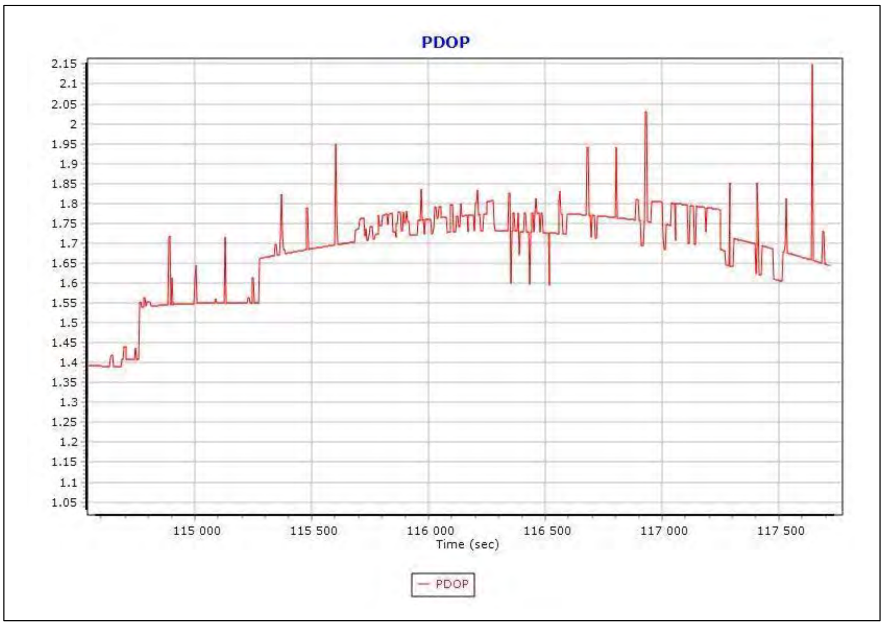
7.3 Number of GPS Satellites

Figure 7.3 Indication of the number satellites during the mission



7.4 PDOP

Figure 7.4 Indication of the PDOP during the mission



7.5 DTM compared to mine control points (dz)

Table 7.5 RMS value (LiDAR)

It is clear that the RMS values for all three surfaces are below 4cm when compared to the control points.

```
Number               Easting     Northing   Known Z   Laser Z        Dz
-----------------------------------------------------------------------
KAR1              -92644.880 -3748754.548   440.614   440.630    +0.016
KAR3              -81469.482 -3752672.671   303.031   303.000    -0.031
KAR4              -72810.013 -3755155.526   274.370   274.370    -0.000

Average dz           -0.005
Minimum dz           -0.031
Maximum dz           +0.016
Average magnitude     0.016
Root mean square      0.020
Std deviation         0.024
```

7.6 Photo Tie-point adjustment report known XY

Table 7.6 Average mismatch (Imagery)

```
Average mismatch         4.5027 cm

Start average    4.5027 cm
Final average    4.2896 cm


Known point comparison
---------------------------------------------------------------------------
Number            Easting     Northing Elevation       Dx       Dy       Dz
---------------------------------------------------------------------------
1              -92644.883 -3748754.544   470.542   +0.013   -0.063   -0.024
2              -81469.484 -3752672.669   332.622   +0.011   +0.058   +0.003
3              -72810.012 -3755155.527   303.551   -0.030   -0.009   +0.011
---------------------------------------------------------------------------
Average from known to tie point                    -0.002   -0.005   -0.003
```

8. Deliverables

- DTM of study area in ascii format per block reference
- Non-ground points in ascii format per block reference
- Images in ECW and Geotif format per block reference
- All lidar in las format per block reference
- 0.5m contours in dgn, dxf and dwg format
- Block reference file in dgn, dxf and dwg format
- Survey report

Appendix:

```
             **************************************************
             * NETWORK - WEIGHTED GNSS NETWORK ADJUSTMENT     *
             *                                                *
             * (c) Copyright NovAtel Inc., (2019)             *
             *                                                *
             * Version: 8.80.2720                             *
             *                                                *
             *Kareedouw_Network_2.net
             **************************************************

DATE(m/d/y): Wed.  11/13/19   TIME:  7:48:22

***************************************************************

  DATUM:            'WGS84'
  GRID:             WG25
  SCALE_FACTOR:     0.2321
  CONFIDENCE LEVEL: 39.40 %   (Scale factor is 1.0009)


****************************************************************
    INPUT CONTROL/CHECK POINTS
****************************************************************

STA_ID     TYPE    -- LATITUDE --  -- LONGITUDE --  ELLHGT -   HZ-SD   V-SD
JOUBERTIN  CHK-3D -33 49 14.77600   23 52 18.10630    779.456
ME-AL      GCP-3D -33 55 43.60210   24 14 27.85450    349.513 0.00500 0.00500


****************************************************************
    INPUT VECTORS
****************************************************************

SESSION NAME           VECTOR(m)   ------ Covariance (m) [unscaled] ------
                        DX/DY/DZ          standard deviations in brackets
KAR1 to JOUBERTIN (1)  7311.2617   1.9863e-04 (0.0141)
                      -9629.6662   7.1646e-05  6.6355e-05 (0.0081)
                       3584.2309  -8.1086e-05 -3.7990e-05  8.7366e-05 (0.0093)

KAR1 to KAR3 (1)      -6691.7768   2.2108e-04 (0.0149)
                       9210.8081   8.6542e-05  7.7025e-05 (0.0088)
                      -3260.7840  -1.1663e-04 -5.3094e-05  1.1947e-04 (0.0109)
```

```
KAR1 to KAR4 (1)      -11549.6863   4.9071e-05 (0.0070)
                      16499.6551   2.0201e-05  2.0776e-05 (0.0046)
                      -5363.4863  -2.1008e-05 -1.0726e-05  2.3963e-05 (0.0049)

KAR4 to JOUBERTIN (1) 18860.9562   1.9463e-04 (0.0140)
                      -26129.3166   7.7127e-05  7.3939e-05 (0.0086)
                       8947.7216  -7.8862e-05 -3.9375e-05  8.4621e-05 (0.0092)

KAR4 to KAR3 (1)       4857.9080   2.0150e-04 (0.0142)
                      -7288.8506   7.9514e-05  7.0510e-05 (0.0084)
                       2102.7087  -1.0699e-04 -4.9039e-05  1.1031e-04 (0.0105)

ME-AL to KAR1 (1)     13045.0022   1.8316e-04 (0.0135)
                      -18711.4881   5.1873e-05  7.1765e-05 (0.0085)
                       6123.5080  -1.0586e-04 -2.5015e-05  1.2368e-04 (0.0111)

ME-AL to KAR4 (1)      1495.3154   5.1778e-05 (0.0072)
                      -2211.8214   1.5460e-05  2.0958e-05 (0.0046)
                        760.0091  -3.0278e-05 -7.4394e-06  3.7449e-05 (0.0061)
```

```
****************************************************************
    OUTPUT VECTOR RESIDUALS (East, North, Height - Local Level)
****************************************************************

SESSION NAME               -- RE --   -- RN --   -- RH --     - PPM -   DIST - STD -
                             (m)        (m)        (m)                  (km)   (m)
KAR1 to JOUBERTIN (1)        0.0011     0.0032     0.0032       0.368   12.6  0.0090
KAR1 to KAR3 (1)            -0.0005     0.0007    -0.0023       0.207   11.8  0.0098
KAR1 to KAR4 (1)             0.0017    -0.0024     0.0015       0.159   20.8  0.0047
KAR4 to JOUBERTIN (1)       -0.0014    -0.0033    -0.0037       0.152   33.4  0.0091
KAR4 to KAR3 (1)             0.0005    -0.0006     0.0021       0.251    9.0  0.0094
ME-AL to KAR1 (1)            0.0071    -0.0043     0.0068       0.455   23.6  0.0094
ME-AL to KAR4 (1)           -0.0020     0.0014    -0.0023       1.195    2.8  0.0051
                          --------------------------------
               RMS           0.0030     0.0026     0.0035

 $ - This session is flagged as a 3-sigma outlier
```

```
****************************************************************
    CHECK POINT RESIDUALS (East, North, Height - Local Level)
****************************************************************

STA. NAME    -- RE --   -- RN --   -- RH --
                (m)        (m)        (m)
JOUBERTIN      0.0231     0.0688     0.3610
            --------------------------------
RMS            0.0231     0.0688     0.3610

****************************************************************
    CONTROL POINT RESIDUALS (ADJUSTMENT MADE)
****************************************************************

STA. NAME    -- RE --   -- RN --   -- RH --
                (m)        (m)        (m)
ME-AL         -0.0000     0.0000     0.0000
            --------------------------------
RMS            0.0000     0.0000     0.0000

****************************************************************
    OUTPUT STATION COORDINATES (LAT/LONG/HT)
****************************************************************

STA_ID      -- LATITUDE --  -- LONGITUDE -- - ELLHGT -   ORTHOHGT
JOUBERTIN  -33 49 14.77377   23 52 18.10720   779.8170   749.8611
KAR1       -33 51 41.55098   23 59 55.77220   470.3644   440.6138
KAR3       -33 53 52.01987   24 07 09.18216   332.6126   303.0310
KAR4       -33 55 14.87624   24 12 45.44108   303.7205   274.3703
ME-AL      -33 55 43.60210   24 14 27.85450   349.5130   320.1997



****************************************************************
    OUTPUT STATION COORDINATES (GRID)
****************************************************************

STA_ID       - EASTING -  - NORTHING - - ELLHGT -   ORTHOHGT
                  (m)           (m)        (m)        (m)
JOUBERTIN   -104459.0854 -3744353.6918   779.8170   749.8611
KAR1         -92644.8805 -3748754.5483   470.3644   440.6138
KAR3         -81469.4824 -3752672.6708   332.6126   303.0310
KAR4         -72810.0126 -3755155.5255   303.7205   274.3703
ME-AL        -70172.7628 -3756020.8275   349.5130   320.1997
```

```
****************************************************************
    OUTPUT VARIANCE/COVARIANCE
****************************************************************
                                             2
STA_ID      SE/SN/SUP  --------- CX matrix (m )-----------
            (39.40 %)  (not scaled by confidence level)
               (m)          (ECEF, XYZ cartesian)
JOUBERTIN     0.00565   5.7733e-05
              0.00580   1.1635e-05  3.7165e-05
              0.00845  -1.4988e-05 -5.9431e-06  4.1905e-05

KAR1          0.00536   3.9061e-05
              0.00538   4.5873e-06  3.0658e-05
              0.00680  -7.5798e-06 -2.3165e-06  3.3990e-05

KAR3          0.00564   5.9340e-05
              0.00574   1.2576e-05  3.7509e-05
              0.00881  -1.8645e-05 -7.3537e-06  4.5221e-05

KAR4          0.00527   3.4745e-05
              0.00528   2.9233e-06  2.8927e-05
              0.00633  -5.6335e-06 -1.4166e-06  3.1882e-05

ME-AL         0.00500   2.5000e-05
              0.00500   2.7285e-20  2.5000e-05
              0.00500  -1.8190e-20  1.8190e-20  2.5000e-05




****************************************************************
    VARIANCE FACTOR = 1.0002

    Note: Values < 1.0 indicate statistics are pessimistic, while
          values > 1.0 indicate optimistic statistics. Entering this
          value as the network adjustment scale factor will bring
          variance factor to one.
****************************************************************
```