

Relating vegetation distribution to cycles of erosion and deposition in the Kromme River wetlands



A thesis submitted in fulfilment of the requirements for the degree of
Master of Science, Rhodes University

By Samuel Jarvis

February 2023



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 and Professor I. Meiklejohn. 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.

Name: Samuel Jarvis

Student number: G17J0726

Date: 14.02.2023

Abstract

The role of geomorphic disturbance has been increasingly recognized as fundamental in the creation and functioning of wetlands. This is true of the Kromme River wetland which has been formed through repeated cycles of erosion and deposition. However, the response – and influence – of wetland plants to these sorts of disturbance has not been investigated. This study sought to fill this knowledge gap by classifying vegetation communities over a range of hydrological and geomorphic disturbance regimes that have happened over the last few decades, and relating those vegetation communities to environmental factors. The study identified seven vegetation communities based on their species composition and abundance, which were related to geomorphic disturbance events. A conceptual model that accounts for vegetation distribution in the Kromme wetland was developed.

Soil saturation was the most important factor explaining vegetation community distribution, which, in turn, is influenced by cycles of erosion and deposition. Following an erosional event on the valley floor, *Prionium serratum* dominated wetland is converted to a number of other vegetation communities. On the floodplain surface adjacent to the eroded gully, the *Prionium serratum* dominated wetland is transformed over time to *Cynodon dactylon* and *Sporobolus fimbriatus* communities. *Prionium serratum* clumps immediately adjacent to the recently incised gullies are able to persist, having sufficient access to water. Within the newly formed gullies, *Juncus lomatophyllus* colonizes the gully beds flooded to a shallow depth, *Miscanthus capensis* colonizes the gully bars and *Setaria incrassata* colonizes the exposed gully banks. Localised depositional features close to the thalweg in the gully are colonized by *Prionium serratum* seedlings and vegetative propagules. These plants represent the regenerating phase of *Prionium serratum* wetland, which also colonizes depositional floodouts downstream of the newly-formed gully. The *Stenotaphrum secundatum* community dominates drier, more elevated areas of the floodout. Over time, as the gully fills, *Prionium serratum* expands beyond the gully onto the valley floor, to replace the floodplain communities *Cynodon dactylon* and *Sporobolus fimbriatus*.

Over time, *Prionium serratum* is thought to colonize the valley floor as the gully fills, stabilising it and promoting diffuse flow. Many restoration efforts in damaged palmiet wetlands have been focused on the preservation of intact palmiet communities upstream of erosional headcuts, with limited understanding of vegetation dynamics associated with the cut-and-fill cycles that naturally occur in these wetlands. Understanding the regeneration of *Prionium*

serratum following erosional events is thus important for wetland restoration, as it should focus more attention on promoting palmiet restoration on depositional floodouts downstream of eroded gullies.

A secondary aim of this study was to explore the possibility of mapping palmiet communities in Kromme River wetland using remote sensing techniques. Using a combination of ground-truthed data from this and previous studies in the Kromme River wetland, together with raster layers derived from a LiDAR survey, an overlay analysis was developed to effectively map the distribution of the *Prionium serratum* dominated community. The overlay was created using a machine learning library in RStudios known as Rpart. The results found that the model were 91% effective in classifying the distribution of the *Prionium serratum* community. A secondary finding was that the inclusion of a Relative Elevation Model in the overlay analysis allowed for the identification of *Prionium serratum* communities vulnerable to degradation following previous geomorphic disturbance events and those *Prionium serratum* communities that are likely to persist following a geomorphic disturbance event.

Acknowledgements

This work is based on the research supported wholly by the South African National Space Agency (SANSA). I would like to thank SANSA for supporting my MSc.

First and foremost, I would like to thank Professor Fred Ellery for his amazing supervision and guidance. Professor Ellery's passion for wetlands, science and education is remarkable and has spurred my own passion for science and conservation. I have thoroughly enjoyed working under his supervision over the last three years.

Secondly I would like to thank Professor Ian Meiklejohn for his supervision and expertise in the field of Earth Observation. Professor Meiklejohn's advice was essential, and led to the development of a simple and effective model that I am very proud of.

Thank you to members of the Geography department staff, and in particular to Abe Ngoepe for his help in the lab and Mthunzi Gumede for his administrative help. I wish the department well for 2023 and the years to come.

Finally, I am extremely grateful to the support I have received from family and friends. To Caydon Van Eck, thank you for surviving field work with me and the coffees together and endless discussions about palmiet. Thank you to my parents Timothy & Amanda Jarvis for allowing me the opportunity to study and follow my own path.

"Ask, and it will be given you. Seek, and you will find. Knock, and it will be opened for you."

- Matthew 7:7

Table of contents

Preface.....	i
Abstract	ii
Acknowledgements	iv
Table of contents.....	v
List of figures	ix
List of tables	xii
List of Abbreviations	xiii
1. Introduction	1
1.1 Aim	3
1.2 Objectives	3
1.3 Remote sensing aim and objective	4
2. Literature review	5
2.1 Wetlands dynamics and functioning	5
2.2 Geomorphic disturbance and impacts on the Kromme River Wetland (KRW)	7
2.2.1 A history of the Southern African land surface	7
2.2.2 The role of geomorphology in creating conditions suitable for wetland formation	8
2.2.3 The potential impact of geomorphic disturbance on vegetation distribution in the Kromme River wetland	11
2.3 Vegetation dynamics and ecological succession	11
2.3.1 Ecological succession theory	12
2.3.2 The role of ecosystem engineers and niche construction	13
2.4 Mapping the distribution of palmiet using remote sensing	15
2.4.1 The phenological characteristics of palmiet communities and its community distribution in the KRW	15
2.4.2 Using LiDAR data to assess vegetation and land surface characteristics	16
2.4.3 Classification via overlay and machine learning techniques	18
3. Study Area	20
3.1 Location	20

3.2 Geology	21
3.3 Climate	22
3.4 Geomorphological and hydrological characteristics	22
3.5 Vegetation	23
3.6 Landuse	24
3.7 Restoration	24
4. Methods	26
4.1 Data collection	26
4.1.1 Data collection in the field	26
4.1.2 Data collection via remote sensing techniques	27
4.2 Laboratory analyses	27
4.2.1 Soil particle size and organic content analysis	27
4.3 Data analysis	28
4.3.1 Classification of plant communities in the Kromme River Wetland	28
4.3.2 Relating vegetation communities distribution to environmental variables	29
4.3.3 Determining which environmental variables significantly contribute to vegetation community separation	29
4.3.4 Describing vegetation community distribution for environmental variables that are significantly related to vegetation community separation	30
4.3.5 Relating vegetation communities to geomorphic disturbance	30
4.4 Remote sensing methods	30
4.4.1 Introduction	30
4.4.2 Data collection	30
4.4.3 Overlay analysis	31
4.4.3.1 First phase: Creation of raster layers derived from the LiDAR dataset, used to discriminate between palmiet and non-palmiet vegetation	32
4.4.3.2 Second phase: Extraction of data to train and test the Recursive Partitioning and Regression Trees (Rpart) and the resulting overlay/ reclassification analysis	34
4.4.3.3 Third phase: Combining the palmiet and relative elevation layer and assessing the accuracy of the model	34

5. Results	36
5.1 Classifying plant communities in the Kromme River Wetland	36
5.1.1 First level of division	36
5.1.2 Second level of division	36
5.1.3 Third level of division	37
5.1.4 Forth level of division	39
5.2 Relating vegetation community distribution to environmental	40
5.2.1 Exploring the relationship between vegetation community composition and environmental variables	40
5.2.2 Considering relationships between environmental variables and community distribution in greater detail	42
5.3 Vegetation community distribution in relation to other environmental variables ..	44
5.4 Relating vegetation communities to geomorphic disturbance	47
5.5 Descriptions of plant communities	48
5.5.1 Vegetation communities and environmental conditions in the gully	48
5.5.2 Vegetation communities and environmental conditions on the former abandoned valley bottom surface	50
5.5.3 Vegetation communities and environmental conditions in the depositional feature	51
5.5.4 Vegetation communities and environmental conditions on the valley bottom	51
5.6 Remote sensing results	51
5.6.1 Introduction	51
5.6.2 Results from Rpart	52
5.6.3 Conducting the Overlay analysis	54
5.6.4 Reclassifying REM into appropriate elevations for stable palmiet communities	54
5.6.5 Combining binary layers	55
5.6.6 Confusion matrix to assess accuracy	55
6. Discussion	58
6.1 Vegetation distribution in the KRW	58
6.1.1 Recent disturbance events in the Jagersbos basin of the KRW	58
6.1.2 Ecological successional processes following the 2012 disturbance event in the KRW	60

6.1.3	Later colonisation by post-pioneer species	67
6.2	The influence of palmiet on vegetation succession within unchannelled valley bottom wetlands	67
6.2.1	The role of palmiet in creating and maintaining unchannelled-valley bottom conditions	67
6.2.2	Adaptations of palmiet to the hydrogeomorphic regime	69
6.2.3	Frequency and size of geomorphically significant events in fluvial systems; Biota and geomorphic scour and fill cycles	70
6.2.4	Palmiet as a niche constructor: a mechanism to explain ecosystem structure and functioning within the KRW	71
6.2.5	Implications for restoration	72
6.3	Remote sensing discussion	73
6.3.1	Introduction	73
6.3.2	The sole use of data derived from LiDAR to classify palmiet	73
6.3.3	The uniqueness of palmiet plant traits and implication for classification ..	74
6.3.4	Classification of palmiet using machine learning and overlay procedures ..	75
6.3.5	Recommendations for further research	76
7.	Conclusion	77
7.1	The relationship between geomorphic disturbance and vegetation distribution in fluvial wetland systems	77
7.2	Recommendations for further research	78
	References	80
	Appendix: Palmiet Wetland near Kareedou Lidar survey	93

List of figures

Figure 1: The three tier model of wetland formation that is driven by hydrology leading to anaerobic soils, to which the biota responds (after Gosselink & Turner, 1978)	6
Figure 2: Elevation profile of the KRW (Thulo 2021).....	8
Figure 3: The process of cut-and-fill cycles within the KRW and associated longitudinal slope reduction and valley widening (after: Pulley et al, 2018).....	10
Figure 4: Map of the Kromme K90A-E Catchment.....	20
Figure 5: Satellite imagery of the four basins which comprise the study are in the KRW.....	21
Figure 6: Geology of the K90A catchment with strata ordered from youngest to oldest from left to right of the figure legend.....	22
Figure 7: A broad vegetation map of the K90A and K90B catchment (SANBI, 2012).....	23
Figure 8: Diagram depicting the structure of gabion weirs in many palmiet wetlands, including the Kromme (After: Russel et al, 2009).....	25
Figure 9: A flow diagram showing the three phases of mapping palmiet distribution in the KRW's based on LiDAR data.....	32
Figure 10: A dendrogram summarising vegetation community groupings after the TWINSpan analysis. The level of division, Eigenvalue, groups, number of samples and indicator species for each group are provided for each division.....	38
Figure 11: Vegetation community distribution displayed on two axes of variation (DCA1 and DCA2) for all sites. Environmental variables have been fitted to DCA1 and DCA2 as a biplot that shows relationships between vegetation communities and measured environmental variables. Samples in vegetation types as determined in the TWINSpan cluster analysis have been grouped by colour. The order of vegetation types in the legend is the same as the order of vegetation types in the cluster analysis.....	41
Figure 12: Vegetation community distribution displayed on two axes of variation (DCA1 and DCA2) for sites where surface flow hydraulics were determined by hydraulic modelling. These environmental variables have been fitted to DCA1 and DCA2 as a biplot and vegetation communities derived from the TWINSpan analysis have been grouped by colour. The order	

of vegetation types in the legend is the same as the order of vegetation types in the cluster analysis.....	42
Figure 13: Box plots showing the range of variation in each of selected environmental factors grouped by vegetation community. Groupings from a post-hoc TUKEY's analysis are shown for each variable as a letter above each community. The mean value for each community has been displayed together with error bars.....	46
Figure 14: The KRW wetland divided into 8 sectors, A to H, running from the top of the Krugersland to the base of the Jagersbos basins.....	52
Figure 15: Classification and regression tree resulting from Rpart. Abbreviations: Canopy Cover Index (CDI), Vector Ruggedness Index (VRI), Vegetation Height Model (VHM), 'Stable palmiet' communities (Stable), and 'Non-palmiet' community (NonPal).....	53
Figure 16: Classification and regression tree resulting for Rpart for relative elevation.....	54
Figure 17: Resulting maps from the reclassification and overlay analysis to map the distribution of palmiet, covering the entire longitudinal lengths of the KRW.....	56
Figure 18A.....	59
Figure 18B.....	59
Figure 18C.....	60
Figure 18: Remote sensing imagery of the Jagersbos basin in 2012 showing the vegetation cover and the extent of two small gullies before flooding and geomorphic disturbance took place, (A); soon after the flood and disturbance events with the location of the two small gullies mapped prior to the disturbance superimposed (B); and the vegetation cover and eight years after the geomorphic disturbance event, vegetation (C).....	60
Figure 19: A photo of species from the Juncus community colonising on the bed of a gully.....	62
Figure 20: A photo taken from the bed of a gully just below the Hendrik's kraal basin. Palmiet has established itself on gully banks and over time will constrict the water way entirely.....	63
Figure 21A: Legend.....	64
Figure 21B: Immediately post geomorphic disturbance event. A gully has been initiated in the confined reach and deposited material on the floodout and vegetation has not had time to	

colonise. Only palmiet communities on the previous valley bottom surface in the confined reach persist after the disturbance event.....	64
Figure 21C: On the previous valley bottom surface, terrestrial communities have begun to encroach into persisting palmiet community. Due to the drop in water table, the palmiet community will degrade. Within the gully and on the floodout, pioneering plants have begun to colonise (including palmiet).....	65
Figure 21D: In the gullied reach, the degrading palmiet community has perished and been replaced by terrestrial communities. As the gully banks have depreciated, and the gully begins to fill, semi-terrestrial communities have colonised the gully banks. Within the gully, and in the depositional features, the pioneering communities remain similar. As channels migrates across the depositional feature, pioneering communities continue to colonise.....	65
Figure 21E: In the gullied reach, gully infilling continues and the water table becomes more horizontal. As a result, wetland communities encroach up the banks and push semi-terrestrial communities towards the valley sides. In the depositional feature, palmiet communities stabilize and begin to push up the gully.....	66
Figure 21F: In the gullied reach, the gully is filled and the water table becomes near-horizontal. Stable palmiet communities spill over onto the previous valley bottom surface, pushing terrestrial communities to the periphery. Post-pioneer colonisation begins to take place, through the colonisation of fynbos communities better adapted to compete in the geomorphically stable environment.....	66
Figure 22: A densely packed palmiet canopy, with the top of the canopy roughly 2 to 3 meters above the water surface. Photo taken by Caydon van Eck.....	75
Figure 23: Displaying conceptual model of the relationship between cycles of geomorphic disturbance (represented by river erodibility) and vegetation composition (represented by plant life-history characteristics).....	78
Figure 24: A conceptual model of the relationship between river erodibility and plant strategy in response to geomorphic disturbance.....	79

List of Tables

Table 1: The cover/abundance scale used for vegetation sampling (Ellenberg, D. and Mueller-Dombois, D., 1974).....	27
Table 2: Names, descriptions and citations for raster layers derived from LiDAR data set.....	33
Table 3: Summary of environmental variable selection in the Stepwise Discriminant Function Analysis	43
Table 4: Confusion matrix displaying the observed vs expected classification of communities based on environmental variables according to the Stepwise Discriminant Function Analysis	44
Table 5: Summary of F and Pr>F values produced by ANOVA	44
Table 6: Results from the Chi-squared test	47
Table 7: Two-way table displaying the frequency of vegetation communities in geomorphic disturbance units	48
Table 8: Species in each community present in more than 35% of the community plots. The table has been order to display a diagonal trend between communities and species. The unit are the percentage of species present in each community	49
Table 9: Confusion matrix assessing Rpart model accuracy	53
Table 10: Confusion matrix to assess model accuracy	55
Table 11: Confusion matrix assessing error propagation via classification accuracy.....	76

List of Abbreviations

Wetlands and geomorphology

AES – African Erosion Surface

KRW – Kromme River Wetland

SANBI – South African National Biodiversity Institute

Remote sensing

LiDAR – Light Detection and Ranging

GIS – Geographic Information Systems

GPS – Global Positioning System

INS – Inertial Navigation System

DEMs – Digital Elevation Models

REMs – Relative Elevation Models

ML – Machine Learning

Rpart – Recursive Partition and Regression Tree

VHM – Vegetation Height Model

CDI – Canopy Density Index

VRI – Vector Ruggedness Index

UAV's – Unmanned Aerial Vehicle

RS – Remote Sensing

Data analysis

RA – Reciprocal Averaging

HSD – Honesty Significant Difference

ANOVA – A one-way analysis of variance

DCA – Detrended Correspondence Analysis

SDFA – Stepwise Discriminant Function Analysis

TWINSpan – Two Way Indicator Species Analysis

Environmental variables

StrPow – Stream power

ParSiz – Particle Size

OrgCon – Organic Content

DisTha – Distance to the thalweg

WatTab – depth to the Water Table

Elevation – Elevation relative to the thalweg

YearDis – Year since most recent disturbance

FloodLev – Depth of flooding under a given flow

Geomorphological units

Gbar – On a bar in a gully

Gbed – On the bed of a gully

Gbank – On the sloping bank of a gully

FP – On the floodplain away from the gully edge

FO – On a recent (< 10 years) depositional floodout

RI – On the floodplain adjacent to the edge of a recently incised gully

VB – On an unchannelled valley bottom where the valley floor had not been incised

Vegetation communities

Jun – *Juncus*

PaS – Palmiet Stable

PaD – Palmiet degrading

PaR – Palmiet Regen

Mis – *Miscanthus*

Set – *Setaria*

Pla – *Platycaulos*

Spo – *Sporobolus*

Cyn – *Cynodon*

Ste – *Stenotaphrum*

Chapter 1: Introduction

Environmental factors have a direct impact on vegetation distribution in wetlands. For example, plants vary in their tolerance to the depth and duration of flooding (DWAf, 2008). Some plants are obligate wetland species (only found within a wetland), some are facultative wetland species (primarily found within a wetland but can be found on dryland), some are facultative dryland species (primarily found on dryland but can be found within a wetland), while others are dryland species and rarely appear in wetlands.

Mitsch & Gosselink (2011) use a three-level model in terms of the environmental factors that influence vegetation distribution. This model captures factors that give rise to wetlands and explains variations in wetland plant and animal distribution. The model describes the relationship between hydrological characteristics (frequency, depth, and duration of flooding); physiochemical characteristics of flooded soils (anaerobic conditions); and the biotic response to the limitations imposed by anaerobic conditions associated with flooded soils.

When examining hydrological characteristics, it is essential to note that hydrology acts as a 'double-edged sword' that can limit and enhance vegetation richness (Mitsch & Gosselink, 2011). The hydrological regime refers primarily to the spatial and temporal variation in the distribution of nutrients and oxygen within wetland systems. The movement of water and sediments through a wetland can create spatial heterogeneity, allowing a diverse ecosystem to develop. However, this same movement can create a uniform environment, resulting in communities dominated by one or a few species.

Fluctuations in hydrological characteristics are the main determinants of biotic functioning, but competition and episodic or cyclic disturbances (such as through geomorphological processes of erosion and deposition) must also be considered (Niering, 1989). This combination of external ("allogenic") and internal ("autogenic") factors also affect plant colonisation and vegetation distribution.

The role of geomorphic disturbance is important in influencing the way that wetlands function (Grenfell et al, 2010; Tooth et al, 2004; Pulley et al, 2018). However, the response of wetland plants to these sorts of disturbances has yet to be investigated. Some species are likely to colonise areas that have recently experienced geomorphic disturbance, but others are likely to tolerate long-term stability. Some species that colonise recently disturbed sites may persist as

the dominant species for long periods thereafter. Given the above, any attempt to link vegetation distribution to environmental factors must consider hydrological characteristics.

The Kromme River wetland (KRW) was formed through repeated cycles of erosion and deposition (Pulley et al, 2018). Due to tributary fans that extend from steep catchments across the trunk valley floor, the trunk stream is narrowed. Flow along the trunk stream therefore experiences increased velocity and unit stream power opposite tributary alluvial fans. This increases the risk of erosion, which leads to the natural formation of gullies within the KRW. These gullies migrate headward (upstream) along the trunk stream, which in the long term lowers the longitudinal slope of the system (Pulley et al. 2018). During fill phases, coarse-grained sediments are deposited at the toe of the gully, gradually filling it in an upstream direction as the gully propagates headward. Repeated cycles of gully incision and deposition laterally plane the valley bottom, contributing to valley widening (Pulley et al. 2018). These processes of repeated cutting and filling lead to a near horizontal valley bottom cross-section, with the low longitudinal slope. These conditions are well suited to wetland formation.

So far, the investigation of vegetation distribution in the KRW has been limited to a single basin, the Kompanjiesdrift Basin (Barclay, 2017). This basin has not eroded for a long time (likely several hundred years; Rebelo et al, 2015). Barclay (2017) found that five vegetation communities were present in the basin, each with characteristic species as follows: 1) *Prionium serratum*, 2) *Miscanthus capensis*, 3) *Juncus kraussii*, 4) *Metalasia densa* and 5) *Pennisetum clandestinum*. *Prionium serratum* was found to occupy the entire central wetland zone and occurred locally on the beds of gullies. *Miscanthus capensis* was restricted to the inner edge of the wetland fringe. *Juncus kraussii* was found along the wetland fringe. *Metalasia densa* was found around the river bank and *Pennisetum clandestinum* was restricted to the terrestrial wetland boundary.

Given that the Kompanjiesdrift basin has not experienced disturbance for some time, the findings of vegetation distribution as described by Barclay 2017, are not valid for areas with more recent disturbance. To date, no study has attempted to classify and describe vegetation communities throughout the upper KRW along different gradients of environmental stressors.

There is a particular interest in the wetland plant *Prionium serratum* (from now on referred to as "palmiet") as it is thought to be an ecosystem engineer responsible for the creation and functioning of the KRW (and other wetlands dominated by palmiet; Sieben et al, 2012; Barclay, 2017). Furthermore, there has been some debate about whether palmiet is a pioneer species that

colonises newly created habitats following geomorphic disturbance events, or whether it is a climax species that outcompetes earlier successional species following a disturbance event. The majority of studies addressing this issue have only focused on the role of palmiet as a dominant species in stable valley bottom environments, However, its distribution in relation to a range of geomorphic disturbance regimes has not been investigated (Rebelo, 2022; Barclay, 2017).

Ecosystem engineers often play a significant role in determining community succession, as the physical alteration of environments via engineering organisms alters selection pressures influencing ecosystem structure and function (Odling-Smee, 1988; Odling-Smee et al., 2003). Being an ecosystem engineer (Sieben et al, 2012; Barclay, 2017), palmiet will likely have some impact on successional processes within the KRW (Corenblit et al, 2009). The possible impact of palmiet on ecosystem structure and functioning has yet to be explored.

1.1 Aim

This study aims to establish the distribution of vegetation communities in the Kromme Wetland over the entire range of hydrological conditions and disturbance regimes due to erosional and depositional events over the last few decades.

1.2 Objectives:

- Sample and classify vegetation communities over a wide range of hydrological and geomorphic disturbance regimes.
- Relate the distribution of vegetation to environmental conditions with a particular emphasis on hydrological conditions and geomorphic disturbance history.
- Develop a conceptual model of vegetation dynamics in relation to hydrological conditions and disturbance history, with an emphasis on the impact of *Prionium serratum* (palmiet) on ecosystem structure and function within the KRW.

1.3: Remote sensing Aim and objective

A secondary study objective was to map the distribution of *Prionium serratum* using remote sensing techniques. The KRW are essential ecosystems that help provide fresh water to the city of Gqeberha (Port Elizabeth), but are viewed as severely degraded. The Department of Environmental Affairs programs Working for Wetlands and Working for Water have been involved in schemes to protect and rehabilitate the wetland (Dini & Bahadur, 2016). The efforts largely revolve around conservation of palmiet (*Prionium serratum*). This has been done without knowledge of the habitat requirements or conditions necessary for palmiet regeneration. An understanding of the distribution of palmiet communities within the wetland is vital for conservative efforts. To date, no study has tried to map the distribution of palmiet communities in the KRW via remote sensing techniques.

Remote sensing has often been utilised to map and analyse variability in wetland vegetation based on vegetation structure (Ozesmi & Bauer, 2002). Two of the most widely accepted methods are manually mapping vegetation communities with aerial photography and expert knowledge (Oliver et al, 2012), and using satellite imagery & automated classification techniques (Kuenzer et al, 2011). However, these techniques have primarily focused on assessing the distribution of vegetation communities over large temporal and spatial scales (Adam et al, 2010). This is mainly due to limitations imposed by the resolution and cost-availability of remotely sensed imagery.

In 2017 a LiDAR (Light Detection and Ranging) survey was conducted by GEOSENSE (see Appendix A) as part of SANBI (South African National Biodiversity Institute) research in the KRW. The survey produced high-resolution LiDAR data (sub-meter) intended to aid hydrologic analysis of the river system. LiDAR also has the capacity to analyse vegetation characteristics, mainly via the ability of light to penetrate vegetation canopies (Nelson et al, 1984). This allows for the creation of raster layers representing various features of vegetation communities. Using appropriate Geographic Information Systems (GIS) techniques, these layers can be combined and manipulated to classify vegetation types (Bolstad, 2016). This study explores the possibility of mapping palmiet community distribution using LiDAR data and GIS overlay techniques.

Remote sensing objective:

- To map the distribution of palmiet using LiDAR data and classification techniques

Chapter 2: Literature review

Environmental factors that influence the distribution of wetland vegetation have been described in a three-level model (Figure 1; Mitsch & Gosselink 2011), which identifies relationships between the hydrological regime, biogeochemical soil processes linked with anaerobic conditions and the biotic response to this combination of factors. Not only do these factors explain wetland formation, but they also explain variation in wetland plant and animal distribution within them.

2.1 Wetland dynamics and functioning

According to Mitsch and Gosselink (2011), wetlands are found at the interface between terrestrial and aquatic systems, but wetlands have a number of features that distinguish wetlands from drylands. Firstly, wetland soil is waterlogged at a depth shallower than 0.5 m. Secondly, soils are chemically and morphologically altered due to anaerobic conditions because under anaerobic conditions, metals such as iron, manganese and magnesium are dissolved and redistributed within the soil profile, and organic matter accumulates due to reduced decomposition rates in anaerobic conditions. Thirdly, only plants and animals that are adapted such that below-ground parts are oxygenated despite growing in anaerobic conditions, are able to survive.

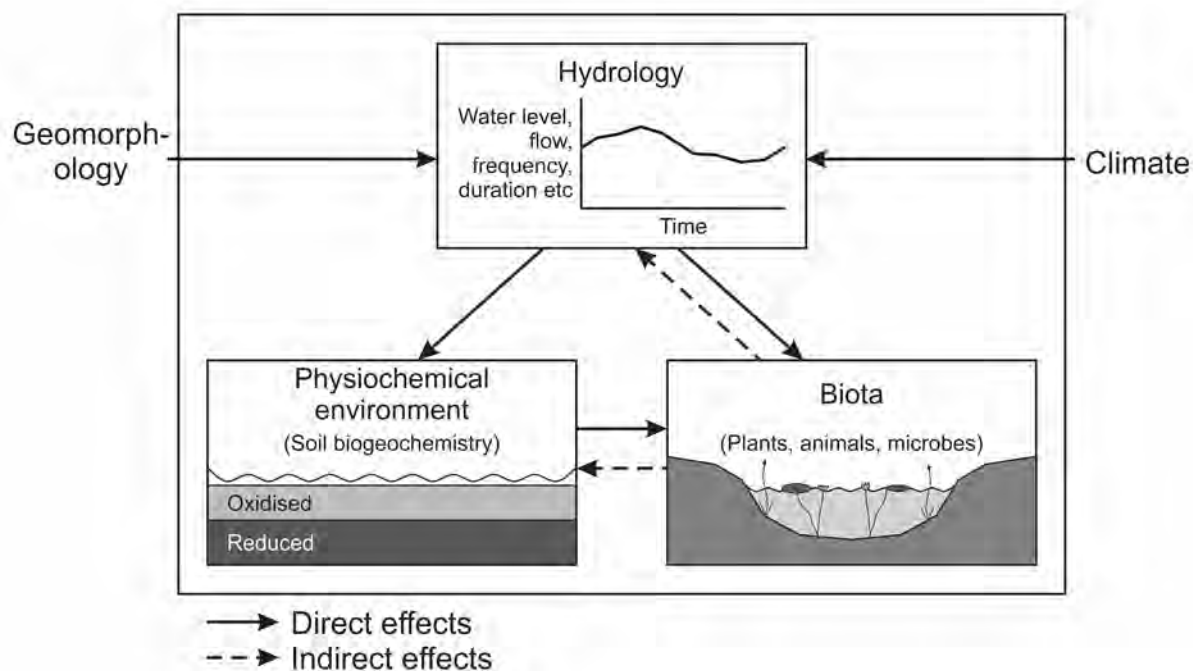


Figure 1: The three tier model of wetland formation that is driven by hydrology leading to anaerobic soils, to which the biota responds (after Gosselink & Turner, 1978).

The main way hydrology influences a wetland ecosystem is through changes to the physiochemical environment. Soils within a wetland are exposed to prolonged and repeated saturation by water. Oxygen that is dissolved within the surface and shallow wetland soil environment, is consumed in the soil by decomposition processes. Given that oxygen travels several orders of magnitude more slowly through flooded soils than water, an anaerobic environment is created (DWAF, 2005). Such conditions are stressful such that the distribution of biota is determined by the ability of organisms to tolerate different degrees of saturation below the soil surface.

Hydrology is dynamic, and flow characteristics are unique to each wetland (Mitsch & Gosselink, 2011). The pattern of variation in water level over time varies as a consequence of variation in inflows and outflows of water, such that the frequency, depth and duration of flooding vary spatially and temporally within each wetland. Such variation gives each wetland a unique hydroperiod (Mitsch & Gosselink, 2011).

The way in which flow characteristics affect biota is through the transportation of oxygen, nutrients, toxins and sediments (Leopold et al, 1964; Mitsch & Gosselink, 2011). Sediment transport is also important as it leads to variation in turbidity and may lead to local scale land surface degradation if erosion occurs, or else to aggradation if deposition occurs. These

disturbances, whether natural or anthropogenically induced, significantly alter land surface characteristics and are ecologically disruptive. However, the movement of water and sediments, including erosion and deposition, allows for spatial heterogeneity as it leads to the development of a range of habitats that can be exploited by living things in different ways.

Biota has a feedback effect on hydrology and the physiochemical environment (National Research Council, 1995). Vegetation influences wetlands through increasing roughness, contributing to peat accumulation, shading, intra-system nutrient cycling and sediment trapping (Mitsch & Gosselink, 2011). Plants also pump oxygen into the root zone which helps to overcome anaerobic conditions. All of these processes affect the hydrological regime, usually through a decrease in velocity by the creation of conditions that promote diffuse flow.

2.2 Geomorphic disturbance and impacts on the Kromme River Wetland (KRW)

In an ecological sense, disturbance can be defined as an event that removes biomass (Cronk & Fennessy, 2016). Such events are often short lived and change the composition and structure of the biophysical environment. There are four properties of disturbance: duration, intensity, frequency and extent (Keddy et al, 2000). Disturbance may happen through erosion and deposition, extreme weather such as floods or hurricanes, fire, herbivory, or anthropogenic activities such as ploughing or clearing vegetation. Erosion and deposition are extreme geomorphic events that locally destroy wetland habitats, but these sorts of disturbances can also create dynamic gaps in plant communities that can be exploited by suitably adapted taxa.

Most wetlands in Southern Africa are found along fluvial systems, due to the aridity of the climate where evapotranspiration exceeds precipitation. Thus, it is important to understand the Southern African land surface and its influence on fluvial systems and wetlands.

2.2.1 A history of the Southern African land surface

Prior to, and ending about 65 million years ago, the Southern African land-surface was lowered due to rapid and deep weathering, given that the subcontinent was equatorial. This erosion surface is known as the African Erosion Surface (AES; McCarthy and Rubidge, 2005; Holmes and Meadows, 2013; Maud, 2012). Subsequently, the southern African subcontinent experienced two isostatic uplift events caused by hot mantle plumes that settled under the subcontinent and reduced crustal density. This caused the land surface to rise by an average of about 400 m in the west to about 1000 m in the east. Due to these uplift events, southern Africa is unusually high in comparison to continents where uplift was not a product of plate collision.

These uplift events effectively lowered sea level relative to the land surface and rivers begun to incise as they worked to achieve a gradient in relation to the newly-formed sea level (McCarthy and Rubidge, 2005). Where rivers have incised below the AES, evidence of uplift can often be seen in the landscape as remnants of the AES are visible above the valley with the wetland of interest.

The Kromme River wetlands (KRW) are a product of erosion of the AES, as can be seen in Figure 2, in which local flattening of the land surface below the peaks of the Kouga Mountains remains visible today. This locally flattened land is mapped as the Grahamstown Formation in the geological map of the study area, suggesting that the KRW are the product of fluvial erosion of the AES.

Furthermore, the KRW occupy a valley with a near-perfect logarithmic slope where slope declines progressively downstream (Figure, 2; Thulo, 2021). The wetlands are on alluvium that is up to 8 m thick, suggesting that the system is a product of fluvial processes. This lowering of slope from long term incision, has created conditions suitable for wetland formation.

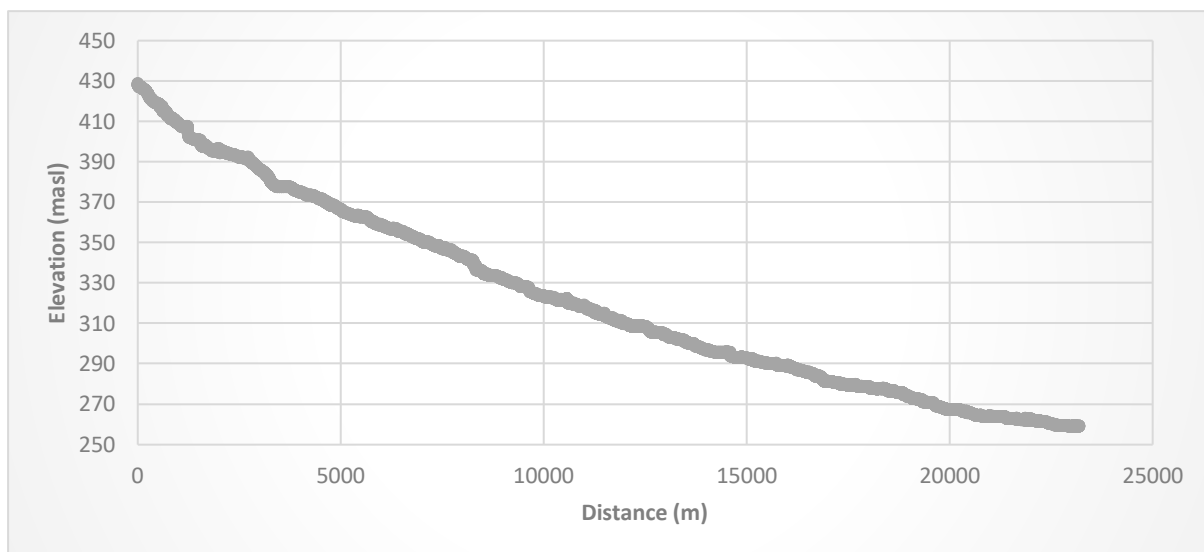


Figure 2: Elevation profile of the KRW (Thulo 2021).

2.2.2 The role of geomorphology in creating conditions suitable for wetland formation

The role of geomorphology in the creating conditions suitable for wetland formation has been increasingly recognized in Southern Africa (Tooth et al, 2004; Tooth & McCarthy, 2007; Grenfell et al, 2008; Grenfell et al, 2010; Ellery et al, 2012; Joubert & Ellery 2013; Pulley et al 2018). Wetlands occur where the valley is broad and near-horizontal in cross-section, and where the longitudinal slope is very low (typically less than 2 %; Ellery et al, 2009). Valleys

with these characteristics have been shaped by geomorphic processes such as erosion, which lowers longitudinal slope and widens the valley (Pulley et al. 2018).

An example of geomorphic control on wetland structure and function can be seen in the origin and development of the Nyl River floodplain (McCarthy et al, 2013). The Nylsvlei is located in the Limpopo province, along the Nyl River. Sediment accumulation within the wetland has been caused by partial blockage of the trunk stream by coarse-grained tributary alluvial fans impinging on the trunk valley. This has led to a series of disconnected very shallow areas of standing water along the trunk stream caused by a lowering of trunk stream slope upstream of the alluvial fans. This ponding leads to aggradation along the trunk stream. Slope is steepened downstream of tributary alluvial fans, which can lead to gully formation, which can migrate headward and lower the overall longitudinal slope of the trunk stream in the long-term. The combination of aggradation, diffuse flow and gradient control via erosion creates conditions suitable for wetland formation (McCarthy et al 2013).

Geomorphic processes influence wetland structure and function primarily by longitudinal slope reduction and valley widening, which are characteristics of long-term erosion. However, erosion is not a linear process that leads to gradual and continuous movement of sediment from the source to the ocean. Instead, it has been considered a jerky conveyor belt characterised by cycles of cutting (erosion) and filling (deposition; Nanson & Croke, 1992; Brierley & Fryirs, 1999; Grenfell et al, 2009).

Cut-and-fill cycles are characterised by gully incision followed by infilling. Breaching of geomorphic slope thresholds are generally thought to trigger the cutting phase (Ellery et al. 2009). The filling phase is characterised by sediment dis-connectivity where sediment movement is discontinuous through the fluvial system (Brierley et al, 2006).

The KRW has been shown to experience cycles of cutting and filling (Lagesse, 2017; McNamara, 2018; Pulley et al., 2018). Pulley et al. (2018) found that gully erosion has occurred repeatedly within the KRW with at least four episodes of gully erosion and gully infilling over the past 8 000 years. The gullies are thought to be initiated by the impingement of tributary fans on the trunk stream, which causes narrowing of the trunk valley and increasing trunk valley longitudinal slope. During flooding events gullies form and are subsequently filled with coarse grained sediments (McNamara 2018). As a result of the cut-and-fill processes, large areas of bare sediment are frequently present in KRW that can be colonised by ruderal species and give

rise to plant succession. These processes have also contributed to the creation of a broad valley with a horizontal cross-section and a gentle longitudinal slope (Figure 3).

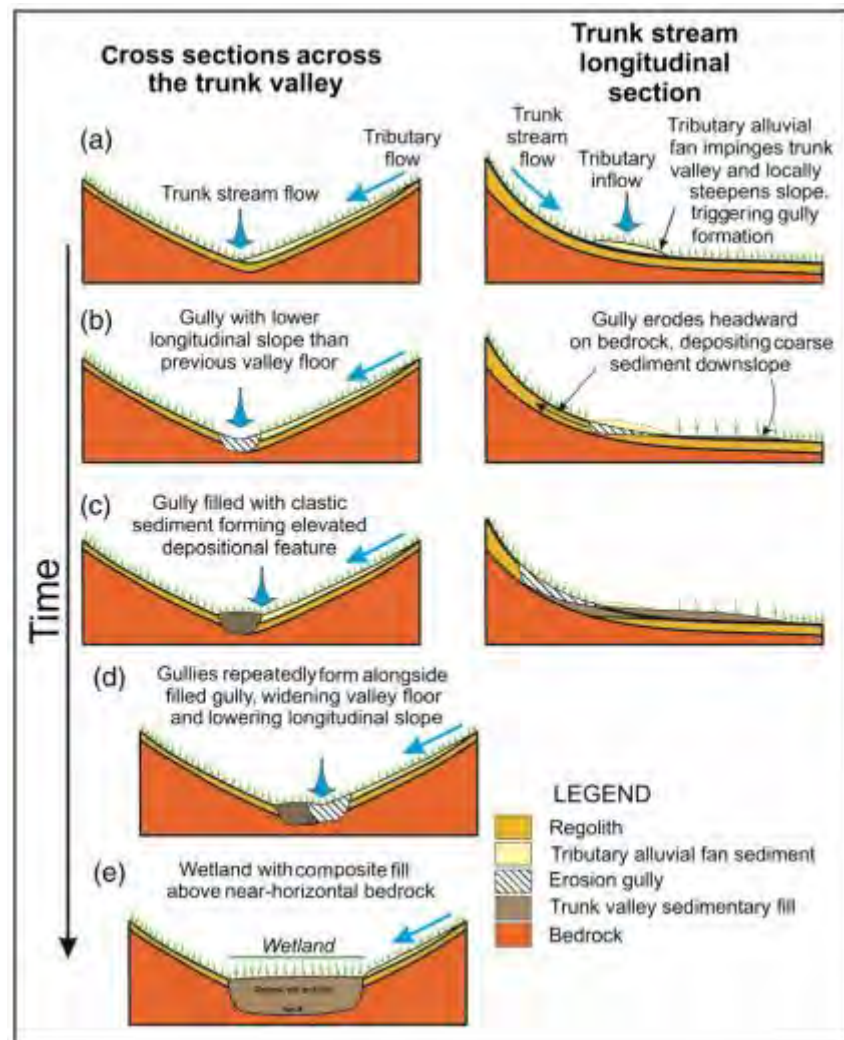


Figure 3: The process of cut-and-fill cycles within the KRW and associated longitudinal slope reduction and valley widening (after: Pulley et al, 2018)

Despite evidence that repeated cycles of cutting and filling are a natural part of the wetland's formation and evolution (Pulley et al, 2018), the general perception amongst landowners and wetland practitioners is that gullies are the primary agent of wetland destruction. This has led to rehabilitation interventions that halt gully formation and propagation. An outcome of this has been to limit natural processes that might promote natural repair because sediment supply at the toe of the gully is far more limited that may happen naturally. As such, systems may not be able to recover after disturbance events, leading to a reduction in wetland resilience (Grenfell et al, 2020).

2.2.3 The potential impact of geomorphic disturbance on vegetation distribution in the KRW

Cycles of cutting and filling may impact vegetation community composition in two ways. First the removal of vegetation by erosion and deposition, initiates primary succession on the gully bed, side-walls and depositional features immediately downstream of the gully. Secondly the water table in the wetland adjacent to the gully drops to a similar elevation as the base of the gully, altering the duration and frequency of flooding of the floodplain adjacent to the gully, initiating secondary succession on the previous valley bottom surface. These conditions favour plants adapted to terrestrial conditions (Hagberg, 1995; Poesen et al., 2003). Furthermore, gullies created by cut-and-fill cycles also lead to flow being concentrated in gullies such that surface flow through the non-eroded part of the wetland adjacent to the gully is reduced.

2.3 Vegetation dynamics and ecological succession

Plants have evolved different life history characteristics to ensure their long-term persistence. These strategies are dependent upon the surrounding environment. Dobzhansky (1950) found in temperate regions marred by frequent disturbance, those organisms with high fecundity and rapid development were most successful. Dobzhansky theorised that in the tropics where temperature and moisture availability are relatively constant and favourable for living things, organisms with low fecundity and slow development to reach reproductive maturity would be favoured. These organisms would likely be better competitors.

This generalisation of Dobzhansky's findings is not confined solely to temperate and tropical regions. MacArthur and Wilson (1967) developed the r and K selection theory (where r emphasises maximal fecundity, while K emphasises survival when populations are close to the carrying capacity). Organisms that are r selected are favoured by large disturbance events as they rapidly colonise disturbed areas and complete their life cycle where there is little or no competition. Organisms prioritize reproduction – with a small amount of resources allocated to survival of offspring. In contrast, K selection emphasises attributes that confer competitive advantage, such as a slow growth rate and producing limited numbers of large offspring that are well endowed with resources.

In habitats controlled by exogenous factors (those external to the biota themselves), r strategists typically dominate as mortality of individuals is unrelated to population size ("allogenic factors"; MacArthur and Wilson, 1967). However, in habitats controlled by autogenic factors, K strategists dominate as they better compete with co-habitants. In post disturbance conditions, r strategists initially dominate, but over time they are outcompeted by K strategists as the

ecosystem stabilizes. The predictable pattern of change in species composition in an area recently disturbed, is known as ecological succession. Thus, early post-disturbance environments are colonised initially by r strategists and over time those species that are K selected increasingly dominate.

2.3.1 Ecological succession theory

Modern ecological succession theories were first advocated by Clements (Clements, 1916). Clements likened communities to superorganisms and reasoned that communities change in a series of predictable steps on their way towards a climax community. Succession was predictable as each community paved the way for the establishment of the next community. Early successional communities had a positive effect on the environment that favoured colonisation by later successional communities, such as the accumulation of soil organic matter that led to more favourable soil conditions than those present immediately after disturbance. The process of succession is characterised by gradual changes in species composition and abundance such that when the climax community is reached there is no change in species composition or abundance as the probability is such that on average, species replace themselves.

Connell and Slatyer (1977) added to this concept, proposing that early colonists had two other effects on later successional communities: negative and null. This means that over time, early successional species could either: 1) facilitate the colonisation of areas by having a positive effect on the environment, 2) have no effect on the suitability of the environment for later successional stages (null effect), or 3) they may have a negative effect on the environment and inhibit colonisation by later successional populations.

The work of Clements, and subsequent Clementsian theories, have been criticized (Gleason, 1917; Pickett et al, 1987). Gleason (1917) proposed the individualistic hypothesis of succession, where every individual in a community is present because of its own unique adaptation to the surrounding habitat. Changes in community structure are largely brought on by allogenic disturbance, and a change of any kind in species structure and composition can be viewed as successional.

Pickett et al (1987) further argued that a number of other factors needed to be considered. These factors included: 1) site availability (size of disturbance), 2) species availability (dispersal, propagule pool and resource availability), and 3) species performance (ecophysiology, life

history characteristics, environmental stress, competition, allelopathy and herbivory). Pickett's view of succession was stochastic and therefore chaotic (Hastings et al., 1993).

Odum (1971) adopted a more holistic approach to ecological succession, defining ecological succession as the orderly and predictable process of community development, which results from the modification of the physical environment by communities and which culminates in a stable ecosystem. Odum considered community succession at the scale of an ecosystem, assuming that biotic and physical components adjust over space and time, continuously, with feedback mechanisms that maintain succession. These feedbacks are controlled by disturbance, stress, and competition (Grime, 1988).

Based on these assumptions communities lead to changes in the surrounding environment and create conditions suitable for other communities to establish themselves. Odum (1988) argued that the overall objective of community development is to increase homeostasis within the physical environment, and protect systems from unpredictable change.

2.3.2 The role of ecosystem engineers and niche construction

The work of Odum (1988), when considered within the context of evolutionary timescales (Lewontin, 1983; Dawkins, 1982), has opened doorways to new concepts such as ecosystem engineering (Jones et al 1994) and niche construction (Odling-Smee, 1988; Odling-Smee et al., 2003). Ecosystem engineers can be defined as: “organisms that directly or indirectly modulate the availability of resources (other than themselves) to other species, by causing physical state changes in biotic or abiotic materials. In so doing they modify, maintain and/or create habitats” (Jones et al, 1994: p373). *Prionium serratum*, otherwise known as palmiet, is thought to be an ecosystem engineer (Sieben, 2012).

Palmiet influences the creation of wetland habitats through encroachment of a fluvial system and the trapping of sediment (Sieben, 2012). Due to its clonal nature, palmiet occupies the eroded banks of fluvial systems and slowly encroaches onto the mainstream flow (Barclay, 2017). In doing this, sediments are caught and stabilized by the above-ground structures, which results in the formation of sandy peat deposits. Palmiet eventually constricts the river entirely so that the waterway is closed. This results in a valley-bottom peat-filled wetland (Barclay, 2017). The ability of palmiet to create wetland habitat demonstrates that it has a fundamental control on wetland vegetation community distribution.

Ecosystem engineers operate on the scale of ecosystem dynamics whereas niche construction operates on the scale of ecological succession and evolutionary adaptation (Odling-Smee, 1988; Odling-Smee et al., 2003). Niche construction looks at the feedback mechanisms in evolution created by the physical alteration of selection pressures. From the niche construction perspective, changes in organisms (via evolution) and associated changes in communities is determined by the relationship between ecosystem engineers, other organisms within the community and changes in the environment. Such alterations can be as attributed to ecological inheritance, either through genes or an altered environment, with positive or negative consequences for the ecosystem engineer (Odling-Smee et al, 2003). Within riparian systems, early successional vegetation is thought to play a role in niche construction by interconnecting hydrogeomorphic and biological components at successional and evolutionary scales (Corenblit et al, 2009).

A cycle of niche construction has been described in fluvial systems in a northern temperate setting (Corenblit et al, 2009). After flooding events, and associated geomorphic disturbance, bare patches of sediment are exposed. These patches are colonised by early successional vegetation, possibly including ecosystem engineers. This influences fluvial dynamics through the species ability to stabilize and protect sediments and moderate flow through increasing surface roughness. Early successional vegetation creates and maintains adequate conditions (soil wetness, nutrient availability, protection from hydrogeomorphic disturbance) for colonisation by post-pioneer competitive species (Gurnell & Petts, 2006).

This can be seen in the ecosystem engineering abilities of species in the Salicaceae (willow) family (Edwards et al, 1999; Gurnell & Petts, 2006; Corenblit et al, 2007). During flooding events - and associated geomorphic disturbance - willows produce lots of seeds which are dispersed on bare patches of sediment. Newly established plants are able to tolerate hydrogeomorphic disturbance and have an influence on fluvial dynamics through increased local roughness and stabilization of sediments. From a successional perspective, this allows for the colonisation of post – pioneer species.

From an evolutionary perspective, willows with life history characteristics adapted to hydrogeomorphic disturbance and colonising bare sediment, are favoured (Edwards et al, 1999; Gurnell & Petts, 2006; Corenblit et al, 2007). This allows willows to engineer habitats according to the organism's biomechanical adaptations and limits imposed by hydrogeomorphic disturbance regimes. Thus engineered habitats can be seen as an expression

of the engineering organism that has a control on the evolution of other species within the engineered habitat. In order to persist, engineering organisms must also evolve in response to the changes they induce (Corenblit et al, 2009).

From the niche constructivist perspective, the ecosystem engineering abilities of palmiet (in creating and maintaining peat-filled wetlands), through adaptations to the hydrogeomorphic characteristics of the wetlands that they dominate, could create and maintain conditions for the colonisation of post pioneer competitive species. However, the role of palmiet as a niche constructor has yet to be studied.

2.4 Mapping the distribution of palmiet using remote sensing

2.4.1 The phenological characteristics of palmiet communities and its community distribution in the KRW

Palmiet is a robust perennial shrub with a deep, extensive root system and semi-woody stem (Roux, 2003). The individual plants grow to an average height of three meters with an aerial woody stem that is initially sub-erect but falters as it ages to adopt a prostrate form (Roux, 2003). Palmiet communities grow in densely packed stands ranging from a few square meters in extent to dominating an entire valley floor (Roux, 2003).

In a recent study by van Eck (2022) distinction was made between three types of palmiet community: regenerative, stable and degrading (referred to as persisting by van Eck). The regenerative palmiet community is found on gully beds and depositional landforms such as floodouts, in which young plants colonise exposed sandy deposits following erosional and depositional disturbances. In this community, young plants form relatively small clumps from 1 to 20 m² in extent (van Eck, 2022). Over time regenerative palmiet communities establish themselves, where they trap sediment and aid in the filling of gullies. Once gullies are filled, regenerative communities spill over onto the floodplain where they are considered stable palmiet communities.

The stable palmiet community is found in valley bottom habitats where there is flooding across the valley floor. Mature palmiet is the dominant species and the community is dense and impenetrable (Van Eck, 2022). This community typically occurs in areas of the wetland that have not been disturbed for decades to centuries (Rebelo et al, 2022). Conservation efforts in the Kromme River are centred mainly on stable communities, as they provide important ecosystem services such as sediment trapping, reducing erosion risk, reducing flood risk and

water quality enhancement (van Eck, 2022). However, stable communities are vulnerable to cyclic erosional and depositional disturbance events. Once a gully has eroded through a valley bottom environment dominated by stable palmiet communities, communities far from the thalweg perish (Van Eck, 2022). Only communities adjacent to the recently eroded gully remain; which van Eck (2022) called degrading (or persisting) palmiet communities.

Degrading communities' are composed of old plants that have survived after erosional disturbance (Van Eck, 2022). They persist because they have access to sufficient water to survive. However, the degrading palmiet communities' are vulnerable to encroachment of other vegetation communities', as conditions suit plants adapted to terrestrial conditions (Van Eck, 2022). Eventually, degrading palmiet communities are out-competed. Within the newly eroded gully, regenerative palmiet communities colonise, and the cycle begins again.

Knowing how to differentiate between degrading and stable palmiet communities would be valuable for conservation efforts, as it would indicate which communities to preserve (stable) and which communities to restore (degrading). In terms of palmiet community composition (other vegetation associated with palmiet communities), there is no difference between stable and degrading palmiet communities. This is largely because degrading palmiet communities' were once stable palmiet communities, meaning the phenological characteristics of both communities is very similar.

Van Eck (2022) found the only way to differentiate between stable and degrading communities was by considering elevation relative to the thalweg. Stable communities are situated at an elevation similar to that of the thalweg (< 1 m), whereas degrading palmiet communities are 2 to 3 m above the thalweg (due to the impact of gullying).

To map the distribution of palmiet, the phenological characteristics of palmiet (shape, size and density), and geomorphological characteristics associated with community distribution (such as relative elevation and surface ruggedness) were assessed.

4.4.2 Using LiDAR data to assess vegetation and land surface characteristics

LiDAR data is an optical remote sensing technique that samples the earth surface (Wandinger, 2005). The LiDAR system is composed of an airborne vehicle (airplane, drone, tripod), an active laser scanner, a GPS (global positioning system) and an INS (inertial navigation system) that accounts for movements of the laser scanner (Bolstad, 2016). When a scanner emits a laser pulse towards the earth's surface, the precise times when the pulse left and returned is

recorded. It is then possible to determine the range to the target on the earth surface, which is then given a three dimensional point in space (x, y & z coordinates) using GPS and INS data. The output of a LiDAR survey is a point cloud that can be displayed and analysed using GIS software.

A single pulse emitted by the LiDAR scanner interacts with and is reflected off the earth's surface which results in multiple returns recorded by the LiDAR sensor (Wandinger, 2005). The first returns are the most important, indicating the highest feature on the surface (Bolstad, 2016). If only one return is recorded, the pulse only interacted with bare earth. First and intermediate returns largely account for vegetation, as light can travel through a vegetation canopy. The last return typically indicates bare earth, although a thick branch could result in a last return. These partial returns can be distinguished from one another to represent vegetation and ground returns using GIS software, such as ESRI's ArcMap.

LiDAR has been used to assess vegetation characteristics and distribution using the dichotomy between partial returns. Nelson et al. (1984) first recognised the potential of using airborne laser data to determine forest canopy characteristics. Since then, various studies have tried to improve methods for assessing canopy cover characteristics, many with success (Holmgren et al 2008, Lovell et al 2003). Nelson et al. (1984) also showed that LiDAR was able to calculate vegetation height precisely, as light is scattered by vegetation above the ground surface and at the ground surface (Cowen et al, 2000; Maune, 2001).

LiDAR data has also been widely used in the field of geomorphology. High-resolution Digital Elevation Models (DEMs) can be developed as LiDAR can penetrate the vegetation canopy to reach the earth surface. This gives geomorphologists the ability to assess the land surface without the interference of vegetation. In the field of fluvial geomorphology, DEMs have been used to examine floodplain morphology. However, DEMs are susceptible to downstream changes in elevation. To counter this, relative elevation models (REMs) have been developed by mapping the elevation relative to the thalweg of a stream or river system, thus removing downstream changes in elevation. Jones (2006) first describes the use of REM's in identifying side channels and fluvial landforms alongside a stream corridor.

Beside the above, geomorphologists use ruggedness indices to assess landscapes. Surface ruggedness can be described as the total elevation change in a given area. Several techniques have been developed to analyse ruggedness using DEM's, such as the land surface ruggedness index (Beasom et al. 1983) and the terrain ruggedness index (Riley et al., 1999). These indices

calculate the elevation difference between adjacent cells in a DEM. However, they do not consider the variables of topographic aspect and gradient, meaning that these indices may correspond with slope. Recently these methods have been improved with the advent of the Vector Ruggedness Index (VRI) developed by Sappington et al. (2007), which was created to incorporate both aspect and slope in the calculation.

4.4.3 Classification via overlay and machine learning techniques

Raster analysis covers a wide range of procedures to analyse spatial characteristics. The raster data model allows the modification, experimentation and creation of raster layers, due to the simple and flexible arrangement of rows and columns that are easily recognised by computer code (Bolstad, 2016). Raster cells can be stored as nominal, ordinal, or interval/ratio data, allowing for complex constructs. Map algebra refers to a cell-by-cell combination of raster layers through mathematical, logical, reclassification or overlay procedures. Using LiDAR data, many layers representing canopy or geomorphological characteristics will be created. To map the distribution of palmiet, these layers had to be assessed and integrated in a way that highlights palmiet distribution. Any attempt to manipulate and combine raster layers derived from LiDAR data needed to use Map algebra, and in particular reclassification or overlay procedures. Within ArcMap, this can be done using the Raster Calculator.

Overlay analyses refer to a group of methods used in suitability modelling or site selection (Bolstad, 2016), where a varied set of inputs are converted to a common scale and integrated using overlay techniques. Overlay analysis has been used in GIS processing for some time, with roots in hand-drawn techniques used by architects in the 1950s and 60s. These techniques were advanced by applying them to cartographic procedures, widely accepted as a prerequisite to classical overlay analyses in GIS. There are three major groups of overlay techniques: computer-assisted overlay, multi-criteria evaluation techniques and Artificial Intelligence (herein after referred to as Machine Learning) (Bolstad, 2016). Computer-assisted overlays are performed through cell-by-cell comparison in two or more raster layers, using map algebra (Berry, 1987). Each unique combination of cells from two layers is recorded, and assigned a new identifier in the output layer.

Computer-assisted techniques have been criticised for error propagation (Heuvelink & Burrough, 1993). When manipulating maps to identify attributes, the outcome is usually assumed to be true (Arbia et al, 1998). However, determining the exact input values to identify attributes is extremely difficult; it is more likely that the output will be in error. This may be a

result of data collection or the representation of data spatially (Heuvelink & Burrough, 1993). In any case, these errors have been shown to propagate through Map algebra, which involves the intersection of several maps. To counter this, error needs to be examined before operations and after, to determine if the use of overlay techniques is appropriate (Heuvelink & Burrough, 1993; Veregin, 1995). As a result of error propagation in computer assisted overlay techniques, there has been a shift towards Machine Learning (ML).

ML refers to a group of data-driven algorithms that automate the classification and prediction of data (Samuel, 1959). ML has given new opportunities for overlay classifications by seeking to develop systems that mimic human intelligence, without understanding the underlying processes. ML is tolerant of ambiguity, error and partial truth. A wide variety of ML methods have been used in wetland classification studies (Szantoi et al., 2013; Berhane et al, 2018; Crabbe et al., 2020; Wen & Hughes, 2020). The most popular of these ML models include Random Forest, Support Vector Machine, Neural Networks and k-Nearest Neighbour (Georganos et al., 2018). However, studies on the selection of ML models are limited and focus on a small group of methods (Bai et al., 2022, Guan et al., 2022, Reyes-Bueno and Loján-Córdova, 2022).

This study uses one of the simplest ML algorithms, a Recursive Partition and Regression Tree classifier, known as Rpart (Therneau et al, 2013). Rpart splits variables layer by layer, building a classification and regression tree, until the result satisfies a suitable condition. Rpart has been used in a few remote sensing classification studies (primarily land cover classification; Georganos et al., 2018; Beaumont et al., 2017; Wang et al., 2022; Berhane et al, 2018). Although other ML algorithms perform better (such as Random Forest and Support Vector Machine), Rpart performed adequately in all but one study (Wen & Hughes, 2020). In another study, looking at the potential of feature selection (reducing the size of input variables to the most discriminating predictors (Che et al., 2017)), out of 6 ML models, Rpart proved to be the most robust, using limited variable selection and training sample size. Due to the limitations imposed by solely using LiDAR data, and having a relatively small training sample size, Rpart is considered an appropriate choice. The primary reason for choosing Rpart, is the ability of the algorithm to build classification and regression trees. This allows for an in-depth analysis of variables driving discrimination between samples. Instead of classifying raster layers using the trained Rpart model, layers will be classified according to the classification and regression tree using map algebra and conditions statements In ArcMap.

Chapter 3: Study area

3.1 Location

The Kromme River Wetlands (KRW) are located in the Eastern Cape, close to the town of Kareedouw. The KRW catchment spans 155631 ha, bordered by the Suuranys Mountains (1050 masl) to the north and the Tsitsikamma Mountains (1500masl) to the south. The upper Kromme River, which is where the study has been done, spans 1077 ha and falls into quaternary catchment K90A (Figure 4). The upper Kromme is roughly 300-350 masl. The wetland is an unchannelled valley-bottom system with diffuse flow conditions, although lengthy sections of erosional gullies and depositional features are present.

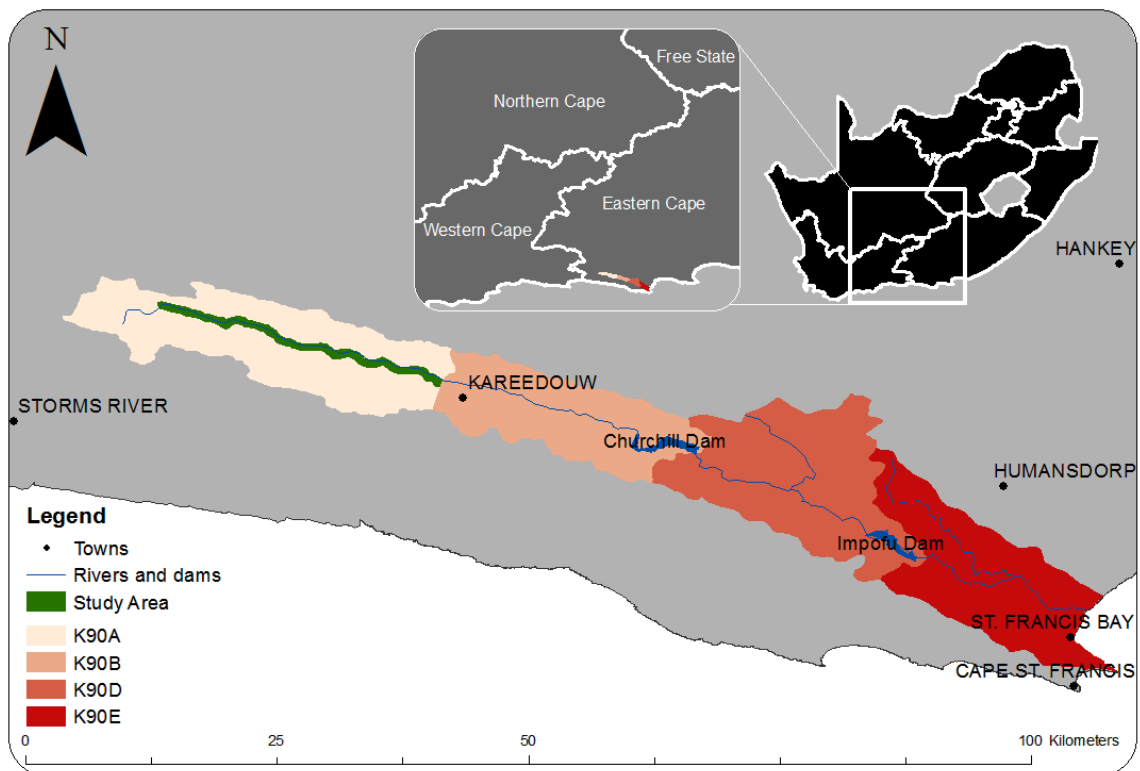


Figure 4: Map of the Kromme K90A-E Catchment.

The K90A quaternary catchment consists of four basins (Figure 4): the Krugersland and Kompanjiesdrift basins in the upper part of the wetland, which are unchannelled valley bottom wetlands dominated by *Prionium serratum*; and the Hendrikskraal and Jagersbos basins, which are channelled valley bottom systems that have incurred recent geomorphic disturbance and are the main focus of this study. In these basins a range of geomorphic features are present, such as: gullies, flood outs and stable valley bottom environments.

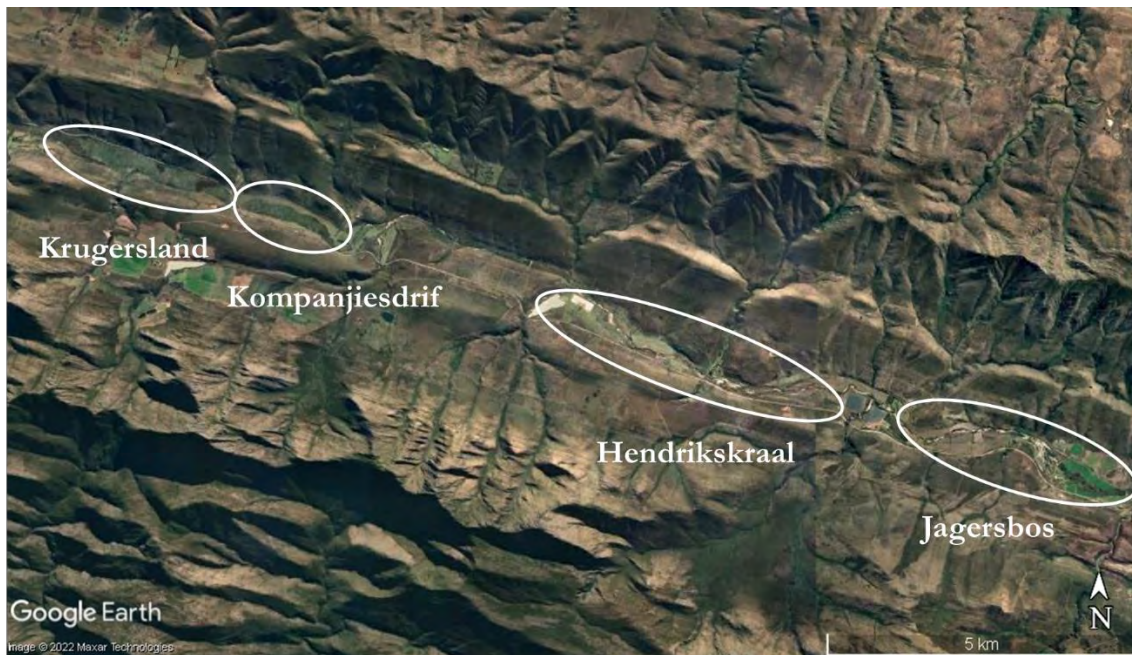


Figure 5: Satellite imagery of the four basins which comprise the study are in the KRW

3.2 Geology

The underlying geology is composed of rocks of the Cape Supergroup, which have been folded and metamorphosed, creating the Cape Fold Mountains that extend from the Western Cape in the west to East London in the east. The KRW occupies a syncline that trends in an east-west direction. This means that the oldest rocks are exposed on the northern and southern margins of the catchment, while the wetland in the centre of the fold are the youngest. Rocks at the base of the sequence are of the Table Mountain Group, comprising clean quartzitic sandstone lithologies of the Peninsula and Cedarberg Formations. Given that these rocks comprise quartz, they are resistant to weathering and form the peaks that slope steeply towards the wetland (Haigh et al., 2008). These are overlain by increasingly more easily weathered lithologies. The wetland occupies the youngest and most easily weathered lithologies of the Gydo, Baviaanskloof, Skurweberg and Goudini Formations (youngest to oldest). The fractured nature of the Cape Supergroup has resulted in a trellis drainage pattern. There is thought to be high groundwater storage and discharge into the river system (Boshoff et al., 2000).

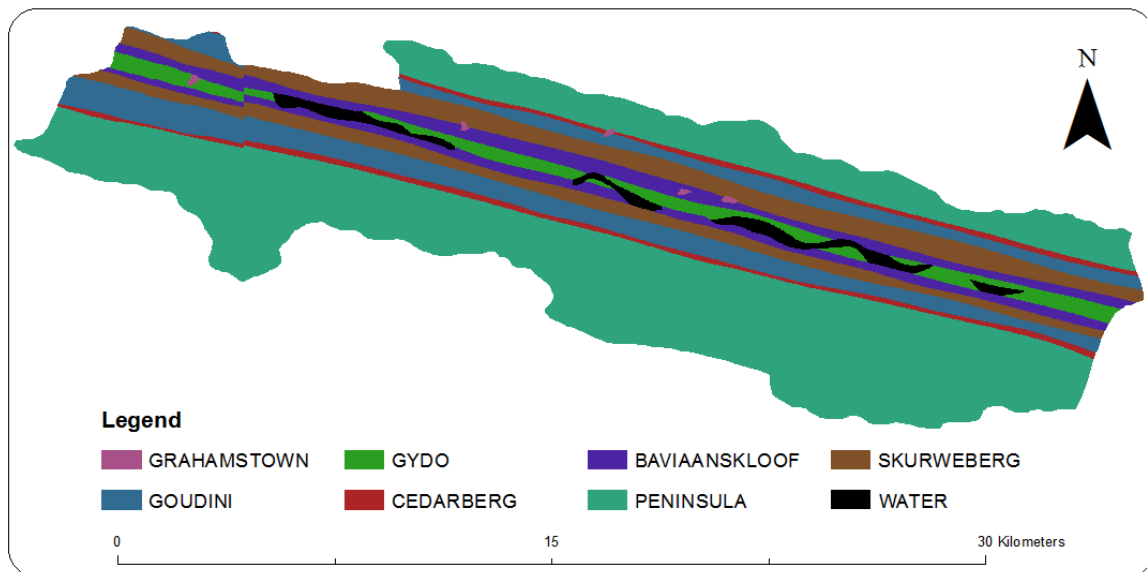


Figure 6: Geology of the K90A catchment with strata ordered from youngest to oldest from left to right of the figure legend.

3.3 Climate

Rainfall within the valley is bimodal, with most precipitation falling in spring and autumn. An average of 614 mm per year suggests the area is semi-arid, with an average runoff of 75mm (Middleton & Bailey, 2008). However, along the length of the river system rainfall is highly variable ranging from an average of 800 mm in the Tsitsikamma Mountains in the south and 400 mm in the Kouga Mountains in the north (Rebelo et al., 2013). Mean annual potential evaporation is 1980mm on the valley floor (Mucina & Rutherford, 2006). Floods are infrequent but can be very large, and droughts are also common with below-average rainfall in more years than above-average. Recorded floods over the last 100 years roughly follow a 10 year interval (Bickerton and Pierce, 1988). In more recent years, floods have occurred in: 1996, 2001, 2006 and 2012 (McNamara, 2018).

3.4 Geomorphological and hydrological characteristics

Within the KRW there are numerous tributary streams entering from both the southern and northern slopes. A number of these have resulted in alluvial fans that impinge the trunk valley, confining the width of the trunk stream, thus influencing cycles of erosion and deposition (Lagesse, 2017; McNamara, 2018; Pulley et al. 2018). Erosion of the trunk stream during flood events produces sediment that is deposited within 2 km of the gully head (McNamara, 2018).

Disturbance has been mapped in the Kromme since the 1940s, using aerial photography and was shown to have increased through the KRW from roughly 40 ha to 60 ha (Jarvis, 2020).

3.5 Vegetation

Vegetation within the catchment is primarily composed of Fynbos communities (Kouga Grassy Sandstone fynbos in the headwaters with Tsitsikamma mountain fynbos and Grassy Humansdorp fynbos along the slopes; Haigh et al., 2008). Grasslands and Albany thicket are also found along the slopes with Afro-temperate forest found in south-facing pockets. On the valley-bottom but outside the valley-bottom wetlands, Langkloof Shale Renosterveld is interspersed with Azonal fynbos and other riparian vegetation.

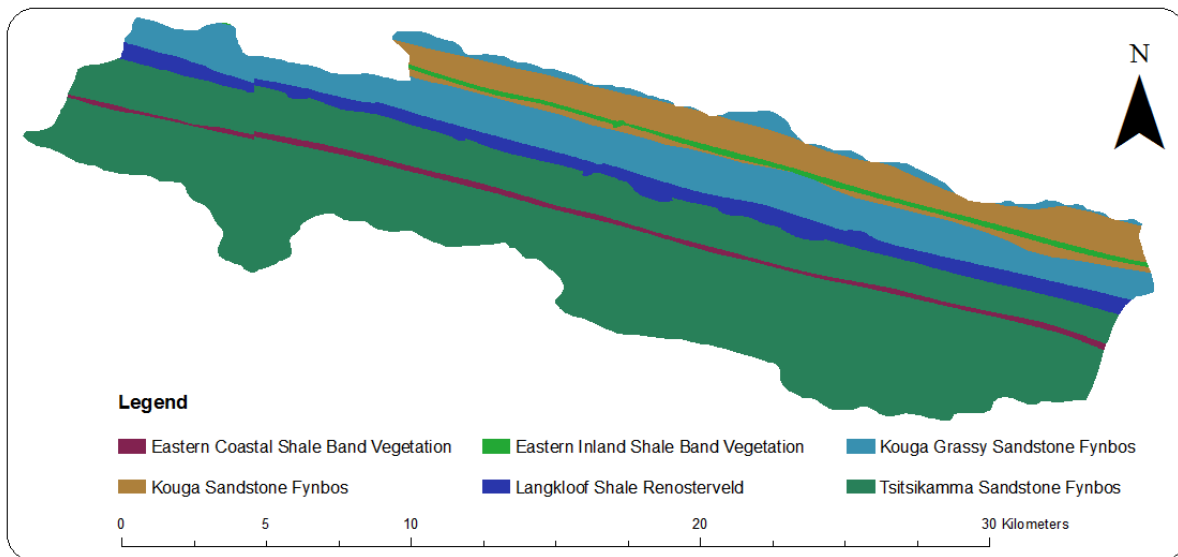


Figure 7: A broad vegetation map of the K90A and K90B catchment (SANBI, 2012).

Investigation of vegetation distribution in the wetland has so far been limited to a single basin, the Kompanjiesdrift (Barclay, 2017). This basin has not eroded for several hundred years (Rebelo et al, 2015). Barclay (2017) found that 5 vegetation communities were present in the basin each with characteristic species as follows: 1) *Prionium serratum*, 2) *Miscanthus capensis*, 3) *Juncus kraussii*, 4) *Metalsia densa* and 5) *Pennisetum clandestinum*. *Prionium serratum* was found to occupy the entire central wetland zone, and occurred locally on the beds of gullies. *Miscanthus capensis* was restricted to the inner edge of the wetland fringe. *Juncus kraussii* was found at the wetland fringe. *Metalsia densa* was found along the river bank, while *Pennisetum clandestinum* was restricted to terrestrial areas adjacent to the wetland.

Acacia mearnsii has encroached into the area, and is responsible for declining palmiet abundance (Rebello et al, 2013). Working for Water has initiated a scheme in order to remove alien vegetation. Currently, palmiet dominates the wetlands, accompanied by patches of grasses, sedges, ferns and reeds (Haigh et al., 2008; Nsor & Gambiza, 2013).

3.6 Landuse

There is evidence of human inhabitants potentially from as far back as one million years ago, and more recently settlement of Koi and San communities (Bickerton & Pierce, 1988). The first European settlers arrived in the 1800s and began practising agriculture (Gull, 2012). The first road was built in the late 1800s and the town of Kareedouw with a railway was established in the early 1900s. Since then land use in and around the wetland is primarily agricultural.

Currently within the valley, production of deciduous fruits is widespread. On the margins of the wetland, livestock production is the main farming practice. Due to the scenic nature of the area there has been an increase in tourism, which is set to continue. The two towns, Kareedouw and Joubertina, have populations of less than 5000 and 1000 respectively.

Along the river system the Churchill (with a capacity of $3.57 \times 10^6 \text{ m}^3$) and Impofu (with a capacity of $1.07 \times 10^6 \text{ m}^3$) dams supply 40 % of the water provided to the city of Gqeberha. Palmiet wetlands are important as they purify water and attenuate floods. The statutory agency Working for Wetlands has constructed gabion weirs to help preserve the wetlands and, in part, stop excessive sedimentation in the dams.

3.7 Restoration

Ongoing wetland restoration efforts by Working for Wetlands have focused on erosion control in palmiet wetlands, including the Kromme (Figure 8). Several gabion and concrete weirs have been built at intervals along the length of the KRW, mainly at the heads of gullies, in order to halt headward erosion of gullies. The weirs act as structures that allow water to flow over a spillway such that it enters the gully and flows down the gully bed without causing further erosion. The gabion structures implemented by Working for Wetlands allow the weir to trap sediments as water flows over the weir. Once water moves over the weir it drops onto a stepped gabion mattress, which lowers the velocity and reduces the potential for erosion.

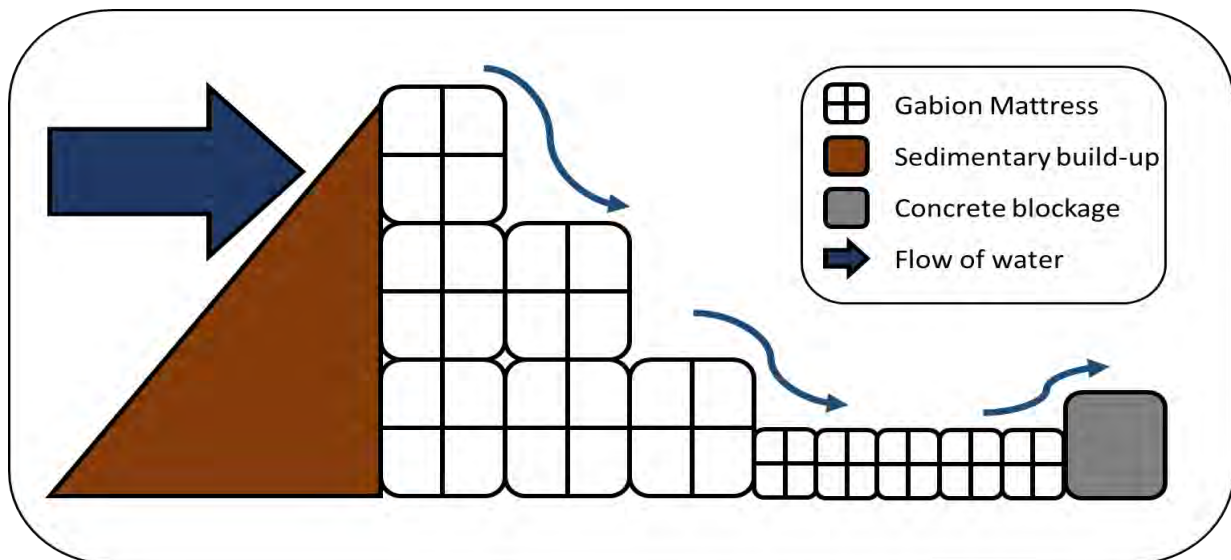


Figure 8: Diagram depicting the structure of gabion weirs in many palmet wetlands, including the KRW (After: Russel et al, 2009).

A study of gully restoration methods and outcomes in Dartmoor Vlei found that weirs have an impact on the hydrological regime and water level (Kotze et al, 2011). Above the weir, due to the pooling effect caused by structures, the surface water is normally above the water table. This promotes the recharge of water into the wetland above the weir. Downstream of the weir, the reverse applies as the elevation of the wetland surface is higher than the bed of the gully. This results in groundwater discharge from the wetland onto the gully bed. Once on the gully floor, water is rapidly transported downstream such that the flow of water from the wetland into the weir can continue unhindered.

Chapter 4: Methods

The overall aim of the study is to describe and explain vegetation distribution in relation to environmental characteristics, including geomorphic disturbance history. In order to do this, vegetation communities need to be sampled and classified, and then related to environmental variables that focus on a range of geomorphic and hydrological factors, including disturbance history. Methods can be broken into the collection of vegetation and environmental data, laboratory preparation and data analysis.

4.1 Data collection

4.1.1 Data collection in the field

A total of 29 transects were placed at roughly 100m distances down the length of the valley. Sample plots (6 to 10 per transect) were placed across the valley at roughly equal intervals (transect length and plot spacing dependent on valley width) along each transect. In each sample with a radius of 2 m, vegetation species composition was measured on a cover-abundance scale modified after the Braun-Blanquet scale (Ellenberg and Mueller-Dombois, 1974), as shown in Table 1.

In each sample, five soil samples were taken spaced evenly in the sample (one in the centre and four arranged orthogonally at a distance 1.5 m away from the centre of the sample). Depth to the water table was measured at the centre of the sample by augering to below the water table and letting it come to rest over period of about 20 minutes. The geomorphic setting of each sample was recorded in one of seven classes: on the floodplain away from the gully edge (FP), on the floodplain adjacent to the edge of a recently incised gully (RI), on the sloping bank of a gully (Gbank), on a bar in a gully (Gbar), on the bed of a gully (Gbed) on a recent (< 10 years) depositional floodout (FO), and on an unchannelled valley bottom where the valley floor had not been incised (VB). GPS coordinates were recorded at each sample using a handheld Garmin GPSMap 60CSx instrument. In total, vegetation and environmental data were collected from 159 samples.

Table 1: The cover/abundance scale used for vegetation sampling (Ellenberg, D. and Mueller-Dombois, D., 1974).

Class	Cover interval (%)
R	<0.1
+a	0.1 – 0.5
+b	0.6 – 1.0
1a	1.1 – 3.0
1b	3.1 – 5.0
2a	5.1 – 15.0
2b	15.1 – 25.0
3	25.1 – 50.0
4	50.1 – 75.0
5	>75.0

4.1.2 Data collection via remote sensing techniques

The GPS coordinates were used to superimpose samples onto a series of raster layers in ArcMap 10.8.1. A Relative Elevation Model (REM) with a resolution of 1 by 1 m was prepared using a high resolution DEM provided by the Rhodes University Geography Department to determine distance to the thalweg and elevation relative to the thalweg for each sample site. Hydrological data, prepared in HEC-RAS by Ms W Langner (Langner 2022), was used to determine velocity, stream power and depth of flooding under a given flow for most sample sites. However, not all samples were flooded for the modelled flood event magnitude (such as sites on the periphery of the wetland), in which case the sample was excluded from the analysis. Based on historical aerial photography (NGI, 2020; dates: 1952, 1954, 1969, 1986, 2000, 2015), time since the most recent geomorphic disturbance (in years; Jarvis, 2020) could be assigned to each sample.

4.2 Laboratory analyses

4.2.1 Soil particle size and organic content analysis

Soil samples were dried in an oven for 48 hours at 60 C to remove moisture. Following the drying period, samples were crushed with a pestle and mortar and added to a stacked set of sieves of mesh sizes 2000 µm, 1000 µm, 500 µm, 250 µm, 125 µm, and 63 µm, which is related to the Udden-Wentworth grain-size classification scheme (Wentworth, 1922). The samples

were sieved using an automatic shaker for 10 minutes and the contents of each sieve were weighed using an electronic balance accurate to 0.001 g. Using the recorded weights of each size class for each sample as inputs, the GRADISTAT - program developed by Blott and Pye (2001) - was used to calculate the geometric mean particle size Folk & Ward (1957).

Soil samples were passed through a 2000 μm sieve to remove excess debris, and about 15 g of each sample was ignited in a muffle furnace at 450 °C for 6 hours to determine organic content. Following ignition and cooling to a temperature where samples could be handled, samples were placed in a desiccator to cool to room temperature for an hour. The samples were reweighed after cooling to allow determination of pre- and post-combustion weights and thus organic matter content, expressed as a percentage.

4.3 Data analysis

Vegetation and environmental data was formatted for use in a series of multivariate analyses software packages. Vegetation data was composed a sample x species matrix using the midpoint of the cover interval values (Ellenberg and Mueller-Dombois, 1974). Environmental data comprised a sample x variable matrix. Environmental variables were: soil geometric mean particle size, soil organic matter content, depth to the water table, elevation relative to the thalweg, and distance to the thalweg. Hydraulic data were included for those samples where the modelled flood conditions were present (flow velocity, stream power and depth of flooding). The geomorphic setting and time since the most recent geomorphic disturbance event were also included.

In order to undertake a comprehensive analysis of the aforementioned data, the methods sought to determine relationships between vegetation community composition and abiotic environmental variables.

4.3.1 Classification of plant communities in the Kromme River Wetland

A Two Way Indicator Species Analysis (TWINSpan; Hill, 1979), was used to classify plant communities in the study area. TWINSpan is based on a hierarchical divisive approach that separates sites and species into groups of increasing similarity. Indicator species, preferential species and Eigenvalues are given at each division. Indicator species are those that are present in greater than 80 % of the samples in one group and less than 20 % of samples in the other group at each level of division. Preferential species are those that occur in more than 60 % of the samples in each group. The output of TWINSpan is a summary of each division and

presented as a two-way table, which shows samples (and species) in groups at each level of division. The two-way table can be summarised as a dendrogram and each sample site can be classified into a plant community based on the eigenvalue (λ) for each division. In this case an eigenvalue of 0.45 was used to identify divisions that were considered sufficiently valid for distinction of plant communities.

4.3.2 Relating vegetation communities distribution to environmental variables

A Detrended Correspondence Analysis (DCA) was used relate vegetation community distribution to environmental variables. DCA is an iterative algorithm that has been effectively used as an exploratory tool in community ecology (Shaw, 2003). The DCA is an improvement upon Reciprocal Averaging (RA) as it counters the ‘arch’ or ‘horseshoe’ effect that is an artefact of mathematical calculations in RA. The DCA as a means of displaying sample similarity and (difference) along major axes of variation in multivariate data was developed by Hill and Gauch (1980). DCA was chosen over other reciprocal averaging techniques because the vegetation data collected was species rich but the sample x species matrix was sparsely populated with many blank cells. The DECORANA function from the vegan package in RStudio was used to run the DCA (Oksanen et al, 2020; R Core Team, 2021). The DCA was based on the sample x species matrix and the sites x variable environmental data matrix was used as a supplementary matrix such that it had no effect on the way that output was calculated. Vegetation species composition was displayed on two axes of variation (DCA1 and DCA2). Environmental variables were fitted to DCA1 and DCA2 on a biplot and vegetation communities derived from the TWINSpan analysis were grouped by colour.

4.3.3 Determining which environmental variables significantly contribute to vegetation community separation

A Stepwise Discriminant Function Analysis (SDFA) was conducted using MS Excel XLSTAT software, to determine which environmental variables were significantly related to community distribution. A discrimination function distinguishes between the means (or centroids) of groups (Davis 1986). In an SDFA, a model of discrimination is built step by step to successively include variables from the greatest to the lowest contribution it reveals to sample group discrimination. Once entered, all remaining variables are reconsidered in the next step. Variable selection terminates when no more variables meet the entry/removal criteria. In this way, only variables that are related to discrimination between groups are included in the model. SDFA required the site x variable environmental data, with an extra column for vegetation community

groups. The output of the SDFA was a table showing the strength of the relationship between each environmental variable and community groups, and results are typically presented as a confusion matrix depicting the number of samples classified as belonging to each group. It is a means of judging the overall success of the model.

4.3.4 Describing vegetation community distribution for environmental variables that are significantly related to vegetation community separation

A one-way analysis of variance (ANOVA) with post-hoc Tukey's Honest Significant Difference (HSD) was used to identify factors that vary significantly between communities as a basis for better understanding relationships between environmental factors and vegetation communities. This was done because ANOVA does not indicate how environmental factors vary between communities but a Tukey's HSD does pairwise comparisons by community.

4.3.5 Relating vegetation communities to geomorphic disturbance

A Pearson's chi-squared test was used to determine whether there were statistically significant differences between vegetation community distributions in relation to geomorphic disturbance units. The observed frequency of geomorphic disturbance units within each vegetation community group was analysed compared to the expected frequency. The output of the test was a table showing the chi-squared and p-value for each community group, as well as a two way table showing the frequency of classification of samples from each community into all communities.

4.4 Remote sensing methods

4.4.1 Introduction

An overlay analysis conducted in ArcMap 10.8.1 (ESRI, 2020) was used to map the distribution of stable and persisting palmiet communities in the KRW. The study was based on ground-truthed data derived from previous research in the KRW and raster layers derived from the LiDAR data set.

4.4.2 Data collection

There were two components of data collection. The first component was a LiDAR survey captured via aeroplane in 2017 by GEOSENSE (see appendix A) for SANBI-sponsored research in the KRW. The LiDAR data was captured by a Trimble Harrier 68i or the Riegl 480i with matching aero control and GPS inputs. The LiDAR data was pre-processed by

GEOSENSE and the output was stored as a LAS point file which was imported into ArcMap 10.8.1 (ESRI, 2020). The LiDAR data has two major return classes after processing: ground returns and medium vegetation returns.

The second component was extracting ground-truthed data from fieldwork conducted by myself, van Eck (2022) and Barclay (2017). Sample sites, with associated GPS coordinates, were separated into those representing stable palmiet communities and non-palmiet communities (degrading palmiet communities were excluded due to the limited number of samples for this vegetation community). Several other sample sites representing landscape features (roads, buildings, agricultural areas and water) were extracted using aerial photography (RGB) collected by GEOSSENCE along with the LiDAR dataset and added to sample sites representing non-palmiet communities.

In total, there were 500 sample sites; 250 representing the palmiet community and 250 representing non-palmiet communities. Four hundred samples were allocated to training the Machine Learning (ML) classification algorithm, and 100 samples were set aside for testing the resulting ML model. Both training and testing samples were imported to ArcMap 10.8.1 as point features.

4.4.3 Overlay analysis

A model was created to map the distribution of palmiet communities. The model comprises three phases: the creation of raster layers, the overlay analysis and the separation of stable and persisting palmiet communities (Figure 9).

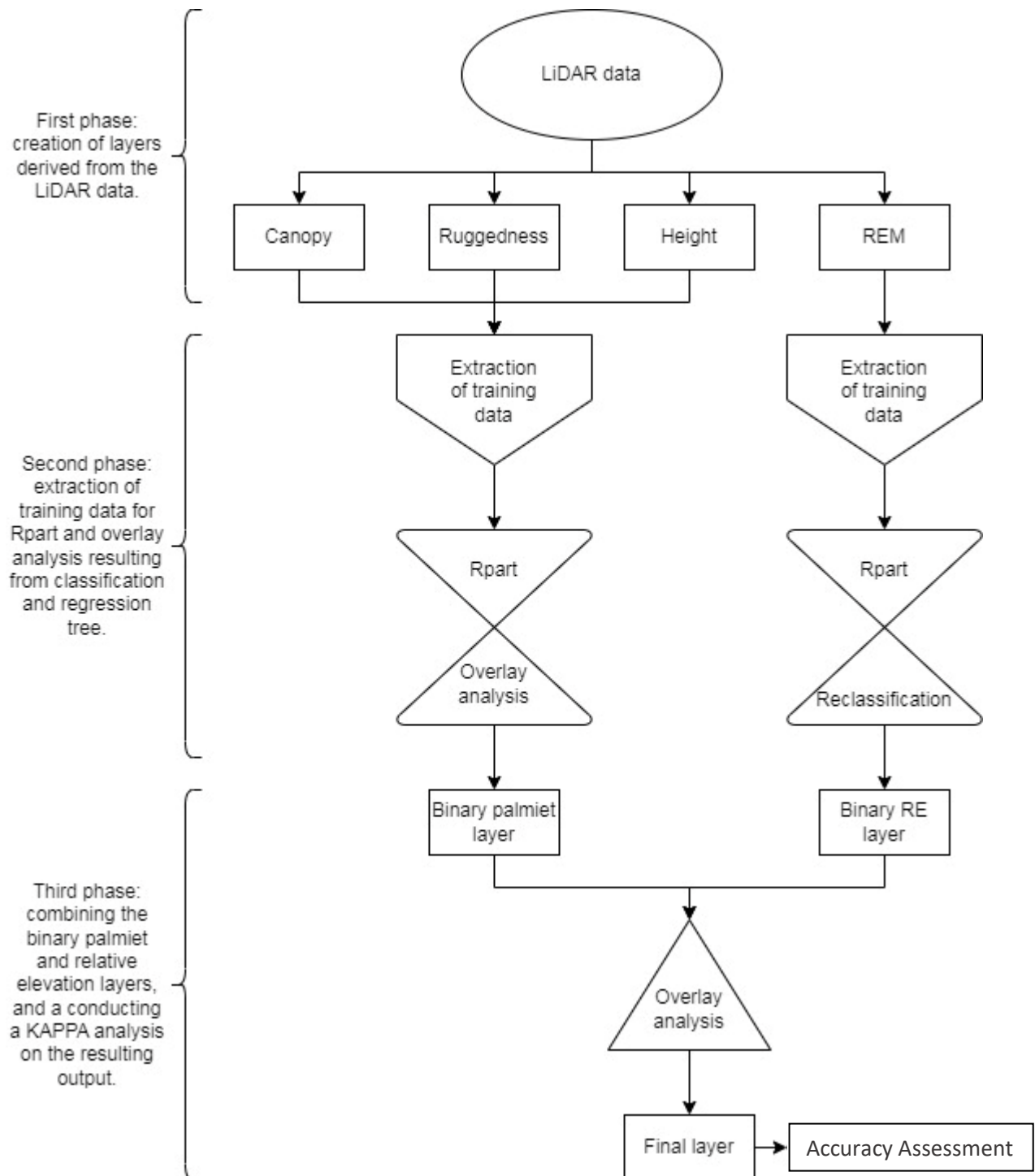


Figure 9: A flow diagram showing the three phases of mapping palmiet distribution in the KRW based on LiDAR data.

4.4.3.1 First phase: Creation of raster layers derived from the LiDAR dataset, used to discriminate between palmiet and non-palmiet vegetation.

After reviewing the literature and assessing many indices and models created using LiDAR data, four layers were deemed appropriate for the Overlay operation. The aim of using these

layers is to discriminate between ‘stable palmiet’ communities and ‘non-palmiet’ communities. Therefore, each layer seeks to represent either phenological differences between vegetation communities or environmental conditions associated with vegetation community distribution (Table 1).

Table 2: Names, descriptions and citations for raster layers derived from LiDAR data set

Layer name	Abbrev.	Brief description	Unit	Reference
Vegetation Height Model	VHM	A model representing vegetation height created by subtracting a DEM from a DSM.	Meters	ArcGIS (2021)
Canopy Density Index	CDI	Canopy density can be defined as the ratio of vegetation to ground as seen from the air, created by comparing LAS ground points to the total number of LAS points.	Ratio (0-1)	ArcGIS (2021)
Vector Ruggedness Index	VRI	VRI measures ruggedness as the variation in three-dimension orientation of grid cells within a specified neighbourhood using a DSM.	Ratio (0-1)	Sappington et al. (2007)
Relative Elevation Model	REM	REM, DEM that is made relative to some feature (thalweg). This study uses the Kernel Density Method.	Meters	Olsen (et al., 2009)

Note:

- The VHM was created to account for palmiet’s height (up to 3m).
- The CDI was created to account for the densely packed canopies of palmiet.
- The VRM was created to quantify the surface characteristic of the KRW.
- The REM was created to discriminate between ‘stable’ and ‘degrading’ palmiet communities.

4.4.3.2 Second phase: Extraction of data to train and test the Recursive Partitioning and Regression Trees (Rpart) and the resulting overlay/ reclassification analysis

Data utilised in the training and testing samples were extracted from each raster layer in ArcMap (ESRI, 2020). A three-meter *Buffer* was created around each sample point. Using the buffered samples as inputs, the *Zonal Statistics Tool* calculated the mean value for each raster layer. The *Multi Value to Point Tool* was used to add the mean value of each raster layer for the training and testing data as an attribute field. The *Table to Excel Tool* was used to convert the attribute table into an MS Excel document.

The MS Excel file containing the training and testing data was imported into RStudio. The training data were used to train an Rpart model - a machine learning function and library that builds classification and regression trees - to separate values representing palmiet and non-palmiet vegetation. The testing data were used to assess the accuracy of the model prior to Overlay analysis, and served as a method of determining error propagation. The output of Rpart is a classification tree that describes, using values, the separation between ‘stable palmiet’ and ‘non-palmiet’ vegetation. Rpart was also used, in the same manner, to discern the appropriate relative elevation for the classification of stable palmiet communities.

The resulting classification tree was used to construct a “conditions statement” via the *Raster Calculator Tool* in ArcMap 10.8.1. This resulted in two binary layers: a layer displaying palmiet and a layer showing the appropriate relative elevation of ‘stable palmiet’ communities.

4.4.3.3 Third phase: Combining the palmiet and relative elevation layer and assessing the accuracy of the model.

Using the *Raster Calculator*, the Binary REM layer and binary palmiet layer were added together using the following expression.

- ***Palmiet + (REM*0.5)***

The REM was reclassified to separate values in the output. The resulting raster layer had four classes:

- 0 – where no palmiet communities are present, and the relative elevation is not appropriate.
- 0.5 - where no palmiet communities are present, but the relative elevation is appropriate for ‘stable palmiet’ communities.

- 1 – where palmiet communities are present, but the relative elevation is not appropriate for ‘stable palmiet’ communities (‘degrading palmiet’ communities)
- 1.5 - where palmiet communities are present, and the relative elevation is appropriate for ‘stable palmiet’ communities.

In order to assess the model’s accuracy, a confusion matrix was built using the testing data and the final output layer.

Chapter 5: Results

5.1 Classifying plant communities in the Kromme River Wetland

In the 158 samples a total of 59 species were identified. Eight vegetation communities were classified using the TWINSpan analysis. Each community was named after the genus of the best indicator species in the community. Where the indicator species was already present in a community, the genus from the second best indicator species was used.

TWINSpan is a divisive technique that divides groups progressively at a series of "levels of division". Given this, the results of the classification are presented by levels of division of each group of samples such that each level of division includes samples that are progressively similar. Given that most species occur in more than one community, the challenge is to identify each level of division at which samples before the division are sufficiently dissimilar, but after the division are sufficiently similar to form a distinctive community. Results are thus presented by the level of each division of specified groups. The results are presented as a dendrogram (Figure 10).

5.1.1 First level of division

The first division ($n=158$, $\lambda^1 = 0.771$) largely separated wetland (negative group) and dryland (positive group) samples. Indicator species for the positive group ($n=39$; Group 3) were characterised by terrestrial grasses including *Cynodon dactylon*, *Eragrostis curvula* and *Aristida junciformis*. *Prionium serratum* and *Juncus lomatophyllus* were indicator species for the negative group ($n=119$; Group 2).

5.1.2 Second level of division

The second level of division involved division of the two groups from level 1, the samples of wetland communities (Group 2) and the samples of dryland communities (Group 3).

Division of Group 2

Samples in Group 2 were divided into two groups ($\lambda = 0.670$). Those samples in the negative group (Group 4; $n=81$) were in semi-permanently saturated soils, while those in the positive group (Group 5; $n=38$) were in intermittently saturated soils. There were no indicator species for samples in Group 4 but the sedges *Isolepis prolifera* and *Pycnus mundtii*, along with

¹ The symbol λ is used to indicate the Eigenvalue associated with each level of division.

Juncus lomatophyllus and *Prionium serratum*, were preferential species associated with this group. Samples in Group 5 were indicated by the grass *Setaria incrassata*, while the restio *Platycaulos callistachyus* was preferentially associated with this group.

Division of Group 3

Samples in Group 3 (n = 39) were divided into two ($\lambda = 0.666$), with the negative group (Group 6; n=29) being indicated by *Cynodon dactylon* and the positive group (Group 7, n=10) by *Stenotaphrum secundatum* and *Aristida junciformis*. Samples in Group 6 occurred in a wide range of dryland habitats and had the prostrate plant *Mesembryanthemum grossum* and terrestrial grasses *Pennisetum clandestinum* and *Sporobolus fimbriatus* as preferential species. Samples in Group 7 occurred on relatively sandy and well drained soils with *Ischaemum fasciculatum*, *Eragrostis curvula* and *Leersia hexandra* as preferential species.

5.1.3 Third level of division

Most vegetation communities were identified in the third level of division, which largely separated between communities in similar hydrogeomorphic settings. The third level of division involved division of the four groups from level 2 (Groups 4 to 7).

Division of group 4

Samples in Group 4 (n=81) were divided into two ($\lambda = 0.650$), with the negative group (Group 8; n = 24) being indicated by *Juncus lomatophyllus* and *Isolepis prolifera*. The positive group (Group 9, n = 57) was indicated by *Prionium serratum*. Samples in both Groups 8 and 9 were in permanently saturated soils very close to water's edges. Preferential species for Group 8 comprised a variety of sedges (*Isolepis prolifera*, *Eliocharis dregeana* and *Pycneus mundtii*), the grass *Andropogon eucomus* and the small fynbos tree *Berzilia intermedia*. *Helichrysum odoratissimum*, *Nidorella ivifolia*, *Ruben capensis* and *Phragmites australiansis* were preferential species for Group 9.

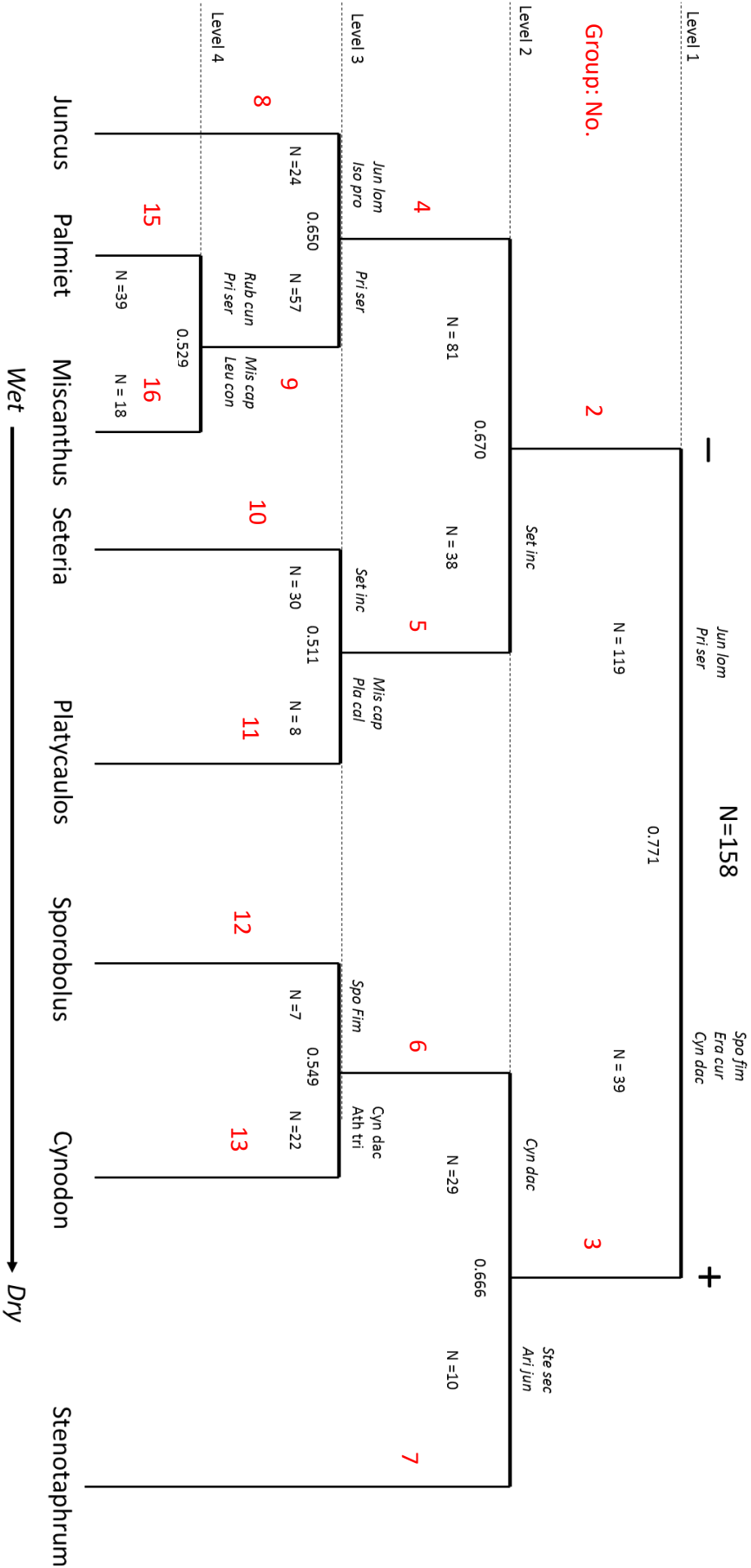


Figure 10: A dendrogram summarising vegetation community groupings after the TWINSpan analysis. The level of division, Eigenvalue, groups, number of samples and indicator species for each group are provided for each division.

Division of group 5

Samples in Group 5 ($n = 38$) were divided into two ($\lambda = 0.551$), with the negative group (Group 10; $n = 30$) indicated by *Setaria incrassata* and the positive group (Group 11, $n = 8$) indicated by *Miscanthus capensis* and *Platycaulos callistachyus*. Group 10 dominated shallow banks between the floodplain and the riverine system, with preferential species *Helichrysum odoratissimum*, *Rubin capensis* and *Stenotaphrum secundatum*. Group 11 occurred on banks and bars within gullies with *Hypochaeris radicata*, *Seriphium plumosum* and *Berzilia intermedia* as preferential species.

Division of group 6

Sample in group 6 ($n=29$) were divided into two ($\lambda = 0.549$) with *Sporobolus fimbriatus* indicating the negative group (Group 12; $n = 7$) and *Cynodon dactylon* and *Athanasia trifurcate* indicating the positive group (Group 13; $n = 22$). Group 12 occupies terrestrial former floodplains and includes the fynbos species *Cliffortia strobilifera*, the weed *Dichondra repens*, the large leaf pennywort *Hydrocotyle bonariensis*, *Helichrysum odoratissimum* and the terrestrial grasses *Eragrostis curvula* and *Pennisetum clandestinum* as preferential species. Group 13 is also a terrestrial habitat but is more tolerant of saturation, with the only preferential species *Erigeron karvinskianus*,

5.1.4 Fourth level of divisions

Only group 9 ($n=57$) was divided at the fourth levels of divisions ($\lambda = 0.529$), with the negative group (group 14, $n = 39$) indicated by *Miscanthus capensis* and *Leucadendron conicum* and the positive group (group 15, $n = 18$) indicated by *Prionium serratum*. Group 14 occurred on gully bars, and was characterised by hardy vegetation such as *Leucadendron conicum*, *Restio sejunctus* and *Cliffortia strobilifera* and the sedges *Scirpoides dioecious* and *Pycnus mundii* as preferential species. Group 15 occupied a range of habitats in a range of conditions in gullies, the flood out and stable valley bottoms. Preferential species *Helichrysum odoratissimum* and *Nidorella ivifolia* sprawl across palmiet clumps and compete with the invasive *Ruben capensis*. *Phragmites australiansis* can tolerate the shade cast by *Prionium serratum* as it grows above the canopy while *Paspalum urvellii* grows in pockets where palmiet is not present.

Palmiet communities were further divided into sub-communities, as palmiet is so widespread. The divisions were made according the findings of van Eck (2022). van Eck distinguished between three types of palmiet communities: stable palmiet communities ($n=17$), degrading

palmiet communities (n=10) and regenerative palmiet communities (n=11). These community types are based on the geomorphic setting in which it is found, with stable palmiet communities on undisturbed valley bottom settings. Degrading palmiet communities occurred on floodplains adjacent to recently incised gullies. The regenerative palmiet communities occurred on sand bars on the gully bed or on depositional floodouts downstream of a large gully.

5.2 Relating vegetation community distribution to environmental variables

A Detrended Correspondence Analysis (DCA) was used to explore relationships between vegetation community distribution and environmental variables measured at each site. A separate DCA was undertaken for hydrological variables (velocity, stream power and depth of flooding) for a flow that approximated a 1 in 50 year flood. The modelling was done as a separate study by Ms Wiebke Langner (in prep.). The reason that this was done as a separate analysis was because some samples were not flooded for that flood scenario.

5.2.1 Exploring the relationship between vegetation community composition and environmental variables

The order of vegetation communities along DCA1 resembles the community groupings from the TWINSpan analysis (Figure 11). DCA1 largely separates wetland communities with palmiet, *Juncus*, *Miscanthus* and *Platycaulos* that had low DCA scores from dryland communities with *Cynodon* and *Sporobolus* that had high DCA 1 scores. Communities that tolerate intermittent soil saturation (*Setaria* and *Stenotaphrum*) are found at intermediate DCA 1 scores. High values of elevation relative to the thalweg (Elevation) and depth to the water table (WatTab) are all indices of soil wetness and are somewhat related to DCA 1 scores, which suggests that soil saturation is an important underlying factor in relation to variation along DCA1. DCA2 separates communities in a wetland setting, namely Palmiet communities (low DCA 2 scores) from *Juncus* and *Miscanthus* communities (high DCA 2 scores). High values of substrate particle size (ParSiz) are related to variables along DCA2.

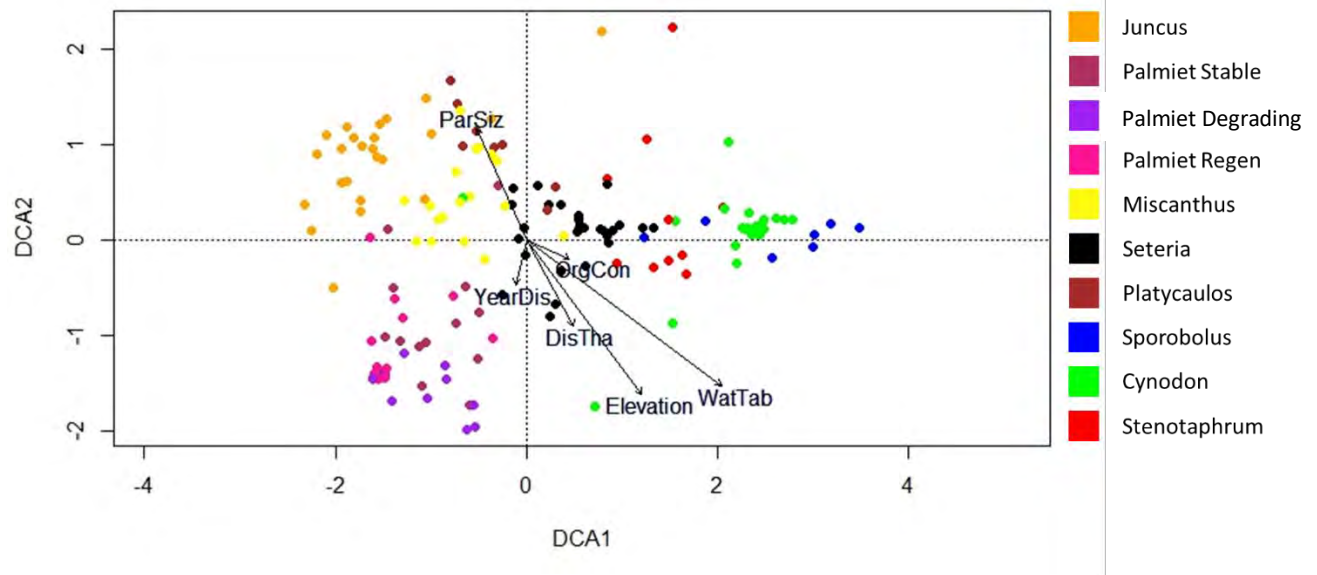


Figure 11: Vegetation community distribution displayed on two axes of variation (DCA1 and DCA2) for all sites. Environmental variables have been fitted to DCA1 and DCA2 as a biplot that shows relationships between vegetation communities and measured environmental variables. Samples in vegetation types as determined in the TWINSpan cluster analysis have been grouped by colour. The order of vegetation types in the legend is the same as the order of vegetation types in the cluster analysis.

The depiction of samples in each community along DCA 1 and DCA 2 (Figure 12) are similar to those in Figure 11. Variation along DCA1 in this analysis is related to water depth during the modelled flood, while variation along DCA2 is related mainly to current velocity. As such the *Juncus* community appears tolerant of the greatest depth of flooding and highest flow velocity conditions during a flood.

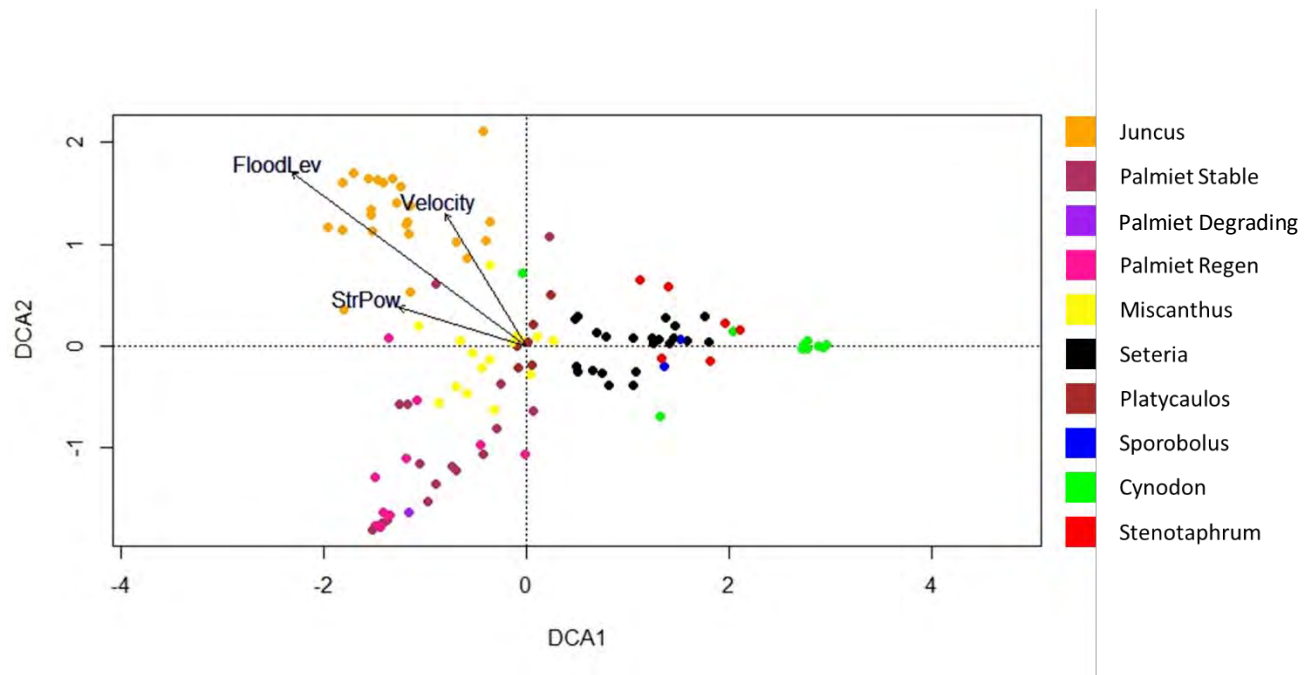


Figure 12: Vegetation community distribution displayed on two axes of variation (DCA1 and DCA2) for sites where surface flow hydraulics were determined by hydraulic modelling. These environmental variables have been fitted to DCA1 and DCA2 as a biplot and vegetation communities derived from the TWINSpan analysis have been grouped by colour. The order of vegetation types in the legend is the same as the order of vegetation types in the cluster analysis.

5.2.2 Considering relationships between environmental variables and community distribution in greater detail.

A stepwise discriminant function analysis (SDFA) was used to determine which environmental variables vary significantly in relation to vegetation community distribution. Out of the nine environmental variables, four were selected in the SDFA model with $P < 0.05$ as the criterion for inclusion.

All four variables contributed significantly ($\text{Pr} > F < 0.05$) to variation in community distribution (Table 3). Depth to the water table (WatTab) had the greatest contribution ($P < 0.0001$), followed by elevation relative to the thalweg (Elevation) and distance to the thalweg (DisTha) ($R^2 < 0.5$). Years since disturbance (YearDis) seem to contribute least to discrimination ($R^2 = 0.1$). These environmental variables were related to soil saturation, confirming that soil saturation is an important factor underpinning vegetation community distribution.

Table 3: Summary of environmental variable selection in the Stepwise Discriminant Function Analysis.

Step of variable inclusion	Variables	Variables IN/Out	Partial R ²	F	Pr>F
1	WatTab	WatTab	0.6902	36.3837	<0.0001
2	Elevation / WatTab	Elevation	0.2399	5.1193	<0.0001
3	DisTha / Elevation / WatTab	DisTha	0.1887	3.7480	0.0003
4	DisTha / Elevation / YearDis / WatTab	YearDis	0.1099	1.9752	0.0462

Environmental variable abbreviations: Water table (WatTab), elevation relative to the thalweg (Elevation), distance to the thalweg (DisTha), and year since most recent disturbance (YearDis).

A confusion matrix displaying the expected and returned classification of samples in different communities according to the SDFA is shown in Table 4. There was no clear diagonal trend, although some communities were well classified. The *Juncus*, stable palmiet, *Cynodon*, and degrading palmiet communities have classification accuracies greater than 50%. However, *Setaria*, *Miscanthus*, *Platycaulos* *Sporobolus* and regenerative palmiet communities are not well classified with accuracies of less than 50%. The model of discrimination has an overall accuracy of 45 %. This indicates that variables unaccounted for also influence vegetation community distribution.

Table 4: Confusion matrix displaying the observed vs expected classification of communities based on environmental variables according to the Stepwise Discriminant Function Analysis.

from\to	Cyn	Jun	Mis	PaD	PaR	PaS	Pla	Set	Spo	Ste	Total	%
Cyno	14*	1	0	1	0	0	0	6	1	0	23	60.87
Junc	0	23*	0	0	0	1	0	0	0	0	24	95.83
Misc	1	3	4	0	1	5*	0	4	0	0	18	22.22
PalPe	4	0	0	6*	0	0	0	0	0	0	10	60.00
PalRe	0	4*	2	0	1	0	0	4*	0	0	11	9.09
PalSta	0	6	0	0	0	11*	0	0	0	0	17	64.71
Plat	0	3*	0	1	1	0	0	3*	0	0	8	0.00
Seta	7	4	3	1	0	2	1	9*	1	1	29	31.03
Spor	4*	0	0	1	0	0	0	2	0	0	7	0.00
Sten	1	0	1	0	0	0	0	6*	0	2	10	20.00
Total	31	44	10	10	3	19	1	34	2	3	157	44.59

*Highest value in each row. Vegetation community abbreviations: Cynodon (Cyn), Juncus (Jun), Miscanthus (Mis), Palmiet degrading (PaD), Palmiet Regenerating (PaR), Palmiet Stable (PaS), Setaria (Set), Platycaulos (Pla), Sporobolus (Spo) and Stenotaphrum (Ste).

5.3 Vegetation community distribution in relation to other environmental variables

The ANOVA and post-hoc Tukey tests were used to assess and describe the relationship between vegetation communities and environmental variables that related significantly to community distribution. Significant variables were: depth to the water table, elevation relative to the thalweg, distance to the thalweg and year since most recent disturbance (variables chosen by the SDFA).

A statistically significant difference was found for the aforementioned environmental variables in relation to vegetation community distribution (Table 5). Statistically significant groupings of community distribution are reported in brackets in the text for each environmental variable.

Table 5: Summary of F and Pr>F values produced by ANOVA.

Variables	F	Pr > F
Water table	36.3837	<0.0001*
Elevation relative to thalweg	25.218	<0.0001*
Distance to thalweg	4.7872	<0.0001*
Year since disturbance	2.661	0.0068*

*Significant P-value ($P < 0.05$)

The range of variation in each of selected environmental factors have been grouped by vegetation community and groupings from a post-hoc TUKEY's analysis are shown for each variable (Figure 13). *Cynodon* (A), degrading palmiet (A) and *Sporobolus* (A) communities occur where depth to the water table is greater than 2 m (Figure 13). *Setaria* (B), *Stenotaphrum* (BC) and *Platycaulos* (BCD) communities occur where the depth to the water table is intermediate (about 1 m). *Miscanthus* (CD) and regenerative palmiet (CD) communities occupy sites with a relatively high water table with a depth of about 0.5 m. *Juncus* (D) and stable palmiet (D) communities occupy a very shallow water table of less than 0.5 m.

Degrading palmiet (A) communities occur at a high elevation relative to the thalweg (> 3 m; Figure 8). *Sporobolus* (B) and *Cynodon* (BC) communities occupy an elevation relative to the thalweg of about 2 m, while *Stenotaphrum* (CD), *Platycaulos* (CDE) and *Setaria* (CDE) communities occupy an elevation relative to the thalweg of about 1 m. *Miscanthus* (DE), regenerative (DE) and stable (DE) palmiet communities occupy an elevation relative to the thalweg of less than 1 m. *Juncus* occupies the lowest elevation relative to the thalweg of less than 0.5 m.

Degrading (A) and stable (A) palmiet, *Setaria* (A) and *Sporobolus* (A) communities occupy a 20-25 m distance from the thalweg (Figure 8). *Cynodon* (AB), *Miscanthus* (AB), regenerative palmiet (AB) and *Platycaulos* (AB) communities all occupy a 10-20 m distance from the thalweg, while *Juncus* (B) occupies a distance of 5-10 m from the thalweg.

The degrading palmiet (A) community occupies areas that have not been disturbed for a considerable length of time. *Cynodon* (AB), *Juncus* (AB), *Miscanthus* (AB), stable palmiet (AB) and *Stenotaphrum* communities occupy areas that have not been disturbed for 50 to 100 years. Regenerative palmiet, *Platycaulos* (B), *Setaria* (B) and *Sporobolus* (B) occupy areas that have not been disturbed for less than 50 years.

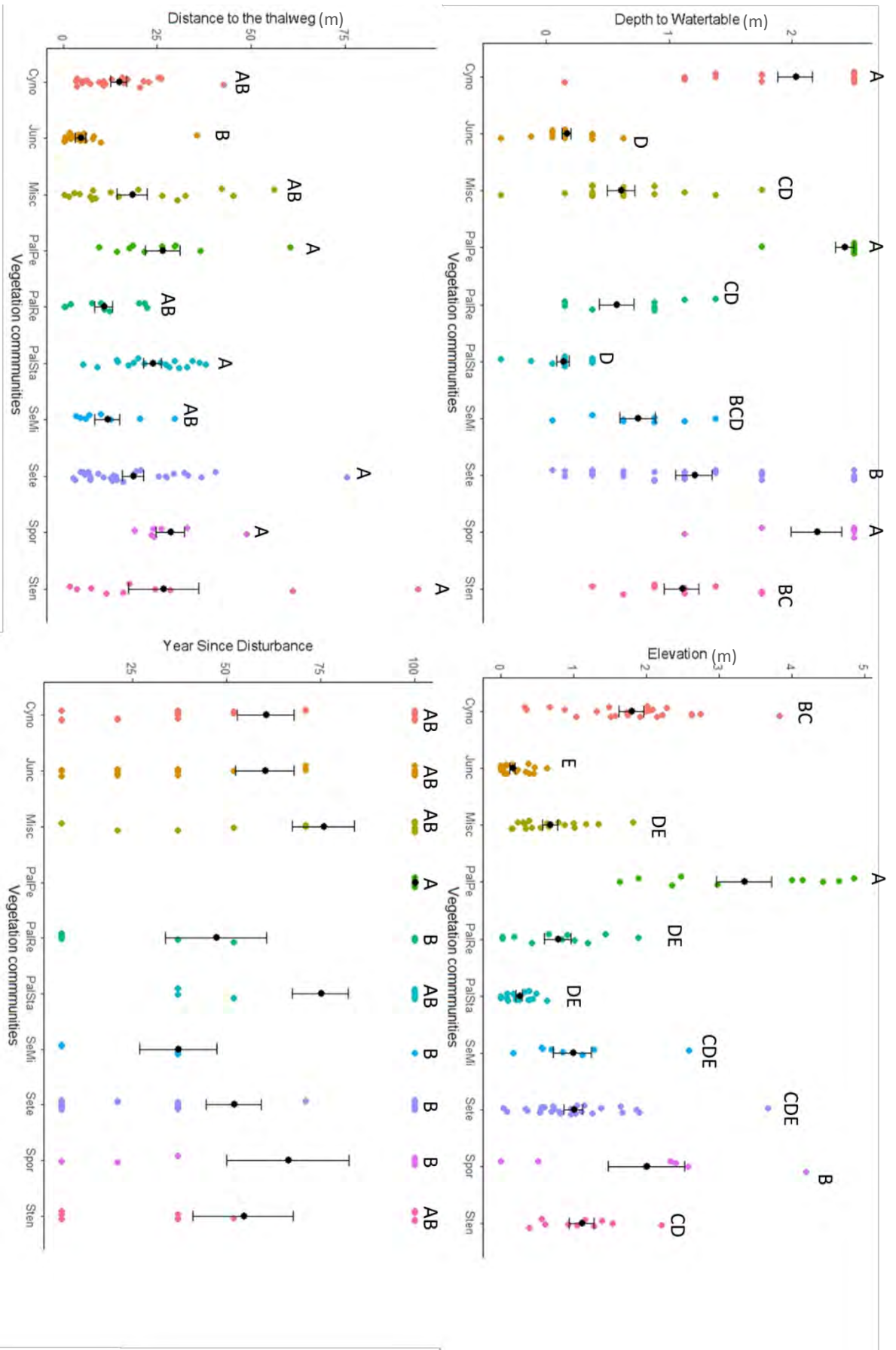


Figure 13: Box plots showing the range of variation in each of selected environmental factors grouped by vegetation community. Groupings from a post-hoc TUKEY's analysis are shown for each variable as a letter above each community. The mean value for each community has been displayed together with error bars.

5.4 Relating vegetation communities to geomorphic disturbance

A chi-squared test (goodness of fit test) based on a two-way table was used to determine if vegetation community distribution was significantly related to geomorphic disturbance units. Each vegetation community was tested independently. Eight vegetation communities were significantly related to geomorphic disturbance units (Table 6), while only the regenerative palmiet and *Platystachyos* vegetation communities were not significantly related to geomorphic disturbance history.

Table 6: Results from the Chi-squared test.

Vegetation community	Chi-squared value	P-value
<i>Cynodon</i>	39.391	0.0001*
<i>Juncus</i>	76.333	0.0001*
<i>Miscanthus</i>	27.889	0.0001*
Degrading palmiet	60	0.0001*
Regenerative palmiet	10	0.1247
Stable palmiet	102	0.0001*
<i>Setaria</i>	20.966	0.0019*
<i>Platystachos</i>	11.250	0.0810
<i>Sporobolus</i>	30.000	0.0001*
<i>Stenotaphrum</i>	13.800	0.0320*

*Significant P-value ($P < 0.05$)

The two-way table showed that *Cynodon* and *Sporobolus* communities occupy floodplains (Table 7), the *Juncus* community occupies gully beds, the *Miscanthus* community the gully bars, degrading palmiet communities occupies floodplains adjacent to recently incised gullies, the stable palmiet occurs on undisturbed valley bottoms, the *Setaria* communities occupies gully banks, the *Stenotaphrum* community occurs on depositional floodouts, while the regenerative palmiet and *Platycaulos* communities occupy a range of geomorphic disturbance units.

Table 7: Two-way table displaying the frequency of vegetation communities in geomorphic disturbance units.

Geomorphic feature	<i>Cyn</i>	<i>Jun</i>	<i>Mis</i>	<i>PaD</i>	<i>PaR</i>	<i>PaS</i>	<i>Set</i>	<i>Pla</i>	<i>Spo</i>	<i>Ste</i>	Total
Floodplain	13*	0	1	0	0	0	2	1	6*	2	25
Gully bed	0	18*	2	0	2	0	0	1	0	0	23
Gully bar	2	0	10*	0	4*	0	2	2	0	2	22
Adjacent gully	0	0	0	10*	0	0	1	0	0	0	11
Floodout	4	4	2	0	3	0	7	0	1	5*	26
Valley Bottom	0	2	3	0	0	17*	7	0	0	0	29
Gully bank	4	0	0	0	2	0	10*	4	0	1	21
Total	23	24	18	10	11	17	29	8	7	10	157

*Highest value in each column. Vegetation community abbreviations: *Cynodon* (Cyn), *Juncus* (Jun), *Miscanthus* (Mis), *Palmiet degrading* (PaD), *Palmiet Regenerating* (PaR), *Palmiet Stable* (PaS), *Setaria* (Set), *Platycaulos* (Pla), *Sporobolus* (Spo) and *Stenotaphrum* (Ste).

5.5 Descriptions of plant communities

Species that occur in more than 35% of vegetation community plots have been presented in Table 8, which has been ordered according to a diagonal trend showing the relationship species and communities. Generally, wetland species and communities are grouped towards the top right, and terrestrial species and communities towards the bottom left.

Vegetation communities can be described in relation to geomorphic setting. Geomorphic classes are largely related to environmental conditions at each site. These can be split into four geomorphic settings: 1) in the gully, 2) on the previous valley bottom surface adjacent the gully, 3) on the depositional feature and 4) on the valley bottom.

5.5.1 Vegetation communities and environmental conditions in the gully

The *Juncus* community occupies the beds of gullies, in permanently saturated conditions, exposed to relatively high velocities and streams powers. The community is primarily composed of sedges, such as *Isolepis prolifera* and *Eleocharis dregeana*. *Juncus lomatophyllus* is the most abundant species but the grass *Miscanthus capensis* is also common.

The regenerative palmiet community is found in gullies or along channels on depositional features such as floodouts, and are exposed to permanent saturation and frequent hydrogeomorphic disturbance. Other than *Prionium Serratum*, *Juncus lomatoophyllus* is a frequent species in this community, along with *Rubus cuneifolius* and *Miscanthus capensis*.

The *Miscanthus* community is found on bars within the gully, in semi-saturated conditions. The community can be exposed to high flows, and is able to persist with limited hydrogeomorphic disturbance. Along with *Miscanthus Capensis*, *Prionium serratum* is a huge component of this community. *Cliffortia strobilifera*, *Acacia mearnsii* and *Juncus lomatoophyllus* are common within this community.

The *Setaria* community is found on gully banks with infrequently saturated conditions, being relatively disconnected from the hydrogeomorphic regime. The community is primarily composed of the grasses *Setaria incrassata*, *Miscanthus capensis* and *Stenotaphrum secundatum*.

5.5.2 Vegetation communities and environmental conditions on the former abandoned valley bottom surface

Immediately adjacent to recently incised gullies, the degrading palmiet community occupies the previous valley bottom surface and is disconnected from the hydrogeomorphic regime. The community persists along gully banks that are quite terrestrialised. *Prionium serratum* is the major species in this community, along with other semi-wetland species such as *Rubus cuneifolius*, *Helichrysum odoratissimum* and *Nidorella ivifolia*. Due to the prevailing terrestrial conditions, species such as *Athanasia trifurcata*, *Acacia mearnsii* and *Chrysocoma ciliata* have established and, over time, may outcompete palmiet.

The *Cynodon* community is found on the upper fringes of the gully banks and on the floodplain, which is largely terrestrial. The community is composed of grasses such as *Cynodon dactylon* and *Setaria incrassata*.

The *Sporobolus* community is found on the pervious valley bottom surface which can be considered a terrestrial habitat. It is primarily composed of the grasses *Sporobolus fimbriatus*, *Cynodon dactylon*, *Eragrostis curvula* and *Setaria incrassata*, however it also host to the terrestrial species such as *Othonna parviflora* and *Restio capensis*.

5.5.3 Vegetation communities and environmental conditions in the depositional feature

Other than the regenerative palmiet community, the *Stenotaphrum* community is one of the only communities restricted to the depositional feature, often occurring on sandbars that experience infrequent saturation. This community is primarily composed of grasses such as: *Stenotaphrum secundatum*, *Setaria incrassata*, *Aristida junciformis*, *Eragrostis curvula*, *Cynodon dactylon* and the weed *Hypochaeris radicata*.

5.5.4 Vegetation communities and environmental conditions on the valley bottom

The stable palmiet community is located on valley bottom wetlands where there is permanent saturation. Diffuse flow conditions are associated with stable palmiet wetlands, therefore these areas experience limited hydrogeomorphic disturbance. *Prionium serratum* is the dominant plant in this community, interspersed with patches of *Phragmites australis* and *Cliffortia strobilifera* encroaching from the valley sides. *Phragmites australis* and *Helichrysum odoratissimum* climbs across stands of palmiet within the wetland.

The *Platycaulos* community has a wide distribution, and can tolerate a range of intermittently saturated conditions. It is primarily composed of the grasses *Miscanthus capensis* and *Setaria incrassata*. The restio *Platycaulos callistachyus* occurs in this community as does the tree *Berzelia intermedia*.

5.6 Remote sensing results

5.6.1 Introduction

The KRW has been divided into eight sectors (A to H; Figure 14). Sectors A and B cover the majority of the Krugersland and Kompanjiesdrif basins which across the valley are dominated by palmiet. Sectors C and D cover an erosional reach of the river between the Kompanjiesdrif and Hendrikskraal basins. Sectors E and F covers the Hendrikskraal basin, while Sectors G and H covers an erosional and depositional reach respectively of the Jagersbos basin.

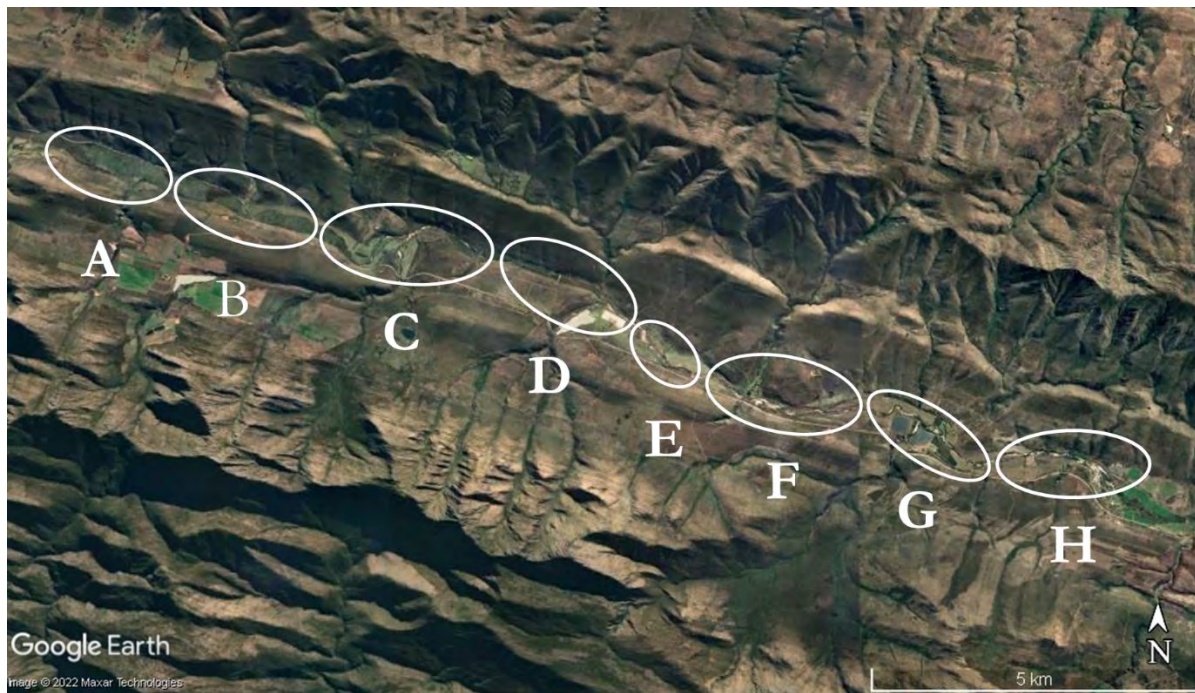


Figure 14: The KRW wetland divided into 8 sectors, A to H, running from the top of the Krugersland to the base of the Jagersbos basins.

5.6.2 Results from Rpart

Rpart - a machine learning function and library in RStudios that builds classification and regression trees - was used to separate values representing 'Stable palmiet' and 'Non-palmiet' vegetation using training data (Therneau et al., 2013). The resulting classification tree is shown in Figure 15. The first division is based on the Canopy Density Index (CDI) such that when it is less than 0.194, the community is recognised as 'Stable palmiet'. Where the CDI is greater than 0.194, a number of communities are potentially included. For those cells where CDI is greater than 0.194, the Vegetation Height Model (VHM) is the next variable to be included. Where VHM is less than 0.104, the cells are classified as 'Non-palmiet'. For those cells with VHM is greater than 0.104, the model includes the variable Vector Ruggedness Index (VRI) such that when VRI is less than 0.00601, the cells are classified as 'Stable palmiet'. For cells with VRI is greater than 0.00601, the variable CDI is again included in the model. Where CDI is greater than 0.447, the cell is classified as 'Non-palmiet'. For those cells with CDI is less than 0.447, VRI is again considered. For cells where VRI is greater than 0.0328 or less than 0.015, cells are classified as 'Non-palmiet'. Those cells with VRI between 0.015 and 0.0328, cells are classified as 'Stable palmiet'.

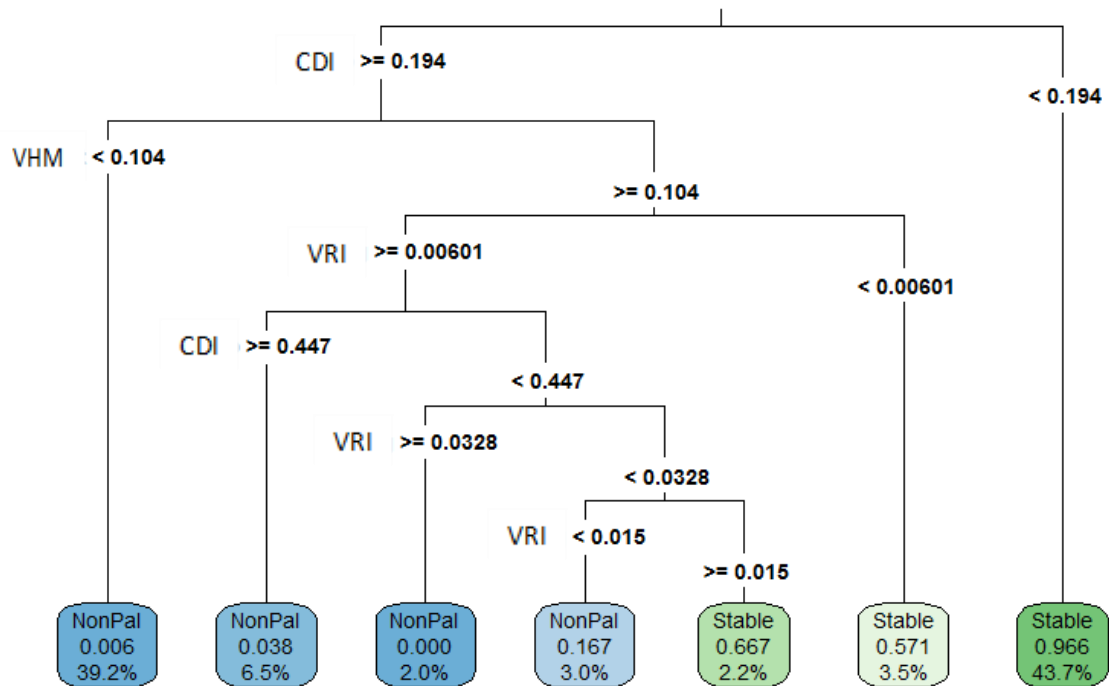


Figure 15: Classification and regression tree resulting from Rpart. Abbreviations: Canopy Cover Index (CDI), Vector Ruggedness Index (VRI), Vegetation Height Model (VHM), ‘Stable palmiet’ communities (Stable), and ‘Non-palmiet’ community (NonPal).

The testing data was used to determine the model's accuracy using a confusion matrix (Table 2). The model created by Rpart was applied to the testing data set. Of the samples analysed, 95% were accurately predicted, of which 91% were predicted with a confidence of greater than 95%.

Table 9: Confusion matrix assessing Rpart model accuracy

From \ to	Stable Palmiet	Non-palmiet	% correct
Stable palmiet	46	1	93.88
Non-palmiet	3	45	97.83
Total	49	46	95.79

Rpart was also used to discern the whether the Relative Elevation Model (REM), was useful for the classification of stable palmiet communities (Figure 16). This is not a predictive variable, but describes the relative elevation where most stable palmiet communities reside.

The relative elevation layer was used to discern whether palmiet will be vulnerable to degradation from processes associated with gullyng. According to the classification tree produced by Rpart, cells with a value less than 0.53 meters are appropriate for palmiet establishment. Where the value is greater than this, the palmiet is likely to decline and eventually disappear, such that any attempt to rehabilitate the wetland using palmiet will be unsuccessful.

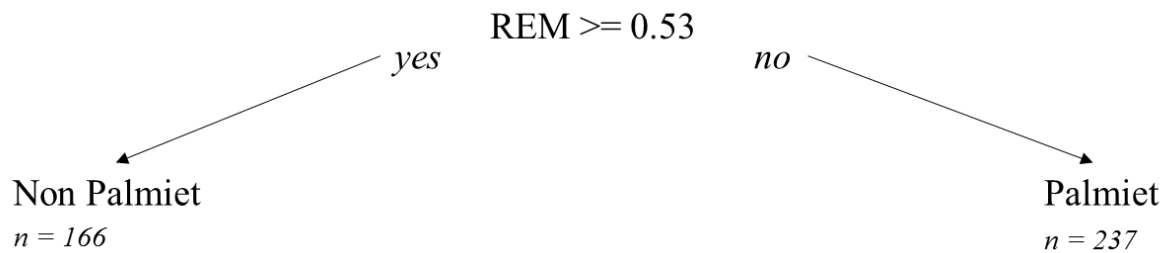


Figure 16: Classification and regression tree resulting for Rpart for relative elevation

5.6.3 Conducting the Overlay analyses

Using the classification and regression tree in Figure 15, a condition statement was applied to perform the overlay analysis using map algebra (via the raster calculator in ArcMap). The condition statement was laid out as follows:

- $\text{Con}(\text{CCI} \geq 0.194, \text{Con}(\text{VHM} < 0.104, 0, \text{Con}(\text{VRI} \geq 0.00601, \text{Con}(\text{CCI} \geq 0.447, 0, \text{Con}(\text{VRI} \geq 0.0328, 0, \text{Con}(\text{VRI} < 0.015, 0, 1)) , 1)) , 1)) , 1)$

The result from the above calculation was a binary raster layer where cells with a value of 1 represented palmiet communities and 0, non-palmiet communities.

5.6.4 Reclassifying REM into appropriate elevations for stable palmiet communities.

Following the construction of a classification and regression tree (Figure 16), map algebra (via the raster calculator in ArcMap (ESRI, 2020) was used to reclassify the REM layer. The statement was laid out as follows:

- $\text{REM} < 0.53$

This produced a binary raster layer such that 1 represented an appropriate relative elevation for ‘stable palmiet’ communities, and 0 represented an inappropriate relative elevation for ‘stable palmiet’ communities.

5.6.5 Combining binary layers

The binary palmiet layer and the binary relative elevation layer were combined using the raster calculator:

- $\text{Palmiet} + (\text{REM} \times 0.5)$

The above calculation produced a raster layers with four categories: Palmiet communities within an appropriate elevation relative to the thalweg (IE ‘Stable palmiet’ communities), palmiet communities within an inappropriate elevation relative to the thalweg (IE ‘persisting or degrading’ palmiet communities) and the appropriate and inappropriate relative elevations (RE) for stable palmiet community establishment (Figure 17).

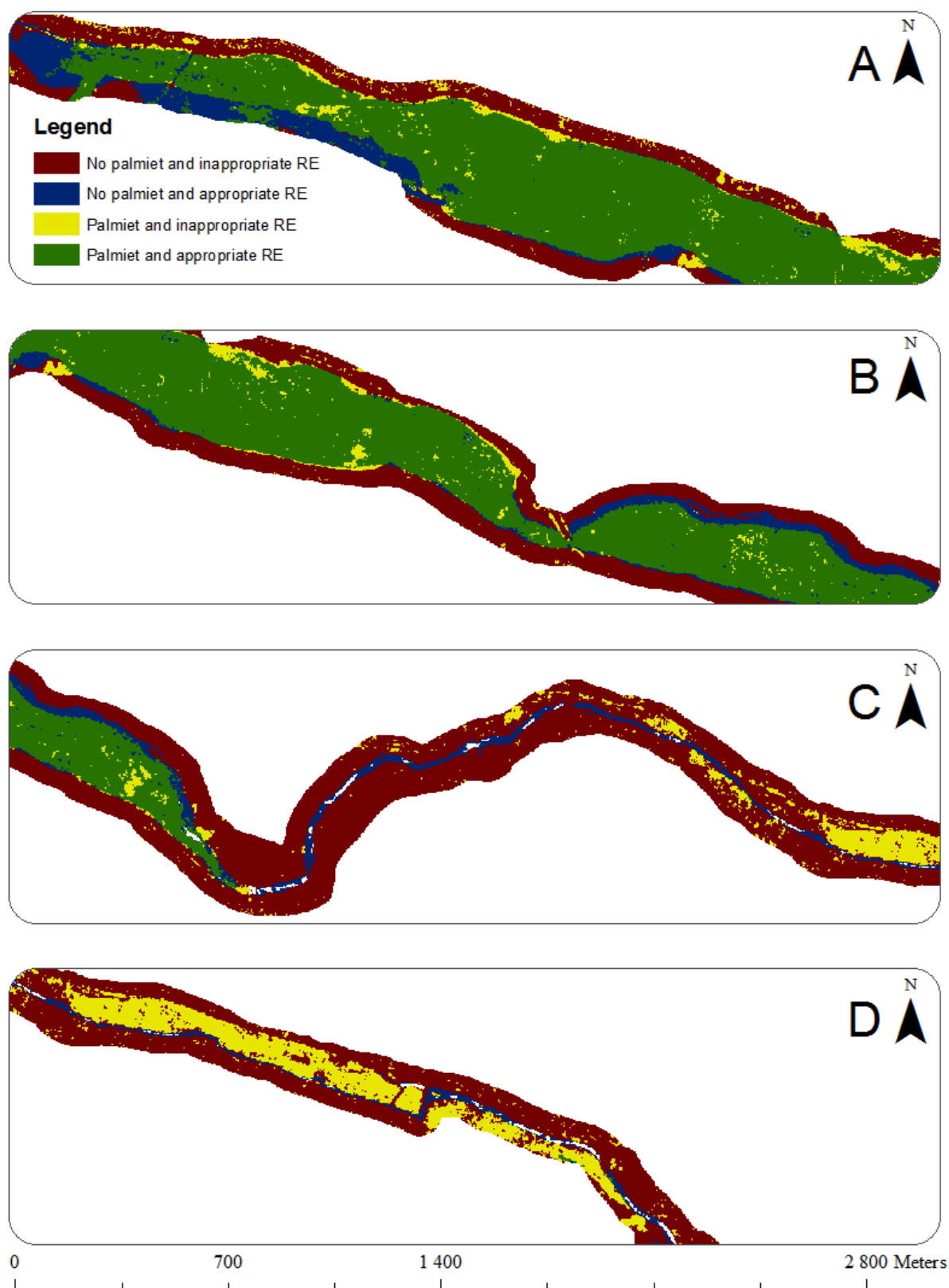
The majority of ‘stable communities’ are found in sectors A, B and partly C. There is a small patch of ‘stable palmiet’ in sector H. From sector C to H, the majority of palmiet communities are classified as ‘degrading palmiet’, especially in D, where there is an abundance of palmiet. Superficially, areas without palmiet at an appropriate relative elevation are found within channels. However, there is a small section of unchannelled wetland with an appropriate elevation found in sector H.

5.6.6 Confusion matrix to assess accuracy

Using the testing data, a confusion matrix was developed to determine how accurate the model was (Table 10). The confusion matrix only assessed ‘stable palmiet’ communities, as there were limited samples representing ‘degrading palmiet’ communities. Roughly 90% of ‘Stable palmiet’ samples from the testing data were accurately classified, and 92% of ‘Non-palmiet’ samples were accurately classified. Overall, the model is 91% effective.

Table 10: Confusion matrix to assess model accuracy

From / to	Stable palmiet	Non-stable	% correct
Stable palmiet	44	4	89.8
Non-stable	5	46	92
Total	49	50	90.9



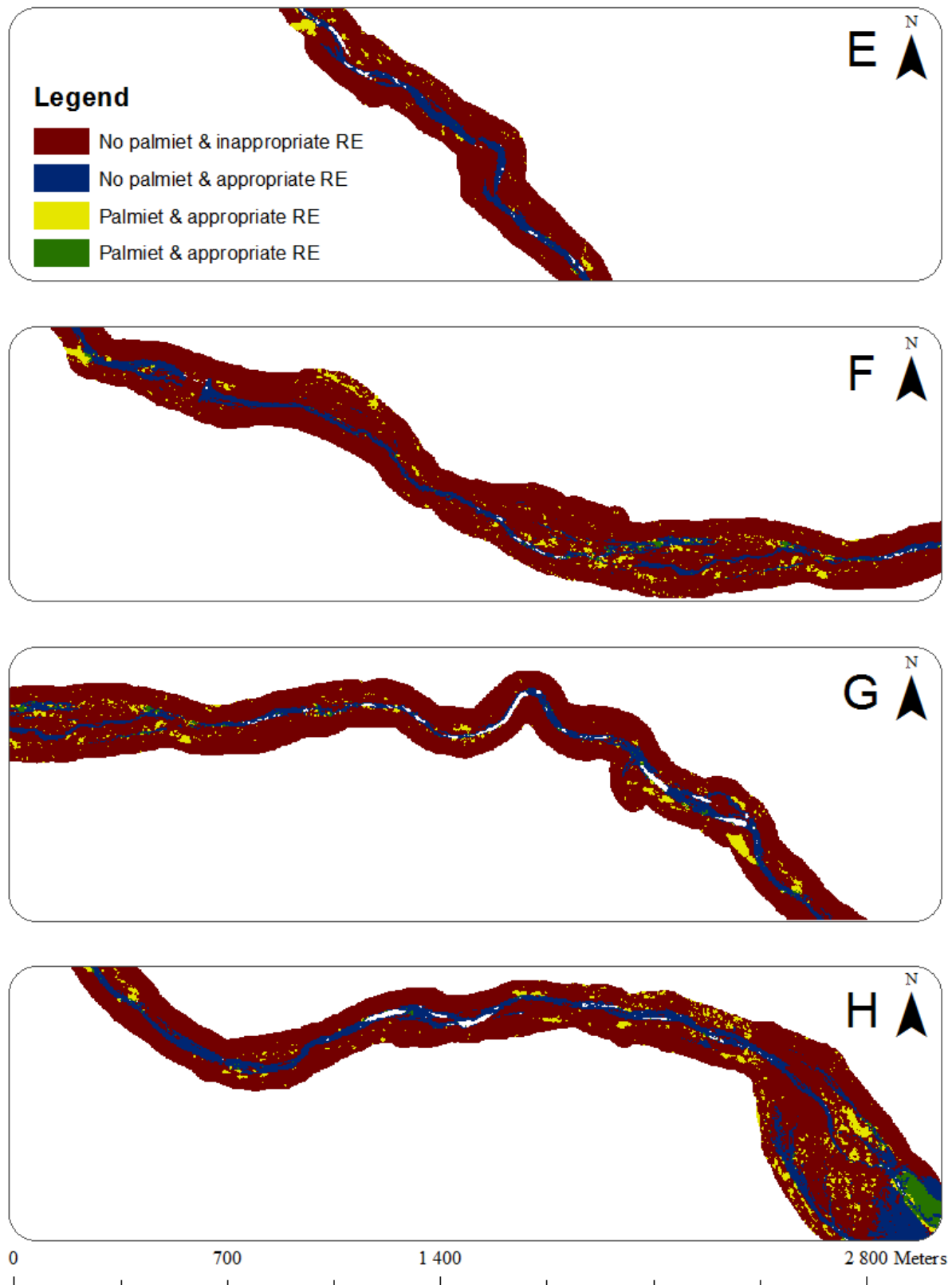


Figure 17: Resulting maps from the reclassification and overlay analysis to map the distribution of palmiet, covering the entire longitudinal lengths of the KRW (Relative Elevation (RE)).

Chapter 6: Discussion

6.1 Vegetation distribution in the Kromme River wetland (KRW)

6.1.1 Recent disturbance events in the Jagersbos basin of the KRW

The prevailing view of palmiet wetlands is that they are unchannelled, semi-permanently flooded valley-bottom wetlands. The wetlands are near-horizontal across the valley (up to several hundred metres wide) and have a gentle longitudinal slope (typically $< 2\%$). Historically the KRW is thought to have been semi-permanently flooded and supported plant communities dominated by the iconic plant *Prionium serratum* (palmiet). This community is thought to have dominated the length and breadth of the valley floor. The Krugersland and Kompanjiesdrift basins in the KRW are considered to be the natural reference condition for the entire valley.

Erosion is considered inherently unnatural, being a consequence of human activities in the catchment and the wetland (Rebelo et al, 2013). Erosion is thought to damage these wetlands such that all gullies present in the wetland must be arrested. The State has invested large sums of money (tens of millions of Rands) in preserving intact portions of the wetland that are threatened by headward propagation of gullies in the wetland.

Recent studies have shown that geomorphic disturbance events are a natural part of wetland formation and evolution (Lagesse, 2017; Pulley et al, 2018). The KRW is likely characterised by gully erosion every few hundred years and each cycle of erosion is followed by infilling of gullies as headward erosion propagates upstream over decades to centuries (Pulley et al. 2018; Grenfell et al, 2020).

The KRW is currently characterised by several large erosion gullies that are likely to have been caused by human activities. However, if erosion is a natural process in wetland creation and change over time, it is important to be able to understand how the system might react naturally to a cutting and filling event. A recent flooding event in the Jagersbos basin in the lower reaches of the study area happened in 2012, which resulted in the formation of a large gully and floodout (McNamara, 2018).

Remote sensing imagery illustrates the changes that resulted from this flood event (Figures 18 A to C). Figure 18 A shows the valley prior to the flood, in which the valley floor had a cover of vegetation, although two gullies are clearly evident in this Jagersbos reach. After the flood, the upper gully depicted in Figure 18A was enlarged substantially, but deposition in the

floodout in the form of a floodout filled the lower gully (Figure 18B). Figure 18C has been included to illustrate the extent of vegetation cover that has established over the period 2012 to 2020.

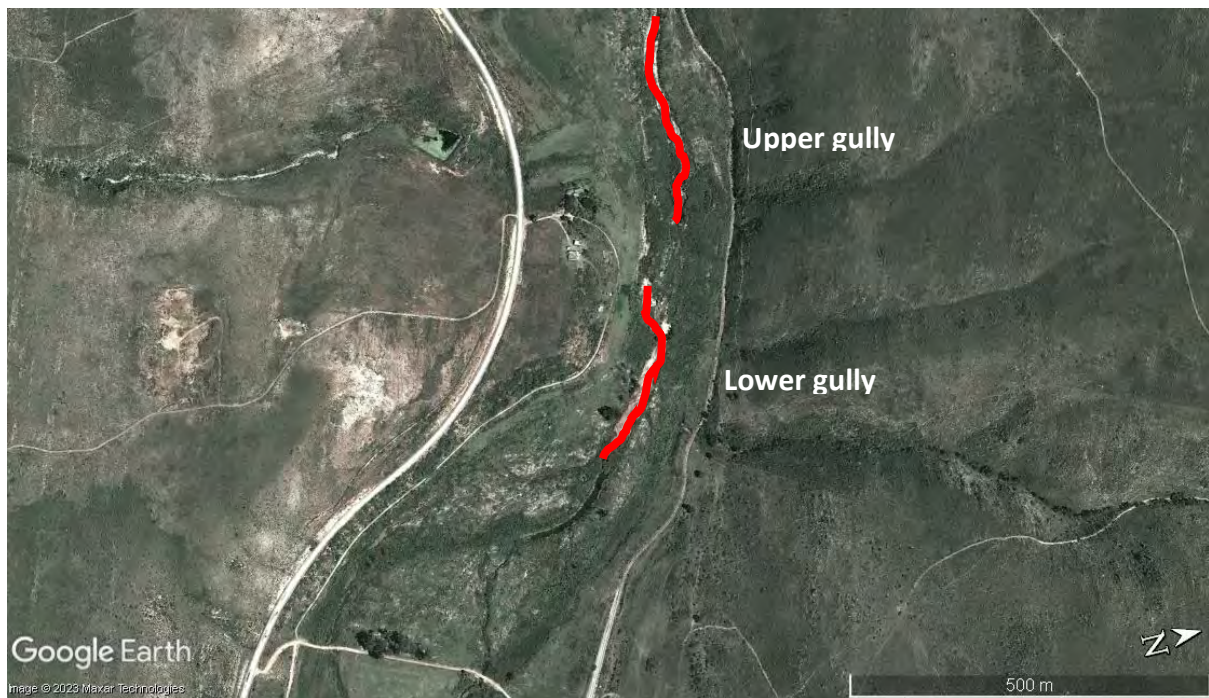


Figure 18A

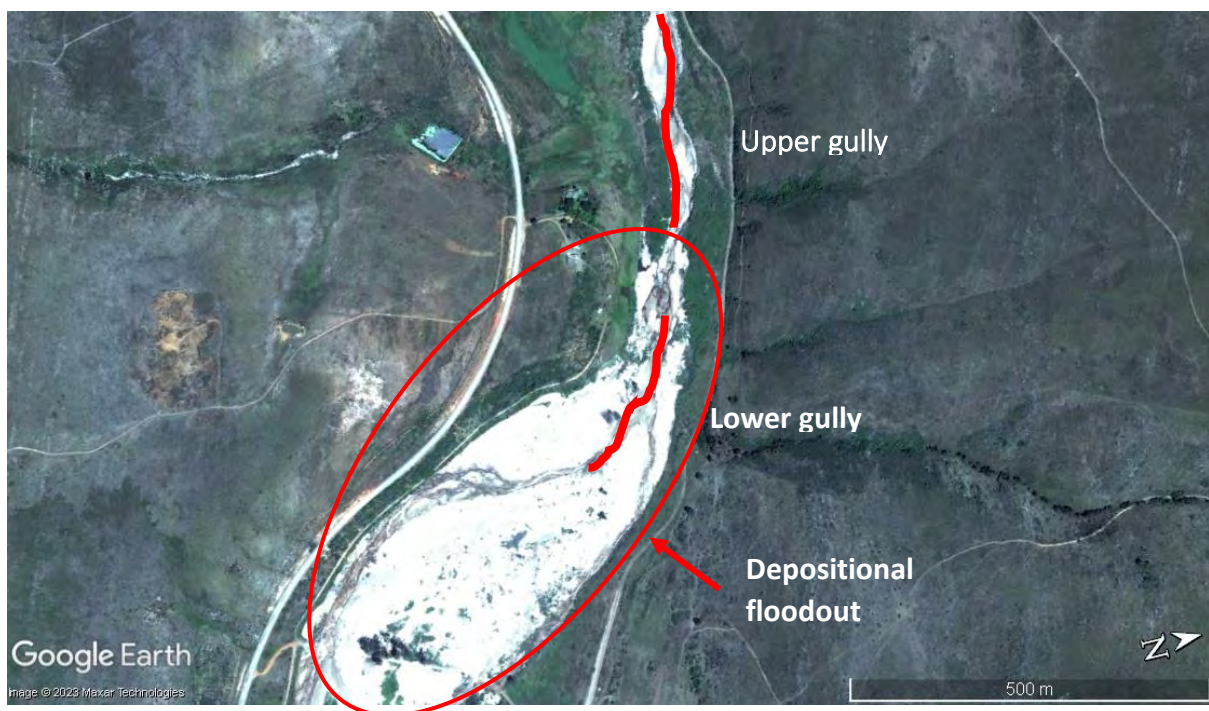


Figure 18B

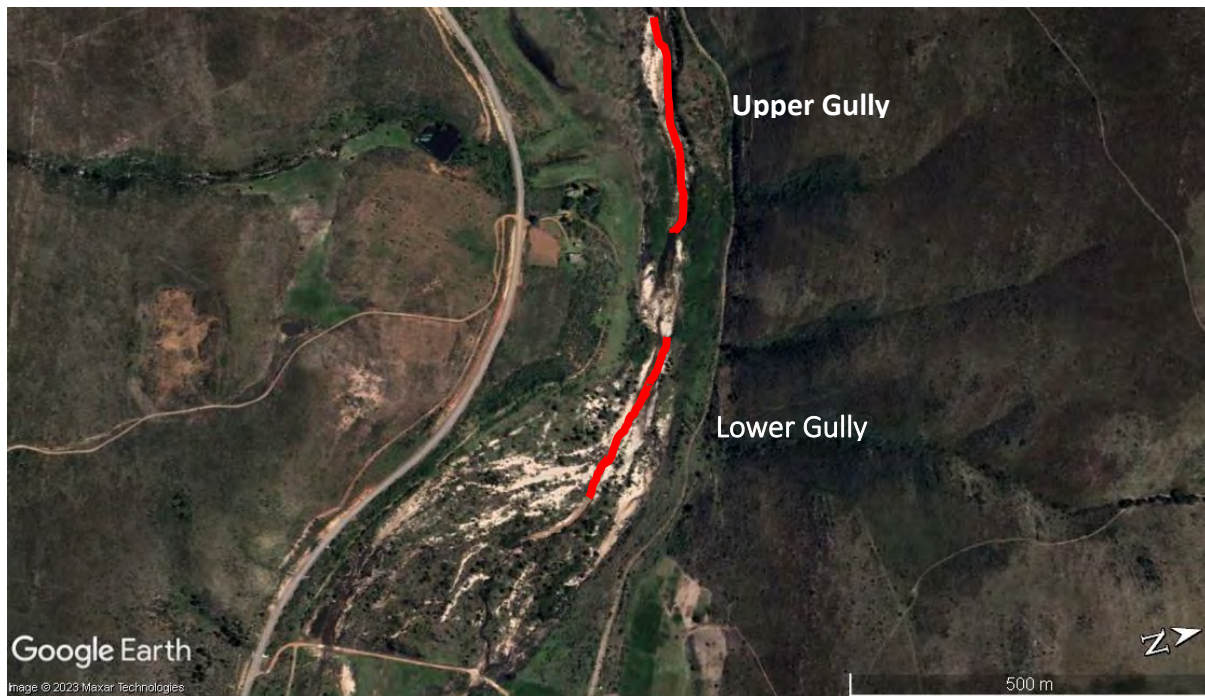


Figure 18C

Figure 18: Remote sensing imagery of the Jagersbos basin in 2012 showing the vegetation cover and the extent of two small gullies before flooding and geomorphic disturbance took place, (A); soon after the flood and disturbance events with the location of the two small gullies mapped prior to the disturbance superimposed (B); and the vegetation cover and eight years after the geomorphic disturbance event, vegetation (C).

6.1.2 Ecological successional processes following the 2012 disturbance event in the KRW

The response of vegetation following disturbance can be broken into two categories: processes associated with primary succession and processes associated with secondary succession. Successional events where primary succession takes place are likely in eroded and depositional reaches where the likelihood of environmental conditions being similar before and after disturbance is small. However, successional events subject to secondary succession take place on the previous valley bottom surface adjacent to gullies, where many environmental factors remain constant, such as soils being intact, soil organic content being constant, climate being similar and potentially having a seed bank present in the soil. Successional events tend to be somewhat predictable in nature, with plant communities establishing in a fairly predictable sequence following disturbance.

In the case of the disturbance that led to changes in the Jagersbos Basin, geomorphic processes are likely to cause the gully to be filled as the gully propagates headward (Pulley et al. 2018).

This means that over time the gully will fill and the system is likely to revert to an unchannelled valley bottom wetland. Given that biota will modify conditions by slowing flow or trapping sediment is unclear, but there is abundant evidence to suggest that through modification of flow and sedimentation, biota will promote the establishment of these conditions. The likely process of vegetation succession and gully infilling is conceptualized in Figure 21A to F, and discussed through the remainder of this section. Each unit (A to F) is broken into three components. On the left a satellite view (resembling figure 18) is used to depict change, the top right is a cross-sectional view through the gullied reach and the bottom left is a cross-sectional view through the depositional feature.

Adjacent to gullies in the gullied reach, the water table drops, favouring vegetation succession from former wetland to vegetation more adapted to terrestrial conditions (Figure 21B). Palmiet communities on the previous valley bottom surface tend to disappear due to a drop in the water table. Only palmiet communities immediately adjacent to the recently eroded gully, persist, but environmental conditions are unlikely to favour its persistence and have therefore been named the degrading palmiet community. Further from the gully, terrestrial grass communities colonise, namely *Sporobolus* and *Cynodon* communities. Over time, the degrading palmiet community will disappear and be colonised by semi-terrestrial communities such as *Setaria* and *Cynodon*.

Within the gullied reach, species from the *Juncus* community (Figure 21B; Figure 19) are the first to establish on the beds of gullies. These species have the ability to tolerate highly saturated conditions and moderate stream powers and velocities. Species from the *Juncus* community may alter the stream systems such as by stabilising the bed and banks, creating conditions suitable for the establishment of other vegetation communities. However, once species such as *Prionium serratum* appear, bed and bank stabilisation will be enhanced due to the ecosystem engineering capabilities of this species (see Sieben, 2012; Barclay, 2017).



Figure 19: Species from the *Juncus* community colonising on the bed of a gully.

Prionium serratum is dispersed by moving water via seeds and vegetative propagules, being adapted to colonising bare patches of sediment caused by geomorphic disturbance. In a parallel study, van Eck (2022), found many propagules of palmiet on the beds of gullies and on depositional bars in the Jagersbos floodout. Due to its clonal nature, once palmiet has occupied the eroded banks and depositional bars of fluvial systems, it slowly encroaches onto the mainstream flow (Figure 20; Barclay, 2017). Sediments are caught and stabilized by the above-ground plant structures, which results in the formation of sandy deposits. Palmiet may eventually constrict the river entirely so that the waterway is closed (Figure 21C).



Figure 20: A photo taken from the bed of a gully just below the Hendrik's kraal basin. Palmiet has established itself on gully banks and over time will constrict the water way entirely.

The regenerating palmiet community (van Eck 2022) increases diffuse conditions thereby locally lowering stream power and velocity, and potentially allowing for the establishment of other vegetation communities. *Miscanthus* and *Platycaulos* communities also colonise within the gullies. The distribution of both these communities is controlled by soil saturation as species within these communities cannot tolerate complete submersion for long periods of time. These communities are found on gully bars and banks. *Prionium serratum* reduces current velocity, promotes diffuse flow and traps sediment in the gully such that, over time the gully fills with sediment and the near-horizontal valley bottom is restored (Figure 21 D and E).

Over time as the gully fills, and once the depositional feature has been colonised by palmiet - the water table is restored to the level it was before the disturbance event, and conditions favour species adapted to saturated soil. Terrestrial communities, such *Cynodon*, *Setaria* and *Sporobolus* are restricted to the wetland fringe, while the previous valley bottom is colonised by palmiet and is restored to valley bottom wetland (Figure 21 E and F).

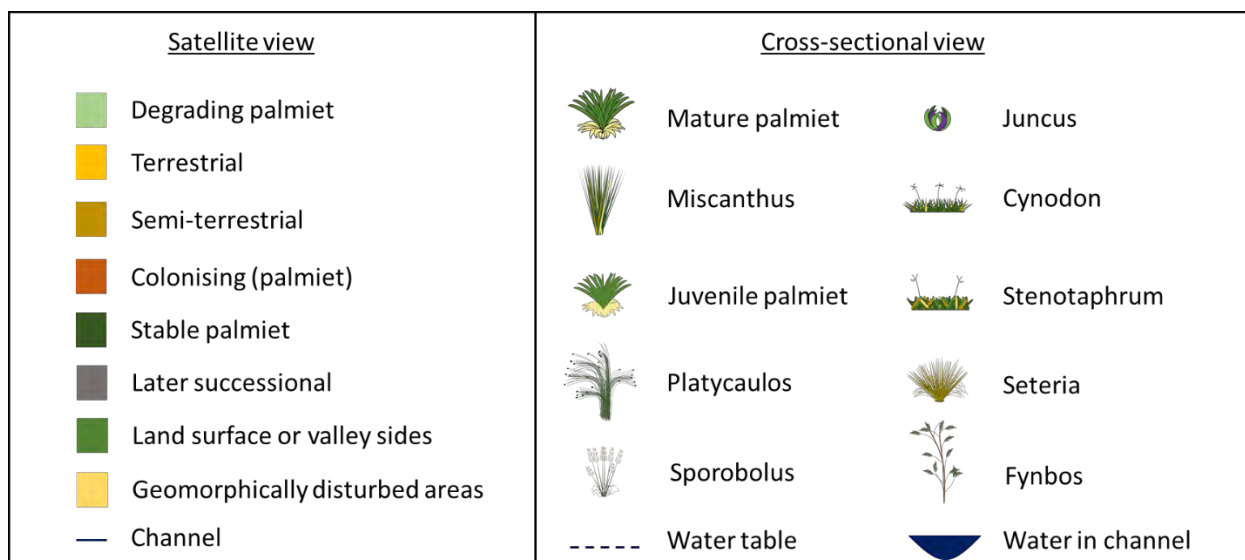


Figure 21A: Legend

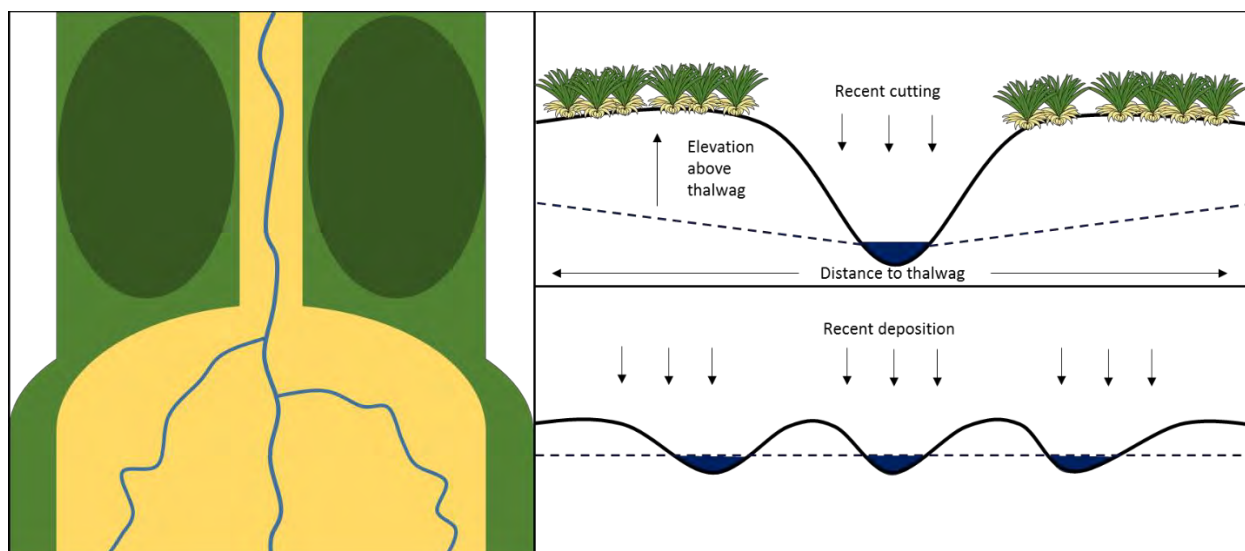


Figure 21B: Immediately post geomorphic disturbance event. A gully has been initiated in the confined reach and deposited material on the floodout; vegetation has not had time to colonise. Only palmiet communities on the previous valley bottom surface in the confined reach persist after the disturbance event.

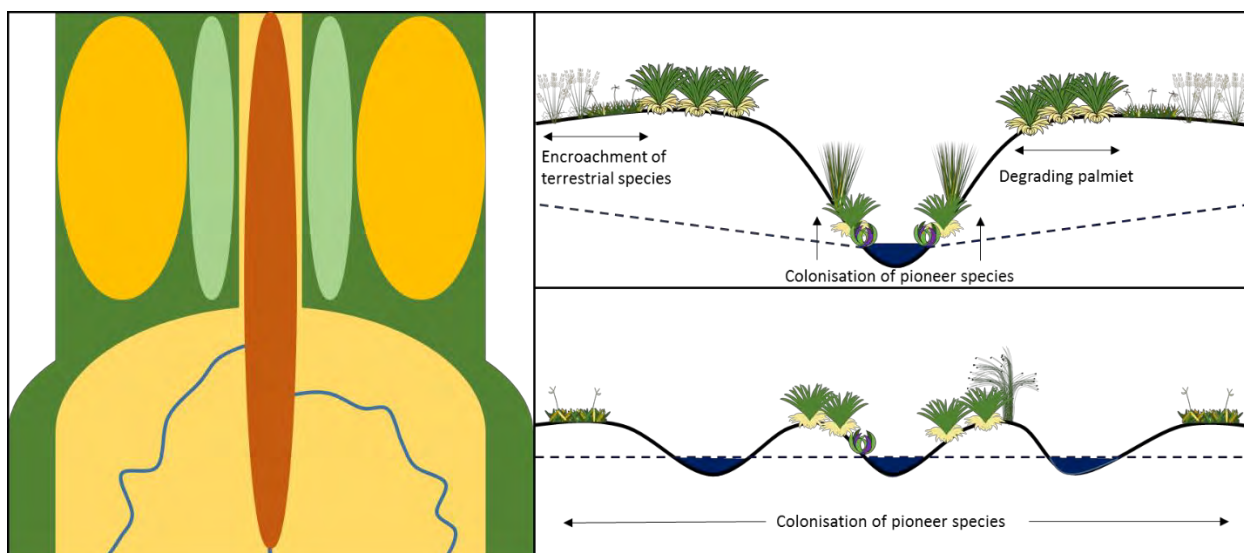


Figure 21C: On the previous valley bottom surface, terrestrial communities have begun to encroach into the persisting palmiet community. Due to the drop in water table, the palmiet community will degrade. Within the gully and on the floodout, pioneering plants have begun to colonise (including palmiet).

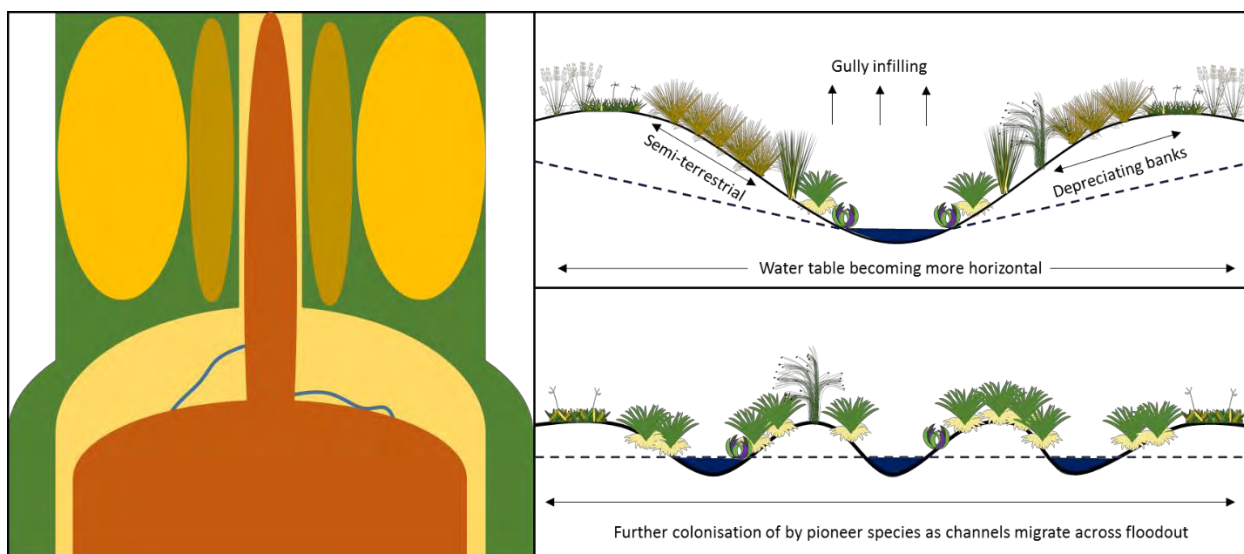


Figure 21D: In the gullied reach, the degrading palmiet community has perished and been replaced by terrestrial communities. As the gully banks have depreciated, and the gully begins to fill, semi-terrestrial communities have colonised the gully banks. Within the gully, and in the depositional features, the pioneering communities remain similar. As channels migrate across the depositional feature, pioneering communities continue to colonise.

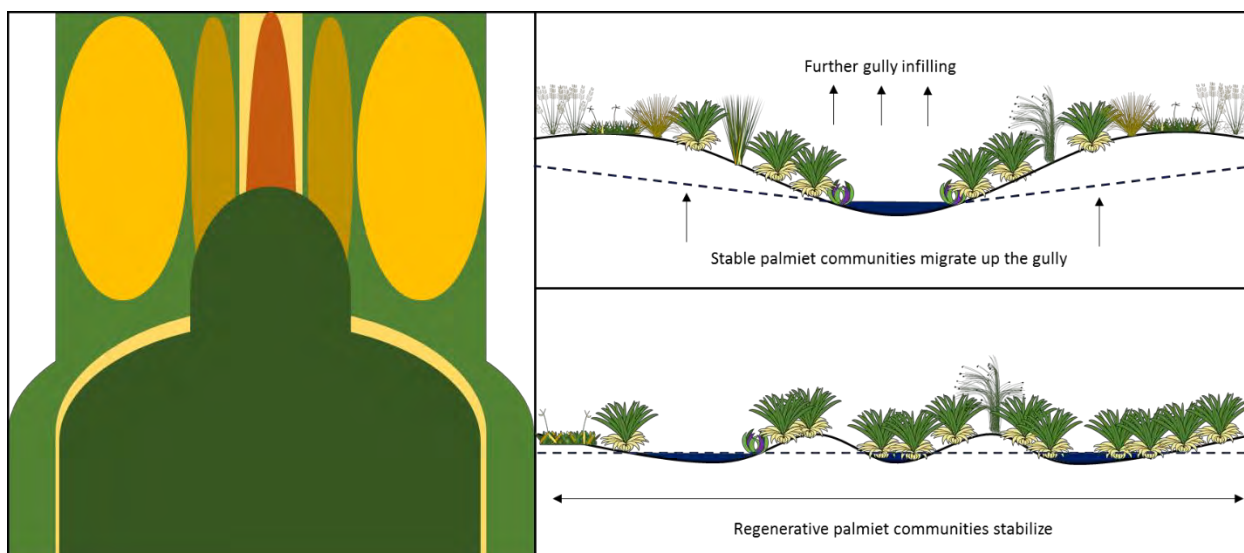


Figure 21E: In the gullied reach, gully infilling continues and the water table becomes more horizontal. As a result, wetland communities encroach up the banks and push semi-terrestrial communities towards the valley sides. In the depositional feature, palmiet communities stabilize and begin to push up the gully.

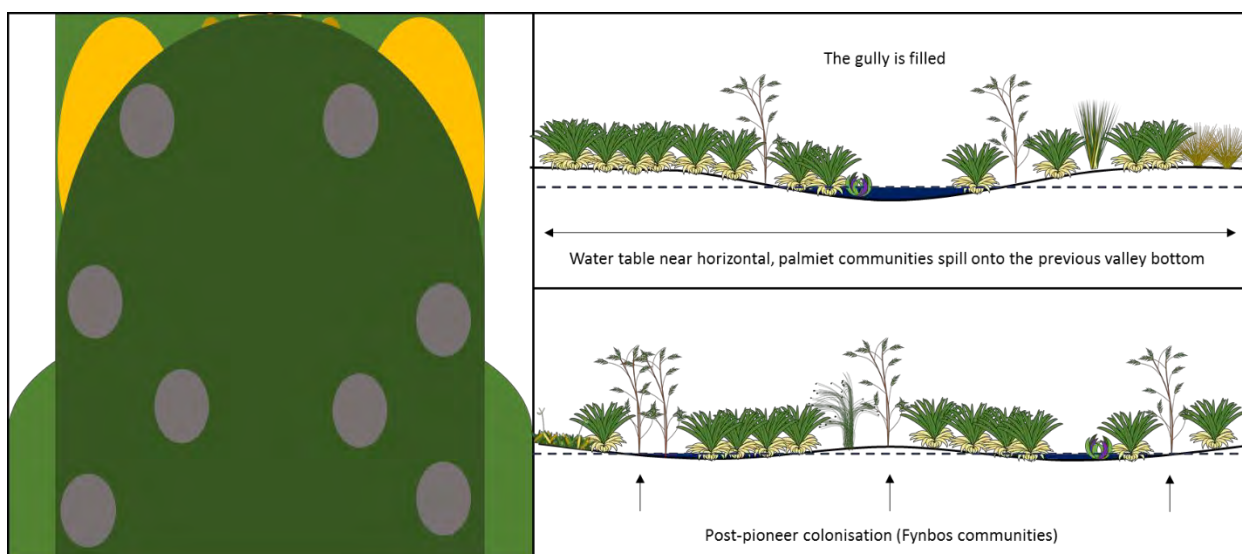


Figure 21F: In the gullied reach, the gully is filled and the water table becomes near-horizontal. Stable palmiet communities spill over onto the previous valley bottom surface, pushing terrestrial communities to the periphery. Post-pioneer colonisation begins to take place, through the colonisation of fynbos communities better adapted to compete in the geomorphically stable environment.

6.1.3 Later colonisation by post-pioneer species

Although not observed in this study, there is evidence that fynbos communities encroach on wetlands dominated by palmiet that have been geomorphically stable for long periods of time (Figure 21F). This is true for the Kompaniesdrift basin (Barclay, 2017; Rebelo et al, 2022). There is no clear evidence of what environmental factors drives patchiness, but three hypothesis have been suggested from an ecological perspective (Rebelo et al, 2022). In the first hypothesis, fynbos forms an early successional community which is outcompeted by palmiet; assuming that fynbos encroaches onto the valley floor before palmiet is able to do so. If this is the case, conditions that favour palmiet establishment occur following encroachment by fynbos communities. The second hypothesis is that palmiet forms an early successional community which is outcompeted by fynbos. If this is the case, and palmiet is an earlier coloniser, fynbos will be a superior competitor. In the third hypothesis, succession is viewed as non-directional as species share equal chances of colonisation of late successional stages.

Within this study, there is no evidence that fynbos communities establish before or at the same time as palmiet. Fynbos communities are only evident in valley bottom environments that have been geomorphically stable for long periods of time (Barclay, 2017). Therefore it is argued that fynbos is a late successional community, that outcompetes palmiet.

6.2 The influence of palmiet on vegetation succession within unchannelled valley bottom wetlands

Newly established palmiet plants are able to tolerate hydrogeomorphic disturbance and have an influence on fluvial dynamics through increasing local roughness and stabilizing sediments. Eventually the establishment of palmiet and its ability to tolerate modest floods and trap sediments leads to an unchannelled valley bottom wetland. From a successional perspective, this allows for the colonisation of late-successional species. From an evolutionary perspective, palmiet influences the evolution of plants adapted to unchannelled valley bottom wetland conditions. This is a result of palmiet's ability as an ecosystem engineer and potentially a niche constructor.

6.2.1 The role of palmiet in creating and maintaining unchannelled-valley bottom conditions.

Plants have the ability to alter environmental conditions in which they reside such as by using resources that are not available to other individuals (Pulliam, 2000). Plants do this through developing specific adaptations that lead to alteration of physical niche conditions. This can be

described by Hutchinson's niche hyper-volume (1978) in which physical niche dimensions alter competition between species. An organism's niche is composed of environmental and physical variables (e.g. light, food, soil nutrients and disturbance patterns). These variables can be considered a point in multi-dimensional space for each environmental variable, called a hyper-volume. If a point within Hutchinson's niche hyper-volume is altered, species with the appropriate life-history adaptation to tolerate these conditions are favoured.

Hutchinson's niche hyper-volume can be demonstrated by the effects of canopy gaps on the understory herb *Primula vulgaris* (Valverde, 1998). The growth rate of *P. vulgaris* is related to light availability such that in brighter patches *P. vulgaris* populations grow, but in dark shaded patches, *P. vulgaris* populations persisted or declined. As canopy gaps close, caused by the encroachment of the tree species *Fagus sylvatica* (beech) and *Fraxinus excelsior* (ash), *P. vulgaris* populations decline. This is due to a change in the niche hyper-volume, which in this case is related to light availability, controlled by tree canopy volume. As an early colonizer with biomechanical adaptations to hydrogeomorphic disturbance, palmiet alters the niche hyper-volume, thus influencing vegetation distribution.

Palmiet is a robust perennial shrub and grows to an average height of 3m (Roux, 2003) with an aerial woody stem that is initially sub-erect but falters later on and adopts to a prostrate form. Palmiet has a deep and extensive root system and semi-woody stems that is thought to very effectively trap sediments (Sieben, 2012). This enables palmiet to grow through newly deposited sediments, and in turn stabilizes limits the movement of sediments introduced into the wetland from the catchment or generated by erosion within the wetland. Boucher and Withers (2004) also noted that stems and leaves overcome by floodwaters simply adopt a prostrate form, thereby protecting the wetland from erosion during large floods.

The biomechanical characteristics of palmiet influence the hydrogeomorphic regime through increasing stream roughness and trapping and stabilization of sediments (Job, 2014; Barclay 2016; Van Eck, 2022). This leads to diffuse, low-velocity flow conditions, which allows for the accumulation of organic matter. Palmiet thus converts a channelled valley bottom to an unchannelled valley bottom wetland. Palmiet therefore influences the niche hyper-volume by decreasing hydrogeomorphic disturbance and maintaining soil saturation across the valley floor. This allows for the accumulation of resources and the construction and preservation of habitats suitable for vegetation recruitment (Van Pelt et al, 2006).

6.2.2 Adaptations of palmiet to the hydrogeomorphic regime

Physical factors exert evolutionary pressure on the life-history attributes of biota such that persistence in a given environment typically reflects natural conditions posed by the environment (Lytle and Poff, 2004; Bornette et al., 2008; Corenblit et al 2007). Within wetlands that are integrated in fluvial systems, plants should be expected to be resistant to mechanical forces associated with large floods, including submersion, partial sediment burial, floods and sediment transport conditions. Biomechanical adaptations to such events gives plants an increased chance of persisting, and may (co-incidentally) give them a capacity to trap sediments and resist flow. Such characteristics would lead to environmental outcomes in the physical environment, such as a reductions in flow rate and sediment transport. The biotic response may thus lead to evolution in response to changes the plants may induce (Corenblit et al 2007).

Palmiet shows many visible traits that suggest it is adapted to hydrogeomorphic constraints imposed by high energy events (Munyai, 2013). This can be seen not only in biomechanical adaptations of palmiet, but adaptations may also be expressed in the regeneration characteristics of this species (van Eck, 2022). Palmiet was found to actively regenerate in zones that have experienced recent geomorphic disturbance such as cycles of erosion and deposition. Such adaptations include the ability of palmiet to reproduce vegetatively and produce a very large number of very small seeds (between 10 000 to 20 00 per inflorescence (van Eck, 2022). These seeds float on water and are likely dispersed through fluvial corridors during times of high or even moderate flows (van Eck, 2022). Observations in the field over more than a decade (Ellery personal communication) suggest that beyond clonal expansion, palmiet regeneration coincides with geomorphic disturbance events, particularly depositional features. These circumstances suggest that palmiet has evolved to cope with (and possibly to capitalise on) high energy geomorphic alteration of a wetland landform subjected to periodic geomorphic disturbance events, which, from an anthropogenic perspective, look catastrophic.

Munyai (2013) conducted a systematic study of palmiet and found that populations from the Cape Fold Mountains were genetically dissimilar despite being geographically in close proximity. However, populations from the coasts (Agulhas Plain and Kwazulu-Natal) were genetically similar, despite being geographically far apart. Palmiet occurs in mountain streams or rivers, and populations are genetically isolated via drainage networks or geographic barriers that limits gene flow. However, Agulhas Plain and Kwazulu-Natal populations are genetically

similar, as vegetation recruitment happened within these systems much more recently, as habitats became available due to a drop in sea levels associated with an uplift event 5 million years ago (Cowling et al., 2009).

Van Eck (2022) noted that these findings relate to palmiet's origins, which can seemingly be traced back to the Cape Fold Mountains above the African Erosion Surface. Rivers within mountains are likely subjected to extremely variable flow conditions due to variable rainfall and the rapid runoff response associated with steep slopes with skeletal soils (Ellery et al, 2009). Given that palmiet originated 33-34 mya in this mountainous setting, it is possible to have evolved biomechanical and regenerative adaptations capable of withstanding high energy conditions in these systems. The physical form and clonal nature of palmiet makes its physical adaptations suitable for persistence in a variable environment. However, its regenerative characteristics suggest adaptations to exploit infrequent, large magnitude disturbances, which afford it opportunity to rapidly colonise environmental conditions that appear suited to primary succession. Therefore, palmiet shows physical characteristics of K selected species, but reproductive characteristics of r selected species.

Palmiet wetlands are distributed over a range of frequencies that episodic and catastrophic events occur (Grenfell, 2020). The distribution ranges from small systems at very high altitude to those where the coastal plain interfaces with the Cape Fold Mountains. It is evident that high altitude wetlands are likely to experience fairly frequent episodic geomorphic disturbance events (decades), but as one moves to lower altitudes and wetlands are larger in size, the events are larger but less frequent. However, in these systems, even the upper wetland reaches are likely to have more frequent and less catastrophic events. Therefore the evolutionary pressure of more frequent episodes may not have taken place in large systems, but in small ones, but the advantages of these evolved traits may confer advantages to the species in settings where frequency is low but intensity is high.

6.2.3 Frequency and size of geomorphically significant events in fluvial systems; biota and geomorphic scour and fill cycles

Species of the genera *Salix* and *Populus* are commonly found on northern temperate floodplains. Interest in their adaptations to seedling establishment in these systems is considered related to anchorage during high river flows that lead to high seedling mortality due to scouring. Following high flows, coarse sediment deposits are common and seedlings are subjected to drought stress – also leading to seedling mortality (Parsons 2013). These species

typically thrive under intermediate frequency and magnitude disturbance events (Edwards et al., 1999; Gurnell and Petts, 2006; Corenblit et al., 2007) such that an increase or decrease in the intensity and frequency of disturbance events negatively impacts *Salix* and *Populus* populations. Where hydrogeomorphic disturbance is limited and bare sediments are insufficient for widespread colonisation, the regeneration and establishment of *Salix* and *Populus* are hindered. The ecosystem engineering processes associated with *Salix* and *Populus* establishment - such as increasing surface roughness and protecting the soil surface against disturbance - are thus weakened given these ideas *Salix* and *Populus* seem to have a threshold where disturbance acts as an evolutionary agent but is not too frequent or severe to have this effect (Francis et al, 2009).

Similarly, palmiet seems to have developed strategies to colonise recently exposed sediments, endure conditions associated with high energy flood events, allowing it to regenerate and persist as dictated by cycles of hydrogeomorphic disturbance. Much like the *Salix* and *Populus* species, palmiet may be adapted to a disturbance threshold, such that if disturbance is not frequent enough, palmiet may not be able to regenerate effectively but over time, stands dominated by palmiet may be outcompeted by, for example, some fynbos taxa. However, if disturbance is too frequent, stable valley bottom wetlands dominated by palmiet may never establish, limiting recruitment due to a limited propagule supply. Further to this, those communities that may occupy a post-palmiet successional stage may also disappear given that they also never have opportunity to establish.

6.2.4 Palmiet as a niche constructor: a mechanism to explain ecosystem structure and functioning within the KRW

Niche construction is a non-linear process that leads to differencing states of stability (Corenblit et al, 2009). Spatial and temporal patterns in the niche construction process vary between river systems as a result of the climate, lithology, human influence and life-history characteristics of species present. These variations shape the structure and functioning of fluvial systems in the long-term. Niche construction can be viewed as: “an ‘adaptive cycle’ (sensu Holling, 1986) of mineral matter, energy and organization of organism communities alternating between relatively long periods of resource exploitation and conservation and shorter periods of release and reorganization, during and after floods and droughts (Naiman et al., 2005) that create new biogeomorphic opportunities.” (Corenblit et al, 2009:514). The concept of an adaptive cycle is used to understand the structure and processes of complex system dynamics over time (Holling,

1992; Gunderson et al, 1995; Carpenter et al, 2001). The adaptive cycle consists of a number of phases as systems act to structure, collapse and reorganise (Holling, 1992).

Within the KRW, established valley bottom wetlands experience extended phases of geomorphic stability. This gives post-pioneer species and communities lots of time to establish in a setting driven by the constraint of resource conservation. Long periods of stability are followed by short periods of release, via hydrogeomorphic disturbance, where the ecosystem is able to reorganise itself. This creates opportunity for species not present in the previous climax community, including ecosystem engineers, to establish, thus promoting bio-geomorphic variability within the landform.

Palmiet, being an ecosystem engineer with biomechanical adaptations to regular hydrogeomorphic disturbance, alters selection pressures during its establishment. The alterations are determined by the relationship between palmiet, other organisms within the community and changes in the environment. These alterations serve as a form of ecological inheritance, through genes or the altered environment, which are passed on to post-pioneering vegetation communities (Odling-Smee et al, 2003). Modifications produced by palmiet maintain populations and facilitates the establishment of other vegetation species; stable valley bottoms wetlands created and maintained by palmiet could be viewed as an expression of palmiet itself (Odling-Smee et al, 2003; Corenblit et al, 2009). The example of palmiet demonstrates the adaptations of riparian vegetation to hydrogeomorphic disturbance regimes may not only influence river morphology but also ecosystem structure and function, and the evolution of species within the communities (Francis et al, 2009; Corenblit et al, 2009).

6.2.5 Implications for restoration

Restoration of the natural flow regimes has been suggested as the central control for promoting the vitality of ecological communities along fluvial systems (Naiman et al., 2008). Within the KRW, it will be important to identify problems that imping the natural ecosystem functioning of the system (such as increased hydrogeomorphic disturbance, the impact of gabion weirs and alien vegetation). Ultimately, the capacity of palmiet as an ecosystem engineer and niche constructor has a limit, both in its ability to regenerate after hydrogeomorphic disturbance events and compete during times of geomorphic stability. If the limit is exceeded on either side – through significantly increased or decreased hydrogeomorphic disturbance – the ecosystem will suffer.

6.3 Remote sensing discussion

6.3.1 Introduction

The model developed to detect ‘stable palmiet’ was successful, with an accuracy greater than 90%. For such a small study area, the use of remote sensing for mapping is a viable technique. The results provide a simple and effective method to detect palmiet distribution within the KRW.

6.3.2 The sole use of data derived from LiDAR to classify palmiet

This model only uses data derived from a LiDAR dataset. The use of LiDAR is limited but increasingly common and often used with other sources of RS imagery to classify objects. Millard (et al., 2013) found that LiDAR alone performed better than LiDAR combined with SAR imagery when mapping wetlands using a forest classifier.

LiDAR data has been widely used but is expensive. However, over time and with the increased utilisation of UAVs, LiDAR data will become cheaper and more accessible (Bolstad, 2016). LiDAR data is capable of assessing plant traits (the phenological and structural components of plants (Cornelissen et al., 2003, Kattge et al., 2011)), and RS has been used to replace field-based plant trait measurements (Kokaly et al., 2009). Two of the most widely used and studied RS plant trait measurements are vegetation height and canopy cover indices (Homolová, 2013).

Of the layers derived from the LiDAR data set, the Canopy Cover Index was the most useful. LiDAR can penetrate the canopy and quantify canopy density by comparing the number of ground to first return points. Palmiet clumps are densely packed and have high canopy cover scores compared to other wetland vegetation communities. Canopy Cover Indices have been used in several other RS vegetation studies (Miller et al., 2000; Mathieu et al., 2007; Maxa and Bolstad., 2009; Korhonen et al., 2011; Smith et al., 2013) and in the classification of wetland plant communities (Townsend et al., 2001; Gilmore et al., 2008; Lechner et al., 2012). The Canopy Cover Index has proved to be very useful for assessing canopy characteristics.

In addition to the above, vegetation height has been used in various wetland classification studies (Genç et al., 2004; Gilmore et al., 2008; Hladik et al., 2013). The Vegetation Height Model was helpful, but had far less discriminatory power than the Canopy Cover Index. The Vegetation Height Model failed to calculate the height of densely packed palmiet clumps accurately. Most vegetation heights measured were greater than 0.104m. Barclay (2017) found that height in established palmiet communities measured from 2 to 3 meters. Vegetation height

estimation has a few problematic issues, one of which is the determination of terrain elevation, which can be hard to assess with low or densely packed canopies (Falkowski et al., 2008, Lefsky, 2002). This is likely the case in palmiet wetlands, where thick stems have accumulated over centuries and hinder light penetration (Rebelo et al., 2013).

The Vector Ruggedness Index made a minor contribution in this study to mapping palmiet distribution. The Vector Ruggedness Index has been widely used in habitat suitability analysis (Sappington et al., 2007), but less widely used in vegetation classification (Rutzinger et al., 2008; Zhang et al., 2011). It was expected that the ruggedness would not perform as well as the Canopy Cover Index and the Vegetation Height Model as the model did not assess the phenological characteristics of palmiet. However, the Ruggedness Index helped to quantify ruggedness associated with palmiet wetlands in relation to the surrounding land surface and proved valuable in the classification model.

The model also served to separate palmiet communities with the appropriate elevations relative to the thalweg and palmiet communities with inappropriate elevation relative to the thalweg to distinguish ‘stable’ and ‘degrading’ palmiet communities, despite that they are phenologically very similar. The study showed that only way to separate between the two is through the model making use of Relative Elevation Model. ‘Stable palmiet’ communities are found where the elevation of samples relative to the thalweg was less than 0.53m.

The KRW frequently experiences gullying, which lowers the water table of the previous valley bottom's surface (Pulley et al., 2018). Palmiet communities are often displaced from having an appropriate elevation relative to the thalweg to one that is inappropriate due to these geomorphic disturbance events. The usefulness of this model is in its ability to predict which palmiet communities need to be preserved (‘stable palmiet’ communities) and which palmiet communities need restoration interventions (‘degrading palmiet’ communities).

6.3.3 The uniqueness of palmiet plant traits and implication for classification

One of the main contributions to the success of the palmiet classification is its phenological characteristics. Palmiet is a robust perennial with rigid leathery leaves that are densely arranged around the stem, generally overlapping with older leaves from other stems (Figure 22). Palmiet’s structural characteristics have resulted in a high Canopy Cover Index score, which contributes to classification accuracy.



Figure 22: A densely packed palmiet canopy, with the top of the canopy roughly 2 to 3 meters above the water surface. Photo taken by Caydon van Eck.

The phenological uniqueness of palmiet make it distinct from other wetland plants and well suited to growth in wetland systems in the Cape Fold Mountains where runoff is immediate and flows in streams very variable from over short time periods. Such plant traits are likely to have contributed to the high classification accuracy seen in this study.

Due to the phenological characteristics of palmiet, it is easy to discriminate from other vegetation communities in the KRW. However, this might not apply to other palmiet wetlands as species composition may differ, or other vegetation communities may have similar phenological characteristics. Whether the model is applicable in other palmiet wetlands requires testing in a broader-scale study.

6.3.4 Classification of palmiet using machine learning and overlay procedures

There is evidence of error propagation by using overlay techniques, as predicted by Heuvelink and Burrough (1993). Error propagation can be assessed by comparing the confusion matrix tested through the Rpart algorithm and the confusion matrix tested through the output classification layer (Table 11). Overall, accuracy decreases by about 5% from the Rpart algorithm to the overlay procedure. The classification of stable palmiet decreased by 4.1 %, and non-palmiet decreased by 5.8%. Classification of non-palmiet communities had the most significant decrease. However, the classification with 90% accuracy for the overlay procedure, the convenience of the condition statement and likelihood of its use, justified the methodology

used. It is therefore concluded that classification of the layers according to Rpart in RStudios, is an appropriate methodology.

Table 11: Confusion matrix assessing error propagation via classification accuracy

From \ to	Rpart %	GIS Overlay %	% Change
Stable palmiet	93.88	89.8	4.08
Non-palmiet	97.83	92	5.83
Total	95.79	90.9	4.89

Rpart is a practical algorithm, mainly because of the classification and regression tree produced (Therneau et al., 2013). Rpart performed better than expected, with a minimal variable selection, confirming the findings of Georganos (et al., 2018) that Rpart is a robust classification algorithm with limited variable selection. However, another classification algorithm may have performed better, which still needs to be tested.

6.3.5 Recommendations for further research

Other layers derived from LiDAR data could be assessed to increase the accuracy and range of variable selection. Other high-resolution remote sensing imagery, such as hyper-spectral data, can be included. Other Machine Learning (ML) classification algorithms in the detection of palmiet should also be tested, such as Random Forest, Support Vector Machines, Neural Networks, and K-Nearest Neighbour (Georganos et al., 2018). The relationship between feature selection and ML classification must also be considered for improved classification accuracy. Georganos et al. (2018) found that accuracy increased substantially when using feature selection before running classification algorithms. Finally, palmiet classification using LiDAR data needs to be applied to several palmiet wetlands to determine the most robust classification method for palmiet.

7. Conclusion

7.1 The relationship between geomorphic disturbance and vegetation distribution in fluvial wetland systems

Odum's (1969) definition of ecological succession is the orderly and predictable process of vegetation change over time that results from disturbance that modifies the physical environment. Such vegetation change culminates in a stable ecosystem such that on average, death of an individual is followed by its replacement by an individual of the same species. The outcome of community development is to increase homeostasis in the physical environment and protect against unpredictable change. Ecosystem engineers and niche constructors facilitate community development (Corenblit et al, 2009). In habitats that have not been influenced by ecosystem engineering, allogenic succession dominates. In habitats that have been affected by ecosystem engineering, autogenic succession dominates as organisms maintain constant environmental conditions. This shift from allogenic to autogenic succession is reflected in the life history characteristics of the species present in the community, as *r* strategists initially colonise the disturbed feature and are outcompeted by *K* strategists.

In most habitats the control of allogenic vs autogenic succession fluctuates, which is mirrored in vegetation distribution. Along fluvial systems, hydrogeomorphic disturbance is an important factor controlling successional processes.

This study has demonstrated that in the KRW, geomorphic disturbance through cycles of cutting and filling, influence vegetation succession (Figure 23). Following a cutting and filling event in the KRW, *r* strategists colonise bare patches of sediment. This includes the establishment of the ecosystem engineer and niche constructor *Prionium serratum*. Over time, as pioneer plants stabilize the system and increasingly protect it from geomorphic disturbance—(river erodibility decreases). As the ecosystem stabilizes, and successional processes change from allogenic to autogenic, *K* strategists increasingly outcompete former plant communities. Stability characterises the system until tributary alluvial fans lead to the initiation of another cut-and-fill cycle.

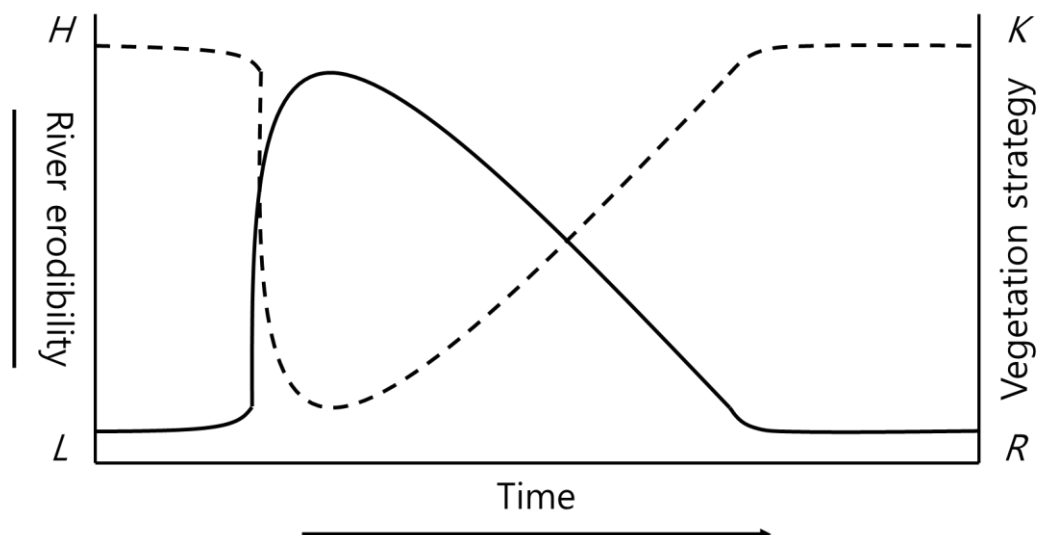


Figure 23: Conceptual model of the relationship between cycles of geomorphic disturbance (represented by river erodibility; Low to High) and vegetation composition (represented by plant life-history characteristics).

7.2 Recommendations for future research

Although the hydrogeomorphic characteristics of each system differ, there is a clear relationship between river erodibility (via hydrogeomorphic disturbance) and vegetation life history characteristics (Figure 24). Following erosion and deposition, r strategists dominate as the system is dominated by autogenic successional processes. The converse also applies such that K strategists dominate as a system stabilises and allogenic succession processes dominate. The application of this model in other river systems with different hydrogeomorphic characteristics and vegetation communities needs to be evaluated. This will help to further our understanding about the relationship between vegetation distribution and hydrogeomorphic disturbance in Southern African wetland systems.

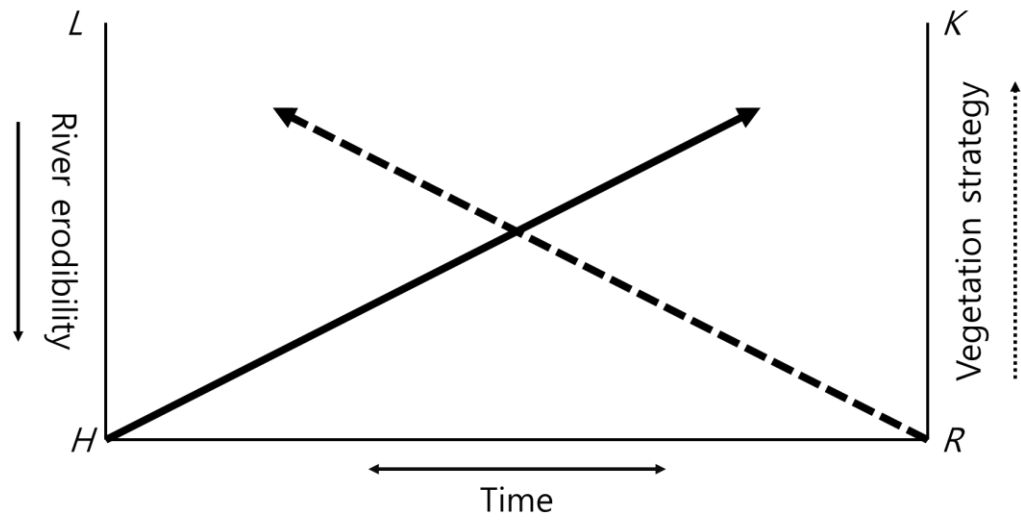


Figure 24: A conceptual model of the relationship between river erodibility and plant strategy in response to geomorphic disturbance.

Reference list

- Adam, E., Mutanga, O. and Rugege, D., 2010. Multispectral and hyperspectral remote sensing for identification and mapping of wetland vegetation: a review. *Wetlands Ecology and Management*, 18(3), pp.281-296.
- Arbia, G., Griffith, D. and Haining, R., 1998. Error propagation modelling in raster GIS: overlay operations. *International Journal of Geographical Information Science*, 12(2), pp.145-167.
- ArcGIS Desktop, 2021. Estimating forest canopy density and height, ESRI, Webpage Tutorial. [Online] <https://desktop.arcgis.com/en/arcmap/10.3/manage-data/las-dataset/lidar-solutions-estimating-forest-density-and-height.htm>. Accessed 17 January 2023
- Bai, T., Wang, L., Yin, D., Sun, K., Chen, Y., Li, W. and Li, D., 2022. Deep learning for change detection in remote sensing: a review. *Geo-spatial Information Science*, pp.1-27.
- Barclay, A. 2017. *Ecosystem engineering by the wetland plant Palmiet: Does it control fluvial form and promote diffuse flow in steep-sided valleys of the Cape Fold Mountains*. Grahamstown: Rhodes University (MSc Thesis) [pdf].
- Beasom, S.L., Wiggers, E.P. and Giardino, J.R., 1983. A technique for assessing land surface ruggedness. *The Journal of Wildlife Management*, 47(4), pp.1163-1166.
- Beaumont, B., Grippa, T., Lennert, M., Vanhuysse, S.G., Stephenne, N.R. and Wolff, E., 2017. Toward an operational framework for fine-scale urban land-cover mapping in Wallonia using submeter remote sensing and ancillary vector data. *Journal of Applied Remote Sensing*, 11(3), p.036011.
- Berhane, T.M., Lane, C.R., Wu, Q., Autrey, B.C., Anenkhonov, O.A., Chepinoga, V.V. and Liu, H., 2018. Decision-tree, rule-based, and random forest classification of high-resolution multispectral imagery for wetland mapping and inventory. *Remote sensing*, 10(4), p.580.
- Berry, J.K., 1987. Fundamental operations in computer-assisted map analysis. *International journal of geographical information system*, 1(2), pp.119-136.
- Bickerton, I.B. and Pierce, S.M., 1988. Kromme (CMS45), Seekoei (CMS46) and Kabeljous (CMS47). CSIR, *National Research Institute for Oceanology*.

- Blott, S.J. and Pye, K., 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth surface processes and Landforms*, 26(11), pp.1237-1248.
- Bolstad, P., 2016. *GIS fundamentals: A first text on geographic information systems*. Eider (PressMinnesota).
- Bornette, G., Tabacchi, E., Hupp, C., Puijalon, S. and Rostan, J.C. 2008. A model of plant strategies in fluvial hydrosystems. *Freshwater Biology*, 53, 1692– 1705
- Boshoff, A., Cowling, R. and Kerley, G. 2000. *The Baviaanskloof conservation area: A conservation and tourism development priority*. Terrestrial Ecology Research Unit, University of Port Elizabeth, p. 18-34.
- Boucher, C. and Withers, M., 2004. Palmiet. *Veld & Flora*, 90(1), pp.26-28.
- Brierley, G. J., and Fryirs, K. 1999. Tributary-trunk stream relations in a cut-and-fill landscape: A case study from Wolumla catchment, New South Wales, Australia. *Geomorphology*, 28(1), 61–73.
- Brierley, G., Fryirs, K., and Jain, V. 2006. Landscape connectivity: The geographic basis of geomorphic applications. *Area*, 38(2), 165–174.
- Carpenter, S., Walker, B., Anderies, J.M. and Abel, N., 2001. From metaphor to measurement: resilience of what to what?. *Ecosystems*, 4(8), pp.765-781.
- Che, J., Yang, Y., Li, L., Bai, X., Zhang, S. and Deng, C., 2017. Maximum relevance minimum common redundancy feature selection for nonlinear data. *Information Sciences*, 409, pp.68-86.
- Clements, F.E., 1916. *Plant succession: an analysis of the development of vegetation* (No. 242). Carnegie institution of Washington.
- Connell, J.H. and Slatyer, R.O., 1977. Mechanisms of succession in natural communities and their role in community stability and organization. *The american naturalist*, 111(982), pp.1119-1144.
- Corenblit, D., Steiger, J., Gurnell, A.M. and Naiman, R.J., 2009. Plants intertwine fluvial landform dynamics with ecological succession and natural selection: a niche construction perspective for riparian systems. *Global Ecology and Biogeography*, 18(4), pp.507-520.

- Corenblit, D., Tabacchi, E., Steiger, J. and Gurnell, A.M., 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. *Earth-Science Reviews*, 84, 56– 86
- Cornelissen, J.H.C., Lavorel, S., Garnier, E., Díaz, S., Buchmann, N., Gurvich, D.E., Reich, P.B., Ter Steege, H., Morgan, H.D., Van Der Heijden, M.G.A. and Pausas, J.G., 2003. A handbook of protocols for standardised and easy measurement of plant functional traits worldwide. *Australian journal of Botany*, 51(4), pp.335-380.
- Cowen, D.J., Jensen, J.R., Hendrix, C., Hodgson, M., Schill, S.R. and Macchiaverna, F., 2000. A GIS-assisted rail construction econometric model that incorporates LIDAR data. *Photogrammetric engineering and Remote sensing*, 66(11), pp.1323-1328.
- Cowling, R.M., Procheş, Ş. and Partridge, T.C., 2009. Explaining the uniqueness of the Cape flora: incorporating geomorphic evolution as a factor for explaining its diversification. *Molecular phylogenetics and evolution*, 51(1), pp.64-74.
- Crabbe, R.A., Lamb, D. and Edwards, C., 2020. Discrimination of species composition types of a grazed pasture landscape using Sentinel-1 and Sentinel-2 data. *International Journal of Applied Earth Observation and Geoinformation*, 84, p.101978.
- Cronk, J.K. and Fennessy, M.S., 2016. *Wetland plants: biology and ecology*. CRC press.
- Davis, J.C. and Sampson, R.J., 1986. *Statistics and data analysis in geology* (Vol. 646). New York: Wiley.
- Dawkins, R., 1982. *The extended phenotype*. Freeman, Oxford, UK.
- Dini, J., and Bahadur, U., 2016. South Africa's national wetland rehabilitation programme: Working for wetlands. *The Wetland Book*; Springer: Dordrecht, The Netherlands.
- Dobzhansky, T., 1950. Evolution in the tropics. *American scientist*, 38(2), pp.209-221.
- DWAF, 2008. *Updated Manual for the Identification and Delineation of Wetlands and Riparian Areas*, prepared by M. Rountree, A. L. Batchelor, J. MacKenzie and D. Hoare. Stream Flow Reduction Activities, Department of Water Affairs and Forestry, Pretoria, South Africa
- Edwards, P.J., Kollmann, J., Gurnell, A.M., Petts, G.E., Tockner, K. and Ward, J.V., 1999. A conceptual model of vegetation dynamics on gravel bars of a large Alpine river. *Wetlands Ecology and Management*, 7, 141– 153.

Ellenberg, D. and Mueller-Dombois, D., 1974. *Aims and methods of vegetation ecology* (p. 547). New York: Wiley.

Ellery, W. N., Grenfell, M., Grenfell, S., Kotze, D., McCarthy, T., Tooth, S., Grundling, P. L., Beckedahl, H., Maitre, D. I. and Ramsay, L., 2009. *WET-Origins: Controls on the distribution and dynamics of wetlands in South Africa*. (Eds.). Breen, C., Dini, J., Ellery, W. N., Mitchell, S., Uys, M. WRC Report TT 334/09: South Africa.

Ellery, W.N., Humphries, M., Barnes, K., Grenfell, M.C., Grenfell, S., Fischer, D., Kindness, A., and Hughes, G. 2012. Peat formation in the context of landscape evolution of the Mkuze Wetland on the coastal plain of Maputaland, South Africa. *Geomorphology*. 141-142:11-20

ESRI, 2020. ArcGIS Desktop: Release 10.8.1. Redlands, CA: Environmental Systems Research Institute

Falkowski, M.J., Smith, A.M., Gessler, P.E., Hudak, A.T., Vierling, L.A. and Evans, J.S., 2008. The influence of conifer forest canopy cover on the accuracy of two individual tree measurement algorithms using lidar data. *Canadian Journal of Remote Sensing*, 34(sup2), pp.S338-S350.

Folk, R.L. and Ward, W.C., 1957. Brazos River bar [Texas]; a study in the significance of grain size parameters. *Journal of sedimentary research*, 27(1), pp.3-26.

Francis, R.A., Corenblit, D. and Edwards, P.J., 2009. Perspectives on biogeomorphology, ecosystem engineering and self-organisation in island-braided fluvial ecosystems. *Aquatic Sciences*, doi: 10.1007/s00027-009-9182-6.

Genç, L., Dewitt, B. and Smith, S., 2004. Determination of wetland vegetation height with LIDAR. *Turkish Journal of agriculture and forestry*, 28(1), pp.63-71.

Georganos, S., Grippa, T., Vanhuysse, S., Lennert, M., Shimoni, M., Kalogirou, S. and Wolff, E., 2018. Less is more: Optimizing classification performance through feature selection in a very-high-resolution remote sensing object-based urban application. *GIScience & remote sensing*, 55(2), pp.221-242.

Gilmore, M.S., Wilson, E.H., Barrett, N., Civco, D.L., Prisloe, S., Hurd, J.D. and Chadwick, C., 2008. Integrating multi-temporal spectral and structural information to map wetland vegetation in a lower Connecticut River tidal marsh. *Remote Sensing of Environment*, 112(11), pp.4048-4060.

Gleason, H.A., 1917. The structure and development of the plant association. *Bulletin of the Torrey Botanical Club*, 44(10), pp.463-481.

Gosselink, J.G. and Turner, R.E., 1978. *Role of hydrology in freshwater wetland ecosystems. Freshwater wetlands*.

Grenfell, M.C., Ellery, W.N. and Grenfell, S.E., 2008. Tributary valley impoundment by trunk river floodplain development: a case study from the Drakensberg foothills, eastern South Africa. *Earth Surface Processes and Landforms*, 33:2029–2044.

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

Grenfell, S.E., Mamphoka, M.F., Grenfell, M.C. and Job, N., 2020. Evaluating the potential for natural ecosystem recovery in cut-and-fill wetlands: case study of Pietersielieskloof palmiet wetland, South Africa. *Wetlands Ecology and Management*, 28(6), pp.863-882.

Grenfell, S.E., Ellery, W.N., Grenfell, M.C., Ramsay, L.F. and Flugel, T.J., 2010. Sedimentary facies and geomorphic evolution of a blocked-valley lake: Lake Futululu, northern KwazuluNatal, South Africa. *Sedimentology*. 57(5):1159-1174.

Grime, J.P., 1988. The CSR model of primary plant strategies—origins, implications and tests. In *Plant evolutionary biology*, (pp. 371-393). Springer, Dordrecht.

Guan, R., Li, Z., Li, T., Li, X., Yang, J. and Chen, W., 2022. Classification of Heterogeneous Mining Areas Based on ResCapsNet and Gaofen-5 Imagery. *Remote Sensing*, 14(13), p.3216.

Gull, K., 2012. *Water supply in the Eastern Cape: an economic case study of land rehabilitation in the Kromme River Catchment*. Cape Town: University of Cape Town. (M Comm. Thesis).

Gunderson, L.H., Holling, C.S. and Light, S.S., 1995. *Barriers and bridges to the renewal of ecosystems and institutions*. Columbia University Press.

Gurnell, A.M. & Petts, G.E., 2006. Trees as riparian engineers: the Tagliamento river, Italy. *Earth Surface Processes and Landforms*, 31, 1558– 1574.

- Hagberg, T.D., 1995. *Relationships between hydrology, vegetation, and gullies in montane meadows of the Sierra Nevada*, MSc Thesis, Humboldt State University, Arcata, California, pp. 177
- Haigh, E.A., Grundling, P.L. and Illgner, P.M., 2008. *Report on the scoping study on the status of the Kromme River peatland complex and recommended mitigatory measures*. Department of Water Affairs and Forestry Project X, 832633.
- Hastings, A., Hom, C.L., Ellner, S., Turchin, P. and Godfray, H.C.J., 1993. Chaos in ecology: is mother nature a strange attractor?. *Annual review of ecology and systematics*, pp.1-33.
- Heuvelink, G.B. and Burrough, P.A., 1993. Error propagation in cartographic modelling using Boolean logic and continuous classification. *International Journal of Geographical Information Systems*, 7(3), pp.231-246.
- Hill, M.O., 1979. *TWINSPAN: A FORTRAN Programme for arranging multivariate data in an ordered two way table by classification of the individuals and the attributes*. Cornell University, Department of Ecology and Systematics, Ithaca, New York
- Hill, M.O., and Gauch, H.G., 1980. Detrended correspondence analysis: an improved ordination technique. In *Classification and ordination* (pp. 47-58). Springer, Dordrecht.
- Hladik, C., Schalles, J. and Alber, M., 2013. Salt marsh elevation and habitat mapping using hyperspectral and LIDAR data. *Remote Sensing of Environment*, 139, pp.318-330.
- Holling, C.S., 1986. The resilience of terrestrial ecosystems: local surprise and global change. *Sustainable development of the biosphere* (ed. by W.C. Clark and R.E. Munn), pp. 292– 317. Cambridge University Press, Cambridge.
- Holling, C.S., 1992. Cross-scale morphology, geometry, and dynamics of ecosystems. *Ecological monographs*, 62(4), pp.447-502.
- Holmes, P. and Meadows, M., 2013. *Southern African geomorphology: recent trends and new directions*.
- Holmgren, J., Persson, Å. and Söderman, U., 2008. Species identification of individual trees by combining high resolution LiDAR data with multi-spectral images. *International Journal of Remote Sensing*, 29(5), pp.1537-1552.

Homolová, L., Malenovský, Z., Clevers, J.G., García-Santos, G. and Schaepman, M.E., 2013. Review of optical-based remote sensing for plant trait mapping. *Ecological Complexity*, 15, pp.1-16.

Hutchinson, G., 1978. *An introduction to population ecology*. – Yale Univ. Press.

Jarvis, S., 2020. *Can the distribution of Palmiet (Prionium serratum) shed light on its life history characteristics: A case study of the Kromme River Wetlands, Eastern Cape*. Makhanda: Rhodes University (Honours thesis) [PDF].

Job, N.M., 2014. *Geomorphic origin and dynamics of deep, peat-filled, valley bottom wetlands dominated by Palmiet (Prionium serratum): a case study based on the Goukou Wetland, Western Cape* (Doctoral dissertation, Rhodes University).

Jones, J.L., 2006. Side channel mapping and fish habitat suitability analysis using lidar topography and orthophotography. *Photogrammetric Engineering and Remote Sensing*, 72(11), p.1202.

Jones, C.G., Lawton, J.H. and Shachak, M., 1994. Organisms as ecosystem engineers. In *Ecosystem management* (pp. 130-147). *Springer*, New York, NY.

Joubert, R. and Ellery, W.N., 2013. Controls on the formation of WakkerstroomVlei, Mpumalanga Province, South Africa. *African Journal of Aquatic Science*. 38(2):135-151

Kattge, J., Diaz, S., Lavorel, S., Prentice, I.C., Leadley, P., Bönsch, G., Garnier, E., Westoby, M., Reich, P.B., Wright, I.J. and Cornelissen, J.H.C., 2011. TRY—a global database of plant traits. *Global change biology*, 17(9), pp.2905-2935.

Keddy, P.A., 2010. *Wetland ecology: principles and conservation*. Cambridge university press.

Kokaly, R.F., Asner, G.P., Ollinger, S.V., Martin, M.E. and Wessman, C.A., 2009. Characterizing canopy biochemistry from imaging spectroscopy and its application to ecosystem studies. *Remote sensing of environment*, 113, pp.S78-S91.

Korhonen, L., Korpela, I., Heiskanen, J. and Maltamo, M., 2011. Airborne discrete-return LIDAR data in the estimation of vertical canopy cover, angular canopy closure and leaf area index. *Remote Sensing of Environment*, 115(4), pp.1065-1080.

Kotze, D.C., Ellery, W. N., Patrick, B., Bambus, O., 2011. Part 5: An assessment of the effect of rehabilitation intervention on the health of Dartmoor Vlei, KwaZulu-Natal Midlands. *WET-Outcomes Evaluate*: 170-176.

Kuenzer, C., Bluemel, A., Gebhardt, S., Quoc, T.V. and Dech, S., 2011. Remote sensing of mangrove ecosystems: A review. *Remote Sensing*, 3(5), pp.878-928.

Lagesse, J., 2017. *Discontinuous gully erosion as a mechanism of wetland formation: A case study of the Kompanjiesdrif Basin, Krommerivier, Eastern Cape, South Africa* (Doctoral dissertation, MSc Thesis, Rhodes University, Grahamstown).

Langner, W., in prep. *High-resolution modelling as an approach to planning restoration interventions in unchanneled valley-bottom palmiet wetlands: A case study of the Kromme River*. Makhandla: Rhodes University (MSc Thesis) [PDF].

Lechner, A.M., 2012. *Characterising upland swamps using object-based classification methods and hyper-spatial resolution imagery derived from an unmanned aerial vehicle*.

Lefsky, M.A., Cohen, W.B., Parker, G.G. and Harding, D.J., 2002. Lidar remote sensing for ecosystem studies: Lidar, an emerging remote sensing technology that directly measures the three-dimensional distribution of plant canopies, can accurately estimate vegetation structural attributes and should be of particular interest to forest, landscape, and global ecologists. *BioScience*, 52(1), pp.19-30.

Leopold, L.B., Wolman, M.G., and Miller, J. E., 1964. *Fluvial Processes in Geomorphology*. W. H. Freeman, San Francisco. 522 pp.

Lewontin, R. C., 1983. 'The Organism as the Subject and Object of Evolution', reprinted in Levins and Lewontin (1985), pp. 85–106.

Lovell, J.L., Jupp, D.L., Culvenor, D.S. and Coops, N.C., 2003. Using airborne and ground-based ranging lidar to measure canopy structure in Australian forests. *Canadian Journal of Remote Sensing*, 29(5), pp.607-622.

Lytle, D.A. and Poff, N.L., 2004. Adaptation to natural flow regimes. *Trends in Ecology and Evolution*, 19, 94– 100.

Mathieu, R., Aryal, J. and Chong, A.K., 2007. Object-based classification of Ikonos imagery for mapping large-scale vegetation communities in urban areas. *Sensors*, 7(11), pp.2860-2880.

- Maud, R.R., 2012. Macroscale geomorphic evolution. In: Meadows M, Holmes P (eds) Southern African geomorphology; recent trends and new directions. *Sun Press*, Bloemfontein, pp 7–19
- Maune, D.F., 2001. Digital Elevation Model Technologies and Applications: The DEM Users Manual. Bethesda, Maryland: American Society for Photogrammetry and Remote Sensing. 537 pages.
- Maxa, M. and Bolstad, P., 2009. Mapping northern wetlands with high resolution satellite images and LiDAR. *Wetlands*, 29(1), pp.248-260.
- McCarthy, .T S., 2013. The Okavango Delta and its place in the geomorphological evolution of southern Africa. *South African Journal of Geology*, 116, 1-54.
- McCarthy T., Rubidge B. McCarthy T., Rubidge B., 2005. *The Story of Earth and Life: A Southern African Perspective on a 4.6 Billion Year Journey*. Cape Town: Struik.
- McNamara, S., 2018. *The influence of landscape disconnectivity on the structure and function of the Kromme River, Eastern Cape, South Africa* (Doctoral dissertation, MSc Thesis, Rhodes University, Grahamstown).
- Middleton, B.J. & Bailey, A.K., 2008. Water Resources of South Africa 2005. *Water Research Commission Report Nos. TT 380 to 382/08*. Pretoria: Water Research Commission
- Millard, K. and Richardson, M., 2013. Wetland mapping with LiDAR derivatives, SAR polarimetric decompositions, and LiDAR–SAR fusion using a random forest classifier. *Canadian Journal of Remote Sensing*, 39(4), pp.290-307.
- Miller, R.F., Svejcar, T.J. and Rose, J.A., 2000. Impacts of western juniper on plant community composition and structure. *Rangeland Ecology & Management/Journal of Range Management Archives*, 53(6), pp.574-585.
- Mitsch, W.J. and Gosselink, J.G., 2011. *Wetlands*. John Wiley & Sons.
- Mucina, L. and Rutherford, M.C., (eds) 2006. The vegetation of South Africa, Lesotho and Swaziland. Strelitzia 19. *South African National Biodiversity Institute*, Pretoria.
- Munyai, R., 2013. A systematic study of the South African genus *Pronium* (Thurniaceae). Cape Town: University of Cape Town (MSc thesis) [PDF].

- Naiman, R.J., Bechtold, J.S., Drake, D., Latterell, J.J., O'Keefe, T.C., and Balian, E.A., 2005. Origins, patterns, and importance of heterogeneity in riparian systems. *Ecosystem function in heterogeneous landscapes* (ed. by G. Lovett, C.G. Jones, M.G. Turner and K.C. Weathers), pp. 279– 309. Springer-Verlag, New York.
- Naiman, R.J., Latterell, J.J., Pettit, N.E., and Olden, J.D., 2008. Flow variability and the biophysical vitality of river systems. *Comptes Rendus Geosciences*, 340, 629– 643.
- Nanson, G.C., and Croke, J. C., 1992. A genetic classification of floodplains. *Geomorphology*, 4(6), 459–486
- National Geo-spatial Information (NGI). 2020. NGI: Aerial Photography, [Online]. <http://www.ngi.gov.za>. [March 2020].
- National Research Council, 1995. *Wetlands: Characteristics and boundaries*. National Academies Press.
- Nelson, R., Krabill, W., and MacLean, G., 1984. Determining forest canopy characteristics using airborne laser data. *Remote Sensing of Environment*, 15(3), pp.201-212.
- Niering, W.A., 1989. Wetland vegetation development. *Wetlands ecology and conservation: emphasis in Pennsylvania*, pp.103-113.
- Nsor, C.A. & Gambiza, J., 2013. Land Use Changes and Their Impacts on the Vegetation Kromme River Peat Basin, South Africa. *Science Journal of Environmental Engineering Research*, (3): 1-12
- Odling-Smee, F.J., 1988. Niche constructing phenotypes. *The role of behavior in evolution*, pp.73-132.
- Odling-Smee, F.J., Laland, K.N. and Feldman, M.W., 2013. Niche construction. In *Niche Construction*. Princeton university press.
- Odum, E.P. and Barrett, G.W., 1971. *Fundamentals of ecology* (Vol. 3, p. 5). Philadelphia: Saunders.
- Oliver, T.S., Rogers, K., Chafer, C.J. and Woodroffe, C.D., 2012. Measuring, mapping and modelling: an integrated approach to the management of mangrove and saltmarsh in the Minnamurra River estuary, southeast Australia. *Wetlands Ecology and Management*, 20(4), pp.353-371.

- Olson, P.L., Legg, N.T., Abbe, T.B., Reinhart, M.A. and Radloff, J.K., 2014. *A methodology for delineating planning-level channel migration zones* (No. 14-06-025). Washington (State). Dept. of Ecology.
- Oksanen, J.F., Blanchet, G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R. B., Simpson, G.L., Solymos, P.M., Stevens, H.H., Szoecs, E., and Wagner, H., 2020. *vegan: Community Ecology Package*. R package version 2.5-7. <https://CRAN.R-project.org/package=vegan>
- Ozesmi, S.L. and Bauer, M.E., 2002. Satellite remote sensing of wetlands. *Wetlands ecology and management*, 10(5), pp.381-402.
- Parsons, R.F., 2013. Adaptations to floodplains in *Populus* and *Salix*: the role of collet hairs. *Trees* 27, 1–5. <https://doi.org/10.1007/s00468-012-0738-z>
- Pickett, S.T.A., Collins, S.L. and Armesto, J.J., 1987. Models, mechanisms and pathways of succession. *The botanical review*, 53(3), pp.335-371.
- Poesen, J., Nachtergaele, J., Verstraeten, G. and Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. *CATENA*, 50(2-4), pp. 91-133.
- Pulley, S., Ellery, W.N., Lagesse, J.V., Schlegel, P.K., McNamara, S.J., 2018. Gully erosion as a mechanism for wetland formation: An examination of two contrasting landscapes. *Land Degradation and Development*, 1–12.
- Pulliam, H.R., 2000. On the relationship between niche and distribution. *Ecology letters*, 3(4), pp.349-361.
- R Core Team, 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>.
- Rebelo, A.J., Le Maitre, D.C., Esler, K.J. and Cowling, R.M., 2015. Hydrological responses of a valley-bottom wetland to land-use/land-cover change in a South African catchment: making a case for wetland restoration. *Restoration ecology*, 23(6), pp.829-841.
- Rebelo, A.J., Sieben, E., Meire, P. and Esler, K.J., 2022. What drives patchiness in palmiet wetlands?. *Wetlands Ecology and Management*, pp.1-27.

- Reyes-Bueno, F. and Loján-Córdova, J., 2022. Assessment of Three Machine Learning Techniques with Open-Access Geographic Data for Forest Fire Susceptibility Monitoring—Evidence from Southern Ecuador. *Forests*, 13(3), p.474.
- Riley, S.J., DeGloria, S.D. and Elliot, R., 1999. Index that quantifies topographic heterogeneity. *intermountain Journal of sciences*, 5(1-4), pp.23-27.
- Roux, J.P., 2003. Flora of South Africa. *Compton Herbarium*, Cape Town, South African National Biodiversity Institute.
- Russel, W., Brooker, C., Sieben, E., Braack, M., Ellery, W.N. and Kotze, D., 2009. *WET-Rehab Methods-National guidelines and methods for wetland rehabilitation*. WRC report TT341/09, pp. 178-187.
- Rutzinger, M., Höfle, B., Hollaus, M. and Pfeifer, N., 2008. Object-based point cloud analysis of full-waveform airborne laser scanning data for urban vegetation classification. *Sensors*, 8(8), pp.4505-4528.
- Samuel, A.L., 1959. Some studies in machine learning using the game of checkers. *IBM Journal on Research and Development*, 3,210–229. Reprinted in E.A. Feigenbaum & J. Feldman (Eds.), *Computers and Thought*, 71–105, New York: McGraw-Hill, 1963.
- SANBI, 2012. Vegetation Map of South Africa, Lesotho and Swaziland [vector geospatial dataset] 2012. Available from the Biodiversity GIS website, downloaded on 04 May 2021
- Sappington, J.M., Longshore, K.M. and Thompson, D.B., 2007. Quantifying landscape ruggedness for animal habitat analysis: a case study using bighorn sheep in the Mojave Desert. *The Journal of wildlife management*, 71(5), pp.1419-1426.
- Seiben, E. J.J., 2012. Plant functional composition and ecosystem properties: the case of peatlands in South Africa. *Plant Ecology*. 213(5):809-820.
- Shaw, P.J., Kibby, C. and Mayes, J., 2003. Effects of thinning treatment on an ectomycorrhizal succession under Scots pine. *Mycological Research*, 107(3), pp.317-328.
- Smith, A.M., Falkowski, M.J., Hudak, A.T., Evans, J.S., Robinson, A.P. and Steele, C.M., 2009. A cross-comparison of field, spectral, and lidar estimates of forest canopy cover. *Canadian Journal of Remote Sensing*, 35(5), pp.447-459.

- Szantoi, Z., Escobedo, F., Abd-Elrahman, A., Smith, S. and Pearlstine, L., 2013. Analyzing fine-scale wetland composition using high resolution imagery and texture features. *International Journal of Applied Earth Observation and Geoinformation*, 23, pp.204-212.
- Therneau, T., Atkinson, B., and Ripley, B., 2013. Rpart: Recursive Partitioning. R Package Version 4.1-3.
- Thulo, R., 2021. *Determining the factors that influence the morphology of the Kromme River valley, Eastern Cape, South Africa*. Makhanda: Rhodes University (Honours thesis) [PDF].
- Tooth S., Brandt D., Hancox P.J., and McCarthy T.S., 2004. Geological controls on alluvial river behaviour: a comparative study of three rivers on the South African Highveld. *Journal of African Earth Sciences*. 38:79-97.
- Tooth S. and McCarthy T.S., 2007. Wetlands in drylands: geomorphological and sedimentological characteristics, with emphasis on examples from southern Africa. *Progress in Physical Geography*. 31(1):3–41.
- Townsend, P.A. and Walsh, S.J., 2001. Remote sensing of forested wetlands: application of multitemporal and multispectral satellite imagery to determine plant community composition and structure in southeastern USA. *Plant Ecology*, 157(2), pp.129-149.
- Valverde, T. and Silvertown, J., 1998. Variation in the demography of a woodland understorey herb (*Primula vulgaris*) along the forest regeneration cycle: projection matrix analysis. *Journal of Ecology*, 86(4), pp.545-562.
- Van Eck, C., 2021. *The Regeneration of Palmiet (Prionium Serratum) Following Hydrogeomorphic Disturbance: A Case Study of the Kromme River Wetland*. (Doctoral dissertation, MSc Thesis, Rhodes University, Grahamstown).
- Van Pelt, R., O'Keefe, T.C., Latterell, J.J. & Naiman, R.J., 2006. Riparian forest stand development along the Queets River in Olympic National Park, Washington. *Ecological Monographs*, 76, 277– 298.
- Veregin, H., 1995. Developing and testing of an error propagation model for GIS overlay operations. *International Journal of Geographical Information Systems*, 9(6), pp.595-619.
- Wandinger, U., 2005. Introduction to lidar. In *Lidar* (pp. 1-18). Springer, New York, NY.

Wang, H., Xing, C., Yin, J. and Yang, J., 2022. Land Cover Classification for Polarimetric SAR Images Based on Vision Transformer. *Remote Sensing*, 14(18), p.4656.

Wen, L. and Hughes, M., 2020. Coastal wetland mapping using ensemble learning algorithms: A comparative study of bagging, boosting and stacking techniques. *Remote Sensing*, 12(10), p.1683.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. *The journal of geology*, 30(5), pp.377-392.

Wilson, E.O. and MacArthur, R.H., 1967. *The theory of island biogeography* (Vol. 1). Princeton, NJ: Princeton University Press.

Zhang, Z., De Wulf, R.R., Van Coillie, F.M., Verbeke, L.P., De Clercq, E.M. and Ou, X., 2011. Influence of different topographic correction strategies on mountain vegetation classification accuracy in the Lancang Watershed, China. *Journal of Applied Remote Sensing*, 5(1), p.053512.



Palmiet Wetland near Kareedouw Lidar survey

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

Notice

© 2018 Geosense. All rights reserved. No part of this document may be reproduced or transmitted in any form or by any means without the express written permission of Geosense.
--

Document enquiries can be directed to:

Attention: HC de Wet
E-Mail: Hennie@promap.co.za
Mobile: +27 (0) 82 573 1335

CONTENTS

Notice	2
1. Introduction.....	4
1.1 Survey Area.....	4
1.2 Flight Specifications.....	5
2. Survey control.....	5
2.1 Coordinates Used During Post Processing.....	5
3. Equipment used.....	6
3.1 Aerial lidar systems.....	6
3.2 GPS receivers.....	6
4. Overview and Workflows	7
4.1 Team Responsible for the Aerial Survey (Expertise & Qualifications)	7
5. Processes and Workflow of Project/Program.....	8
5.1 Workflow followed during Aerial Survey project/program	8
6. Accuracies	9
7. Quality Control	9
7.1 Combined solution result from post processing (IMU/GPS accuracies)	9
7.2 Trajectory Plot	10
7.3 Number of GPS Satellites.....	11
7.4 PDOP	11
7.5 DTM compared to mine control points (dz)	12
7.6 Photo Tie-point adjustment report known XY	12
8. Deliverables	13

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.

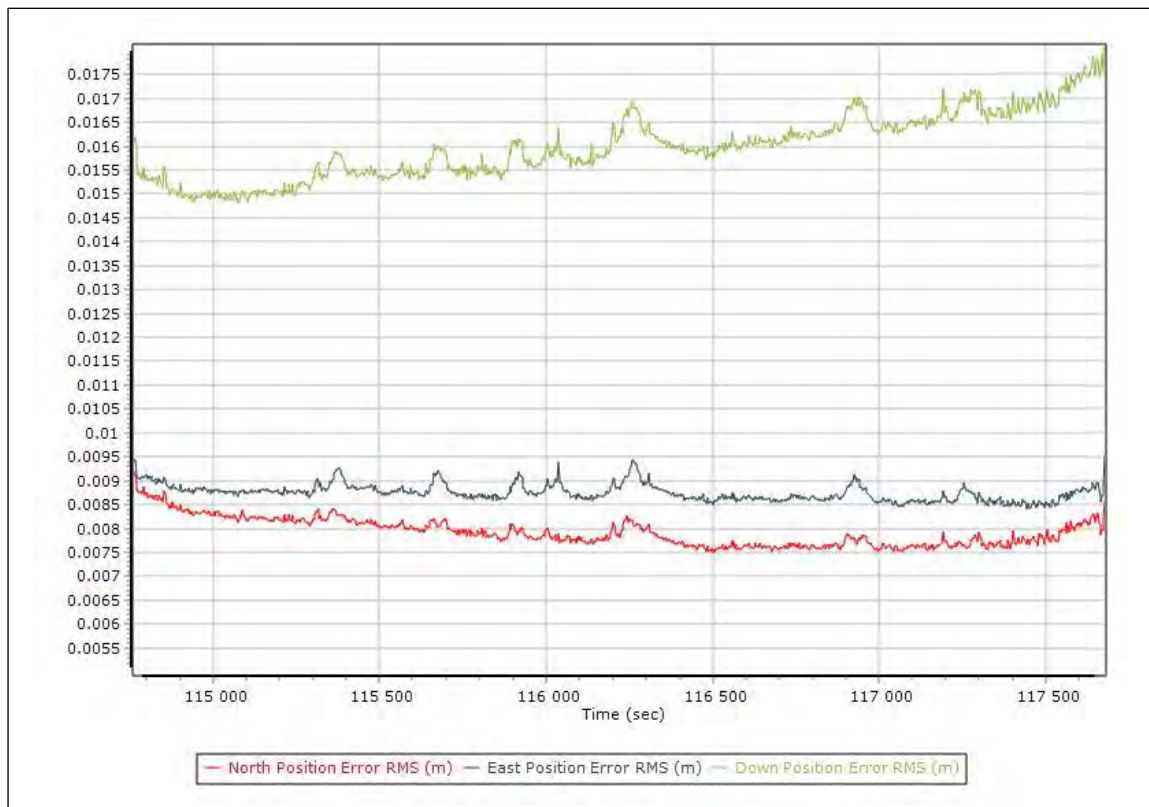
The accuracy of the trajectory is stated as North position Error RMS, east position Error RMS and down position Error RMS.

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)

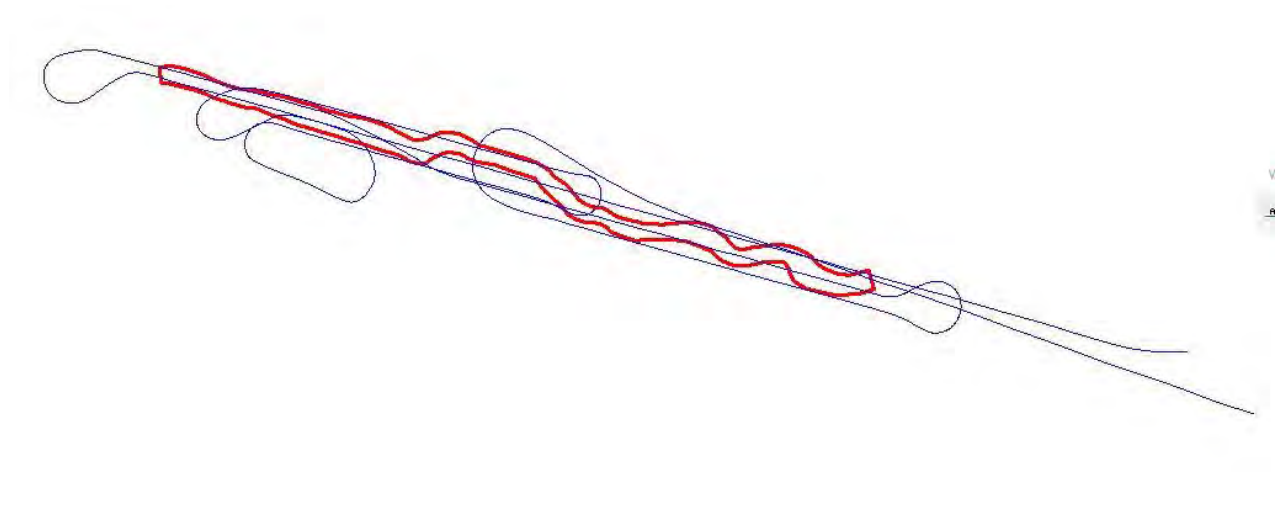
Figure 4.1 IMU/GPS solution (trajectory)



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

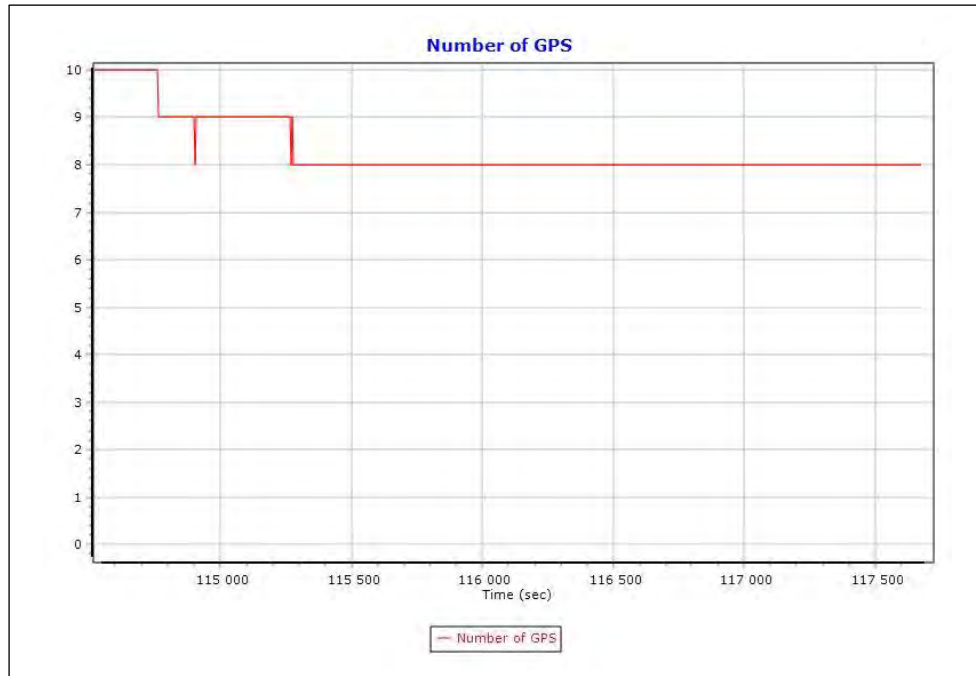
Figure 7.2 Trajectory/Flight plan of the aerial survey that took place on the 4th of November 2019.



In total 6 lines were flown in clear weather conditions

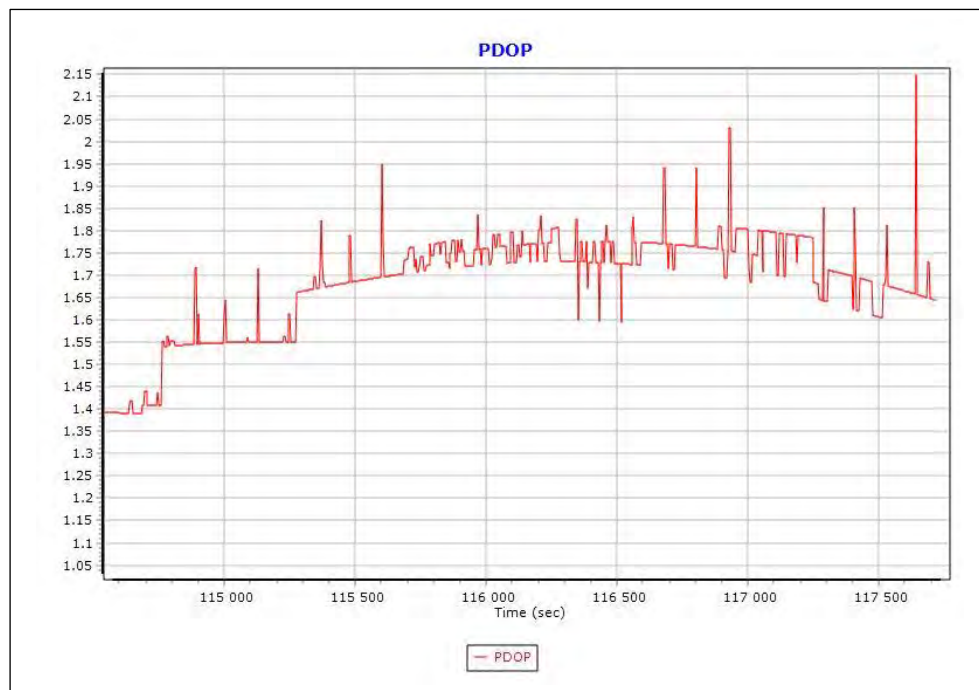
7.3 Number of GPS Satellites

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.
