Response of wetlands to impacts from agricultural land-use practices: Implications for conservation, management, and rehabilitation in the Nuwejaars Catchment, Western Cape.

by

Shae-Lynn Sampson

3434877

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Supervisor: Mandy Carolissen

Co-supervisor: Nancy Job

ABSTRACT

Wetlands occupy about 6% of the world's surface and are fragile ecosystems that support a diversity of plants and animals. Wetlands are increasingly recognised for their role in the provision of ecosystem services and contribution to global biodiversity. Despite this, more than half of the world's wetlands have vanished or been degraded, primarily due to agriculture. Wetlands are constantly adjusting to disturbances occurring within them and within their surrounding landscape. It is important to recognise to what extent various disturbances affect wetlands when assessing disturbance and impact, and when considering wetland protection options. The benefit of the detailed characterisation of the sub-catchments of the Nuwejaars catchment is deepened understanding of how different combinations of land-uses and soils impact catchment hydrology, and ultimately, the wetlands within the catchment. This research evaluated current and historical patterns of land-use on the Agulhas Plain within the Nuwejaars catchment to determine whether certain wetland types are more vulnerable to disturbances from agricultural practices than others, and why. This was achieved through the following objectives: 1) Monitor the spatio-temporal changes of wetlands over time using historical aerial photographs to determine the extent of wetland loss and degradation; 2) evaluate wetland and landscape characteristics, and 3) explore the relationship between the landscape and the dynamic nature of wetlands. Results show that wetland area from its historical extent decreased by 32% in the Nuwejaars catchment, as a result of loss and degradation from ploughed, drained, or reclaimed land. Six primary wetland impacts were identified in the catchment by this study: conversion of wetland to agricultural land, impoundment for water storage, infrastructure encroachment, drainage ditches, overgrazing, and invasive alien vegetation. The study makes use of two indices: Agricultural Disturbance Activity Index, used to quantify disturbance activities and the Agriculture Stressor Index, used to measure stress (impacts) on a scale of low, moderate, and high. The study showed that hydrological stressors had moderate stress (impact) on wetlands, whereas habitat stressors had higher levels of stress (impact). The overall score for each wetland indicates that they are under high levels of pressure from agricultural stressors. The findings in the study have indicated that valley-bottom and seep wetlands in the Nuwejaars catchment are subjected to high stress from disturbance activities in the upper and middle catchment associated with gently sloping plains and are therefore the most vulnerable to impacts from agricultural activities in the catchment.

KEY WORDS: Wetland vulnerability, wetland type, wetland catchment, Agricultural Disturbance Activity Index, Agriculture Stressor Index, impact, land-use, stressor, wetland

PLAGIARISM DECLARATION

I Shae-Lynn Edna Sampson declare that this is my own work. That it has not been submitted for any other degree or examination at any other university and that all the sources I have used and quoted have been indicated and acknowledged by complete references and has been submitted to Turnitin.

Full Name: Shae-Lynn Edna Sampson

Date: 30 January 2021

Signature: Shae-Lynn Sampson

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ABBREVIATIONS

ARS	Agricultural Research Service
ADAI	Agriculture Disturbance Activity Index
ASI	Anthropogenic Stress Index
CFM	Cape Farm Mapper
DEM	Digital Elevation Model
GDP	Gross Domestic Product
GIS	Geographical Information System
GPS	Global Positioning System
HDAI	Human Disturbance Activity Index
HGM	Hydrogeomorphic
IBI	Indices of Biotic Integrity
InSAR	Interferometric Synthetic Aperture Radar
MCA	Multiple Correspondence Analysis
MFA	Multiple Factor Analysis
NBA	National Biodiversity Assessment
NGI	National Geospatial Institute
NWCA	National Wetland Condition Assessment
SANBI	South African National Biodiversity Institute
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
USGS	United States Geological Survey

Chapter 1: Introduction

Wetlands occupy about 6% of the world's surface and are fragile ecosystems that support a diversity of plants and animals (Maltby & Acreman, 2011; Reis et al., 2017). Wetlands have hydrological, biogeochemical, and ecological functions (Maltby & Acreman, 2011), which provide ecosystem services and contribute to biodiversity worldwide. Despite this, more than half of the world's wetlands have vanished or been degraded, primarily due to agriculture (Bartzen et al., 2010; Gardner et al., 2015; Marambanyika et al., 2016).

Scientific communities, land and water managers have extensively recognised the functions of wetlands (Maltby & Acreman, 2011). However, Maltby and Acreman (2011) highlighted that conflicts concerning the use of wetlands arise frequently among stakeholders, which may include farmers, nature conservationists, land and water planners, and engineers. According to Vorosmarty et al. (2000), although impacts of climate change on water resources have been greatly emphasised, research has shown that impacts of land-use changes, predominantly associated with agricultural activities, may exceed those of climate change (Scanlon et al., 2007; Zhang et al., 2010; Fay et al., 2016).

Wetlands are continuously adjusting or being altered due to natural as well as anthropogenic disturbances occurring within them and their surrounding landscape. Understanding the relationship between the landscape and the dynamic nature of wetlands helps to assess the functions and values of a wetland. It is therefore important to identify to what extent various landscape disturbances affect wetlands when assessing impacts to them, and when considering wetland protection options (Euliss et al., 2008; Mekiso et al., 2013).

Agricultural activity impacts on wetlands can be quite extensive. Loss and degradation of wetlands can result from the conversion and draining of wetlands to agricultural land, the abstraction of water from rivers for irrigation, damming of wetlands for water storage, and pressure from water storage, pollution, eutrophication, deposition, and erosion on the hydrological cycle (Galbraith et al., 2005). These impacts and disturbances can have varying effects on the different wetland types. Thus, it is important to measure and quantify these impacts and disturbances within and around wetlands, and their associated catchments. This can be done through multiple tools and assessments that have been developed to assess wetland conditions based on impacts and disturbances from human interference.

Improved understanding of the historical changes and spatial knowledge of the landscape that ultimately includes all characteristics of the wetlands and their catchments in terms of hydrologic, geomorphic, and vegetation can aid in better decision-making for managing and conserving these threatened ecosystems.

Research is typically focused on one specific aspect of wetlands at a time. For example, vegetation, hydrology, or soils (Dube & Chitiga, 2011; Muzvondiwa et al., 2013). Shoko et al. (2015) highlighted that many studies are divided into different components of which they are investigated as separate entities, and do not give an accurate representation of the wetland's holistic condition in terms of the ever-changing land-uses due to climate variability, anthropogenic activities, and population pressure (Shoko et al., 2015). Sakane et al. (2011) noted that the degree of sensitivity of wetlands to anthropogenic interference in developing countries are unknown. This is due to the expectation that wetlands respond differently depending on the landscape setting. Therefore, it is crucial to assess the complete condition of wetlands (Sakane et al., 2011).

This study thus intends to investigate the impact of agricultural activities on wetlands by undertaking a whole catchment approach, to investigate the response of wetlands to impacts derived from agricultural land-use practices, and to determine the underlying cause of why the systems respond differently to agricultural impacts.

1.1 Research aim

The aim of this research is to provide a better understanding of the relationship between wetlands and their landscape through assessing changes over time, and through characterisation of the wetlands and catchment landscape. This will aid in decision-making and help wetland management schemes prioritise wetland ecosystems and contribute to the ongoing research on South African wetlands.

1.2 Research question & objectives

The research question is therefore: Are certain wetland types more vulnerable to disturbances from agricultural practices than others, and why?

The research has the following objectives:

1. Analyse changes between wetlands for the years 1938, 1989, and 2016 using remote sensing and GIS.
2. Evaluate wetland and landscape characteristics using general and morphometric characterisation techniques; and
3. Provide an understanding of the relationship between the landscape and the dynamic nature of wetlands to interpret vulnerability to different impacts.

1.3 Chapter overview

The thesis outline is as follows:

- Chapter 1 consists of an introduction to the research, aims, and objectives.
- Chapter 2 presents the literature review covering the roles and relationship between wetlands and agricultural activities.
- Chapters 3 provides a background to the Nuwejaars catchment.

- Chapter 4 presents the results of the first objective, which provides an in-depth analysis of the historical changes which occurred in the Nuwejaars catchment over three time periods (see Figure 1.1).
- Chapter 5 provides the results of the second objective, which studied the characteristics of the wetland, associated wetland catchment, and landscape catchments (see Figure 1.1).
- Chapter 6 covers the results of the third objective, by drawing together key findings of the historical and characteristic analysis; the results of the previous two chapters are combined to help understand the relationship between wetlands and their landscape catchments (see Figure 1.1).
- Chapter 7 consists of the conclusion and recommendations.

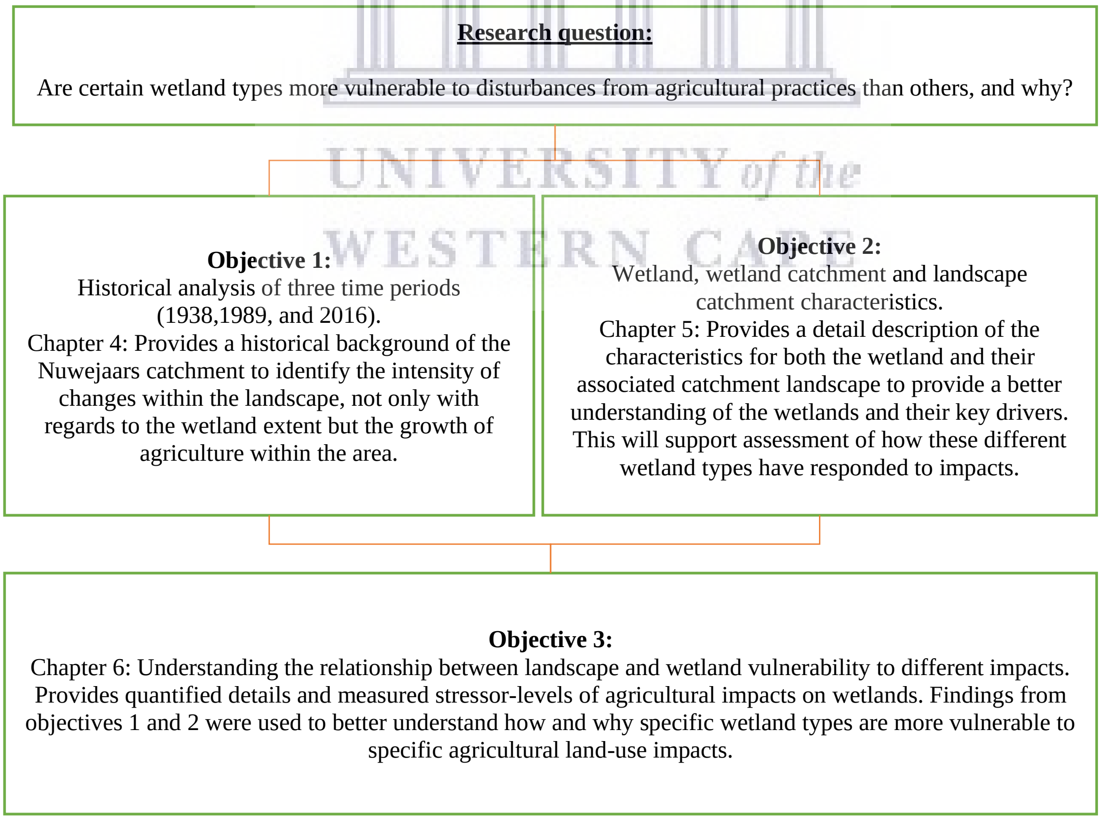


Figure 1. 1: Diagram demonstrating the linkage between the objectives of the study

Chapter 2: Literature Review

2.1 Wetlands

In the National Water Act of 1998, the South African government defines wetlands as: “areas that are transitional between terrestrial and aquatic systems, where the water table is near the surface, or land that is periodically inundated with shallow water, and land which in normal circumstances supports or would support vegetation typically adapted to life in saturated soil” (Ollis et al., 2013, p. 2).

Wetlands are one of the most important ecosystems in the world, as they are a major component of water resources, and are crucial to life-support functions, human health, and the natural environment. Yet, South African wetlands and associated river systems are in a critical state, with over 65% reported damaged, and 50% estimated to have been lost (Kotze & Breen, 1995; Nel et al., 2007; Van Deventer et al., 2019). This could be the result of a lack of understanding about the types, distribution, and functions of wetland ecosystems, and how these functions, in turn provide services (Sieben, 2012). According to Rebelo et al. (2015), the exploitation of wetlands and land-use/land-cover change are most likely a result of trade-offs in wetland ecosystem services.

The global definition of wetlands varies slightly because of regional and local differences in climate, topography, soils, vegetation, hydrology, and other factors, including human disturbances (Burton & Tiner, 2009; U.S EPA, 2011). The varied global definitions can be attributed to the fact that wetlands occupy an intermediate position between truly terrestrial and aquatic ecosystems, and therefore encompass a diverse array of habitats (Finlayson & van Der Valk, 1995). This can be seen on the Agulhas Plain, as the wetland ecosystems vary in hydrology, morphology, and underlying bedrock, making each wetland different from its neighbour (Jones et al., 2000).

2.1.1 Wetland types

South Africa’s wetlands are among the most diverse ecosystems, both physically and biologically (Taylor et al., 1995), and vary in their physical features and habitat, such as vegetation type, water depth, and seasonality.

The current classification system for wetlands and other aquatic ecosystems used in South Africa, developed for the South African National Biodiversity Institute (SANBI), encompasses inland aquatic systems, estuarine systems, and marine systems. This study only focuses on inland aquatic ecosystem wetland types i.e., floodplains, valley bottoms, depressions, seeps, and flats (Ollis et al., 2013).

These can be defined as follows: (i) Floodplains are low-lying wetlands adjacent to river channels that are formed by sediment deposited and subjected to flooding and are an integral part of a river and essential for a healthy functioning river system. (ii) Valley bottom wetlands are mostly flat wetland areas located along a valley floor, often connected to an upstream or adjoining river channel, and can either be channeled or unchanneled. Channeled valley-bottom wetlands are so-named as they support a river running through them, whereas the unchanneled valley bottom wetland type does not have a river running through them. (iii) A depression wetland has closed or near-closed elevation contours and increases in depth from the perimeter to a central area of greatest depth within which water accumulates. Dominant water sources are precipitation, groundwater discharge, and both inflow and overland flow from adjacent uplands. (iv) Seeps are wetland areas that can be located on gently to steeply sloping land, and they are dominated by the colluvial, unidirectional movement of water and material down-slope. They are often located on the side-slopes of a valley, but they do not typically extend onto a valley floor. Water inputs are primarily via subsurface flows from up-slope direction. (v) Wetland flats are level or near-level wetland areas that are not fed by water from a river channel, and which are typically situated on a plain or a bench. Closed elevation contours are not evident around the edge of a wetland flat (Ollis et al., 2013).

An updated classification has recently been developed for South Africa which takes into consideration long-term process dynamics and addresses a gap in the classification of Ollis et al. by identifying the linkages between sediment and water transport within systems across the landscape (Grenfell et al., 2019).

2.1.2 Function of wetland systems

According to the National Research Council (1995), the functions of wetlands can be defined as all processes and manifestations of processes that occur in wetlands. Wetlands play an important role in the hydrological functioning of a river basin and perform many important functions, which include flow regulation, erosion control, water quality, and groundwater recharge (Bullock & Acreman, 2003).

Floodplains provide a variety of benefits (Ollis et al., 2013), such as biologically diverse habitats for plants and animals, and essential resting and feeding grounds for migratory birds. Floodplain wetlands can store water during wet seasons, slowly releasing it throughout dry periods (Rebelo et al., 2015). This process involves the regulation of flow and attenuates floods and helps to maintain flow in the rivers of the basin and in some of their tributaries. However, this function depends on several parameters of the wetland, such as the size, shape, number, and location of the wetland, as well as the type and depth of the soil, and the type of vegetation in the wetland (Bullock & Acreman, 2003).

Floodplains provide protection against flooding by holding water that has overflown a river's banks, thereby preventing floods from damaging nearby communities (Ollis et al., 2013; Rebelo et al., 2015; Rebelo et al., 2019). Floodplains are important for groundwater recharge, as they allow flood water to infiltrate through the soil and replenish aquifers if there is connectivity. They may also provide recreational opportunities like fishing, paddling, hiking, and wildlife viewing (Ollis et al., 2013).

The plants in a wetland hold the soil in place and trap sediment in the roots, thereby playing an important role in flood protection and erosion prevention (Sieben et al., 2018; Rebelo et al., 2019). Well-vegetated rivers and floodplains are excellent flood energy absorbers, while the deposited sediments and the spreading of floodwaters create fertile soils which are often used to support subsistence floodplain farming (Jaganyi, et al., 2009).

Wetlands also play an important role when it comes to water quality. They act as filters and purifiers, as they prevent suspended material such as inorganic and organic sediments from entering the main water sources (Palaniappan et al., 2004; Rebelo et al., 2018). They also retain nutrients and prevent pollutants from entering the water source, thus improving the quality of surface water (Palaniappan et al., 2004; Mereta et al., 2020).

Wetland vegetation supports water quality improvement as it aids in trapping suspended materials, slowing the movement of water through the wetland, and allowing suspended particles and absorbed chemicals to settle out. Nutrients, other chemicals, and pollutants can be used as a resource by the wetland vegetation or by aquatic organisms, as they can be altered, attach to sediment, or be absorbed and stored within the plants (Mereta et al., 2020). Improvement in water quality provides benefits that include the removal of toxic chemicals and pathogens, but the potential for improving water quality can become degraded by water pollution, as it is dependent on the specific characteristics of the hydrology, geomorphology, and vegetation (Reddy et al., 1999; Mereta et al., 2020).

Wetlands can also contribute to groundwater recharge, depending on the wetlands' associated landscape, geology, and soil. This function is important for communities that rely on groundwater for consumption, as wetlands can store water during wet periods, which becomes beneficial during periods of drought because the water is then released and contributes to streamflow (Acreman & Holden, 2013; Eamus et al., 2016).

Despite providing important ecosystem services, wetlands in South Africa are frequently converted to agricultural fields, used as pasture for livestock, and water extracted for the use of irrigation frequently preferred over all other ecosystem services (McCartney et al., 2010; Rebelo et al., 2015; Rebelo et al., 2018; Phethi & Gumbo, 2019; Musasa & Marambanyika, 2020). It is important to carefully consider suitable management practices to sustain the various sectors of the economy that depend on wetlands as well as their effect on water resources (Mereta et al., 2020), as wetlands are vulnerable ecosystems that can easily succumb to major impacts. Loss and degradation of wetlands prevents the provision of essential ecosystem services to others and is especially detrimental to biodiversity and wildlife that is supported by these wetland ecosystems.

2.1.3 Wetland vegetation

Identifying wetlands according to their dominant vegetation community aids in understanding the response of wetlands to anthropogenic stressors, and to the impacts from agriculture land-use activities. The vegetation is the most visible aspect of the wetland environment and plays an important role in the functioning of wetlands (Cronk & Fennesey, 2001).

Water quantity and quality are the most important factors in a wetland environment. Water quality is often enhanced by wetland vegetations function to reduce the velocity of flow and are therefore able to trap sediments, nutrients, and pollutants, from entering downstream ecosystems (Rebelo et al., 2019). Some plant species have the function of impounding toxic substances through their tissue and are then able to ultimately remove the toxin (Cronk & Fennesey, 2001). Wetland plants also have the ability to trap sediments in an anoxic environment where anaerobic bacteria reduce many nutrients to a gaseous form. Both processes have a positive impact on water quality (Cronk & Fennessy, 2001).

Wetland vegetation communities are quick responders to environmental changes and therefore are good indicators of the ecological condition of wetlands, along with their ability of rapid growth and species richness (DWAF, 2008). Changes as a result of human interference or natural causes in the wetland environment can cause plant community composition to shift. Each individual species of plants shows different tolerance to conditions in the environment, and these species are often used as indicators of declining environmental conditions. Thus, the reference types that are described for certain wetland conditions, could aid in strategic conservation planning. It is of great importance to characterise these plants of those wetland environments and monitoring of these plants are encouraged in the long term to see whether significant changes are taking place (Sieben, 2011). Sieben (2011), highlights the important of implementing the HGM classification together with classification based on plant community data.

2.2 Demand for agricultural land-use in South Africa

South Africa is one of the world's developing countries in which agriculture forms the foundation of the economy (Goldblatt, 2010). To contribute to food security, job creation, gross domestic product (GDP), social welfare, and ecotourism, South Africa needs to deliver an environmentally friendly agricultural industry by adding value to raw materials, as well as maintaining and ensuring sustainable use of the available natural resources.

According to a study done by Tizora et al. (2016), agriculture is one of the three proximate driving factors of land-use and land cover change in the Western Cape (the other two are infrastructure and forestry). Agriculture accounts for 2.5 million ha of land in the Western Cape, taking up 19% of the land (Ungerer et al., 2018). The pressures of agriculture can be seen in the form of chemicals, water availability, and land. Van Weele and Maree (2013) indicated that a decrease in croplands within the Central Karoo District is a past trend in contrast to an increase of vineyards occurring in the Western region. The decrease in agriculture, according to Tizora et al. (2016), is a result of a decrease in land capability and water availability, with water availability as a common limiting factor in the Western Cape.

Food production in South Africa is expected to more than double in order to feed the population, which increases every year by nearly 2%. By 2035, it is estimated that the population in South Africa will be 82 million (Goldblatt, 2010). However, according to Stats SA (2020) as of mid-year (July 2020), South Africa's population is 56.62 million. Therefore, it is important to find ways for production to be more sustainable by using fewer natural resources. Additionally, there is a shift in the demand for certain foods as more people become wealthier. A study done by Goldblatt (2010) found that since the 1970s, South Africa has shown an interesting change in food consumption because of post-apartheid reforms and increasing wealth, with results showing that South Africa's middle-class grew by 30% between 2001 and 2004. It also showed a decrease in consumption of staple grain crops and bread, and a move to a more diverse diet with greater consumption of chicken and eggs, while beef, milk, and mutton consumption have declined (Goldblatt, 2010).

According to the Agricultural Statistics (2008) in Goldblatt (2010), South Africa has less than two-thirds the number of farms it had in the early 1990s, due to water scarcity and declining farming profitability. However, the farms that have been lost are usually converted for other land-uses or joined to other farms to create larger units. Although over the last 20 years there has been a significant decrease in areas under wheat, maize, and dairy, production has remained relatively constant; however, there has been an increase in the usage of fertiliser, fuel, mechanisation, irrigation, and genetically modified seed inputs by the remaining farms (Agricultural Statistics, 2008, cited in Goldblatt, 2010).

The transformation of agriculture on the Agulhas Plain was initiated in the 18th and 19th centuries, but in the 20th century, there was a rapid increase in the trend. With the introduction of mechanised agriculture, the Agulhas Plain underwent dramatic changes after the 1940s, which resulted in a rapid shift from veld-based grazing to the cultivation of the soil for cereal crops and artificial pastures (Mustart et al., 1997, cited in Heydenrych et al., 1999). According to Hoffman (1997), as cited in Heydenrych et al. (1999), this change in agricultural practices was likely to have been the result of incentives to clear land for cultivation, made possible by legislation enacted in 1930 to protect South African producers.

According to Heydenrych (1999), new forms of agriculture on the Agulhas Plain started making an appearance in the late '90s. However, conventional agriculture still dominated the region, and Heydenrych (1999) stated that the development of modern irrigation equipment has meant an increase in the cultivation of intensively grown crop plants.

However, changes in land-use have positive and negative consequences, as agriculture creates job opportunities, provides food security, and supports economic stability. However, poor farming practices, conversion of land, and overgrazing can lead to erosion and land degradation.

2.3 Impacts of agricultural land-use on wetlands in South Africa

Many communities in South Africa rely on wetland ecosystems for their livelihoods. Wetlands provide these communities with water, protein, fibre, and resources for agriculture, such as grazing and cultivation. Consequently, an increase in the reliance on wetlands is expected in rural areas (Singh & Dudley, 2010; Grundling, 2014).

According to Midgley et al. (2005), there are two types of agriculture-related wetland loss and degradation in South Africa. Firstly, there is the deliberate loss and degradation that results from development, such as flooding by dams and drainage to create pastureland. Secondly, there is an unintentional loss due to poor management in the catchment. However, wetland loss in South Africa is primarily attributed to deliberate degradation (Midgley et al., 2005). According to Grundling (2014), significant responsibility for the loss of wetland systems through cultivation, overgrazing, and draining lay with the agricultural sector and inadequate management. The Department of Water Affairs and Forestry (DWAF, 2005) stated that, because of poor management of grazing, fire, donga erosion, drainage of wetlands for pasture and croplands, planting of alien trees in wetlands, and development within wetlands, over 50% of wetlands have been destroyed in many catchments (Kotze & Breen, 1995).

The National Biodiversity Assessment (NBA) 2011 Report (Driver et al., 2012) further stated that 65% of wetland ecosystem types are threatened in South Africa, of which 48% are critically endangered. The latest NBA report stated that 80% are now threatened, meaning that wetlands are the most threatened ecosystems in South Africa (Grundling, 2014; Van Deventer et al., 2019).

Therefore, Grundling (2014) highlighted that it is important for South Africa to quantify agricultural impacts along with substantiating the nature and extent of these effects from a resource and geographical standpoint. Grundling (2014) noted that through a verified quantification and qualification approach, along with expected future demands for agriculture and wetland interactions and interventions, sustainable practices may be achieved (Grundling, 2014).

Although farming is an important source of food for many, it is associated with production and activities that put pressure on wetland systems. Conversion of wetlands to agricultural land and draining them are common impacts in the pursuit of expanding the available land suitable for crop farming. The demand for food production has increased due to population pressure intensifying, changes in socioeconomics, and insensitive government policy (Hollis, 1990; Goldblatt, 2010), and therefore, there is a greater need for more agricultural land and greater farming productivity (Scoones 1991; Denny, 1993).

However, the intensification of wetland-use, and 'development' of wetlands for cultivation, may be unsustainable as it is typically associated with wetland degradation and falling groundwater levels, which ultimately reduces agricultural production and limits the capacity of wetlands to function naturally (Dugan, 1990; Roggeri, 1998). For example, a study undertaken by Denny and Turyatunga (1992) cited in Dixon (2002), reported that many small valley swamps in Uganda have been excessively impacted by cultivation and intensive drainage. These wetlands regulated flow from the catchment under the traditional farming practices, but due to the impacts of government-initiated intensified agricultural practices, water now flows away rapidly downstream instead of being retained within the wetland, which reduces the capacity of the wetland to retain nutrients and control peak flows. This has resulted in the oxidation of organic material and shrinkage of soil (Denny & Turyatunga, 1992 cited in Dixon, 2002).

A study by Blann et al. (2009) revealed that stream channelisation and conversion to cropland has led to habitat loss and the drainage of wetlands, and has resulted in increased nitrogen, phosphorus, sediment, and other contaminants in agricultural runoff and altered the hydrology of the wetlands by changing the time and volume of runoff. The change in the flow regimes affects important wetland and stream functions associated with the biota and habitats present, and the stream morphology, and the nutrient cycle (Blann et al., 2009). Often, agricultural runoff associated with pesticides and herbicides releases contaminants in the wetlands. This can be detrimental to the animals directly exposed to the runoff through skin contact, drinking, and eating. It can also be lethal to plants as they absorb the chemicals through their roots or deposition (Blann et al., 2009; Hirpo, 2018).

Another source of impact on wetlands is livestock grazing and the common practice of overgrazing. According to Collin et al. (2007), the impact of grazing arises through four processes: trampling, transport of plant seeds, deposition of urine and faeces, and herbivory. These impacts can alter wetland conditions, including its physical form, water regime, water quality, soil texture, and spread of invasive plants, as well as impact the vegetation composition, structure, and health.

However, despite the negative impact of grazing, responses can be neutral or even positive through appropriate management practices (Morris & Reich, 2013). Trampling by livestock can damage wetland vegetation, disturb, and compact the soil, increase turbidity, and create bare grounds (Morris & Reich, 2013). These impacts can alter wetland functions such as carbon stores, and infiltration processes, among many others. This harms plant growth, affects composition, reduces vegetation cover and the wetland buffer area, and can be detrimental to the water quality as sediment trapping is reduced, and erosion, runoff, sediments, and pollutants are increased (Dunne, 2011; Morris & Reich, 2013; Pages et al., 2019).

Deposition of dung and urine from livestock can also negatively impact water quality as nutrients and pathogens are released. Herbivory, accompanied by trampling, decreases plant cover, diversity, abundance, height, and biomass. It also impacts canopy structure with the loss of particular lifeforms (Morris & Reich, 2013). Kotze (2010) suggested that grazing of wetlands if professionally managed, can be appropriate, as natural systems have evolved being grazed by wildlife.

Poorly managed intensive farming leads to impacts on the natural environment, the well-being of people, and on a farmer's ability to adapt to change (Goldblatt, 2010). However, a sustainable relationship can exist, and it can be achieved through careful wetland management and conservation strategies and plans (Rijsberman & De Silva, 2006).

2.4 Application of remote sensing for detecting historical change in wetlands

Noble & Hemens (1978) stated that scientific research in the management and utilisation of inland wetlands is required to successfully face threats to aquatic systems. Therefore, regular inventory on the spatial extent of wetlands be undertaken to identify areas of loss. However, Lang (2008) and Kotze & Breen (1995) noted that monitoring wetlands is a lengthy task and is costly.

Remote sensing has been increasingly used in the past few decades to map and detect historical change in wetland areas. This involves the manual interpretation of aerial photographs, which can be time-consuming and expensive, but it is accurate (Lang, 2008). For many years, computer-assisted classification methods have been used to map wetlands, generally in combination with data from satellite-borne sensors (Johnston & Barson, 1993). These sensors have become much more reliable, efficient, and affordable for environmental monitoring, with the increase in temporal, spatial, and spectral resolution (Jones et al., 2009).

The use of remote sensing has been reported in many scientific literatures on wetland studies across the world, such as applied multi-spectral remote sensing to obtain data on changes in soil moisture and evapotranspiration to inform the management of wetlands in Poland (Dabrowska-Zielinska et al. 2009). A similar approach was used by Grings et al. (2009) in the wetland marshes of the Paraná River Delta in Argentina to evaluate water levels, and to understand and examine the interaction between the soil under different flood situations and the vegetation composition. Prigent et al. (2001) used satellite observation to identify and locate submerged wetlands; Valta-Hulkkonen et al. (2004) measured the effects of rehabilitation on aquatic vegetation using geographical information systems (GIS) and remote sensing tools, in combination with ground evaluations; and Mattikalli (1995) detected land-use change for River Glen catchments in England, using data from 1931 – 1989, as well as remote sensing and GIS. Rebelo et al. (2017) investigated techniques such as multispectral remote sensing, habitat suitability modelling, and aerial photograph analysis and for detection of wetlands dominated by *Prionium serratum* (Palmiet plant), mapping their extent of change historically, and their drivers of change. The results showed that aerial photography is best for detecting the extent of change for small areas in large regions (Rebelo et al., 2017).

2.5 Landscape characterisation approach for understanding wetlands

Landscape characterisation is the combination of methods and approaches that allow the characterisation of land and water resources, and the processes that drive the system (Lyon, 2001). Lyon (2001) noted that landscape characterisation and landscape ecology together provide for the theoretical and practical characterisation, prediction, and evaluation of landscape resources and the dynamics of their processes (Lyon, 2001). A study undertaken by Lin et al. (2018) looked at wetland landscape pattern changes over periods of rapid development, and the results showed that wetland landscape pattern changes were influenced by urbanisation and reclamation projects, and not just by natural and socioeconomic factors.

It is important to identify the nature of wetland distribution to aid in the appropriate evaluation of risks and management planning. Wetlands can be recorded and assessed for risks posed by stressors in multiple ways (Lyon, 2001). According to Lyon (2001), this can be achieved through wetland inventory. Lyon describes three-level procedures of detail that can be collected about wetland areas to evaluate the risks associated with human activities, as part of wetland landscape characterisation and risk assessment (Lyon, 2001). The levels are: 1) routine-level methods that involve conducting a scope of the wetlands through office evaluations of soil survey and field inspections for indications of the soils, plants, and hydrology associated with wetlands; 2) comprehensive intermediate levels which involve more intensive field and office evaluations to provide results of wetland jurisdictions and quantities; 3) comprehensive advance level which used when greater detail of the wetlands are needed for complex systems (Lyon, 2001).

Additionally, the River Styles Framework which can be applied to any river system and incorporates wetland features from both floodplain and channel (Brierley & Fryirs, 2009). The River Styles Framework has four stages (Brierley & Fryirs, 2005): 1) entails baseline survey of river character and behaviour, and patterns for each catchment; 2) analyses geomorphic river condition; 3) assessment of the future trajectory of change and geomorphic river recovery potential, and 4) river management applications and implications for the identification of target conditions and prioritisation of management efforts.

Moreno-Mateos et al. (2008) state that their investigation of the relationship between landscape pattern, wetland characteristics, and the water quality in agricultural catchments would have been more effective if the study included both catchment and wetland scales. They reason that the number and accumulation of wetland patches were closely correlated to the complexity of the catchment thus there were numerous wetlands scattered throughout the catchment.

2.6 Methods for assessing stressors and impacts on wetland ecosystems in South Africa

The development of frameworks for the assessment of wetland environmental conditions have been expedited and produced in recent years in response to increasing human alterations of wetlands and in light of limited resources for ecological assessments.

Globally, a number of wetland assessment tools using biotic indicators of wetland health, such as the multimetric indices of biotic integrity (IBIs), or the human disturbance activity index (HDAI), and the anthropogenic stressor index (ASI) (Lomnicky et al., 2018; Herlihy et al., 2019) methods developed for the National Wetland Condition Assessment (NWCA) (EPA, 2011).

Kotze et al. (2018), highlighted that because of limited field studies on the diversity of wetland types and biota, South Africa is a long way from using biotic indices. Kotze et al. (2018) noted that the identification and description of wetland biota requires highly specialised input and is time-consuming and proposes that the nature of stressors on wetlands from anthropogenic activities are not necessarily indicated by biotic indices with limited benefit to management requirements (Kotze et al., 2012; Kotze et al., 2018). However, Sieben (2011) highlights the importance of characterising and monitoring wetland plants through classification systems, as each individual species shows different tolerances to conditions in the environment, and these species may be used as indicators of declining environmental conditions.

In South Africa, these include the WET-Health (Macfarlane et al., 2009) methodology, as well as WET-EcoServices (Kortze et al., 2009), and the Wetland Index of Habitat Integrity (WIHI) (DWAF, 2007). The WET-Health framework is widely applied in South Africa and measures the extent of impacts on the hydrology, geomorphology, and vegetation composition of a wetland. Such a framework is useful to assess agricultural practices in wetlands. The HDAI and ASI quantify and measure human disturbance activities and anthropogenic stress on wetlands.

Chapter 3: Study Area

3.1 Location, topography, geology, and climate

The Nuwejaars Catchment is approximately 74 000 ha and is located on the Agulhas Plain, the southernmost part of South Africa (Figure 3.1). The catchment falls within the Breede Water Management Area (WMA) in the Western Cape. Within this WMA, the Nuwejaars River System falls within the Overberg East quaternary catchments G50B and G50C.

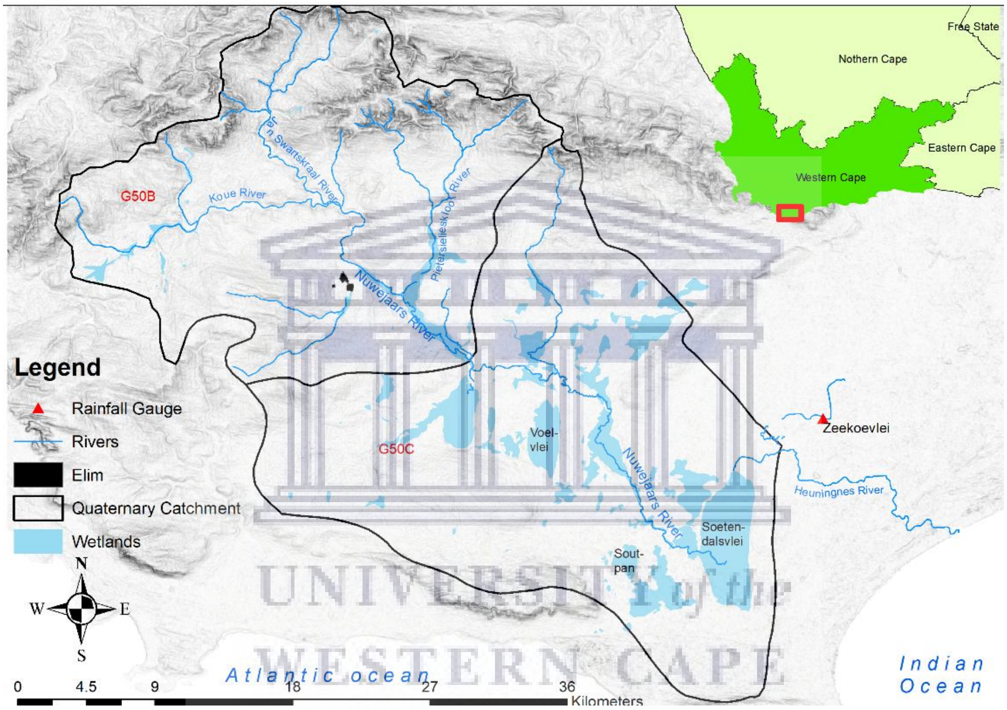


Figure 3. 1: Map presenting the study area, Nuwejaars catchment.

The Nuwejaars river originates as multiple streams in the Bredasdorp mountains (rising to 583 m above sea level) north of Elim, flows into Soetendalsvlei, then continues to flow out as the Heuningnes river. The Nuwejaars river meanders as it flows through rolling hills in its middle reaches and forms a floodplain wetland, reaching 15 m at its widest and with an average elevation of 11 m above sea level. The region experiences a Mediterranean climate with hot dry summers and cold wet winters and is characterised by an annual rainfall of between 400 mm and 600 mm (Kraaij et al., 2009). Annual evaporation is about 1445 mm (Middleton & Bailey, 2009), with a mean annual temperature of 17℃, with low temperatures in winter and high temperatures in summer. The area is underlain primarily by Table Mountain Sandstone, comprising of shale, limestone, granite, and sandstone, interspersed with calcareous sands (Silberbauer & King, 1991).

3.2. Land-use

The topography of the Agulhas Plain supports a diversity of wetlands, varied according to the wetland type, hydrology, origin, morphology, and underlying bedrock (Jones et al., 2000). Most of the wetlands are identified on low-altitude coastal plains, but some are situated on undulating hills inland. The Agulhas Plain and its associated wetlands are impacted by a large amount of invasive alien vegetation, and human activities such as farming and small-town development, which cause pollution, over-abstraction of water, bank destabilisation, salinisation, habitat destruction, too-frequent burning of riverine vegetation, catchment degradation, the introduction of both invasive plants and animals, and the breakdown of natural bio-geographical barriers (Roets et al., 1999, cited in Cleaver & Brown, 2005). According to Jones et al. (2000), the spatial distribution of the threats from alien vegetation and human activities makes it clear that this area needs conservation due to the unique diversity of freshwater ecosystems.

The Nuwejaars catchment is predominantly covered by cultivated land and shrubland. Many of the farming activities are commercial, with farming areas surrounding the river floodplain used for growing pastures for the grazing of sheep and cattle, while wheat and canola form the primary crop production.

There are different types of wetlands found within the Nuwejaars catchment which include: floodplains, valley-bottoms, depressions, seeps, and flats. Some are hydrologically dependent on the river; others, such as endorheic wetlands, are not hydrologically connected to the river (Kraaij et al., 2009). The area also includes several further combinations of these two extremes.

Chapter 4: Land-use change over time

4.1 Introduction

Chapter 4 provides a historical analysis that covers the first objective: to analyse the spatio-temporal changes of wetlands in the Nuwejaars catchment situated on the Agulhas Plain for 1938, 1989, and 2016, using remote sensing and GIS. The chapter aims to identify and show the extent of change, and aid in the identification of the agricultural activities that have impacted the extent of wetlands.

4.2 Methodology

4.2.1 Data collection

Aerial photographs for three time periods (1938, 1989, and 2016) were obtained from the Department of Rural Development: National Geo-spatial Information (NGI). The aerial photographs were used for identification and digitisation to conduct a historical analysis to detect changes in land-use of wetlands and agricultural land in the Nuwejaars catchment.

The aerial photographs for 1938 and 1989 were selected due to 1938 being the oldest imagery, and both with the best resolution of the area, and 2016 for being the latest imagery available.

Data on the historical and recent (2016) impact on wetlands through agricultural land-use were obtained by digitising aerial photographs (see Table 4.1) through ArcMap software. Map classification was done at one level of land-use. Level 1 consisted of four categories of land-use, namely agricultural land, dams, wetlands, and other (see Figure 4.1). A total of 3 756 polygons were mapped for the catchment area, ranging in size from 0.000004 – 3028.4 ha.

Historical rainfall data for the study site was obtained from the Zeekoevlei rainfall station (Figure 3.1). This station provided monthly rainfall data from 1909 to 2018 (109 years). The data was used to identify the conditions of rainfall for the historical imagery, and its potential influence in relation with agricultural land-use changes on the extent of change of the wetlands for the three time periods in the Nuwejaars catchment.

Table 4. 1: Aerial photography properties

Date	Job No	Strip	Resolution
03/1938	130	41- 55	1:25 000
02/1989	931	7-10	1:50 000
11/2016	1154	3419BD 3419BC 3419DA 3419DB	0.5m GSD (Ground Surface Distance)

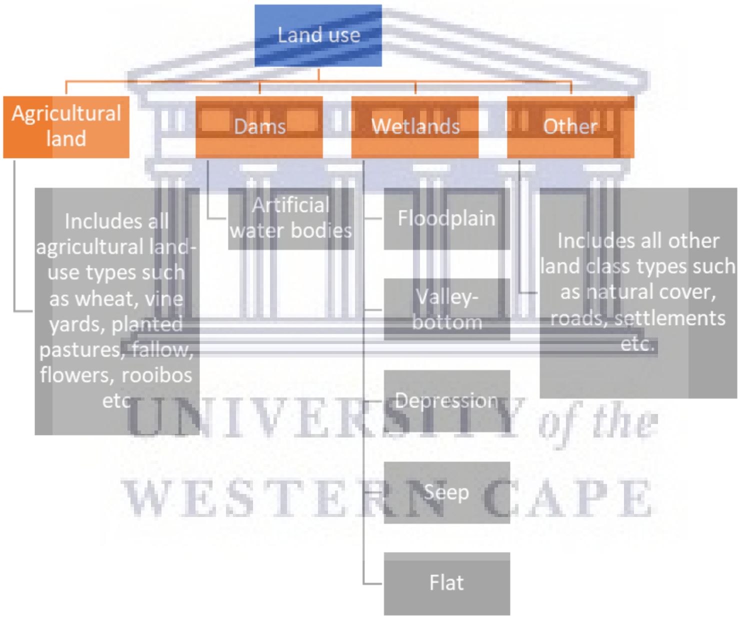


Figure 4. 1: Land-use categories (n=4: orange tiles) and subcategories (n=8: grey tiles) mapped for the historical analysis of the Nuwejaars catchment

4.2.2 Data analysis

The workflow for the historical analysis can be seen in Figure 4.2. The first step was to acquire the aerial photography, which needed to be georeferenced to map the land-use classes, which were used to gather information on changes in the land-uses in the catchment.

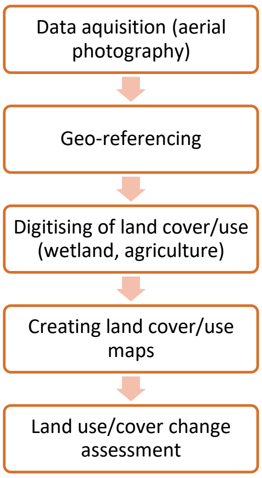


Figure 4. 2: Historical change analysis flowchart

4.2.2.1 Geo-referencing

Aerial photographs were obtained from the NGI in a digital format for computer-aided analysis. The 2016 aerial photographs were available in the geo-referenced format, but geo-referencing needed to be undertaken for the older imagery for the years 1938 and 1989.

The 2016 aerial photographs served as the base map for geo-referencing the 1938 and 1989 images. This was done by using an image-to-image registration of 30 control points to rectify the images on ArcMap (version 10.3.1). A minimum of ten or more control points is required for sufficient accuracy. For this study, the transformation to 3rd order with a minimum of 30 or more points was preferred. However, in several areas, it was only possible to achieve a minimum of 20 points, and in this case, the transformation to 2nd order was preferred, as it was challenging to find control points in areas that have been completely converted away from natural land cover.

4.2.2.2 Digitising land cover and wetland type

The 2016 aerial photography and the geo-referenced photographs for 1938 and 1989 were used as base maps from which wetlands and agricultural land-use in the Nuwejaars catchment were digitised.

Three land-use types were identified as broadly characterising the study area, namely natural veld, wetlands, and agricultural land. Two of these (wetland extent and agricultural land) were manually digitised using tone and texture as the main interpretation cues. Tone refers to colour and is used to identify surface characteristics, whereas texture refers to the quality and coarseness of groups of objects (Paine & Kiser, 2012). These were detected by the human eye to define boundaries between the two cover types, and interpretation keys (Figure 4.3) were used to identify the different types of wetlands and agricultural land-uses.

The historical aerial photographs obtained for this study for 1938 and 1989 are black and white. These two-colour tones vary, with various shades of grey in between, and can be challenging to interpret with the human eye (Paine & Kiser, 2012). The 2016 aerial photograph was obtained as a colour photograph. The expanded hue, saturation, and brightness offered by colour photography contribute to the interpreter's ability to distinguish different objects (Paine & Kiser, 2012).

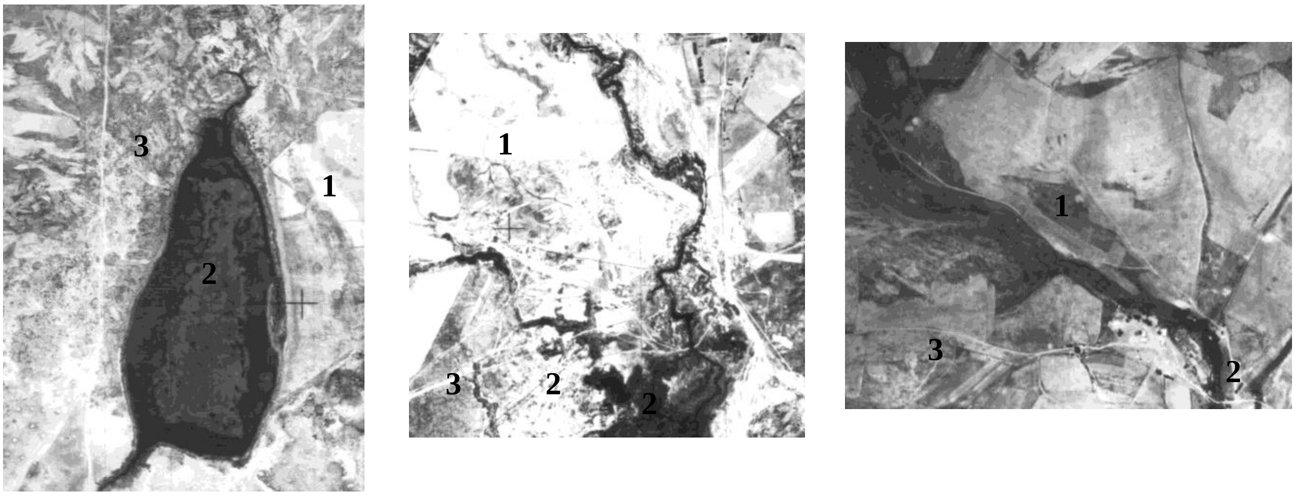


Figure 4. 3: Interpretation keys: 1= Agricultural land; 2= Wetland; 3= Natural

The three broad land cover types are presented in Table 4.2. Agricultural use was further sub-divided into types of farming for the 2016 imagery (see Chapter 5).

Table 4. 2: Land-use classes

Category	Description	Indications
Agricultural land-use: Livestock, wheat, vineyards and orchards, canola, and wildflower.	Areas where the natural land cover has been converted for the use of land for cultivating soils, producing crops, and grazing livestock.	Uniform tone, predominantly lighter. Smooth texture with various patterns: lined, plaid-like, corduroy, striped, concentric, and parallel. Identification of objects: fencing, haystacks, cattle, barns
Wetlands: Floodplain, valley-bottom, depression, seep, flat	Areas inundated by water permanently or seasonally, with the presence of wetland vegetation.	Uniform tone; depending on depth and amount of sediment. The darker tone for deeper waters with less sediment, lighter tone for shallower water. The texture varies with vegetation presence presenting uniformed tone and texture. Patterns are curvy, or round-like depending on the type of wetland.
Other: Natural land, and other land-use excluding agricultural land	Areas that are not considered to be agricultural land-use, wetlands, nor dams.	The tones, texture, and patterns not associated with indications from the other land-use classes (agricultural land-use, wetlands, and dams).
Dams: Artificial water bodies	Area of water that is enclosed or restricted by a wall	Uniform tone; depending on depth. The darker tone for deep waters, lighter for shallow water. Patterns are usually round but can differ in shape, with a linear side indicating a wall/barrier.

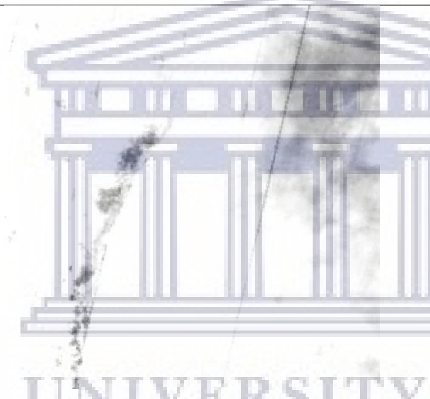
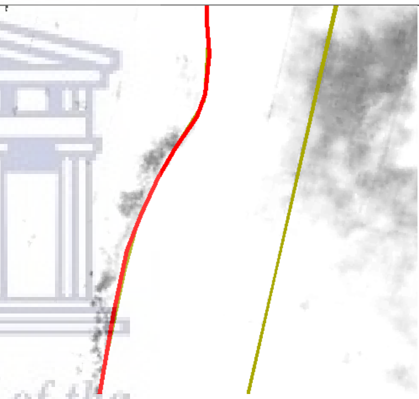
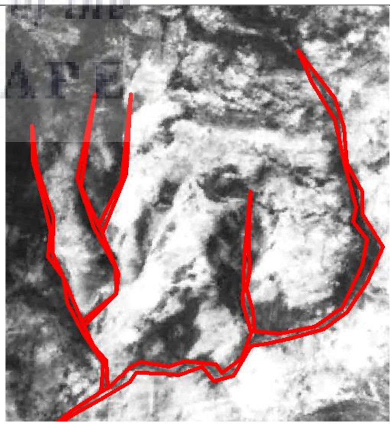
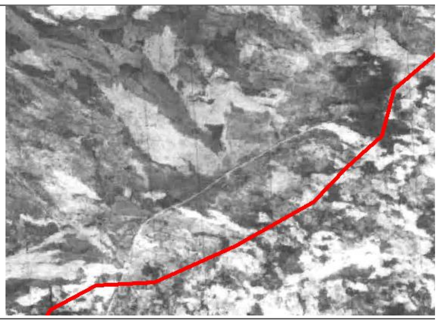
The historical extent of wetlands was mapped using the aerial photographs to determine where the wetland boundaries were before conversion and loss of wetland occurred pre-1938. The historical wetland dataset was, thereafter, clipped using the agricultural land-use datasets to determine the extent of the wetlands for each of the three years (1938, 1989, and 2016).

Wetland type was identified for all four wetland datasets to assess whether changes to the extent of the different wetlands are a result of the way the wetland type responds to impacts and to further investigate the cause of its response to the impact. For the Nuwejaars catchment, five types of wetlands were identified: depressions, floodplains, valley-bottom wetlands, seeps, and flats and defined according to the classification system developed by SANBI (Ollis et al., 2013). These wetland types were defined in Chapter 2, section 2.1.

Due to the complex nature of wetlands, i.e., their distinct land cover types, seasonal variation, and differing sizes, mapping the extent of wetlands from the aerial photographs proved to be quite challenging for both colour, and black and white imagery. For example, in the wetland boundary where alien vegetation is present within and around the wetland, the tone of the black and white imagery made it challenging to determine the boundaries between agricultural land and wetland areas because the reflection of the areas is a bright white shade. Similarly, in the mountainous areas, digitising the extent of the seep wetlands was difficult (Table 4.3).

The solution to problems encountered were as follows: 1) Contours were taken into consideration as well as the shadow effect of the vegetation where the trees would show an edge and the boundary of the shorter wetland vegetation is visible; 2) Patterns were detected where curving of the boundary near the wetlands would potentially indicate the boundary of the wetland and straight lines would indicate farmland boundaries; 3) Google Earth and the 2016 aerial photographs were used to determine the width and endpoint of seeps as the resolutions of the historical imagery were low resolutions; 4) Tone and texture were used to distinguish the boundary as the wetlands would have much more contrasts in the shades of white, grey, and black indicating wetter soils.

Table 4. 3: Problems encountered with example and result.

Problem	**Example**	**Result:** — Wetland — Agricultural land
1) Determining wetland boundary with the presence of alien vegetation. -34° 31' 22.8" S, 19° 44' 45.5994" E		
2) Determining wetland boundary where the tone of the image reflects the same for wetland, agricultural land, and presence of sand. -34° 38' 59.9994" S, 19° 50' 13.1994" E		
3) In the mountainous areas determining the end/width of the seep wetlands for the historical images. -34° 30' 39.6" S, 19° 47' 34.7994" E		
4) Distinguishing between wetland and natural land cover. -34° 35' 2.4" S, 19° 35' 2.3994" E		

4.2.2.2.1 Additional information

For each year, two datasets (agriculture and wetland) were digitised for the study. These datasets were assigned additional fields in the attribute table.

For 1938 and 1989, the area represented in hectors (ha) was recorded, but the type of agricultural land-use was excluded from these two years due to the difficulty and uncertainty in identifying the exact farming practice for some areas. The wetland dataset for 1938 and 1989 includes area (ha) and hydrogeomorphic (HGM) unit (also known in this study as wetland type).

For 2016, the agricultural dataset includes area (ha), agricultural land-use type (type), and slope. The wetland dataset for 2016 comprises area (ha), wetland type, wetland vegetation, landscape and wetland catchment area, geology, and relative relief. However, only the area and wetland type were used for the historical analysis, while the rest of the attributes contributed to the analysis done in Chapter 5.

4.2.2.3 Change detection interpretation

Each completed GIS layer (wetlands and agriculture) for each of the three years was used to calculate the area of wetlands and agricultural land-use. The summary calculator in ArcMap was used to obtain values for the number and sum of units and area of each polygon within each layer.

The clip tool in ArcMap was used to extract a new layer that presents the area of interception of the overlap between agriculture and wetland. This allowed for a calculation of the extent of agricultural land occurring within wetland boundaries. The percentage of land-use for the years 1938, 1989, and 2016 was calculated. The results were then compared to determine the percentage of change over time for each category, which aided in identifying wetland areas that have been changed by the conversion of agricultural land-uses. This is further investigated in Chapter 6.

4.2.2.4 Rainfall analysis

The rainfall data recorded at Zeekoevlei was used to calculate the annual rainfall and mean monthly rainfall for the Nuwejaars catchment to show variation of rainfall for the three years.

4.3 Results

4.3.1 Land-use change for three time periods

In 1938 (Figure 4.4 and Table 4.4) agricultural land covered a small portion of the Nuwejaars catchment, accounting for 14% of the land. The distribution of the agricultural lands was scattered near to and along the edges of wetlands, mostly along the floodplain, valley-bottom wetlands, and depressions as these wetlands are beneficial sources of water for agricultural production. Wetlands covered 23% of the study area, and are assumed to be mostly undisturbed and natural, as this was the earliest imagery of the area and showed little infringement of agriculture within the wetland boundary.

The farming intensity in 1938 was assumed to mostly be through manual labour, meaning the impacts were less extensive than in later years which saw the introduction of heavy machinery and toxic chemicals, such as pesticides and herbicides. Not many dams were identified in the catchment but of those identified, it accounted for 3 ha of land that was located within a wetland. Other land-use accounted for 63% of the catchment.

In 1989 (Figure 4.4 and Table 4.4), a dramatic change from 1938 can be seen, with a 17% increase in agriculture, resulting in a total area of 31% of the land occupied by agriculture. Wetland area covered 20%, which was not a significant change from 1938, and 678 ha of land ploughed in 1938 were degraded wetland as the agricultural land in the area is non-existent in

1989. However, the increase in agricultural land-use showed an impact on the extent of wetland. This could be attributed to farming methods, but the conversion of wetland to agricultural land is quite evident in 1989. Dams have also seen a significant increase from 1938 to 1989, accounting for 37 ha of which 60% have been identified within wetlands. The other land-use has decreased by 14% since 1938 this is a result of the increase in agricultural land-use.

In 2016, agriculture had decreased by 1% from 1989, accounting for 30% of the total area. This decrease could be a result of conservation and land abandonment, as some wetlands have been rehabilitated and others set for rehabilitation. However, the size of individual agricultural lands had increased, with many extended over wetland boundaries. This has been done through conversion of wetlands to agriculture, joining of farms, increased intensity of farming with the use of heavy machinery, increase in livestock, and excessive use of pesticides and herbicides, which are all potentially harmful to wetlands. The distribution of the agricultural land is widespread throughout the catchment and clustered within the parameters of wetlands. Wetland area showed a 5% decrease from 1938 to 2016, of which 2 091.7 ha were identified as degraded wetland that have been ploughed in the past from 1989.

Damming also showed an increase of 39 ha of which 70% are located within wetlands. The other land-use has increased from 1989 to 2016 by 211.4 ha, as a result of the 1% decrease in agriculture since 1989. The condition and structure of wetlands for 2016 are assumed to be highly impacted by advancing agricultural farming methods and increased agricultural land in parts of the catchment, which results in wetland areas becoming vulnerable and susceptible to impacts from invasive species, drying out faster, erosion, and contamination. The agricultural activities can lead to areas of the wetland widening, changing direction, and disappearing;

therefore, further analysis was taken by dividing the catchment into sub-catchments (see Chapter 5).

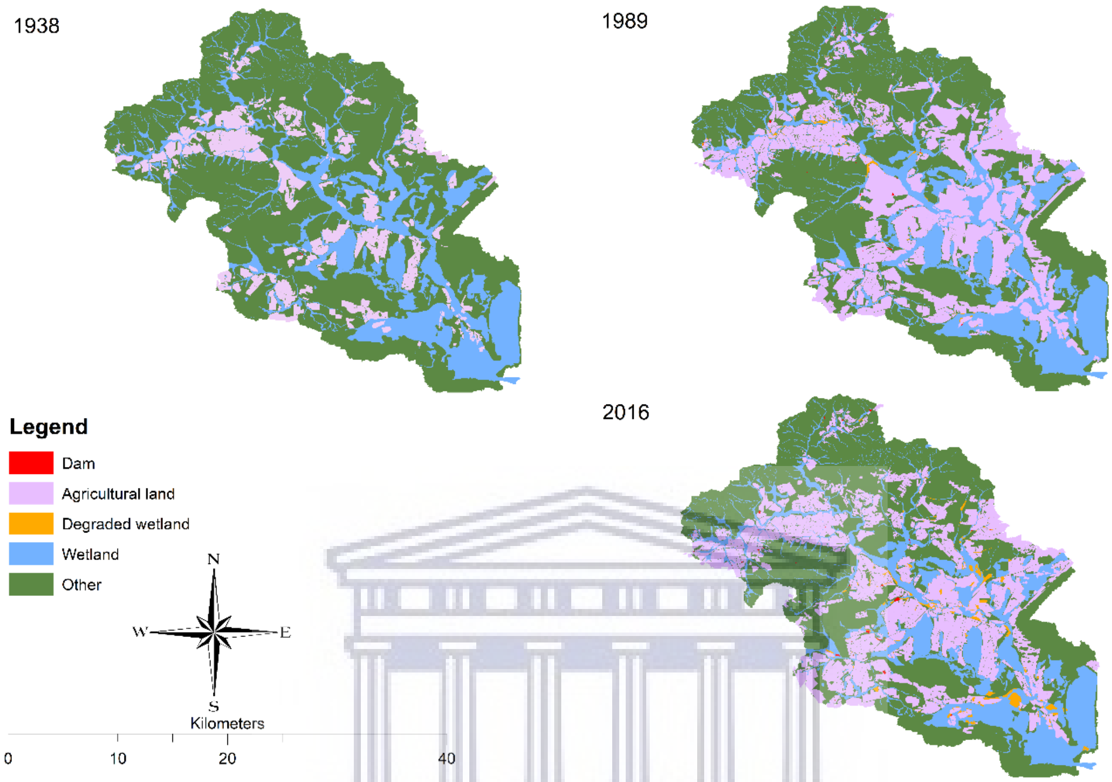


Figure 4. 4: Land-use maps for 1938, 1989, and 2016

Table 4. 4: Land-use (area in hectares)

Land-use classes	**Year**					
	1938	**%**	**1989**	**%**	**2016**	**%**
Wetland (Historical extent = 17 814,1)	17 137,8	23.1	15 046,7	20.3	14 247,2	19.3
Lost/degraded wetland	676.3	0.9	2 767.4	3.8	3 566.9	4.8
Agriculture	9 988.1	13.5	22 640.1	30.6	21 756.7	29.5
Dams (within wetlands)	(3)	-	37.4 (22.9)	0.1	76.7 (53.9)	0.1
Other	46 871.1	63.3	35 598.2	48.1	35 827.7	48.4

4.3.2 Change in wetland extent and type for three time periods

Table 4.5 reports the total mapped wetland extent for each time period. Figure 4.5 illustrates the percent direct loss, while Table 4.6 shows the estimated change from historical wetland extent.

Wetland seeps (31% lost) and flats (28% lost) represented the biggest overall loss of wetland. Figure 4.5 shows that valley-bottoms (8% lost) and floodplains (6% lost) experienced the biggest loss of wetland for 1938 (see also Figure 4.5).

In 1989, Figure 4.5 shows that floodplain wetlands have been impacted with loss and degradation accounting for 39% loss of historical wetland area. However, the loss and degradation accounted for 24% from 1938 to 1989. Floodplain wetlands also experienced the biggest loss of wetland extent (39% change from the historical wetland area) for 2016 and the highest percentage (16%) of loss between 1989 and 2016 (Table 4.6). This is followed by flats which experienced 26% degradation and valley-bottom wetlands (20% degradation) and seeps (15%) (Figure 4.5).

Between 1938 and 1989, flat wetlands experienced a 19% loss and seeps a 12% loss. This is reflected as a change of 16% for flats and 9% for seeps between 1938 and 1989. Valley-bottom wetlands showed a 20% loss in 1989 (Figure 4.5) reflected as a 13% change between 1938 and 1989.

Depressions showed the least change in extent. For both 1989 and 2016 loss was below 2% and no change occurred in 1938 (see Figure 4.5).

Table 4. 5: Estimates of historical wetland extent (Pre-1938) to the wetland extent for 1938, 1989, and 2016.

	Pre-1938 Historical extent (ha)	1938 (ha)	% loss/degraded (1938 to 1989)	1989 (ha)	% loss/degraded (1989 to 2016)	2016 (ha)
Seep	5 595,1	5 389,2	9	4 905,5	3	4 760,1
Flat	4 956,8	4 768,4	15.7	4 018,7	8.2	3 687,5
Depression	2 805,5	2 805,5	1.2	2 772,5	0.1	2 769,5
Floodplain	2 778,4	2 624,6	23.8	2 001	15.8	1 684,7
Valley-bottom	1 678,3	1 550,1	13	1 349	0.3	1 345,4
Total wetland area	17 814,1	17 137,8	62,7	15 046,7	27,4	14 247,2

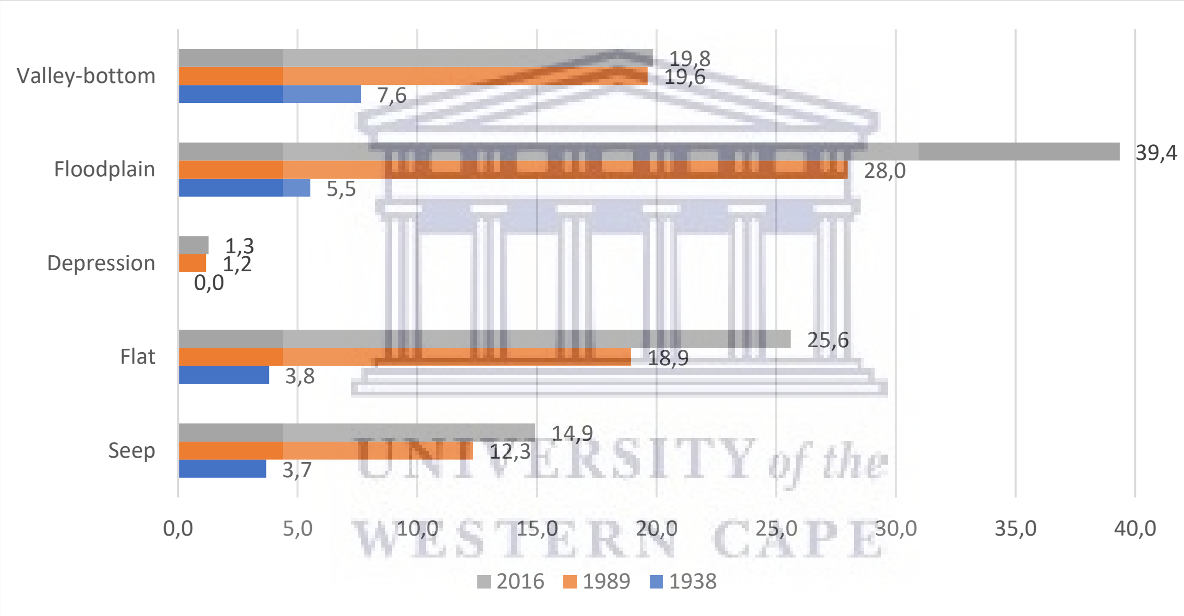


Figure 4. 5: Historical lost/degraded wetland for the three time periods

The changes in the wetlands' extent due to loss and degradation are primarily due to the activities from agricultural land-use. The study thus proves this by showing the extent of the increase of agricultural land-use within the catchment of 20%. The activities that were identified in the catchment through GIS observation presented themselves in the form of conversion, infrastructure, drainage ditches, alien vegetation, damming, and overgrazing (see Figure 4.6). These impacts were not necessarily mapped over time in this research, but they have been recorded for their presence in the buffer for Chapter 6. However, conversion of wetland to agricultural land has been recorded in the figures for wetland loss in Figures 4.5, of which loss referred to conversion and degradation referred to past ploughed land that has been converted back to wet conditions. Damming was also recorded over the three years and change has been recorded in Figure 4.4 and Table 4.5.

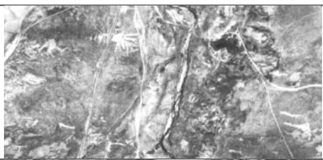
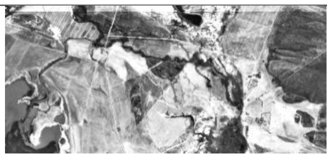
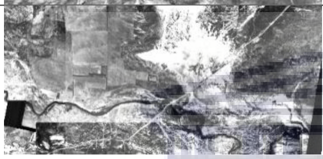
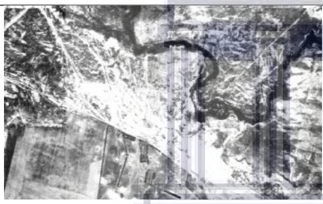
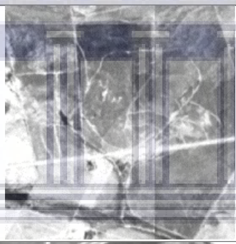
Impact	1938	1989	2016
Conversion			
Infrastructure			
Drainage ditches			
Alien vegetation	×		
Damming	×	×	
Overgrazing	×	×	

Figure 4. 6: Impacts from agricultural practices on wetlands. Note*: images are identified in different locations. This table aims to present how these impacts were identified on the different aerial photographs.

4.3.3 Detailed analysis of a sub-catchment within the Nuwejaars catchment

The Blomkraal sub-catchment, which consists of three smaller sub-catchments (Figure 4.7), was selected for a more detailed land cover assessment to further investigate how the wetland systems in a catchment function together. Collectively, the wetland ecosystems within these three sub-catchments contribute to the Nuwejaars floodplain just downstream of the town of Elim. They represent much of the diversity of wetlands within the broader Nuwejaars catchment.

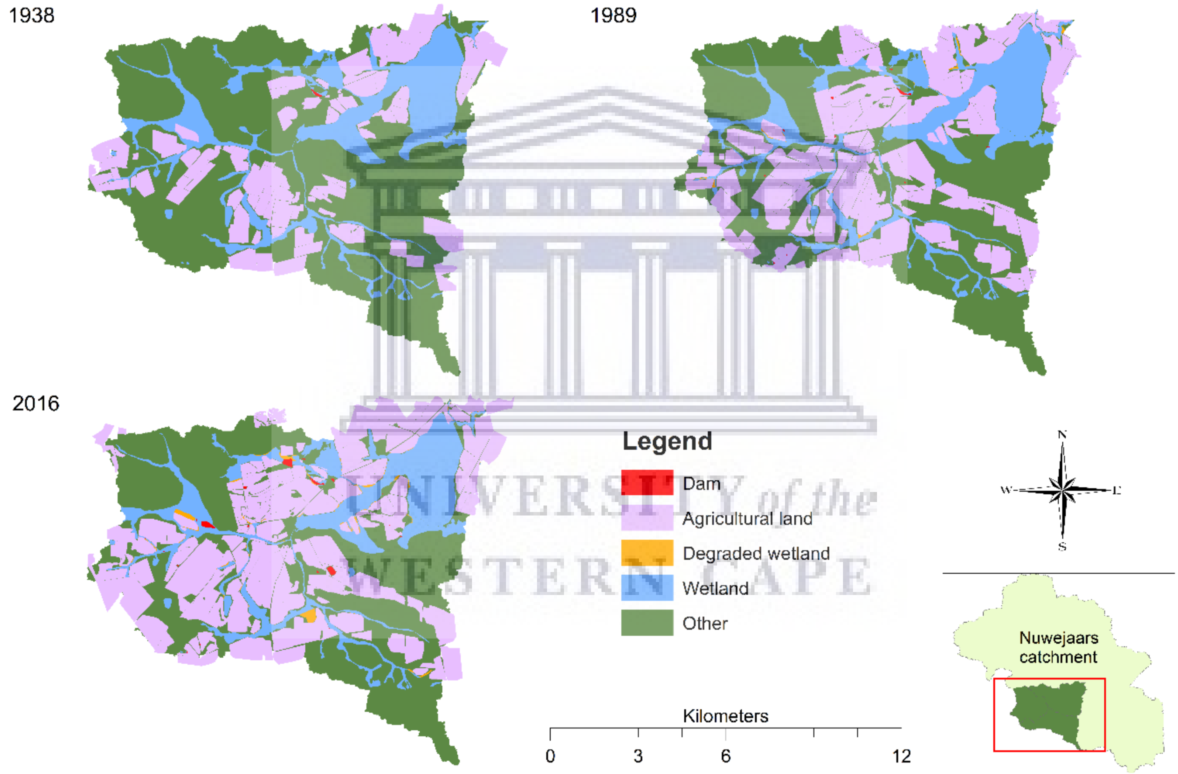


Figure 4. 7: Detailed land use/cover (LULC) for a sub-catchment in the Nuwejaars catchment.

In 1938, wetlands covered 21% of the area, with agricultural land covering 2 136 ha (21%). By 1989, the percentage of wetlands lost and degraded is estimated at 171 ha (9%), with a 19% increase in agricultural land cover, accounting for 4 023 ha. This almost doubled the area of agriculture mapped in 1938. In 2016, agricultural land increased by 1% from 1989, which is not major considering the time span. However, a significant decrease in wetland cover occurred by 2016, with a 14% reduction from 1938, leaving only 6% of the area covered by wetland. 11% of the wetland area from the historical extent were lost and degraded. Dams increased and occupied an area of 28 ha. Other potential reasons for the decline in wetland areas include intensive farming methods, use of herbicides and pesticides, and irrigation, as well as an invasion of alien vegetation, which now occupies 576 ha of these three catchments, of which 375 ha of invasions occur within the wetlands.

The wetlands within these catchments are impacted by multiple factors related to agricultural practices and production. A few examples are highlighted in Figure 4.8, focusing on a floodplain and two seep wetlands found within the catchments.

Presented in Figure 4.8a is a floodplain. In 1938, the floodplain looks natural considering the minimal amount of agricultural land around its boundary. In 1989, agriculture has increased around the whole boundary, and as a result the wetlands' boundary was straightened in the north of the image. However, in 2016, alien vegetation is visible (indicated by an arrow) and could be a result of the narrowing of the stream flowing through the floodplain, as well as contributing to the dryness of the wetland. It is difficult to distinguish alien vegetation in 1989, and therefore to determine whether the narrowing of the stream is due to the influence of agriculture or the presence of alien vegetation.

In Figure 4.8b, you can see the conversion of wetland to agricultural land (circled area), as drainage ditches are visible in 1989 (indicated by an arrow), and the soil appears to be much wetter in 2016 than it was in 1989. However, the streamline has narrowed by 2016. This shows the conversion of a seep wetland to planted pastures.

In Figure 4.8c, a visible change that was identified on the aerial photography in 1989 is an increase in agricultural land around the wetland's boundary. Conversion is evident as agriculture intercepts its boundaries, causing the wetland to narrow. In 2016, a large dam (approximately 7 ha) is visible, with the wetland no longer showing an obvious stream flowing through it.

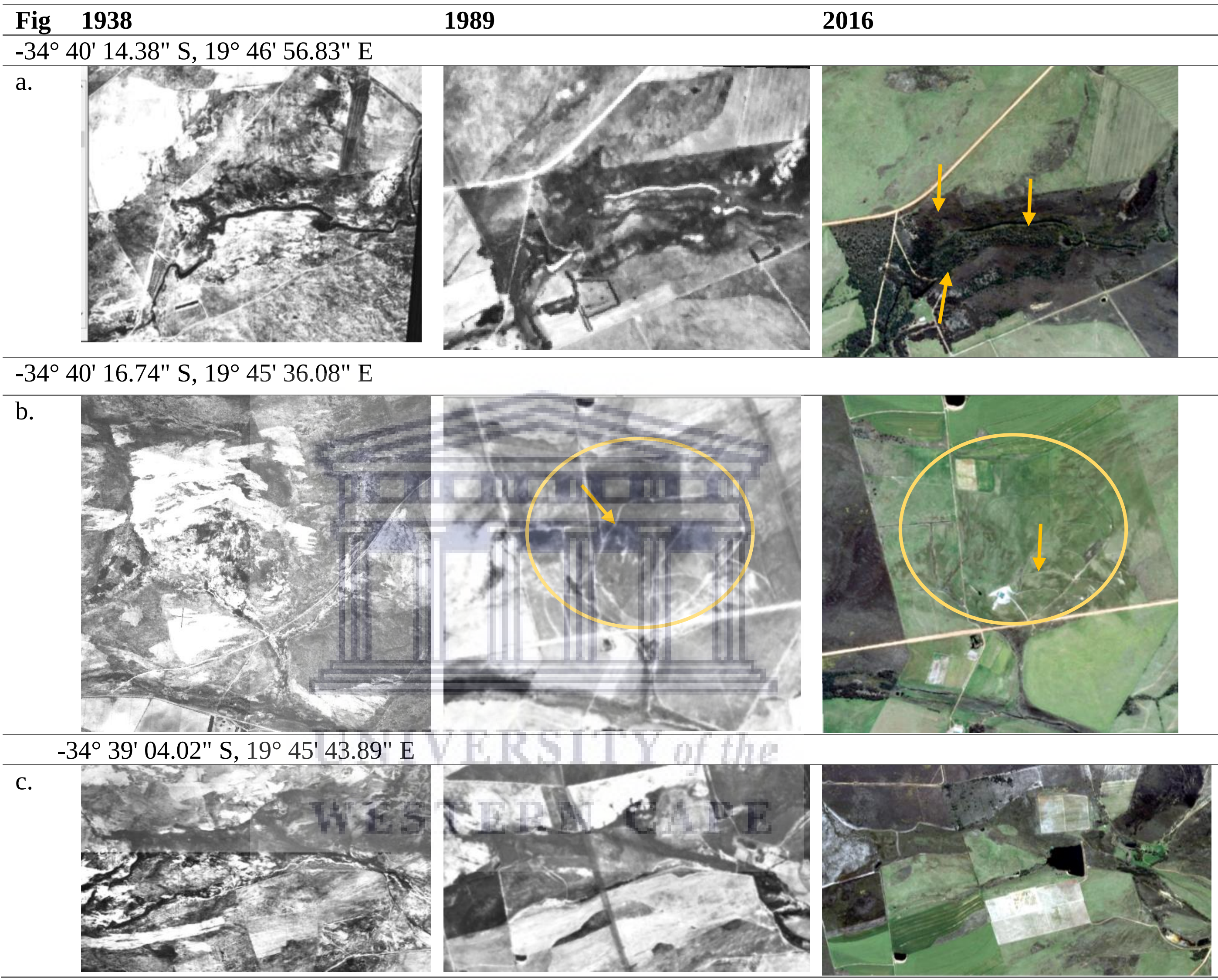


Figure 4. 8: Impacted wetlands within the catchment demonstrating the change over time in the Nuwejaars catchment.

4.3.4 Rainfall variability from 1938 to 2016 in the Nuwejaars catchment

The Nuwejaars catchment rainfall typically varies between 400 mm to 600 mm annually (Kraaij et al., 2009). Figure 4.10 shows the total annual rainfall for each year from 1938 to 2016. In Figure 4.9 the average rainfall indicated by an orange line is shown for each year from

1938 to 2016 for the Nuwejaars catchment. The graph shows that many of the years experienced the typical range in rainfall, while for 34 years the annual rainfall was below 400 mm. Thirty-three of the years did not reach the average amount of rainfall shown as falling below the orange line.

For the years for which the historical image analysis was undertaken, 1938, 1989 and 2016, 1938 and 1989 exceeded the average rainfall which was between 400 mm and 500 mm and 2016 experienced 79 mm less than the average. In 1938, the Nuwejaars catchment experienced a total rainfall of 536 mm for the year with the highest monthly rainfall experienced in September and October experiencing a wet spring whereas its winter months experienced a dryer winter with less rainfall. This could have had a major impact on the extent of the wetlands.

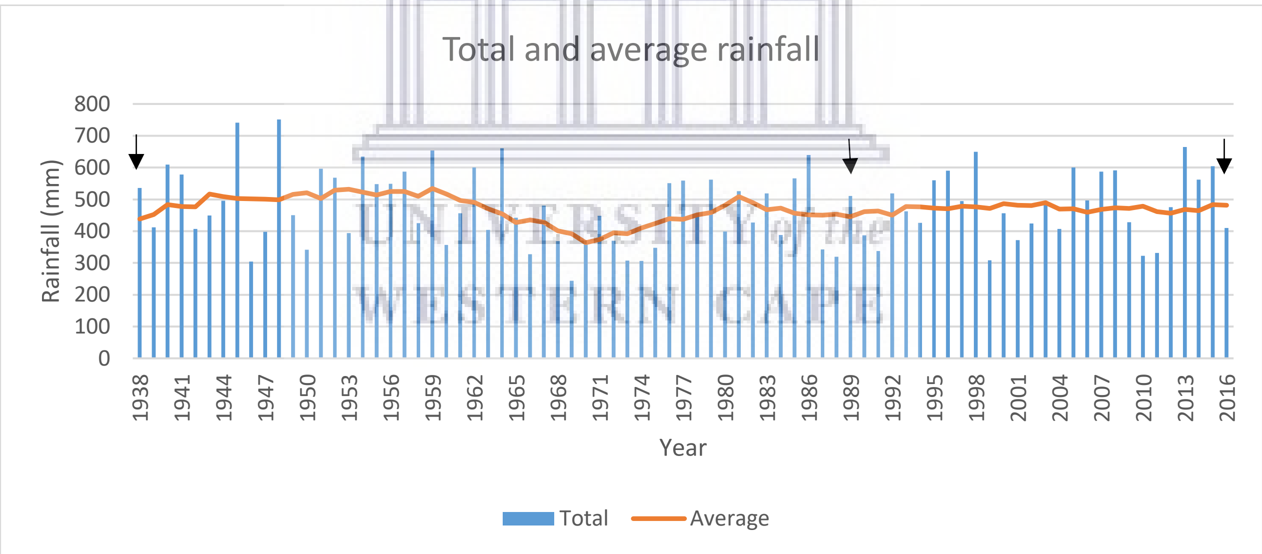


Figure 4. 9: Presented is the total rainfall experienced in the year along with the average rainfall expected for the year. Arrows indicate the three time periods included in the study. (Total and average rainfall at Zeekoevlei from 1938 to 2016)

In 1989, there was a total of 511 mm of rainfall experienced for the year, with the typically wet months starting with lower rainfall and a peak of rainfall in June with 106 mm of rain. In 2016, rainfall for the year was 410.5 mm, which was lower than the average rainfall for the year. Rainfall throughout the year was quite low compared to 1938 and 1989 and only reaching a peak of 104 mm in July.

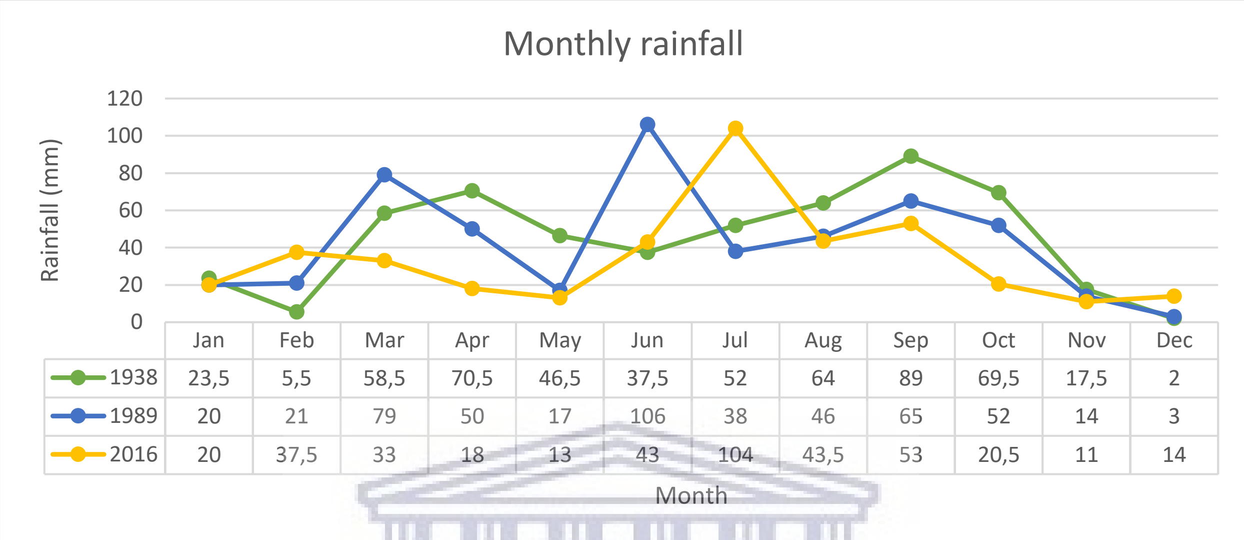


Figure 4. 10: The monthly rainfall for 1938, 1989 and 2016.

4.4 Discussion

4.4.1 Extent of change within the Nuwejaars catchment

Agriculture has increased over the time period studied, with the most significant change from 1938 to 1989. The transition from 1989 to 2016 can be seen in the multicoloured shading of the aerial photographs which indicates an array of agronomic variables, such as types of crops, methods of tillage, planting or harvest dates, geological factors such as soil type and moisture levels. The finer detail of field surface patterns provides even more data on farming practices (Weems, 2011). Cole et al. (2000) highlighted that 39% of the Agulhas Plain has been transformed by cultivation, urbanisation, and alien vegetation in 1999. The increase of agricultural land cover from 1938 to 1989 could be a result of higher demand for crops being produced in the region, as more yield means more revenue. However, the decrease in wetlands from 1989 to 2016 is a bigger concern, as it means that wetlands have been degraded or lost.

The loss in wetlands seen in the desktop analysis shows that there has been conversion of wetland to agricultural land, extension of agricultural land over wetland boundaries, and trampling of livestock in wetlands.

According to Macfarlane and Bredin (2017), the natural vegetation surrounding a wetland is referred to as the wetlands buffer zone. The vegetation typically begins from the boundary of the wetland-dependent vegetation and extends outwards, ending at the border of another land-use. These buffer zones will vary in size depending on their purpose. For example, to reduce sediment washed off in surface run-off, much research has been done, which has led to a standard buffer of 2 m and 50 m being proposed (Macfarlane & Bredin, 2017).

The role of the natural vegetation buffer is to maintain and protect the wetland ecosystem, in that it reduces surface run-off, maintains good water quality, provides feeding and breeding habitat and shelter for wetland fauna, contributes to wildlife corridors, reduces disturbances of native fauna from surrounding development, and minimises invasion by weed species.

The natural vegetation buffers in the Nuwejaars catchment have been poorly maintained and some even removed for farmland extension. However, agricultural lands are clustered mostly near the perimeters of wetlands, as well as within the boundaries of the wetlands.

Wetlands provide suitable soils for agricultural land to thrive successfully, as they need the fertile soils and sources of water provided by a wetland. Cole et al. (2000, p. 29) also noted that, “between 72 and 78% of the two Renosterveld vegetation types in the Agulhas Plain has disappeared under cultivation, whereas 52 - 84% of the four Elim veld types have been cultivated.”

4.4.2 The dominant agricultural practices impacting the wetlands in the Nuwejaars catchment

Impact on wetland extent by agricultural land-use in the Nuwejaars catchment has been significant over the three years of assessment and was discussed in Section 4.3.1, where wetlands have either been lost or degraded. Loss of wetland refers to areas that have been converted to agricultural land, and degraded wetlands refer to wetlands that have been ploughed, drained, or filled in.

In this study, six impacts associated with agricultural practices was identified as a concern to wetlands (see Figure 4.6) (Jones et al., 2000; Cleaver & Brown, 2005): 1) conversion of wetland to agriculture; 2) installation of infrastructure along or within the wetlands; 3) damming for water storage; 4) overgrazing of cattle in wetlands; 5) drainage ditches; 6) and alien vegetation.

The conversion of wetland to agricultural land is the biggest change in the Nuwejaars catchment as 20% of the historical wetland area has been ploughed. This is seen as the biggest threat because it is associated with the increase of infrastructure, damming, overgrazing of cattle in wetlands, drainage ditches, as well as causing wetlands to become vulnerable to the invasion of alien vegetation has agricultural activities disturb the ecosystem by interception or influence of disturbances such as run-off.

The most significant impact to wetland of conversion to cultivated land in the Nuwejaars catchment is that it results in the loss of wetlands extent. It also results in degradation and poor performance in the functions of the wetlands. The first step in the process of wetland conversion to agriculture is the successful drainage of the wetland, which involves developing ditches and diverting water into dams or other wetlands, streams, or rivers. This alters the hydrological function by either lowering the water table of the wetland that is being impacted by blocking the movement of the receiving flow, which can lead to the wetland becoming drier. On the other hand, it can lead to flooding of wetlands that are used for diverting the water into other systems, if the carrying capacity of the wetland exceeds the water table. Both results of the impact of damming and ditching affect the biodiversity and habitat of the impacted wetlands as it changes the structure and influences the function of the wetland. For a wetland that has become drier, there will be a decrease in the diversity of wetland vegetation which provides less structural variety and makes the wetland more suspectable to weedy plants.

The increase of agricultural lands almost always involves an increase in infrastructure which is needed for transportation of produce and livestock within and outside of the catchment. This includes the development of roads and bridges along and over rivers, and wetlands. Bickerton (1984) cited in Cleaver & Brown (2005), identified several gravel road crossings in the Nuwejaars River and wetland areas on the floodplain and these were confirmed in this study.

Wetland crossings are commonly developed from sediment dug up from wetlands. This is done by compacting the wetland soil under the weight of the road which can compromise the wetlands hydrology such that it can impede surface and subsurface water movement.

Inadequate water flow, such as inadequately sized culverts beneath the road leads to ponding of water on the section of the wetland upstream of the road. Conversely, the downstream side of the wetland, below the road, may not receive sufficient water to maintain good wetland conditions. Both upstream and downstream impacts can impair a wetlands ability to infiltrate, and store water – negatively affecting the wetlands carrying capacity, as well as the movement of water through the wetland system (Partington et al., 2016).

The implementation of bridges is associated with the development of culverts to prevent flooding. The culverts cause the flow of water in the stream to increase its velocity, by restricting water through a narrow area instead of allowing it to spread over the width of the wetland. This has been identified in parts of the catchment to contribute to gully erosion (Garosi et al., 2018).

The occurrence of damming has shown an increasing trend, as many small dams are now evident in the catchment, covering an area of 77 ha. The dams reduce the flow of water in a river, which changes the landscape it flows through and can affect vegetation and animals (Kondolf et al., 2014). It can also trap sediments which are essential in maintaining habitats and physical processes downstream of the dam. Dams can also change the pattern of flow in a river which changes its seasonal variation and reduces its overall volume (Kondolf et al., 2014).

Livestock farming is one of the dominant agricultural practices in the Nuwejaars catchment along with grain farming. A large amount of water is essential for the survival of cattle, access to wetlands is quite essential to these animals especially in the Nuwejaars catchment as the area can become quite dry due to the sporadic change in the climatic conditions.

Wetlands in the Nuwejaars catchment are under constant pressure from the grazing of cattle along with the other impacts. Grazing has been identified on the aerial photographs within wetlands and from site visits, it was evident that overgrazing took place in many of the wetlands but mostly in the floodplain, valley-bottoms, and flats. The impact of grazing of these wetlands have shown poor conditions with regards to over-trampling as highlighted in Cleaver & Brown (2005), that small farmlands and poor veld conditions have led to a high concentration of cattle along wetlands which has resulted in bank erosion and eutrophication.

Invasive alien vegetation covers about 10986 ha of the catchment, of which 9381 ha are found within the wetlands in 2018. Although invasive vegetation is not necessarily a result of agricultural practices, in some instances it has been planted by farmers as windbreaks and stabilising the riverbanks (van Wilgen et al., 2016). Invasive vegetation is also a sign of anthropogenic impacts, which are influenced by man-made interference and alterations to the landscape. Dominant invasive species found within the Nuwejaars catchment are *Acacia mearnsii* (black wattle), *Populus* (poplar), *Acacia saligna* (Port Jackson), and *Phragmites australis* (common reed). These species are very dominant, and the natural vegetation cannot compete.

Invasive vegetation demands large quantities of water to survive, and they impact wetland structure by stabilising riverbanks, which contributes to the down-cutting of river channels (Mkunyana et al., 2019). Thus, narrowing and deepening of channels occur, reducing the river's ability to meander and flood out (Zedler & Kercher, 2004).

Invasive vegetation increases plant litter, resulting in fire frequency and intensity. Some species, such as *Phragmites austalis*, impact the geomorphology by building up plain elevation through sediment and organic matter production (Zedler & Kercher, 2004). The wetland dries as increasing elevation becomes more rapid than rise in sea level. Invasive alien species that can significantly modify the physical structure of a wetland have a greater potential on impacting hydrological conditions and animal use (Zedler & Kercher, 2004).

Studies show that vegetation has increased dramatically over the years from 1999 to 2018. A report done by Cole (2000) shows the level of alien vegetation in the Agulhas plain, ranging from high to no aliens. As can be seen in Figure 4.11, alien vegetation had increased vastly in the mountainous region in the Nuwejaars catchment by 2018, with areas scattered throughout the Nuwejaars catchment, while in 1999 there was minimal presence of alien vegetation.

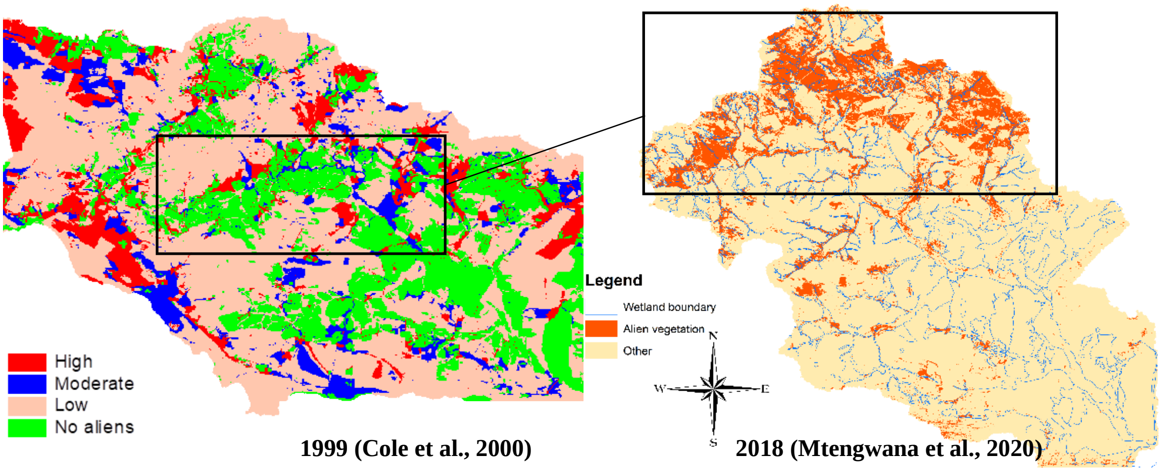


Figure 4. 11: Representation of the increase of alien vegetation from 1999 and 2018 (Cole et al, 2000; Bhongolethu et al., 2020)

4.4.3 The role of climate variation within the Nuwejaars catchment

Within a Mediterranean climate, such as the Agulhas region, rainfall is naturally variable (Dallas & Rivers-Moore, 2014), and has an impact on the water balance of the wetlands in the Nuwejaars catchment. The drought conditions, with below average rainfall in 2016 for the Nuwejaars catchment was evident with water in wetlands significantly reduced.

The drought conditions in South Africa from 2016, due to below average mean annual rainfall, caused a significant decline in water resources across the country (Sousa et al., 2018). A decline in rainfall creates a condition where a wetland, becomes more vulnerable and susceptible to impacts from agricultural practices. In other words, wetlands have become more exposed in the Nuwejaars catchment, particularly during drier periods, and in this state can be easily converted for agricultural land-use.

The Nuwejaars catchment is dominated by agricultural land-use and wetlands, which both depend on the rainfall as a water source. The decrease in rainfall has contributed to the loss and degradation of wetlands.

Rainfall plays a pivotal role in the Nuwejaars catchment as it is one of the primary sources of water feeding the rivers, streams, and wetlands. Agriculture also benefits a great deal from this water source to maintain crops and cattle. With a generally low rainfall experienced throughout the years leading to the drought, combined with the increasing agriculture, wetlands are most vulnerable to impacts from anthropogenic stressors, the most obvious of which is wetlands being converted to agricultural land-use. This puts a strain on the wetland's system functioning in its natural state.

4.5 Summary

In conclusion, most of the change within the Nuwejaars catchment took place between 1938 and 1989, with an increase in agriculture of 12 652 ha (31% of the catchment) and a 2 761 ha (20%) decrease in natural wetland area. The overall decrease in natural, intact wetland measured from the historical extent until 2016 was 3560 ha or 32% of the estimated historical extent.

Six agricultural impacts were identified as the highest threats to wetlands in the catchment: conversion to ploughed and cultivated land, infrastructure, damming, overgrazing, drainage ditches, and alien vegetation. Of these, damming of wetlands and conversion to ploughed and cultivated land in association with drainage ditches were the most extreme driver of loss of wetland function and habitat.

Chapter 5: Wetland and landscape catchment characterisation

5.1 Introduction

Chapter 5 addresses the second objective, which is to evaluate wetland and landscape characteristics using general and morphometric characterisation techniques. The chapter aims to provide a holistic understanding of the Nuwejaars catchment's wetlands and landscape by characterising these wetlands and their associated catchments to determine relationships, trends, and differences to help understand why the wetland systems are impacted differently by agricultural land-use activities.

5.2 Methodology

5.2.1 Data obtained for wetland characterisation

A 30m digital elevation model (DEM) was obtained from the United States Geological Survey (USGS) website. Land-use and land-cover (LULC), topographic, vegetation, and geology datasets were collected from various sources (see Table 5.1).

Topographic datasets which include drainage, river lines, and contour lines, assisted with identifying wetlands and wetland boundaries. This dataset was made available by the Department of Rural Development: National Geo-spatial Information (NGI).

The data used for wetland characterisation such as catchment area, slope, stream order, and relative relief were obtained through GIS analysis using the DEM from secondary sources made available to the researcher from other researchers.

The vegetation dataset that focuses on natural vegetation covering the extent of terrestrial and aquatic vegetation types for the Agulhas Plain, updated by Euston-Brown (2007) was used in this study. The dataset consists of a variety of spatial biodiversity data such as ecosystem, biome, habitat type, and vegetation unit. As this dataset is somewhat outdated, updated fieldwork done by a team of experts on multiple occasions in 2013, 2014, 2018, and 2019 was made available to the researcher to verify and point out changes in the dataset prepared by Euston-Brown (2007).

Fieldwork was conducted in November 2018 and 2019 to get a better understanding of the landscape and to record additional information about the types of wetland, vegetation present, and potential impacts on the sites visited. The data collected was used in correlation analyses to determine if there are any relationships between the vegetation and wetland characteristics, such as the size, slope, and geology of the wetland, wetland catchment, and landscape catchment.

A second vegetation dataset, on invasive alien plants, was included (Mtengwana et al., 2020). This dataset was obtained as a raster file containing only two categories, the first representing the presence of invasive alien plants, and the second representing all other land-covers. The file was converted to a vector file to calculate the percentage of alien vegetation in wetlands and their associated catchments and was included in a response analysis to impacts from agricultural land-use practices.

Table 5. 1: Datasets used in support of characterising wetland and landscape catchment areas. USGS* - United States Geological Survey, and NGI* - Department of Rural Development: National Geo-spatial Information

Dataset	**Source**	**Purpose**
Digital Elevation Model (30m)	USGS* (2019)	Generate catchment boundaries, slope, and relative relief of wetland and wetland catchment
Crop consensus, Livestock farming (2016)	Cape Farm Mapper (2019)	Identify agricultural land types for 2016
Geology	South African Council for GeoScience (2004)	Identify geology of wetland and wetland catchment
Vegetation	Euston-Brown (2007)	Identify wetland plant communities
Invasive alien vegetation	Mtengwana et al. (2020)	Identify wetland pressures
Drainage ditches	NGI*	Identify wetland pressure
Topographical data: River lines, contour lines,	NGI*	Identify wetland and wetland catchment boundaries

5.2.1.1 Land-use categorisation

Satellite data (aerial photographs) and ancillary data (wetlands, agricultural land-use types, catchment boundaries, slope, geology, vegetation, relative relief) were used in this study to characterise wetlands, wetland catchments, and the landscape catchment. The primary data digitised for this study was discussed in Chapter 4 and consists of the 2016 land-use/cover map (Figure 5.1) with three major classifications, dividing the area into wetlands, agricultural land (including associated farm buildings), and other (including natural cover, roads, and other land-uses excluding agricultural land).

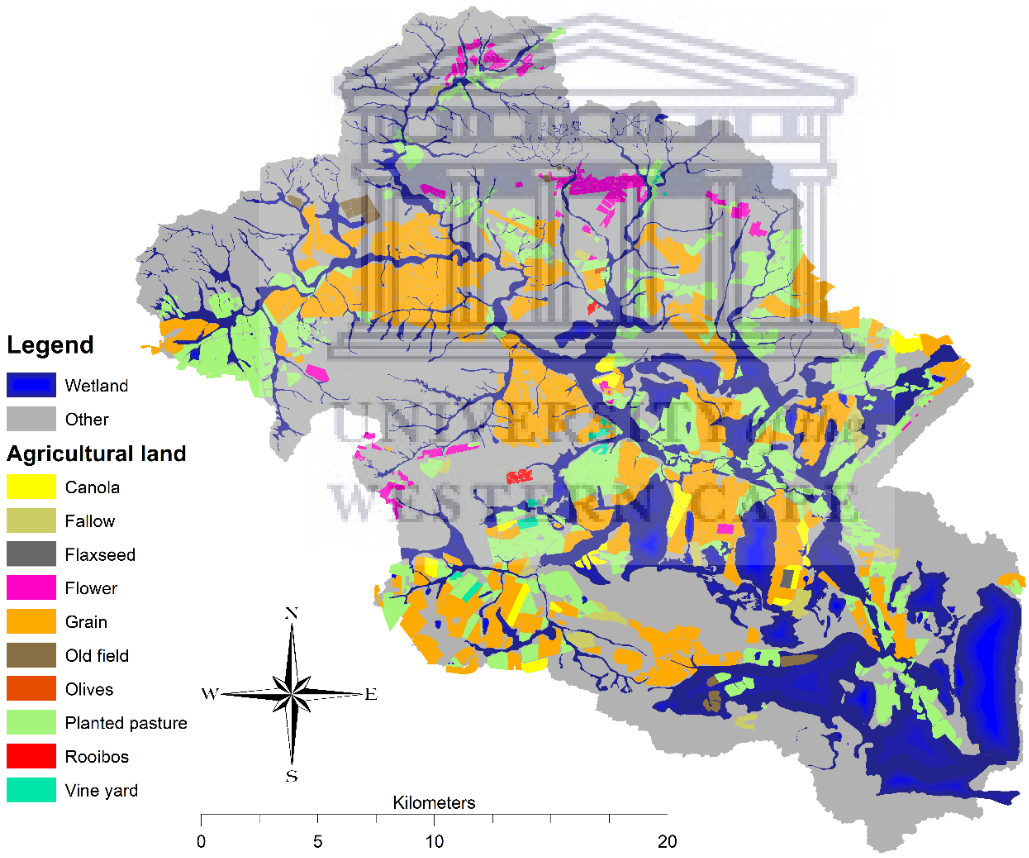


Figure 5. 1: 2016 Land-use map depicting agricultural land-use types surrounding the wetlands in the Nuwejaars catchment (Cape Farm Mapper, 2019).

The agricultural land-use layer consists of ten farming categories (grain, planted pastures, fallow, flaxseed, vineyards, canola, olives, rooibos, flower, old fields). This layer plays an important role in the study as it aids in identifying the major farming types that may be affecting a particular wetland/s and the wetlands catchment and determining whether a particular agricultural land-use type is responsible for wetlands responding differently to agricultural impacts. Table 5.2 provides an indication of the cultivation practices associated with the agricultural land-use types and where they are typically located within the Nuwejaars catchment. This helps to identify the major agricultural farming practices and their impacts on the wetlands within the Nuwejaars catchment, which is broken down further in Table 5.3.

Table 5. 2: Agricultural land-use types and their associated cultivation practices in the Nuwejaars catchment (Cape Farm Mapper, 2019).

Agricultural land-use type	Area (ha)	General location	Cultivation Practices (observations and additional references)
Grain	10765	Throughout the catchment along wetland boundaries	Most of the grain crops are dryland crops that get fed with rainwater, but there is a small majority that are irrigated (CFM, 2016). Many of the crops are associated with drainage ditches (Plant Production, 2016a).
Planted pastures	8347	Throughout the catchment along wetland boundaries	Most pastures are rainfed with a limit of three pasture fields using irrigation. Associated with livestock and overgrazing.
Fallow	562	Scattered around the catchment.	Land that is ploughed and tilled but left unseeded during the growing season to allow for recovery. Associated with drainage ditches.
Flaxseeds	35	Located near Voëlvlei.	Irrigated crops associated with herbicides and pesticides (Jacobs & van Der Merwe, 2012).
Vineyards	144	Along valley-bottoms	Requires large amounts of water for production and is associated with irrigation in the catchment (Kraaij et al., 2009; Plant Production, 2012).
Canola	642	Along floodplain	Dryland crops but limited water can decrease the yield, so irrigation is needed during the flowering and pod development from April till June (Plant Production, 2016b).
Olives	8	Confluence of Pietersieliekloof	Tolerant to drought and salt. Can grow in shallow, poor quality soils. Produces up to 95% wastewater high in polyphenols (harmful to the environment). Uses irrigation. Associated with fertiliser and pesticides (Plant Production; ARC, 2010).
Rooibos	60	Hills above Waskraalsvlei floodplain	Dryland crop associated with ripping and tillage
Flower	918	Hillslopes in Spanjaarskloof and Pietersielieskloof sub-catchments	These are dryland crops and are rainfed. They require pesticides (Plant Production, 2014).
Old fields	281	Small groups near mountains	Old fields are covered with weeds

The agricultural land-uses were further categorised into classes based on the hypothesised impacts on wetlands (see Table 5.3). The agricultural land use types were grouped according to their potential degree of impact on wetlands from the highest to the lowest impact.

Table 5. 3: Causes and possible responses to impacts from agricultural land-use impact groups in the Nuwejaars catchment.

Agricultural land-use impact groups	Impact on wetlands
1) Irrigated crops (grains, vineyard, flaxseeds, canola, pastures)	Abstraction of water from wetlands, usually through dams or pumps. This contributes to lowering the water table, deteriorating water quality, and changes in vegetation composition. Impacts the biodiversity negatively as these changes occur in the wetlands' ecosystem. These crops are associated with herbicides and pesticides (Jacobs & van Der Merwe, 2012; Planted Production, 2016a; Planted Production, 2016b). The chemicals in the products can seep into the wetland through run-off or infiltration and this results in contamination. These crops are also associated with drainage ditches.
2) Non-irrigated crops (grains, pastures, olives, rooibos, flowers)	These crops are not associated with irrigation as they can thrive in dryland conditions if climate conditions are favourable. They are rainfed but are vulnerable to pests and are associated with herbicides and pesticides, which can result in contamination of the wetlands. These crops are also associated with drainage ditches.
3) Fields (Fallow, old fields)	Fallow fields within the Nuwejaars catchment are associated with drainage ditches and have a high runoff rate due to the land being uncultivated and predominately bare. Depending on the soil compositions, can impact the wetlands. Old fields covered with weedy vegetation have much lower run-off rates.
4) Livestock	Production of livestock has an impact on the water as it is abstracted from wetlands for feeding and drinking. Wetlands are also used for grazing livestock. Overgrazing of wetlands can cause soil compactness due to trampling, and contamination due to the release of dunk, releasing high nutrient contents into the wetlands. Livestock is also used to convert wetlands to agricultural lands.
5) Drainage ditches	Habitat loss due to stream channelisation and conversion of wetlands to croplands. Impacts of sediment, nutrients, and other contaminants in agricultural runoff. Hydrologic alteration such as flow regimes, volume, and timing of runoff.
6) Dams	A dam reduces the flow of water in a river which results in a change in the landscape it flows through and can affect vegetation and animals. Dams trap sediment which are critical for maintaining physical processes and habitats downstream of the dam. Dams can also change the pattern of flow in a river which changes its seasonal variation and reduces its overall volume.

5.2.1.2 Catchment delineation

A freely available 30 m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was obtained from the USGS site (http://usgs.gov). The most common, open-source global DEM used is the SRTM due to its accessibility, vertical accuracy, resolution, and lower number of artifacts and noise compared to other global DEMs (Jarihani et al., 2015; Sampson et al., 2016; Hu et al., 2017). The STRM DEM was used to delineate the Nuwejaars catchment, sub-catchments, and wetland catchments to understand the relationship between landscape and wetland dynamics, with ancillary data used to identify trends or patterns within the catchments related to sloping, geology, or catchment size.

The DEM was used in ArcSWAT (an extension tool available within the ArcMap GIS programme) to delineate the Nuwejaars catchment boundary, sub-catchments, and wetland catchments. The watershed (catchment) delineation in ArcSWAT allows the user to delineate sub-catchments based on an automatic procedure using a DEM User-specified parameter provide limits that influence the size and number of sub-catchments created.

The process followed is outlined in Figure 5.2. ArcSWAT is an ArcGIS extension and connection for the Soil and Water Assessment Tool (SWAT). It is a model typically applied at river or catchment scale used to calculate the impacts of land management practices on water, sediment, and agricultural chemical yields in complex catchments with different land-use, and management conditions (Neitsch et al., 2009). It was developed by Jeff Arnold for the USDA Agricultural Research Service (ARS) and can be obtained from the SWAT website https://swat.tamu.edu/.

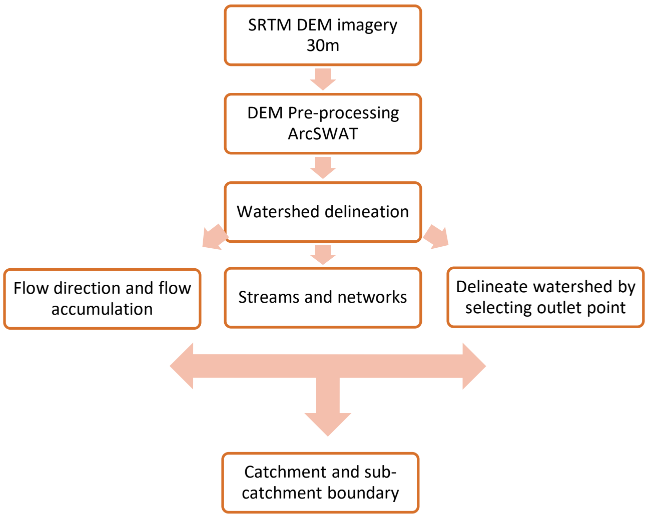


Figure 5. 2: Catchment delineating process using ArcSWAT.

The Nuwejaars catchment is that it is dominated by different combinations of land-uses and soils, impacting differently on the catchment hydrology, and ultimately on the wetlands within the catchment. By dividing the catchment into sub-catchments, the researcher can reference the different areas of the catchment to another spatially (Neitsch et al., 2009), and see how similar wetlands may be impacted differently by a different land-use and topography combination. Wetland catchment delineation identifies where the wetland gets its water, and what other inputs are entering the wetlands catchment that could potentially affect its condition and resilience to impacts.

Several ‘test runs’ were undertaken in ArcSWAT using different stream definition values to create a delineation that is suitable for observing wetlands at the catchment scale, considering that the wetlands differ in shape and size. Two of the delineations carried out appeared suitable with respect to accommodating the wetland size. The first delineation (Figure 5.3) accommodates wetlands of a greater size, which is suitable for the larger wetlands such as the bigger depressions and longer valley bottom wetlands; the second delineation (Figure 5.4) accommodates wetlands that are smaller in size. The values used in the stream definition were calculated from the DEM using flow direction and accumulation to define streams and watersheds. Stream definition values of 1478 ha in area and 18366 cells generated 23 sub-catchments. Stream definition values of 369 ha in area and 4586 cells generated 129 sub-catchments.

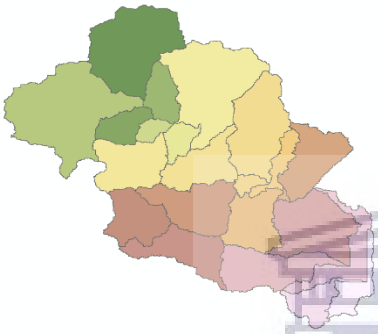


Figure 5. 3: First sub-catchment boundary layer, referred to in this study as the landscape catchments.

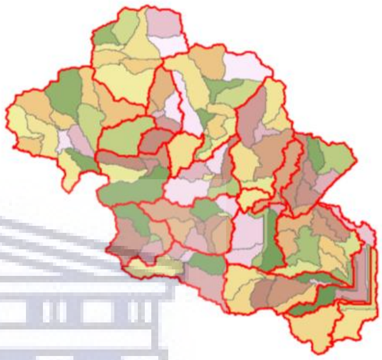


Figure 5. 4: Second sub-catchment boundary layer. Referred to as wetland catchments.

5.2.1.3 Catchment morphometric parameters

Table 5. 4 is a list of basic morphometric parameters that were used in this study. Understanding these parameters for the sub-catchments aid in differentiating catchments from each other and identifying which aspects cause a wetland or wetland catchment area to be either more susceptible to impacts from agricultural practices or supporting its resilience to the impacts. These characteristics play an important role as they influence how the landscape and wetland catchments respond to land-use pressures.

Table 5. 4**:** Basic morphometric parameters and mathematical formula

Parameters	**Method/Formula**	**References**
Catchment area (A) (Ha)	ArcGIS	Schumm (1956)
Slope (°)	ArcGIS	Strahler (1964)
Stream order (u)	Hierarchical rank	Strahler (1964)
Relative relief (H)	$H = R\text{-}r$, where R = Highest relief, r = Lowest relief	Schumm (1956)

5.2.1.3.1 Catchment area and perimeter

Catchment area influences the water yield, and the size and number of streams within a basin and is, therefore, one of the most important characteristics of a wetland. It is defined as the region that channels all the upstream land and water surface area that drains to a specific location in the stream (Gordon et al., 2004; Mundetia et al., 2018). The catchment area for this study was calculated through the ArcMap software using the geometry calculator. The Nuwejaars catchment covers an area of 73 884 ha, of which 19% is covered by wetlands, and 30% is covered by agriculture.

5.2.1.3.2 Catchment and wetland slope

The slope is calculated as the percentage of change in rise over a distance along a horizontal surface. Slope influences runoff: thus, a steep slope in a catchment and wetland catchment favours and increases the speed of runoff, while a gentle slope allows water to saturate and filter through the soil (Rais & Javed, 2014). The surface module in the spatial analyst tool in ArcMap was used to calculate the slope, and Table 5.5 indicates the percentage of slope classification used for this study.

Table 5. 5: Slope percentage and degree classifications (FOA, 2006)

Unit	Slope (%)	Terminology
1	0 - 0.2	Flat
2	0.2 – 0.5	level
3	0.5 - 1	Nearly level
4	1 - 2	Very gently sloping
5	2 - 5	Gently sloping
6	5 - 10	Sloping
7	10 - 15	Strongly sloping
8	15 - 30	Moderately steep
9	30 - 60	Steep
10	> 60	Very steep

5.2.1.3.3 Relative catchment relief

Relative relief is used to assess the morphological characteristics of the landscape (Gayen et al., 2013). The relative relief is the ratio between the relief and perimeter of the watershed (Melton, 1957) and, along with slope classes, can determine landform classes (Table 5.6) (Sayre et al., 2014). Combinations of low relief and mild slope produce different types of plains, while high percent slope combined with high relief are an indication of hills and mountains.

Table 5. 6: Slope and relative relief values for landform determination (Sayre et al., 2014)

Slope class	Relative relief	Landform
Flat to Gently Sloping	1 – 15 m	Flat plains
	16 – 30 m	Smooth plains
	31 – 90 m	Irregular plains
	91 – 400 m	Escarpment
Sloping	1 – 15 m	Low hills
	16 – 30 m	Hills
	31 – 90 m	Breaks
	91 – 400 m	Low Mountains
	> 400 m	High Mountains

5.2.1.3.4 Stream order

The stream order associated with a particular wetland can identify the relationship between physical and biological parameters. Each segment of the stream was numbered, starting from the first order to the highest order present in the catchment according to the method developed by Strahler (1964). The ranking is given as follows: streams without tributaries are allocated first-order streams, two first-order streams that merge form second-order streams, and so forth. Stream orders 1 to 3 are referred to as headwaters, stream orders 4 to 6 are called average-sized streams, and orders greater than 6 are referred to as large rivers (Mundetia et al., 2018).

5.2.1.4 Characterising wetlands

Methods drawn on in this section aim to provide an understanding as to why certain wetlands are affected more than others in the Nuwejaars catchment.

The first step to charactering wetlands and their catchments is identifying the hydrogeomorphic (HGM) unit (Ollis et al., 2013) within the catchment and understanding how the HGM units function under natural conditions. Research from different sources assisted with identifying and characterising the wetlands in the Nuwejaars catchment under five hydrogeomorphic units (floodplain, valley-bottom, depression, seep, and flat wetlands).

Additional characteristics, such as wetland vegetation type, were assigned to the five hydrogeomorphic units, with seven wetland vegetation types identified as occurring within the study area (Euston-Brown, 2007).

One of the methods of examining a catchment area and its associated drainage network is through a morphometric assessment, which is used to assess the form and structure of a catchment area and its associated drainage networks. Morphometric properties are quantified by elements of the landscape derived from terrain, elevation, and drainage systems within a catchment area (Biswas et al., 2014). The analysis provides information on drainage patterns and topography and can also be used for various hydrological investigations and objective-based prioritisations (Mundetia et al., 2018).

5.2.1.4.1 Hydrogeomorphic (HGM) units

HGM units form part of the South African wetlands classification system, which are distinguished at Level 4 (Ollis et al., 2013) based on three aspects: (i) landform – the shape and localised setting of the ecosystem; (ii) hydrological characteristics – the movement of water into, through and out of the ecosystem; and (iii) hydrodynamics – direction and strength of flow through the ecosystem (Ollis et al., 2013). There are seven HGM types recognised for inland systems, of which six refer to the wetlands (see Figure 5.5).

These HGM units all occur within the Nuwejaars catchment. Some are hydrologically dependent on the river, but not hydrologically connected to the river (Kraaij et al., 2009), as well as several further combinations of these two extremes.

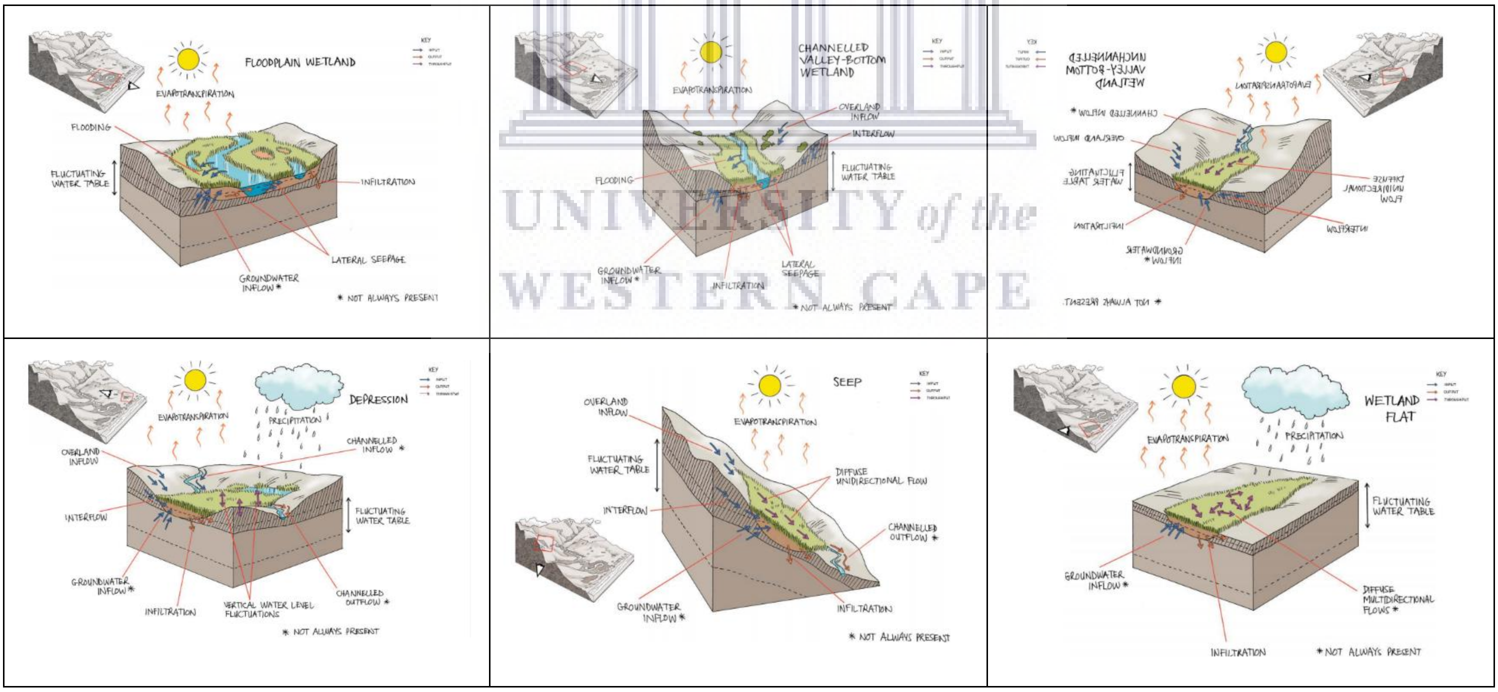


Figure 5. 5: South Africa’s hydrogeomorphic (HGM) wetland classification (Ollis et al., 2013)

5.2.1.4.2 Wetland vegetation community types

Euston-Brown (2007) categorised the wetlands in the Agulhas Plain according to 34 vegetation community types, of which seven were in the Nuwejaars catchment, as indicated in Table 5.7. These wetland vegetation types were assigned to the HGM units, including distribution, vegetation and landscape features, key ecological drivers, and impact stressors. These play a big role in the wetlands' vulnerability to impacts from the agricultural land-uses. However, wetland vegetation communities are also vulnerable to impacts from other land-use and are easily replaced by encroaching invasive alien plants.

Table 5. 7: Wetland vegetation community characteristics, and distribution within the Nuwejaars catchment adapted from Euston-Brown (2007).

Wetland vegetation type	**Code**	**Dominant and characteristic species**	**Species richness, endemism, and red data status**	**Distribution**	**Ecological drivers**	**Impact stressors**
Berzelia riparian	BERZE	*Mimetes hirtus, Berzelia lanuginosa, Psoralea spp, Drozera spp, Erica brunioides, Erica perpicua var latifolia, Erica colorans, Cliffortia spp, Eligia spp.*	HIGH. Diverse and sensitive habitat	Associated with drainage lines on acidic quartzitic sands of the mountains	Drainage patterns, rainfall, fire, insects and invertebrates, amphibians, and reptiles	Informal tracks, roads, dams
Elim riparian	ELIMR	*Berzelia lanuginosa, Psoralea spp, Drozera spp, Erica spp, Erica quadrangularis, Leucodendron laxum, Chondropetalum nudum, Restio harveyii.*	VERY HIGH. Diverse and sensitive habitat	Associated with drainage lines on laterite, at the base of and below sandstone mountains	Drainage patterns, rainfall, fire, insects and invertebrates, amphibians, and reptiles	Heavy grazing, informal tracks, dams
Palmiet riparian	PALMI	*Prionium serratum*	Un-surveyed and poorly studied	Restricted to major perennial rivers	Perennial acid water streams, gently flowing water, gradual incline, deep sandy banks	Alien vegetation, scouring
Restioid wetland	RESTIO	*Chonropetalum spp, Limonium spp, Crassula spp.*	Poorly studied	Occurs in the lowland flats in seasonally waterlogged areas on acidic sands	Drainage pattern, rainfall, evaporation rates	Informal tracks, trampling
Sarcocornia	SARCO	*Sarcocornias spp, Diohyma dunsdonii, Mesembryanthemum louiseae, Sporobolus virginicus, Ficinia repens, Juncus krausii, Limonium kraussianum, Plantago crassifolia, Chenolea dissusa*	HIGH	Flat pans at or below sea level that are periodically inundated	Drainage pattern, rainfall, evaporation rates	Trampling, informal tracks
Short reed	SHORTR	*Ficinia spp.*	Diversity relatively low	Associated with lowland flats in riparian areas and vleis where the soil is high in clay and fine silt	Drainage pattern, rainfall, invertebrates, and birds	
Tall reed	TALLR	*Pragmites austalis, Typha capensis*	Un-surveyed and poorly studied	Associated with the edges of perennial freshwater and saline water bodies	Nutrient loads, stability of sandbanks, silt loads associated with flooding and drainage	

Figure 5.6 presents the wetland vegetation communities according to Euston-Brown (2007). The map shows the distribution of the vegetation as wetland vegetation types. This was mapped according to the dominant vegetation communities found within the wetland ecosystems.

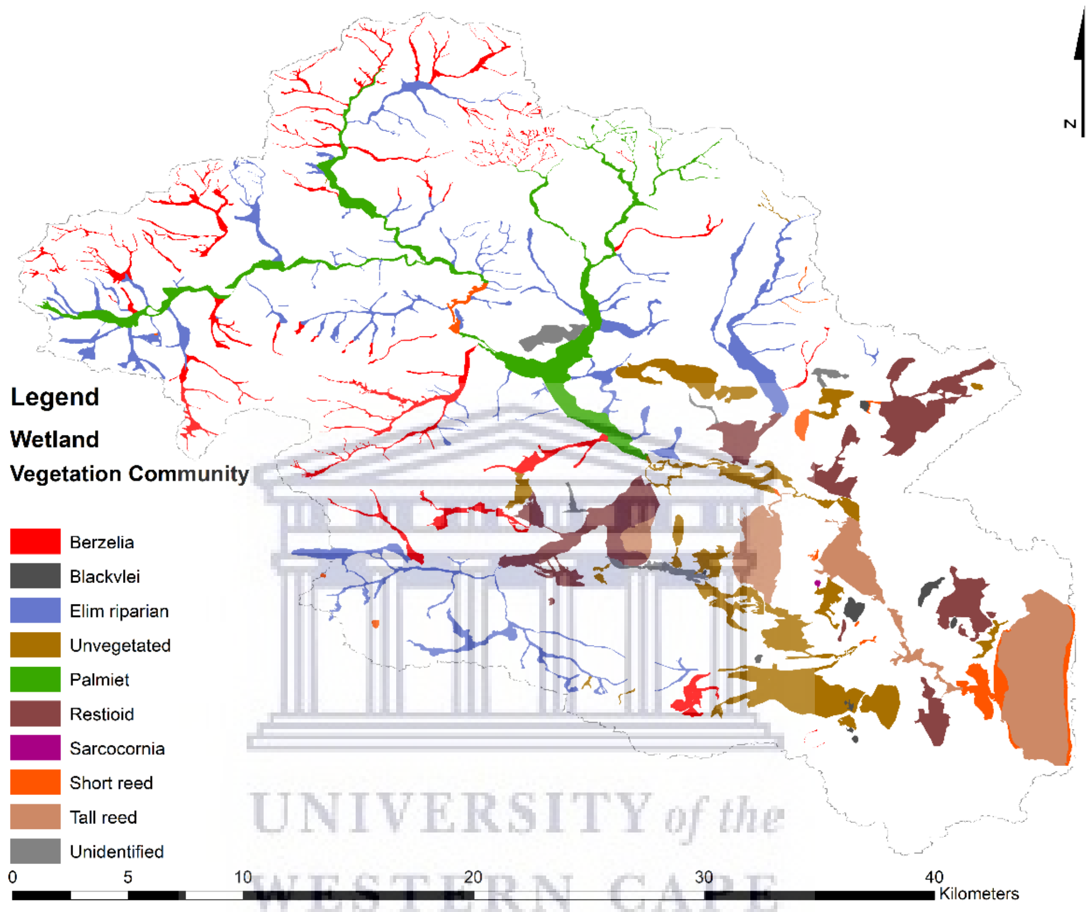


Figure 5. 6: The historical distribution of wetland vegetation communities in the Nuwejaars catchment (Euston-Brown, 2007).

5.2.2 Data analysis

5.2.2.1 Univariate analysis

Univariate analysis is a visualising tool used to assess the effects of one dependent variable of a dataset, to identify patterns among the individual variable (Sandilands, 2014). The form of univariate analysis for slope and area was analysed through scattergrams which represented the ratio between the wetland, wetland catchment, and landscape catchment for both the slope and area. This was done by dividing the wetlands slope to the wetland catchment slope, and wetland slope to the landscape catchment slope, the same was done for the area of each variable.

This analysis was done using the univariate tool in XLSTAT to determine the difference between the slope and area of the wetland to the associate wetland catchment and landscape catchment to identify significance in the patterns. Ellery et al. (2009) noted that a relationship exists between wetland slope and area, with wetland slope being the key control on erosion.

5.2.2.2 Contingency table analysis for associated relationship between categorical datasets

The categorical data (such as, HGM units, wetland vegetation types, and geology) for the wetland, wetland catchment, and landscape catchment was organised in a contingency table, which is also referred to as a two-way table. This table contains the frequency of response for each combination of values across the two categorical variables.

Contingency analysis for wetland vegetation type to wetland type, and geology of the wetland catchment and landscape catchment was generated using XLSTAT and used to determine relationships between the variable categories. This is a common method used to determine the association between variables (Elliott, 2006). A chi-square statistic was used to compare observations with those that would be expected if there were no association between the two variables (Elliott, 2006).

5.2.2.3 Multiple Factor Analysis

Multiple Factor Analysis (MFA) is a technique that allows for the analysis of tables composed of several groups of variables of different natures, such as numerical and categorical data within grouped observations (Visbal-Cadavid et al., 2020).

This statistical tool makes it possible to characterise groups of individual variables to answer questions such as “Which are the individual groups that are most similar overall” (Escofier & Pages, 1992 cited in Vishal-Cadavid et al, 2020). In other words, Abdi and Valentin (2007) states that MFA aims to integrate different groups of variables describing the same observation.

The goal of using the MFA was to determine how wetland types were related to each other and to identify which characteristics of both the numerical and categorical variables related to the wetlands with relations to each other. This analysis was done through XLSTAT.

5.3 Results

5.3.1 Morphometric results

5.3.1.1 Slope and relative relief

Figure 5. 7 shows the distribution of slope on four levels. The top left map shows the percentage slope derived through terrain analysis to show steepness. In the upper parts of the catchment, the slope ranges from 10 to 60% (strongly sloping to very steep) according to the slope categories in Table 5.7. Towards the middle of the catchment, there is a wide variation in steepness from 1 to 60% (level to steep). In the lower catchment, the interior ranges between level and sloping, and moderately steep along the edges.

The top right map in Figure 5.7 represents the average (mean) percentage slope for the landscape catchment. The sub-catchment with the highest average slope is moderately steep (15 – 30%). The sub-catchments to the west and the east are sloping or hilly (5 – 10%), and the sub-catchments in the middle and lower part of the overall Nuwejaars catchment range from 2 to 5%, indicating that the area is gently sloping.

The map on the bottom left of Figure 5.7 represents the mean percentage slope for the wetland-catchments, showing that overall wetland-catchments in the upper catchments to the north and northeast are moderately steep, and in the catchments below them strongly sloping wetland-catchments dominate. To the west, southwest, and part of the middle, the average wetland-catchment is sloping; while to the lower south and southeast, the wetland-catchments are predominantly gently sloping.

The bottom right map of Figure 5.7 represents the mean percentage slope for each of the wetlands, and results indicate that the majority of the wetlands in the catchment are gently sloping (2 – 5%). In the north and northwest along the edges of the boundary, wetland slope shows as 15 to 5%, indicating that the wetlands start from being strongly sloping to sloping.

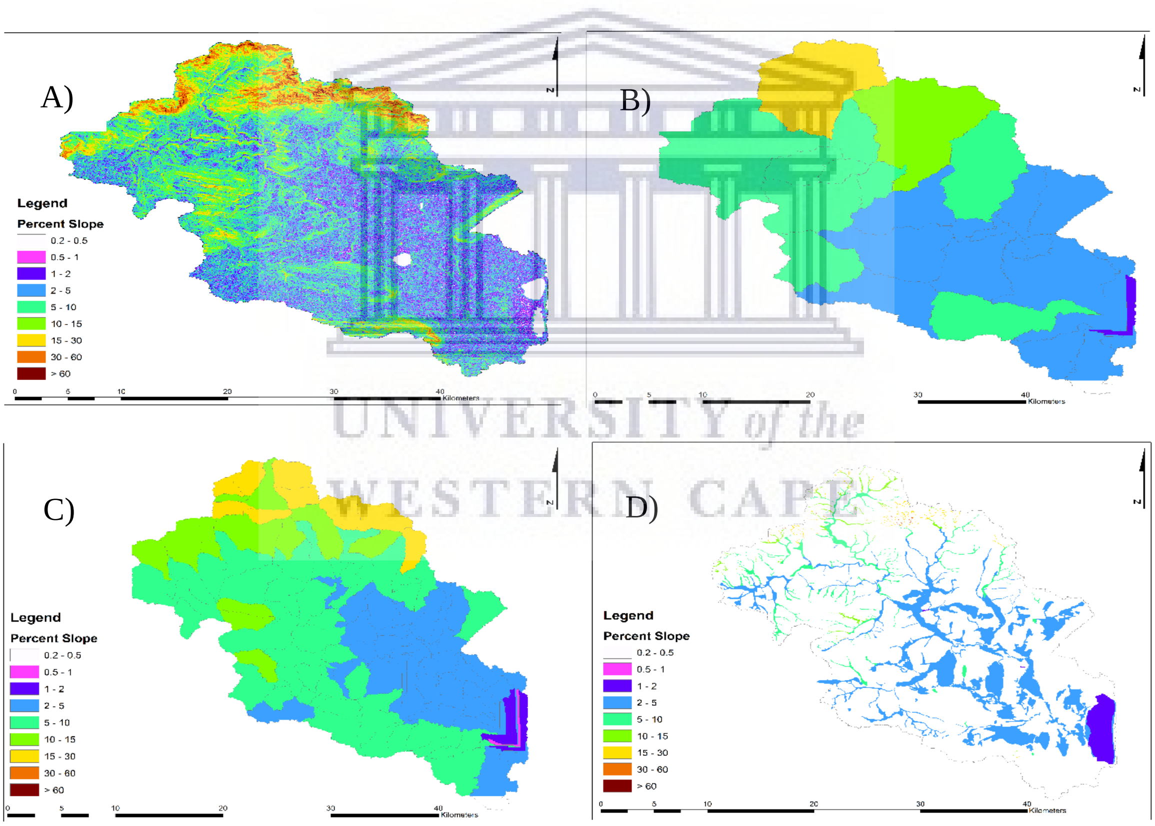


Figure 5. 7: The percentage slope (A), landscape sub-catchments (B), wetland catchments (C) and wetlands (D) in the Nuwejaars catchment.

Figure 5. 8, indicates high relief is associated with much of the upper half of the Nuwejaars catchment, identified as a low mountain. at the corresponding slope, from the top right of Figure 5. 7, also indicates low mountains.

The middle and parts of the lower catchments have a relative relief of 31 – 90m (Figure 5.8). The slope in these sections (Figure 5.7) is gently sloping, indicating irregular plains.

To the east and southeast of the catchment, the relief is quite low, ranging from 16 – 15m (Figure 5.8). This section indicates smooth to flat plains as the slope associated with them is flat ((Figure 5.7).

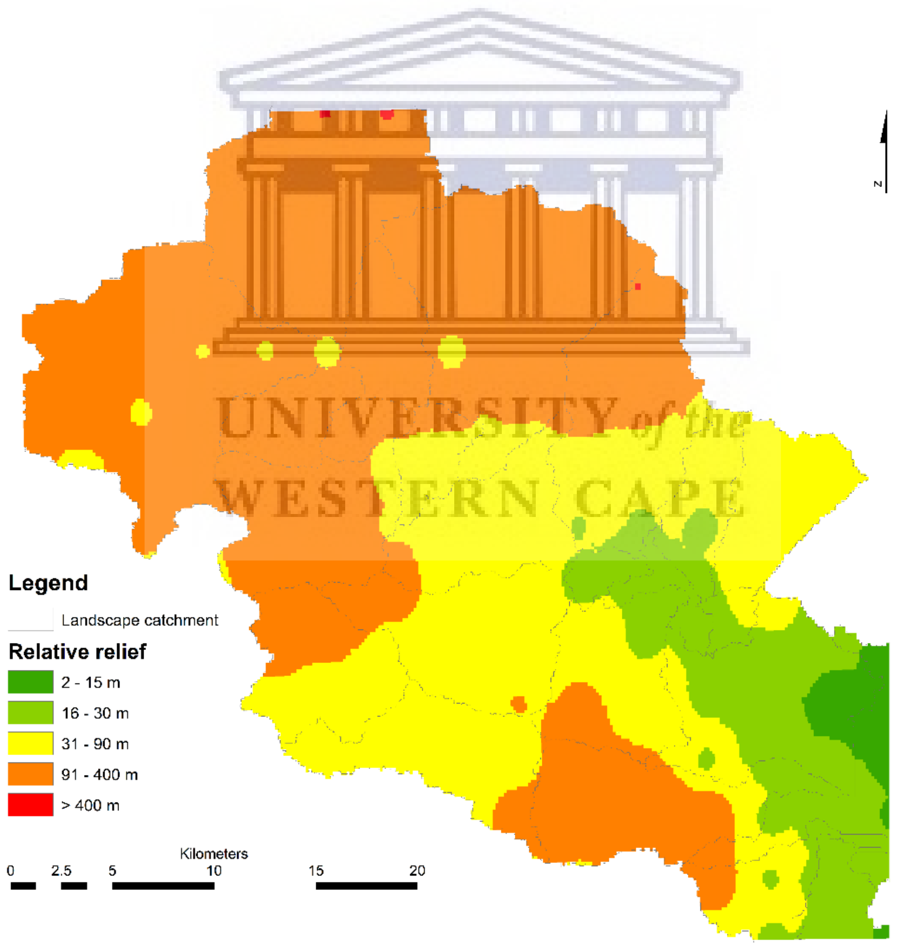


Figure 5. 8: Map of the relative relief classes in the Nuwejaars catchment, representing the landscape catchments.

5.3.1.2 Stream order and length

Figure 5. 9 represents the distribution of stream order of the Nuwejaars River and its tributaries, while Table 5. 8 shows that there are a total of 62 first-order streams with a total length of 147 km. This accounts for 52% of the stream length in the Nuwejaars catchment.

A total of 28 streams are second-order streams with a summed length of 65 km (23% of total stream length for the Nuwejaars catchment).

The third-order streams are represented by 13 streams with a summed length of 31 km (11% of total river length), while the fourth-order stream is mostly accounted for by the Nuwejaars River and covers a total of 41 km (14% of total river length).

Figure 5. 10 shows that all the streams and rivers have wetlands associated with them (100% of the river length is associated with wetlands) although not all headwater areas could be assessed, and likely, that a small percentage of headwater streams do not have associated wetland.

Table 5. 8: Stream order statistics

Stream order	Total number of streams	Total length (km)	% of length
1	62	146.7	51.6
2	28	65.4	23.0
3	13	31.1	10.9
4	1	40.9	14.4

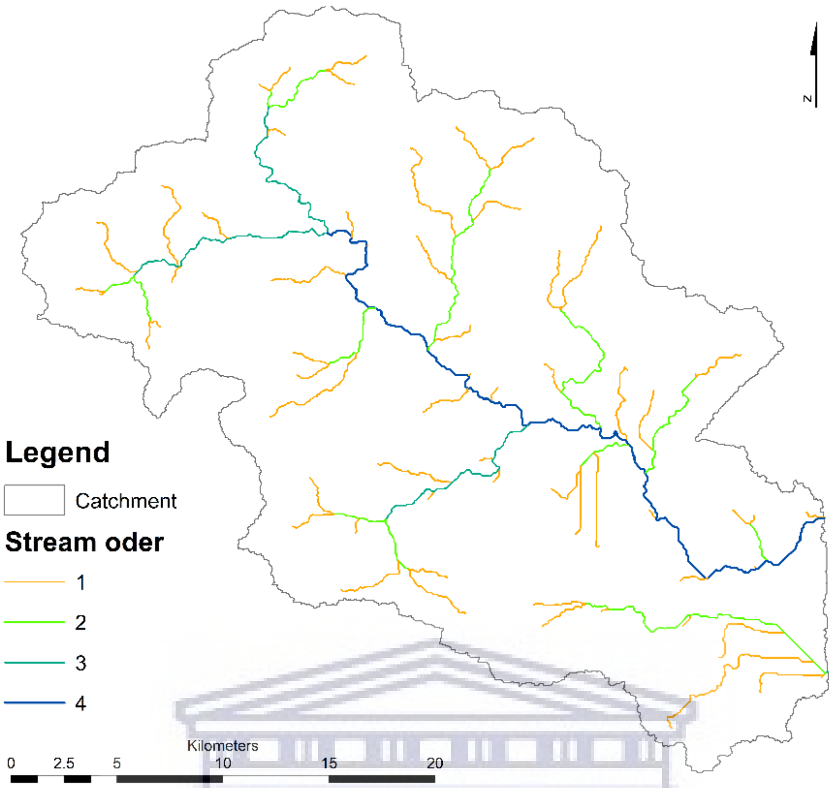


Figure 5. 9: Map representing the stream orders in the Nuwejaars catchment.

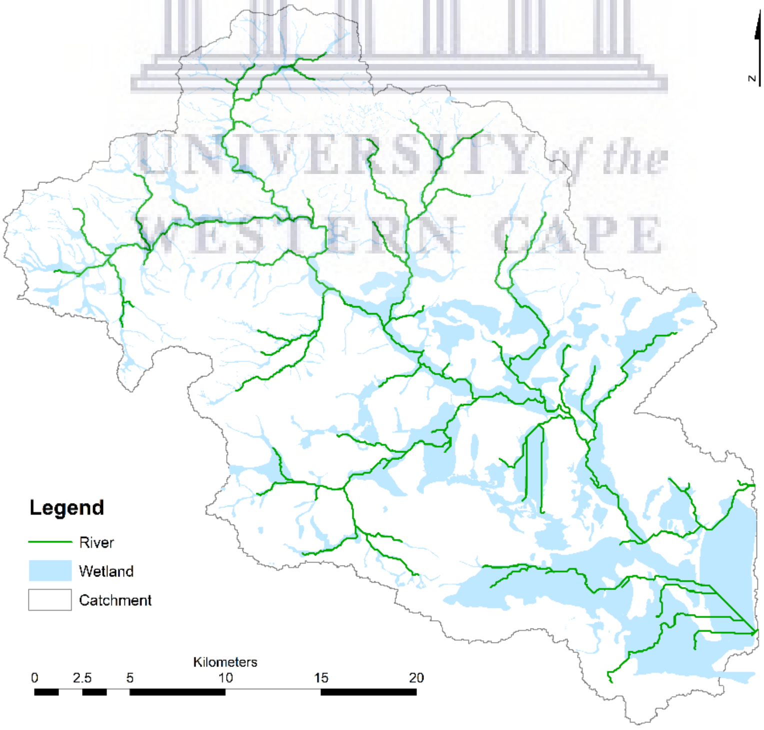


Figure 5. 10: Representation of the distribution of wetlands along the river

5.3.2 Relationships between the wetland, wetland catchment, and the landscape

In this section, relationships between the wetland and landscape catchment characteristics were determined to investigate the potential factors playing a role in the function of the wetland.

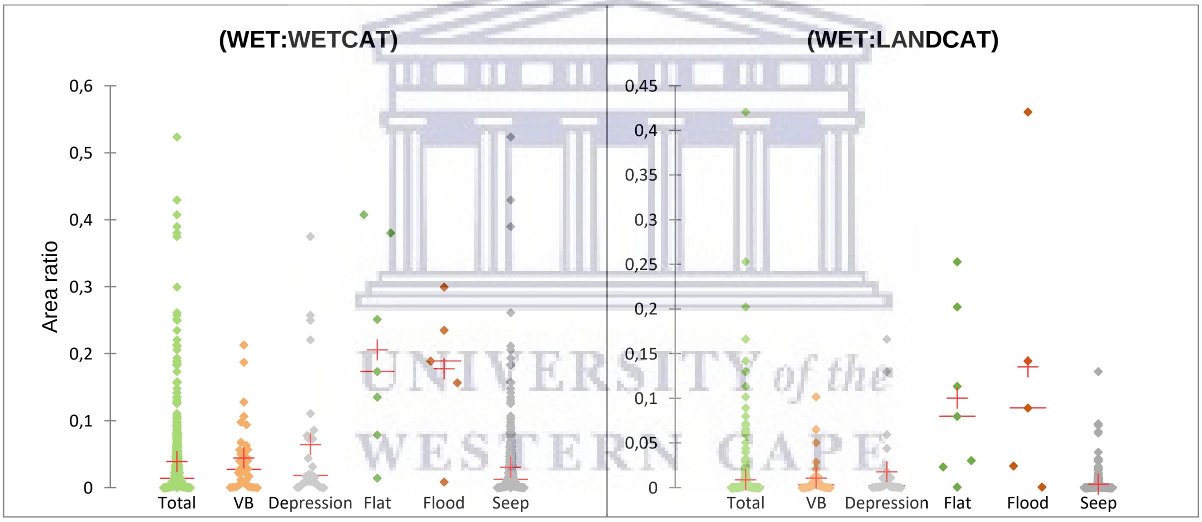
5.3.2.1 Ratio between the variables associated with wetland, wetland catchment, and landscape catchment.

The ratio between the datasets for the area of the wetland, wetland catchment, and landscape catchment was analysed using a univariate scattergram. These graphs show the distribution of the modes in the dataset, as well as an indication of the mean and median (see Figure 5.11).

In Figure 5. 11, the results for the WET: WETCAT graph shows that the highest ratio of wetland to the wetland catchment area is between 0.5 to 0.6, which is attributed to the seep wetland. The mean and median for each wetland, including the total, ranging from 0 to below 0.1. The scatter for the plots of each wetland type mostly falls below 0.3. Therefore, both the mean and median for each of the wetland types, ranges between 0 to 0.2. However, only a few points have been plotted above 0.4, which can be attributed to the flat and the seep wetlands. The flats and floodplains mean, and median is slightly higher than the rest of the wetlands to wetland catchment ratio, but still falls below 0.3.

The results for the WET: LANDCAT graph show that the highest ratio of wetland to landscape catchment is between 0.4 and 0.45. This is seen by the points from the floodplain wetlands. Random scatters that deviate from the mean and median can be witnessed by all wetland types, with about 1 to 4 points scattered away from the mean and median. These points fall just above 0.1 to below 0.45. The floodplain has the highest mean of 0.15 and the highest median of 0.1.

The results for the WETCAT: LANDCAT graph show that the highest ratio between the wetland catchment and the landscape catchment is between 2.5 and 3, which is attributed to the floodplain. The mean and median for each wetland, including the total, range from 0 to 0.5. The scatter for the plots of each wetland type, besides the floodplain wetlands, mainly fall below or are equal to 0.5. Therefore, both the mean and median for each of the wetland types ranging from 0 to 0.5. However, few points have been plotted above 0.5, which can be attributed to each of the wetland types ranging from above 0.5 to below 3. The flats and floodplains mean, and median are higher than the rest of the wetlands. However, the mean of the floodplain is 0.8 and the mean of the flat is 0.4; in contrast, the median of the flat is 0.4, while the floodplain is just below the flat at 0.3.



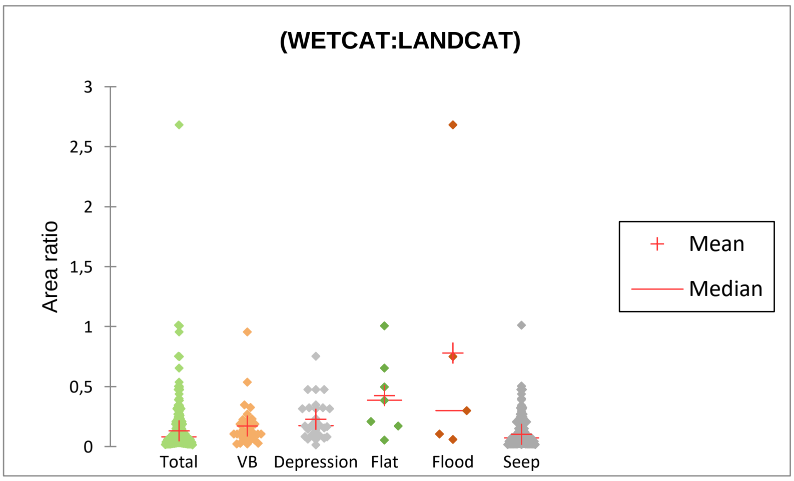


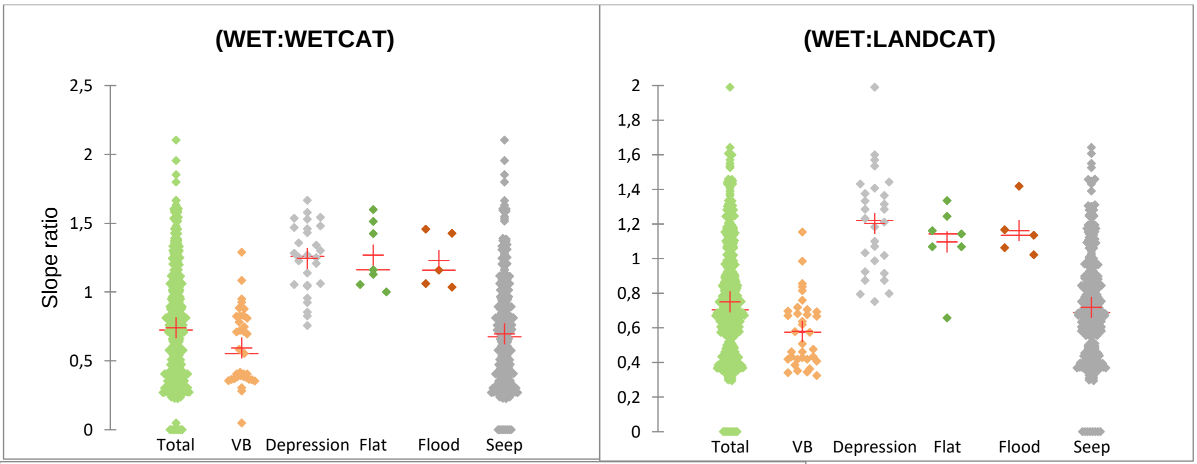
Figure 5. 11: Scattergram demonstrating the ratios for wetland, wetland catchment, and landscape catchment area of each wetland type. The abbreviations as follows: WET – wetland, WETCAT – wetland catchment, and LANDCAT – landscape catchment.

The Figure 5.12 scattergrams representing the distribution of the slope ratio for the different wetlands, wetland catchment, and landscape catchment show that the slope ratio between wetland and its wetland catchment, and the slope ratio between the wetland and its landscape catchment represent the same pattern.

However, the values are vastly different. The WET: WETCAT graph in Figure 5. 12 shows that there is a cluster of wetlands with a slope ratio between 0.2 to 1.6. Although there are a few points from each wetland type over a ratio of 1.6, they also just fall below 2.5. The seep wetlands have the highest ratio reaching just 2.1. The mean and median ratios are roughly the same for the depression, flat, and floodplain falling between 1 and 1.5, while the seep and valley-bottom wetlands mean, and median are between 0.5 and 1.

The WET: LANDCAT shows a mean ratio for the total wetland types at 1.2, with a median of 1. The valley-bottom ratios are scattered between 0.3 and 1.2. The mean and median ratios are the same at 0.6. The depression wetlands ratios are scattered between 0.7 and 2. The mean and median are at a ratio of 0.3, with the highest point at a ratio of 2. The flat wetlands are clustered between 1 and 1.3, with the lowest point at a ratio of 0.7. The mean ratio for the flat is 1.1, with the median at 1.2. The floodplain has a mean and median of 1.2, with the highest point at a ratio of 1.5. The seep wetlands ratio stretches from 0.2 to 1.7, and the mean and median are at 0.7. The lowest points can be seen at 0.

The WETCAT: LANDCAT graph shows a significant low deviation from the mean and median ratios of 1.2. The valley-bottom wetlands show that its highest ratio is at 7. Most of the points for each of the wetland types are clustered around the mean and median ratios. However, the seep wetlands stretch from a ratio of 0.3 to 2.5.



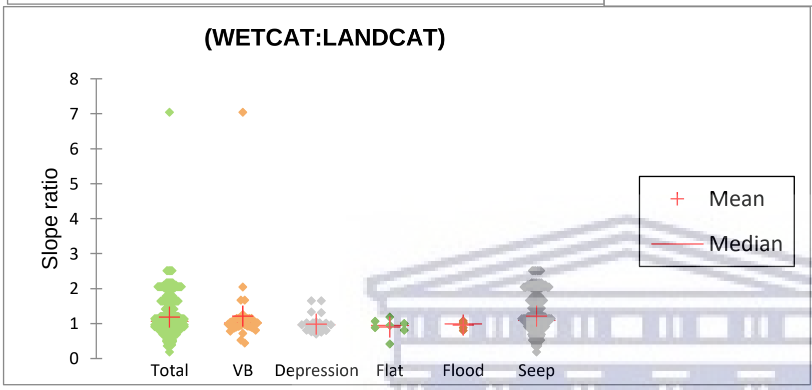


Figure 5. 12: Scattergram demonstrating the ratios for wetland, wetland catchment, and landscape catchment slope for each wetland type. The abbreviations as follow: WET – wetland, WETCAT – wetland catchment, and LANDCAT – landscape catchment.

5.3.2.2 Association of wetland vegetation type to wetland type, and geology of the wetland catchment and landscape catchment

Berzelia, Elim riparian, Palmiet, restioid, short reed, and tall reed are diversely distributed within the seep wetlands and valley-bottom wetlands, with the Berzelia and Elim riparian being most prevalent in the seeps. Berzelia accounts for 54% of the seep wetlands and Elim riparian accounts for about 25% of the seeps (Figure 5.13). Berzelia accounts for 27%, Elim riparian 25%, and Palmiet accounts for 33% of the valley-bottom wetlands.

30% of the depression wetlands are made up of black vlei, with 2% occupied by sarcocornia, 20% short reeds, and 5% tall reeds vegetation communities. 40% of the floodplain is associated with restioid, 20% short reed, and 20% tall reed. 58% of the flat wetlands are occupied by short reeds, and 42% occupied by restioid.

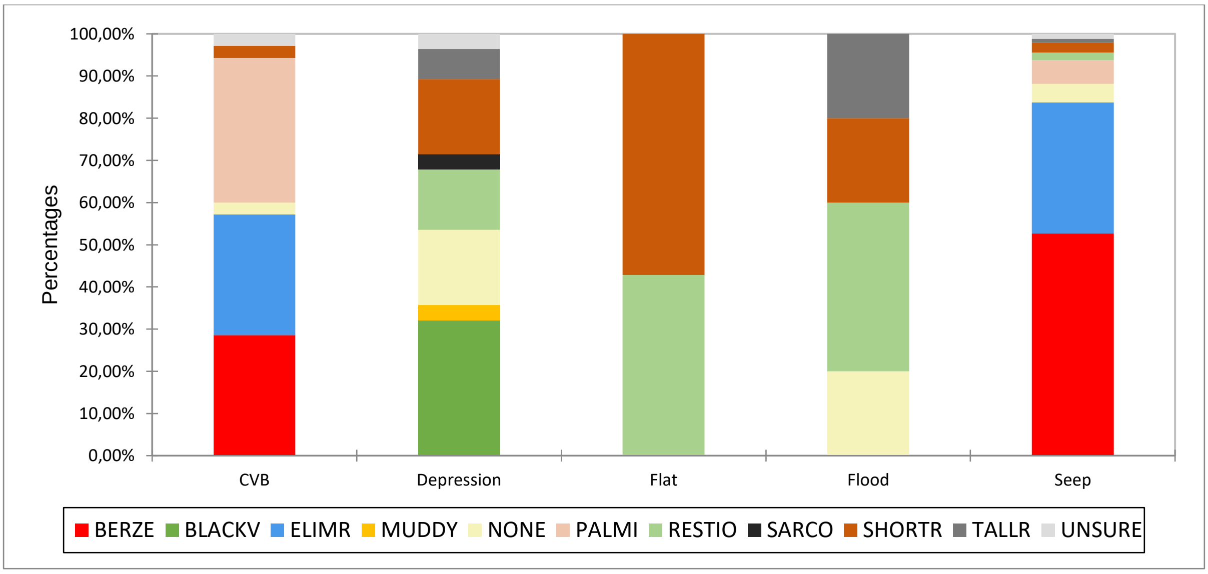


Figure 5. 13: Contingency graphs representing the frequency and percentage of wetland types for each of the wetland vegetation communities (Euston-Brown, 2007).

Frequency graphs were developed to show the distribution of the wetland vegetation communities with regards to the landscape catchment and wetland catchment geology. The unique topography of the Nuwejaars catchment and its diversity in ecosystems are related to its geology (Jones et al., 2000).

The results for Figure 5. 14 show that the vegetation groups are all associated with Bredasdorp geology classes, with 13% being Berzelia, 13% Black Vlei, 2% Elim riparian, 9% restioid, 20% short reed, and 2% tall reed. The Cape Bokkeveld Ceres class is 50% Elim riparian, and the rest of the geology classes ranges between 2 and 10%.

The Cape Granite class is 100% occupied by Berzelia. Berzelia is quite dominant in the Cape Table Mountain classes, accounting for 72% and 75%, whereas the Elim riparian vegetation communities are most dominant in Malmesbury Tygerberg classes, accounting for 73%. Palmiet accounts for 25% in both the Cape Table Mountain and Malmesbury Tygerberg classes.

Results for Figure 5.15 showed that the Bredasdorp class vegetation communities are widely spread and are dominated by three groups (Berzelia, Black Vlei, and short reed).

The Cape Bokkeveld Ceres classes are dominated by Elim riparian (50%), while the Cape Table Mountain class is made up of 65% Berzelia, 12% Elim riparian, and 20% Palmiet. Cape Table Mountain Nardouw and Malmesbury Tygerberg dominant vegetation community had Berzelia accounting for between 55 and 75%. 35% of the Malmesbury Tygerberg is occupied by Elim riparian vegetation.

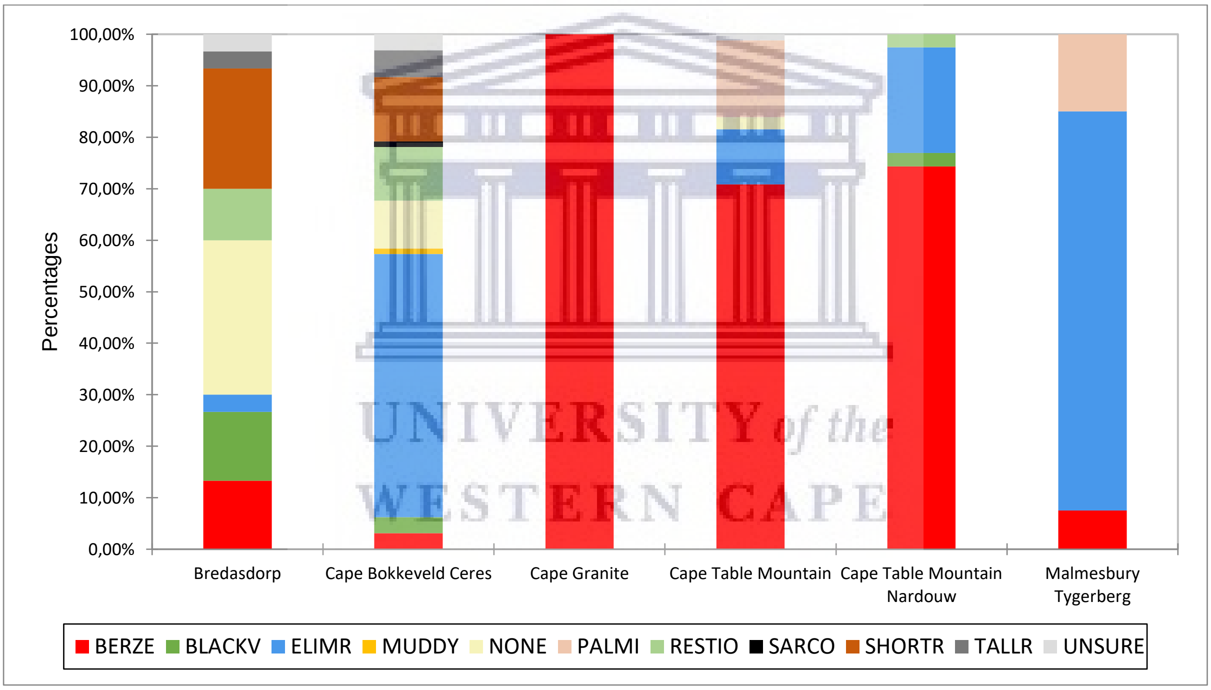


Figure 5. 14: Representation of the relationship between the wetland vegetation types and wetland catchment geology.

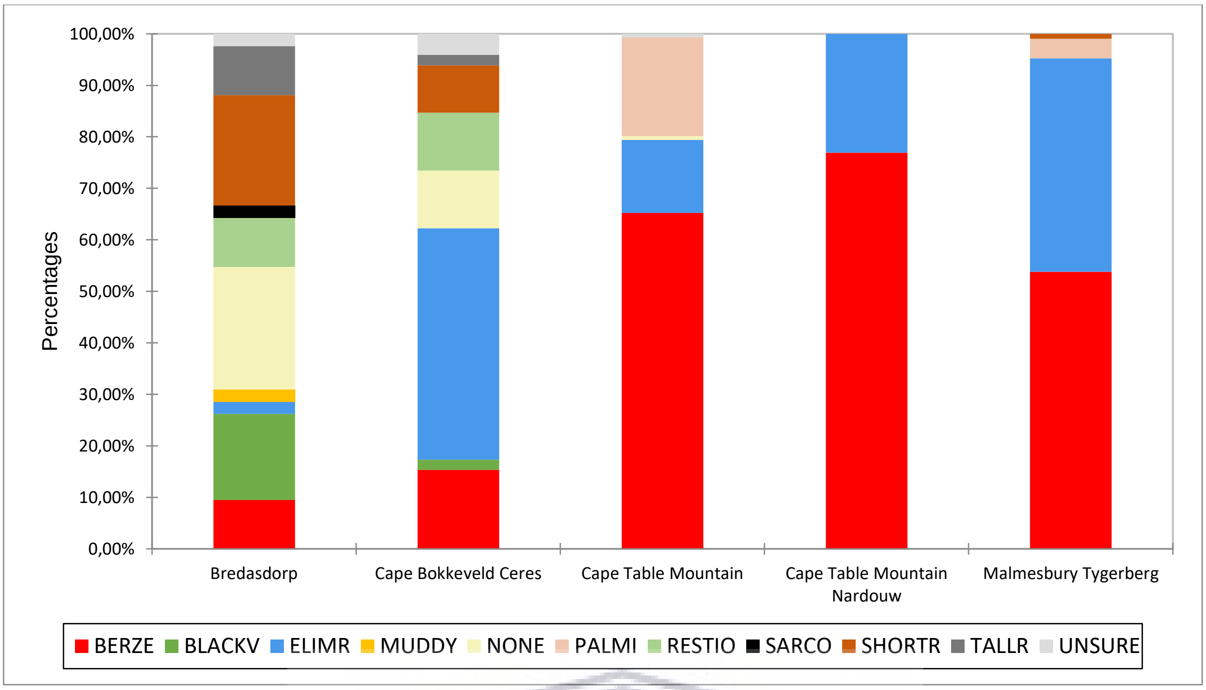


Figure 5. 15: Representation of the relationship between the wetland vegetation types and landscape catchment geology.

Figures 5.16 and 5.17 show the distribution of the different geology classes on a wetland catchment and landscape catchment scale for the five wetland types.

The valley-bottom on a wetland catchment scale shows all the geology classes. However, the Cape Table Mountain is the dominant geology class on both scales, with 54 (Figure 5.16) and 59% (Figure 5.17).

The depression is associated with both Bredasdorp and Cape Bokkesveld Ceres, with Cape Bokkesveld Ceres (55%) being dominant on the wetland catchment scale and Bredasdorp (57%) on the landscape catchment scale.

The flat wetlands are dominated in both Figures by Cape Bokkesveld Ceres (88% on both); however, they are also associated with the Bredasdorp class (12% for each).

The dominant geology class in the floodplain in both Figures are Cape Bokkesveld Ceres, 80 (Figure 5.16) and 81% (Figure 5.17). However, secondary in the wetland catchment scale is Malmesbury Tygerberg (20%), and on the landscape catchment scale it is Bredasdorp (19%).

The seep wetland is associated with five of the wetland catchment geology classes (Bredasdorp, Cape Bokkeveld Ceres, Cape Table Mountain, Cape Table Mountain Nardouw, and Malmesbury Tygerberg), with Cape Table Mountain being dominant at 35%. On the landscape catchment scale, seep is associated with all five geology classes, with Cape Table Mountain (36%) and Malmesbury Tygerberg (30%) being dominant.

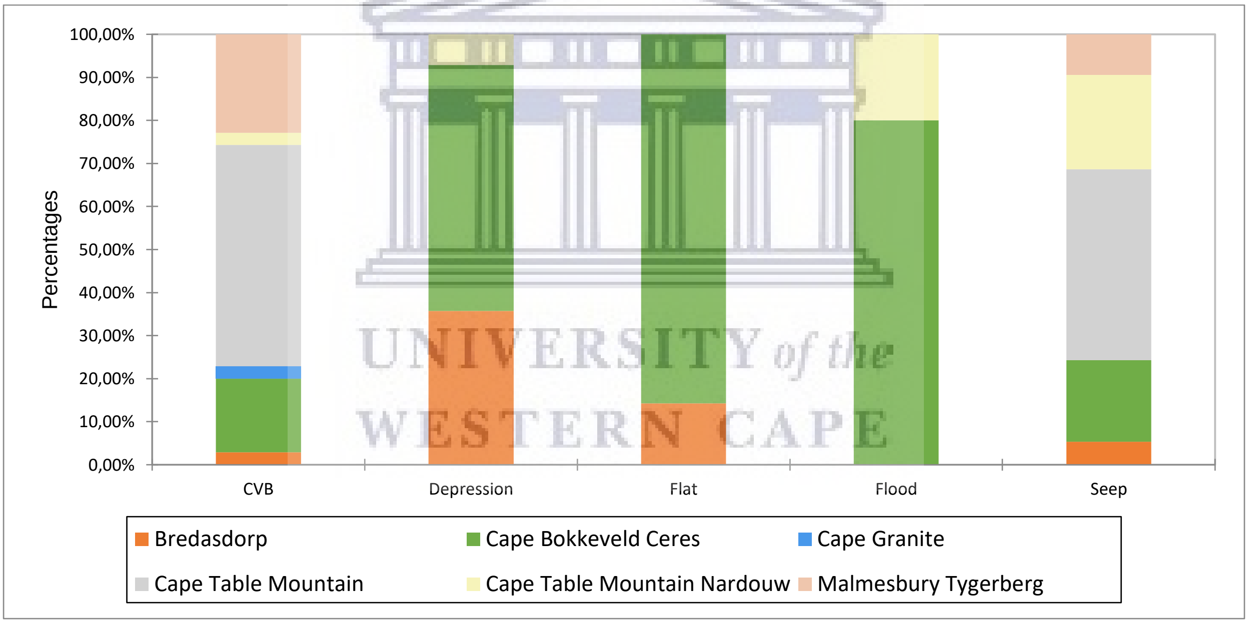


Figure 5. 16: The relationship between wetlands and wetland catchment geology

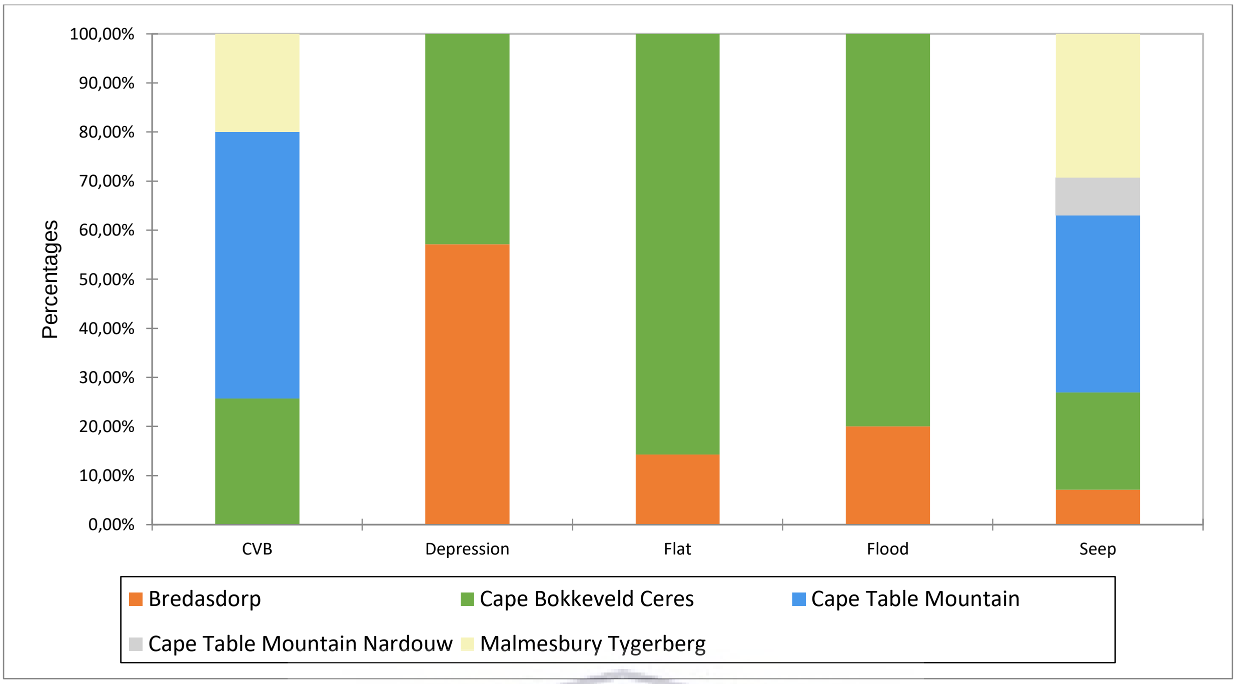


Figure 5. 17: The relationship between wetlands and landscape catchment geology

5.3.2.3 Multiple Factor Analysis (MFA) of the characteristics associated with the wetlands in the Nuwejaars catchment.

A Multiple Factor Analysis (MFA) was used to correlate the results of all the characteristics to show where relationships can be found within the data sets.

Figure 5. 18 shows the distribution of each characteristic and as can be seen in the graph, the wetland stream order (Wet SO) and wetland stream length (Wet SLen) are highly correlated with the first and second factors.

Figure 5.18 shows that landscape catchment slope (Lcat slp), landscape catchment relative relief (cat relief), and Cape Table Mountain geology class for both scales correlate with each other in the second factor.

The wetland types are scattered around all four quadrants, with the seep wetland types and wetland relative relief (wet rr) found to be negatively correlated with the other quadrants.

The geology types, including both wetland catchment geology and landscape catchment geology, are scattered in three of the quadrants. However, most of the landscape catchment geology and wetland vegetation types are correlated with the first factor.

Wetland stream length (Wet Slen), wetland stream order (Wet SO), and wetland areas are correlated in the first factor.

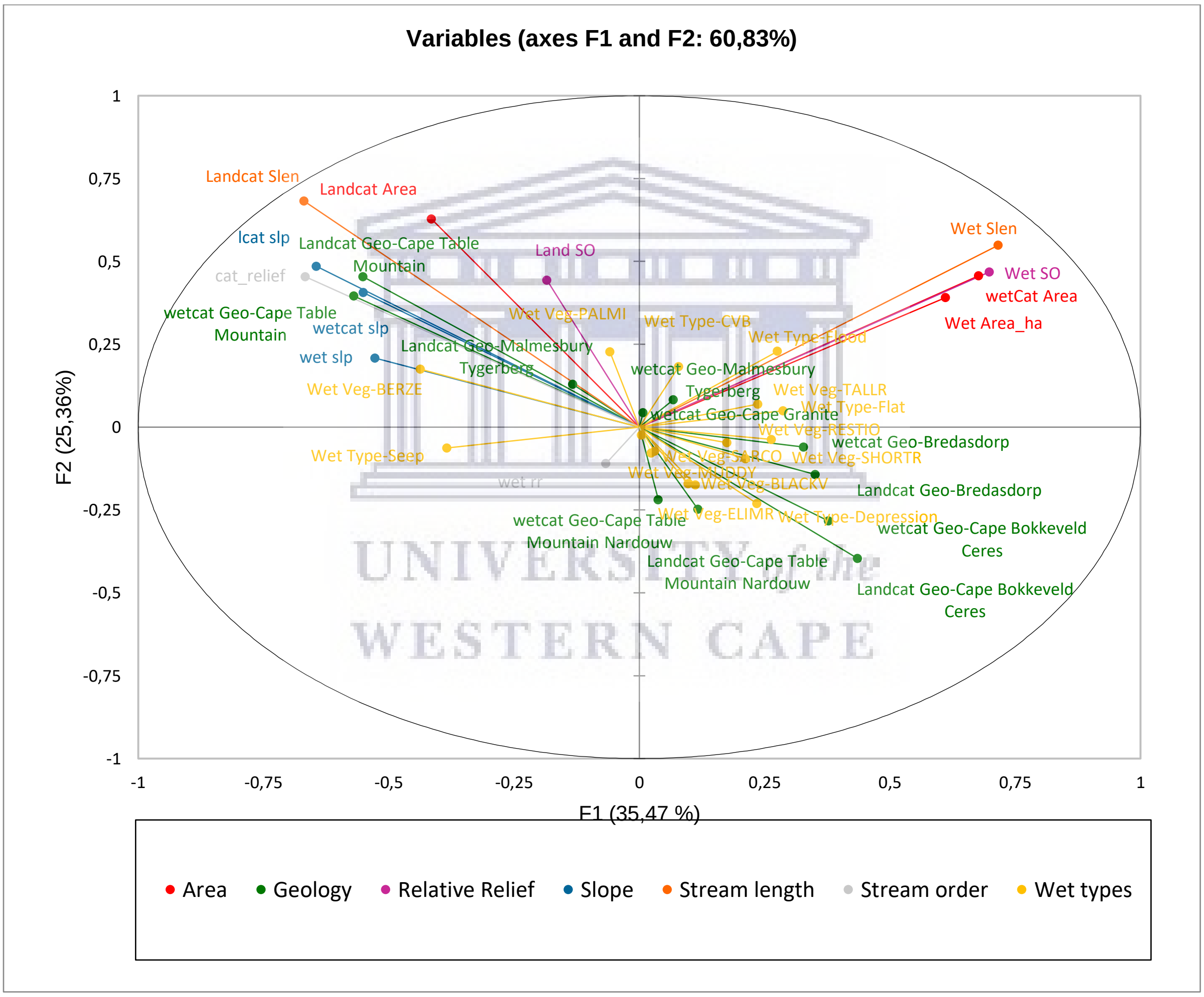


Figure 5. 18: Correlation map representing the distribution and relationship of the characteristic variables.

5.4 Discussion

5.4.1 The ratio analysis of the wetlands, associated catchment, and landscape catchment for the area, slope, stream length, and relative relief

The results for the ratios between the wetland area and the wetland and landscape catchments indicate that the wetland areas make up less than 50% of the catchment areas for both wetland catchment and landscape catchment. This can be seen by the low ratios, which range from 0.1 to below 0.5. These values are not limited to a specific part of the catchment and are seen to be scattered throughout the Nuwejaars catchment, due to its irregular plain.

The wetland type associated with these smaller ratios are mainly seep wetlands that are found on steep to gentle slopes. However, wetlands in the lower catchments have much bigger wetland catchments, as the area is gently sloped. 90% of the wetland catchments to landscape catchment area are less than 50% of the landscape catchment. This is mostly seen in the bigger landscape catchments, as multiple wetlands are nested in the catchments where most seep wetlands are found.

Bigger catchments in relation to the wetlands may also indicate that the wetlands are much less vulnerable to impacts depending on the percentage slope, as a steeper slope can filter potential impacts such as pollutants out of seep wetlands with sparse vegetation. However, a gently sloped to flat catchment associated with the wetland can result in agricultural impacts having more of an effect on the wetlands in the area.

The slope ratios for the wetlands and both wetland and landscape catchments are higher, indicating that the wetland's slope exceeds that of the catchments. This can result in slightly lower vulnerability to impacts that are identified in the wetland and landscape catchments, as impacts from agricultural activities, such as fertilisers flowing with run-off, will only be able to enter the wetland through infiltration. Low relief areas are sought after for agricultural activities, especially along streams due to their flat terrain and accessibility to water (Rai et al., 2017).

The wetland catchment to landscape catchment slope ratio has a mean of 1, which indicates that most of the catchments have a similar percentage slope, meaning that negative impacts entering a wetland's catchment from the landscape catchment can easily access the wetlands.

The results for this section show the relationship between the characteristics, aiding in a better understanding of the wetland types. Firstly, the statistical results show the ratio between the wetland and the wetland catchment area. The smaller the ratio of the wetland to its associated wetland catchment, the quicker it is influenced by impacts that are found within their wetland catchment. Therefore, it is also important to identify the types of vegetation associated with each wetland, as the vegetation serves as a buffer by somewhat protecting the wetland (Sieben, 2011). For example, it can slow down run-off and infiltration of toxins that could enter wetlands and can also trap sediments (Cronk & Fennessy, 2001).

5.4.2 Relationship between wetland types, wetland vegetation communities, and geology in the Nuwejaars catchment

Berzelia riparian (Berze) wetland types are quite dominant in the catchment, and are associated with the following vegetation: *Mimetes hirtus*, *Berzelia lanuginose*, *Psoralea spp*, *Drozera spp*, *Erica bruniades*, *Erica perpicua var latifolia*, *Erica colorans*, *Cliffortia spp*, and *Eligia spp*. This vegetation community is favourable on steep slopes and is therefore dominant in the seep wetlands. It can also be found in the valley-bottom wetlands, which are located in the upper regions of the catchment and are associated with the Cape Table Mountain and Cape Table Mountain Nardouw geology classes, which are made up of quartzitic sandstone, the hardest and most resistant to erosion.

Elim riparian wetland types (such as *Berzelia lanuginose, Psoralea spp, Drozera spp, Erica spp, Erica quadrangularis, Leucodendron laxum, Chondropetalum nudum,* and *Restio harveyii*) are also associated with some of the seeps, but mostly valley-bottom wetlands. These have a steep slope and are associated with the Cape Table Mountain groups, as well as the Cape Bokkeveld Ceres geology group, which is made up of arenites, shales, and siltstones.

5.4.3 Explanatory analysis of wetland characteristics of the Nuwejaars catchment for the different wetland types

5.4.3.1 Floodplain wetlands

The wetlands associated with the Nuwejaars River are the only floodplain wetlands in the catchment. They have been assessed as one continuous whole, covering an area of approximately 1 462 ha. The floodplain initiates at the confluence of the Janswartskraal River and the Koue River near the town of Elim and continues all the way downstream until it joins with Soetendalsvlei, a large depression wetland. It is confined to one channel and has a few meanders at the beginning of the wetland, but towards the middle of the floodplain large meander pools can be identified within the wetland.

The middle section of the floodplain is relatively flat (ranging from 5% slope in steeper areas to 2% in the flattest regions). As a result, the Nuwejaars river meanders throughout the middle of the wetland, then begins to disperse from below the confluence of the Pietersielieskloof River, where diffuse flow occurs as it is no longer constricted to a single channel. Multiple channels are present towards the lower part of the wetland. However, further downstream the wetland is again confined to one channel and continues meandering downstream until it reaches Soetendalsvlei.

During the rainy seasons from May to August, the Nuwejaars River floods, feeding the floodplain. In 2016, rainfall was experienced from February until September for an average of

10 – 15 days per month (Mehl, 2019). Most areas of the floodplain remain permanently inundated.

One of the Nuwejaars floodplain's main functions is flood attenuation, as the catchment is prone to flooding during heavy rainfall periods from June to September. The highest rainfall for 2016 was experienced in July, with a total of 104 mm of rain (Figure 4.12). However, the whole floodplain is clustered with agricultural practices around and within its boundary, which has a negative impact on its flood attenuation. With the removal of vegetation in parts of the floodplain, sediment and other materials can flow easily into the main river, allowing some areas to become obstructed. This interrupts flow and water then reaches the lower sections of the floodplain much slower, which can cause the structure in the upper section to widen.

The vegetation types that are dominant in the upper, middle, and lower floodplain plays a huge role in the floodplain's ability to carry out its function, as the vegetation provides different characteristics which complement the wetland's function (see 5.2.2.1.2).

The upper reach of the floodplain is dominated by *Prionium serratum (*Palmiet) (Euston-Brown, 2007). However, it has been densely invaded by *Acacia longofolia* and *Acacia mearnensi*, extending all the way to the confluence of the Pietersielieskloof River (Mehl, 2019). At the convergence of the Pietersielieskloof River and the Nuwejaars River, large pools were formed and are surrounded by Palmiet and aquatic reeds (Euston-Brown, 2007; Mehl, 2019).

Downstream of the Zoetendal vineyard, the floodplain is covered in reeds, grasses, and salt marsh (Euston-Brown, 2007; Mehl, 2019). The banks of the river are densely invaded by *Acacia longofolia* and *Acacia mearnensi* throughout the middle of the wetland (Mehl, 2019). It can be estimated that approximately 50% of the Nuwejaars floodplain is invaded by alien vegetation. The tall reeds within the middle floodplain are identified as *Phragmites australis,* which tends to invade the wetlands, displacing other species (Weis & Weis, 2003).

5.4.3.2 Valley-bottom wetlands

Both channeled and unchanneled valley-bottom wetlands can be found within the Nuwejaars catchment, covering an area of 2 184 ha. These wetlands receive flow from many branched streams and seeps flowing from the Bredasdorp Mountains.

The two largest channeled valley-bottoms are located along the Janswartskraal River and the Koue River. These two wetlands contribute up to 48% of flow into the Nuwejaars River, as they capture most of the water flowing via multiple seeps and smaller valley-bottom wetlands from the mountainous headwater sub-catchments (Mehl, 2019).

Flow is restricted to wet months as the catchment dries up during the drier seasons and drought periods. In the north of the Nuwejaars catchment are two discontinuous valley-bottom wetlands, found along the Pietersielieskloof River and Klien Pietersielieskloof Rivers, with another channeled valley-bottom to the west in the Pietersielieskloof sub-catchment.

To the southwest of the Nuwejaars catchment, the Elim sub-catchment can be found with a channeled valley-bottom flowing into the Nuwejaars floodplain. The Elim channeled valley-bottom, along with the Pietersielieskloof sub-catchment valley-bottoms, contribute less to the Nuwejaars floodplain than the valley-bottoms found in the mountainous headwater catchments, but they contribute to flow during the drier seasons when the mountainous headwater catchments are dried up.

The Toekoms sub-catchment in the northeast and Blomskraal sub-catchment in the south of the Nuwejaars catchment consist of unchanneled valley-bottoms. The Blomskraal catchment occurs on an undulating plain and requires a large amount of rainfall before contributing to the Nuwejaars floodplain. However, due to the presence of large wetlands within the Blomskraal sub-catchments, flows are sustained for a longer period than the mountainous Janswartskraal and Koue sub-catchments following the wet season (Mehl, 2019).

The types of vegetation that can be found within these systems are primarily *Prionium serratum* (Palmiet), restios, *Juncus lomatophyllus*, *Leucadendron spp.*, *Psoralea pinnata*, *Pennisetum macrourum* and *Berzelia* species (Euston-Brown, 2007).

The valley-bottom wetlands in the Janswartskraal and Koue sub-catchments are predominantly Palmiet wetlands, with the outer-banks occupied by Elim riparian vegetation, while the Pietersielieskloof's sub-catchment valley-bottoms are dominated by Palmiet. These three sub-catchments are invaded by alien vegetation, but the Pietersielieskloof wetlands have had some removal of Palmiet vegetation and experienced extensive gully erosion and Port Jackson alien tree invasion.

The unchanneled valley-bottom in the Toekoms sub-catchment is dominated by Elim riparian, with the lower wetland dominated by restioid vegetation (Euston-Brown, 2007).

5.4.3.3 Depressions

There are approximately 21 depressions in the Nuwejaars catchment, covering an area of 2 749 ha. The four biggest depressions within the system are Soetendalsvlei, Waskraalsvlei, Voelvlei, and Soutpan (salt pan). The depressions in the Nuwejaars catchment are in the lower sections of the catchment where the landscape is relatively flat. One exception is a small depression within the mid-catchment, but it is located on a flat section of a hilltop.

Many of the depressions in the Nuwejaars catchment (except for the small, isolated depression wetlands) have an inlet and outlet, ultimately linking them to the Nuwejaars floodplain. The Nuwejaars river flows into Soetendalsvlei, making it a large and deep wetland, but this makes it more vulnerable to the factors that have negatively impacted the lower parts of the floodplain.

Soetendalsvlei has a flat slope, and its catchment is gently sloped, which makes it easier for polluted run-off to enter the depression. The depression's primary source of water is precipitation.

Some of the depressions are permanently inundated, but during the dry seasons, water capacity is lost due to evaporation and evapotranspiration. The depressions connected through an outlet contribute to the inundation of the floodplain during dry spells.

The types of vegetation that can be found in these systems are grasses, *Phragmites australis*, and restios. Seven of the depressions are considered Black vlei vegetated wetlands, three as muddy, four as salt pans, and three as tall reed wetland types (Euston-Brown, 2007). The remainder are unvegetated wetlands with permanent open water bodies.

5.4.3.4 Seeps

Many hillslope seeps arise in the Bredasdorp Mountains in the upper section of the Nuwejaars catchment, with an average slope of between 10 and 30%, and flow into the valley-bottom wetlands feeding into the Nuwejaars river. These make up 1358 ha of the total wetlands of the catchment. These hillslope seeps are generally in pristine condition.

A rapid visual assessment on Google Earth and the work of a student (Mtengwana et al., 2020) both estimate approximately 80% of these wetlands support invasive alien vegetation. Seeps occurring in the upper reaches of the catchment, where the gradient is typically between 10 and 30%, are generally unimpacted by agricultural activities but are highly impacted by alien vegetation, whereas seep wetlands in the mid-slope and mid catchment, with slopes ranging between 2 and 5%, are impacted by agriculture in the form of cultivated fields.

Seep wetlands likely ranges between permanent and seasonal wetlands, as their primary inflow source comes from winter rainfall in the upper catchments, but the season is extended as this water seeps into the fractured sandstone rocks of the mountains and the hillslope soils of the mid-catchment, providing a longer-term source of water. However, there are several seeps found in the low-lying areas of the Nuwejaars catchment or where the landscape provides enough slope for water to seep. These seeps act as a source contributing to the Nuwejaars river. Water inputs to the seep are from subsurface flow and/or precipitation.

Seeps located in the mountainous region of the catchment are mainly dominated by *Berzelia* vegetation, but the vegetation community changes to Elim reed as slopes become concaved flowing into the valley floor. Seeps found on the plain are dominated by Elim reed; these occur along valley-bottoms and seven of the seeps are restioid. Seeps dominated by short reeds are located along Soetendalsvlei, whereas the tall reed seeps are located flowing into Voëlvlei.

5.4.3.5 Flats

A total of 4437 ha of land in the Nuwejaars catchment is occupied by flats, which is 27% of the total wetlands of the catchment. These wetlands receive their water from rainfall which can occur during any season. Their average slope ranges from 2 to 5%, indicating a gentle slope. However, they lose water through evaporation and evapotranspiration. The biggest wetland flat remains permanently saturated in parts where ferricrete is located. The vegetation dominant in these systems are restioids, such as *Chonropetalum spp, Limonium spp, Crassula spp.* (Euston-Brown, 2007). They are associated with the Cape Bokkeveld Ceres and Bredasdorp geology classes.

5.5 Summary

In conclusion, the distribution of the wetland type is largely dependent on its position in the landscape. Seep wetlands are dependent on steepness in slope, while valley-bottom slope ranges from steep to gently sloping. The floodplain’s slope is on average gently sloping but considerably flat as water spreads over the banks, and the flat wetlands have an average slope of 2 – 5% indicating that it is gently sloping but they are located on a flat surface.

The wetland catchment accounts for more than 50% of the wetlands, a massive area that could result in the wetlands being less vulnerable to impacts outside of the wetland boundary as it serves as a buffer zone. However, the impacts inside of the wetland catchment could result in poorly performing wetlands and degradation in its condition.

Most of the seep wetlands are headwaters, as they are associated with the first stream order. The waters eventually flow into the Nuwejaars catchment, which is the longest river within the catchment and associated with stream order 4.

Chapter 6: Understanding the wetlands and their landscape: Response of wetlands and the implications of poor management.

6.1 Introduction

Chapter 6 draws together the findings of Chapters 4 and 5, towards an understanding of the relationship between wetlands, their associated wetland-catchments, and the greater landscape of the Nuwejaars catchment. The Chapter focuses on the impact of agricultural stressors on wetlands by scoring the pressure of agricultural practices within a 500 m buffer of sampled wetlands. The Chapter makes use of an Agriculture Disturbance Activity Index (ADAI) for quantifying impacts, and an Agricultural Stressor Index (ASI) for measuring stressors. This supports and aids in understanding the response of different wetland types to the influence of agricultural activities.

6.2 Methodology

A study done in the United States by the United States Environmental Protection Agency (EPA) and Lomnicky et al. (2018) for the National Wetland Condition Assessment (NWCA) was used as a guideline for the methods and analysis of Chapter 6.

The analysis makes use of a Human Disturbance Activity Index (HDAI) and an Anthropogenic Stress Index (ASI) developed from indices of human disturbances and anthropogenic impact bases on field observations. The ASI focuses on the influence or stress that human disturbance activities are expected to have on wetlands (Lomnicky et al., 2018).

For this study, the analysis for the ASI will be adapted. For the HDAI, 21 activities were retained from more than 50 pre-determined activities listed in the HDAI developed by Lomnicky et al. (2018) and were grouped into 4 classes.

The HDAI was implemented as the Agriculture Disturbance Activity index, as it refers to human disturbance activities brought on by agricultural practices, and the ASI will be referred to as the Agricultural Stressor Index.

A flow diagram is presented in Figure 6. 1 indicating the steps involved in the analyses undertaken as part of Chapter 6.

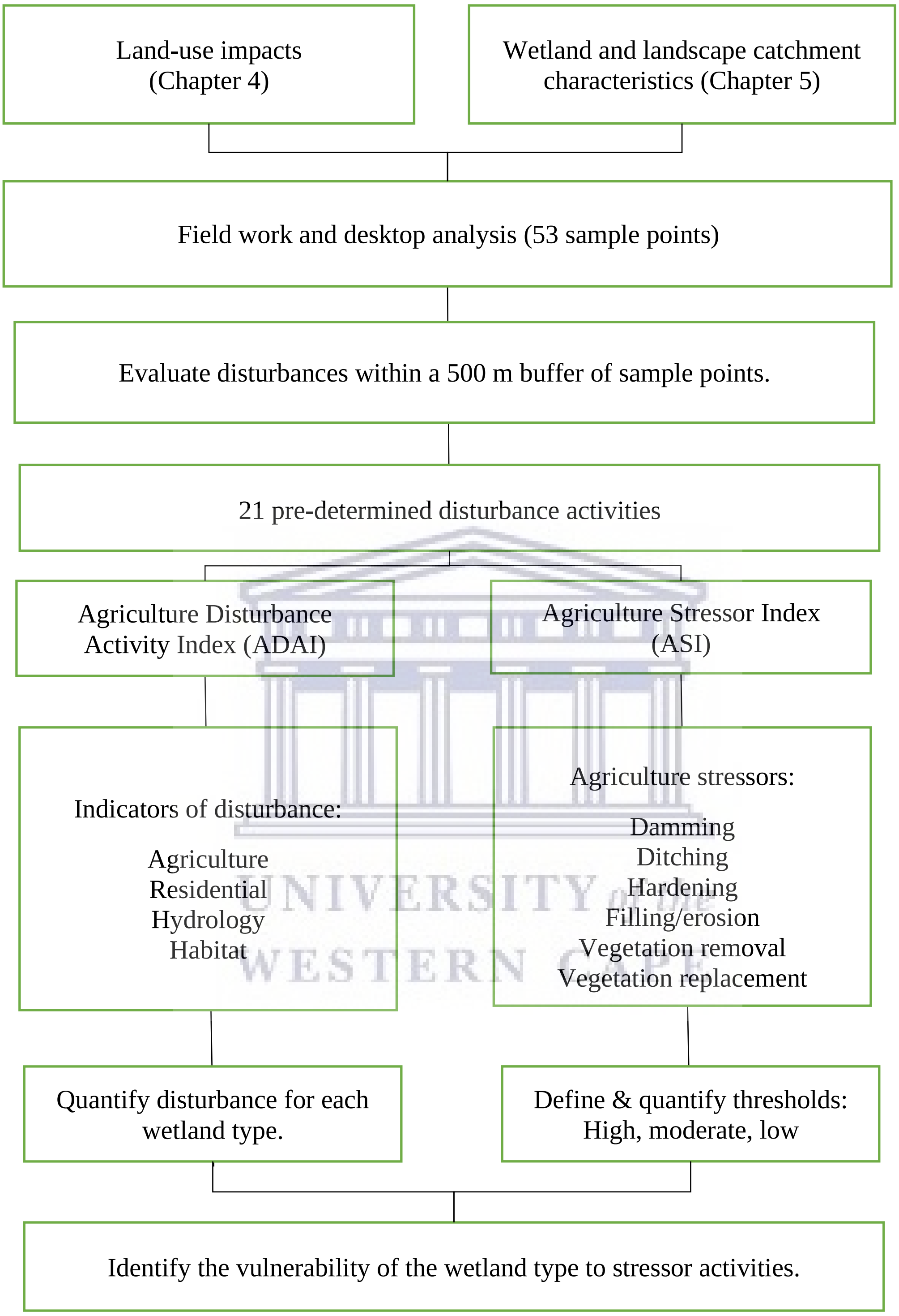


Figure 6. 1: Steps followed for the analysis of Chapter 6.

6.2.1 Data collection

6.2.1.1 Fieldwork

Fieldwork was conducted on three occasions (24 August 2018, 21 -23 August 2019; 6-8 November 2019). 53 sampling points were collected for the five different wetland types (20 = valley-bottom; 16 = seeps; 8 = depression; 5 = floodplain; 5 = flat) and along roads crossing over wetlands throughout the Nuwejaars catchment (Figure 6.2).

Field notes and photographs were taken to capture the impacts that were identified as having an influence on the wetland system at the point that was captured using a GPS. The field notes included the co-ordinates of the sample point, elevation, types of vegetation identified within the system, land-use within and around the wetland, and any other impacts related to agricultural land-use such as dams, roads, irrigation systems, and drainage ditches.

Additional sample points and field notes from a team of specialists from SANBI, CapeNature, and SanParks, were made available for this research (N. Job, personal communication, October 26, 2020). The team of specialists form part of a nature conservation, national park, and SANBI freshwater programme that are working together to improve the South African national wetland map.

In addition, a literature review was conducted to collate research from historical studies of the Agulhas Plain with focus areas in the Nuwejaars catchment (Jones et al., 2000; Cleaver & Brown, 2005). The field sample points, and associated data were used to populate a datasheet that identifies agriculture disturbance activities (see Table 6.1) (see Appendix A).

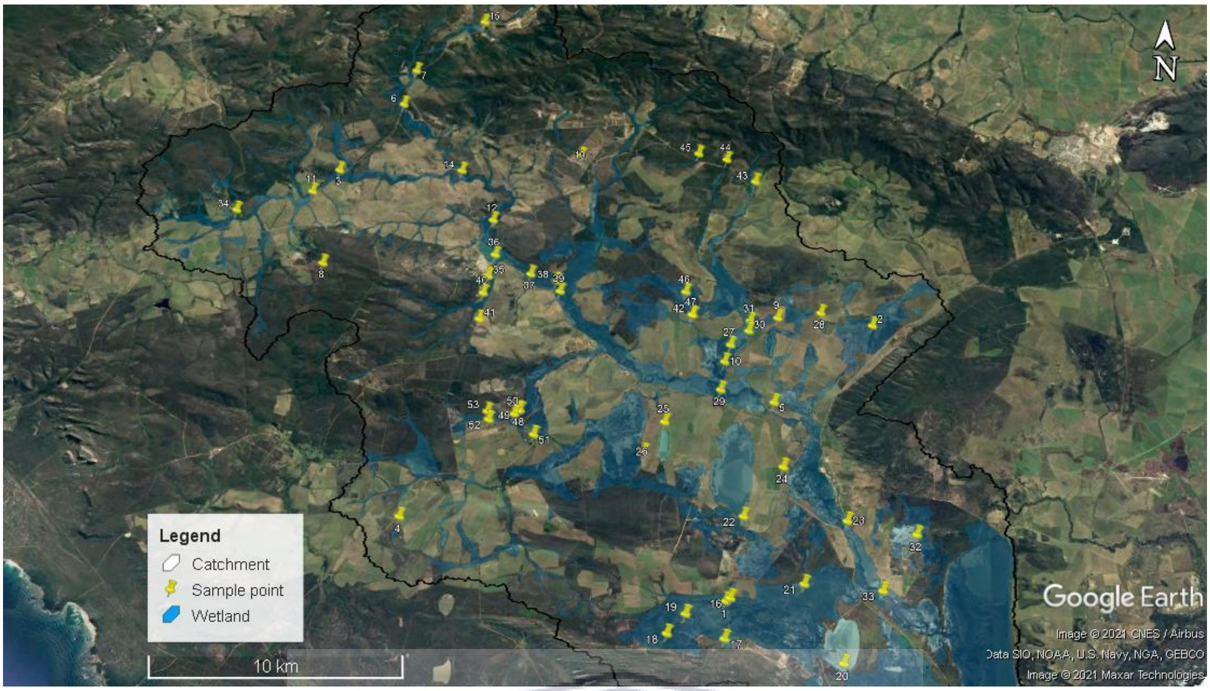


Figure 6. 2: Map showing the distribution of the 53 randomly selected sample points in the Nuwejaars catchment.

6.2.1.2 Desktop analysis

The types, extent, and magnitude of agriculture activities serving as indicators of potential stress on the wetlands in the Nuwejaars catchment were identified in Chapter 4, these include conversion of wetland to agricultural land, damming, ditching, overgrazing, infrastructure, and alien vegetation (see Figure 4.6 in Chapter 4).

A few additional indicators were developed in Chapter 5, which included the type of agricultural land types such as irrigated crops, non-irrigated crops, and fields (see Table 5.3 and Figure 5.4 in Chapter 5).

Wetland sites presenting a total area of 17 814 ha within the Nuwejaars catchment were used as sample locations, of which a non-proportional quota sample of 53 points was captured. Non-proportional quota sampling is used when the researcher is not concerned by matching the proportion of the sample, but instead, the researcher wants enough samples to assure the sample provides enough information on the smallest groups in the population (Taherdoost, 2016).

The sample points were selected based on: A) sufficient information on the site provided by field verification such as the identified type of wetland, presence or absence of vegetation types including invasive alien species, impacts identified, and condition of the wetland; and B) they cover a representative range of wetland types, landscape location (upper, middle, and lower catchment) taking into account the range of slope from steep to flat, as well as the range of less impact to high impacted wetlands.

Site and desktop observations of the presence of 21 human activities associated with agriculture practices were used to quantify agricultural influences on wetlands by defining two types of indices. The first index, agriculture disturbance activity index (ADAI), and the second, the agricultural stressor index (ASI) (Lomnicky et al., 2018).

6.2.2 Data Analysis

6.2.2.1 Quantifying the extent of agriculture stressors on wetlands in the Nuwejaars catchment.

Centred on each of the sample points, a 500 m radius buffer was allocated through ArcGIS for identifying evidence of agricultural activities within the centre and buffer zone.

According to Ebregt & De Greve (2000), the buffer should be determined according to the objectives, type of land-use systems, and threats, therefore, stating that the buffer zone is variable. However, it has been indicated that efficient buffer widths range from 3 m to 100 m depending on the area to be protected, therefore it should be taking into consideration when using a circular buffer to measure and quantify impacts and disturbance, that the centre point of the buffer be set where the boundary of the buffer extends evenly over each edge of the wetland (Hawes & Smith, 2005).

In consideration of selecting the 500 m buffer: a 200 m, and 1 000 m buffer was observed in comparison to the 500 m around each sample point. During the desktop observation of the three buffers, each proved to have a weakness.

The 200 m buffer complemented smaller wetlands such as depressions which fell perfectly within the boundary, whereas for the bigger wetlands it did not capture the full extent of the wetland in terms of covering enough of the impacted boundaries of the wetland. Macfarlane et al. (2019) highlighted that a 200 m buffer provides an estimate of the local upslope catchment of a wetland. However, Macfarlane et al. (2019) acknowledged that for an exceedingly small wetland the 200 m buffer would possibly extend far beyond the wetland's local upslope catchment.

The 1 000 m proved to be more effective for bigger wetland areas where the sample point fell within the centre of the wetland in which it covered the extent of impacts or disturbances from both sides of the wetland's boundary. However, it was not effective for smaller wetlands and for sample points that were located along the sides of the bigger wetland as the buffer would then extend far over the upslope catchment, and the impacts and disturbances from the opposite side of the wetland boundary are excluded. On the other hand, Macfarlane et al. (2019) stated that for bigger wetlands systems, the local upslope boundary would fall short of the 200 m buffer.

With these statements taking into consideration the buffer for this study was set to 500 m. The 500 m buffer proved to be suitable for the wetlands in the Nuwejaars catchment as many of the sampled wetlands area are big, and the 500 m restricted the buffer from extending far over the catchment boundary and reduces overlapping of buffers where sample points are in close proximity.

Furthermore, the presence/absence of agricultural activities was tallied. This data was sourced through a desktop analysis, field notes that are likely to alter hydrology, vegetation, and extent of wetland, as well as those identified by additional sources (Jones et al., 2000; Cleaver & Brown, 2005).

6.2.2.1.1 500 m buffer-Agriculture Disturbance Activity Index

Four classes (agriculture, residential, hydrologic modifications, and habitat modifications; see Table 6.1) were developed for the ADAI, by grouping the 21 agricultural disturbance activities. It was then summed within and across the four metrics to determine an overall ADAI score based on the number of impact activities located within the buffer.

The 500 m-ADAI was further used to describe the types and intensity of the four classes of agriculture activity throughout the Nuwejaars catchment.

Table 6. 1: Checklist of agriculture disturbance activities observed in the 500 m buffer for each sample point.

Agriculture disturbance activity class	**Observations**
Agriculture	Pasture/hay, crops, fallow fields, old fields, dairy, vineyards, rural residential, irrigation
Residential	Road-gravel, road-tar, dumping
Hydrological modification	Ditches/channelisation, dikes/dams/roads, excavation/dredging, sediment, soil loss, inlets/outlets, point source/pipe/culverts
Habitat modification	Trails, soil compaction, soil erosion

6.2.2.1.2 500 m buffer-Agriculture Stressor Index

For the 500 m ASI, the disturbance activities were reclassified into six stressor categories (damming, ditching, hardening, filling/soil erosion, vegetation removal, vegetation replacement; see Table 6.2) according to their expected effects on each of the six aspects of wetland condition.

Each disturbance activity observation was assigned to only one stressor category based on the best judgment of the most significant type of stress imposed by each of the listed agriculture disturbance types (Lomnicky et al., 2018).

The desktop analysis through ArcGIS and Google Earth provided observations for two types of agricultural activity classes: hydrologic modification, and habitat modification that was sub-divided into six stressor categories, of which the 21 disturbance activities were divided among conditions.

Descriptions of the agricultural disturbance activities assigned to each of the six stressor categories are listed in Table 6.2 with these categories chosen to represent the dominant stressor types.

Damming included activities that impede or impound flow from within the buffer, while ditching referred to observations related to signs of draining. Hardening incorporated any activities and infrastructure that influence soil compaction that results in soil hardening. Vegetation removal included activities related to damage, removal, or loss of wetland vegetation. Vegetation replacement included altered vegetation conditions as a result of agriculture activities within the site.

Table 6.2: Agricultural disturbance metrics and disturbance indicator checklists adapted from Lomnicky et al. (2018).

Agricultural disturbance activity class	Stressor category	Description	Disturbance type checklist items (Jones et al., 2000; Cleaver & Brown, 2005)
1) Hydrologic modification	a) Damming	Any field observation related to impounding or impeding water flow from or within the site.	Road, dam wall, berms, dams, drifts (cement, gravel, stone)
	b) Ditching	Any field observation related to draining water	Ditches, channelization, irrigation water pumps, culverts
2) Habitat modifications	c) Hardening	Any field observation related to soil compaction, including activities and infrastructure that primarily result in soil hardening.	Roads, soil compaction, confined animal feeding, dairy, rural residential, concrete, gravel
	d) Filling/ erosion	Any field observation related to soil erosion or deposition	Soil erosion, surface mine, dump site
	e) Vegetation removal	Any field observation related to loss, removal, or damage of wetland vegetation	Grazing, pasture/hay, bare soil
	f) Vegetation replacemen t	Any field observation of altered vegetation within the site due to agricultural activities	Grain, planted pastures, fallow, flaxseed, vineyards, canola, olives, rooibos, flower, old fields.

A separate Agricultural Stress Index metric (500m-ASIm) was calculated for each of the six stressors as impact weighting.

The weight amongst the two agricultural activity classes was calculated as the percentage of agriculture disturbance activity associated with each agricultural disturbance activity class, divided by the total disturbance activities.

The impact weighing scores were then further calculated for each stressor category: the number of agriculture disturbances associated with each stressor, divided by the number of impacts for its associated disturbance class, multiplied by the weighing value (Wv) of the disturbance class (see Table 6.3).

The scores were used to set stressor-level thresholds for each stressor category (see Table 6.4).

Table 6. 3: Impact weight assigned to each stressor category.

<table>
<tr><td></td><td colspan="6">Agriculture disturbance activities = 21
Weighting value (Wv) = 100% / Weighting factor (Wf) = 1</td></tr>
<tr><td>Agricultural disturbance class</td><td colspan="3">Hydrological modification = 9
Wv = 43% / Wf = 0.43</td><td colspan="3">Habitat modification = 12
Wv = 57% / Wf = 0.57</td></tr>
<tr><td>Stressor category</td><td>Damming = 2
Wv = 10
Wf = 0.1</td><td>Ditching = 3
Wv = 14
Wf = 0.14</td><td>Hardening = 4
Wv = 19
Wf = 0.19</td><td>Infilling /erosion = 4
Wv = 19
Wf = 0.19</td><td>Vegetation removal = 5
Wv = 24
Wf = 0.24</td><td>Vegetation replacement = 3
Wv = 14
Wf = 0.14</td></tr>
</table>

Table 6. 4: Threshold definition and assignment of stressor-level categories

Disturbance class	Indicators of stress	Low stressor-level Threshold	Moderate stressor-level threshold	High stressor-level threshold
Hydrological modification	Damming Ditching Hardening	Score = 0	< 0.1	≥ 0.1
Habitat modification	Filling/Erosion Vegetation removal Vegetation replacement	Score = 0	< 0.1	≥ 0.1
Total scoring of overall impact:		Score = 0	< 0.1	≥ 0.1

Spearman rank-order correlations were calculated among the six 500 m-ASIs to evaluate the strength of their association. This was selected over Pearson's correlations because normality of the data was not assumed, and Spearman's coefficient is generally more robust to large data outliers (Lomnicky et al., 2018).

6.2.2.2 Multiple Correspondence Analysis

Multiple Correspondence Analysis (MCA) allows for the analysis of categorical variables containing more than two variables. It forms part of descriptive methods such as principal component analysis (PCA) and factor analysis, which expose patterns in complex datasets. However, Multiple Correspondence Analysis is used to signify and model points in a multidimensional Euclidean space (Costa et al., 2013).

The result of this analysis was interpreted through the relative position of the plots, and their distribution along the dimensions. MCA is powerful in its methods as it reveals groupings of variable categories in the dimensional spaces, providing key insight on relationships between categories (Johnson & Wichern, 2007).

This analysis was used to determine the relationship and spatial distribution of the categories of each set of variables associated with agricultural stressors and wetland characteristics. Costa et al. (2013) highlighted the relevance of using this analysis for large amounts of categorical variables.

6.3 Results

6.3.1 Quantifying agriculture disturbance activity categories on wetlands within a 1000 m buffer.

Twenty-one agricultural disturbance activities that cause stress to hydrological function and wetland habitat were identified in the sample wetlands and 500 m buffer.

Figure 6.3 represents what percentage of the 53 sampled wetlands are estimated to be impacted by each of these disturbance types. Across the catchment, pasture and hay were documented to be the most common of the 21 agriculture disturbance activities, with more than 40% of the wetlands sampled estimated with a high presence of pasture/hay in the 500 m buffer.

In addition, eight of the 21 disturbance activities were estimated to be present in more than 10% of the wetlands. They include gravel-road, dikes/dams/roads, sediment, point source/pipe/culverts, trails, ditches/channelisation, and soil erosion.

Gravel roads were the 2nd most prevalent disturbance activity identified, which highlights the influence of gravel roads on wetlands in the Nuwejaars catchment and their potential of fragmentation to the overall landscape.

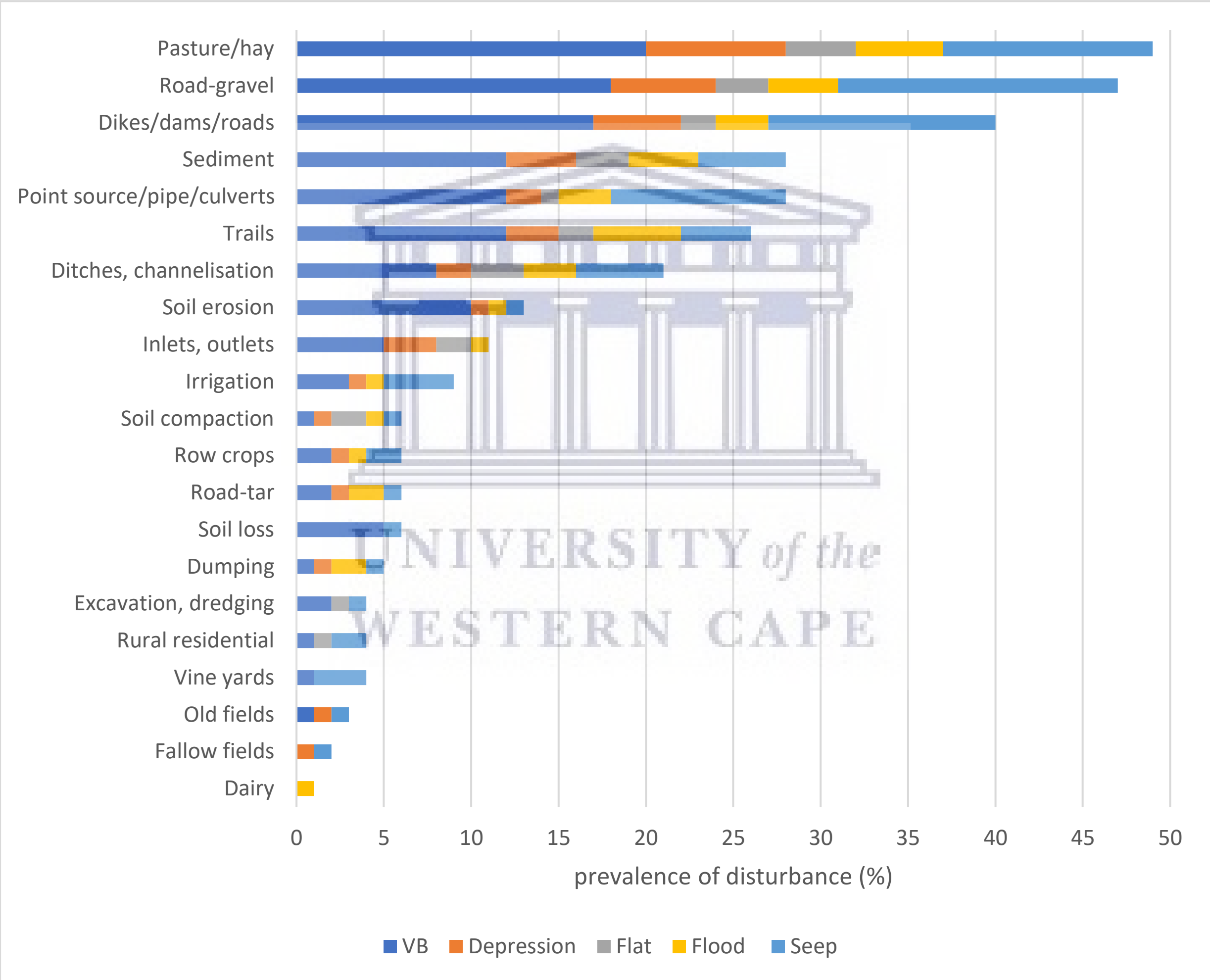


Figure 6. 3: Estimates of the prevalence of individual agriculture disturbance activities in the sample wetlands.

Similar to the result for the overall score of the wetlands sampled in Figure 6.3, pasture/hay also topped the list of observed disturbance activities in terms of the percentage of wetland area covered by three of the six wetland groups (Figure 6.4).

Seven disturbance activities (pasture/hay, gravel road, dikes/dams/roads, sediment, point source/pipe/culverts, trails, ditches/channelisation, and soil compaction) were found to be associated with all the wetland types, six of these appeared on the six highest disturbance activity graphs (Figure 6.4). However, the percentage of the area where these types of disturbances were identified varied substantially among the different wetland types.

Valley-bottom wetlands showed the highest count for disturbance activity (Table 6.5) and percentage of the area impacted, with the six highest being above 12%, and the highest percentage (20%) affected by pasture/hay.

Seep wetlands ranked second highest, with the six highest disturbances being no less than 5%, and the highest disturbance activity observed in the seeps attributed to gravel roads (16%).

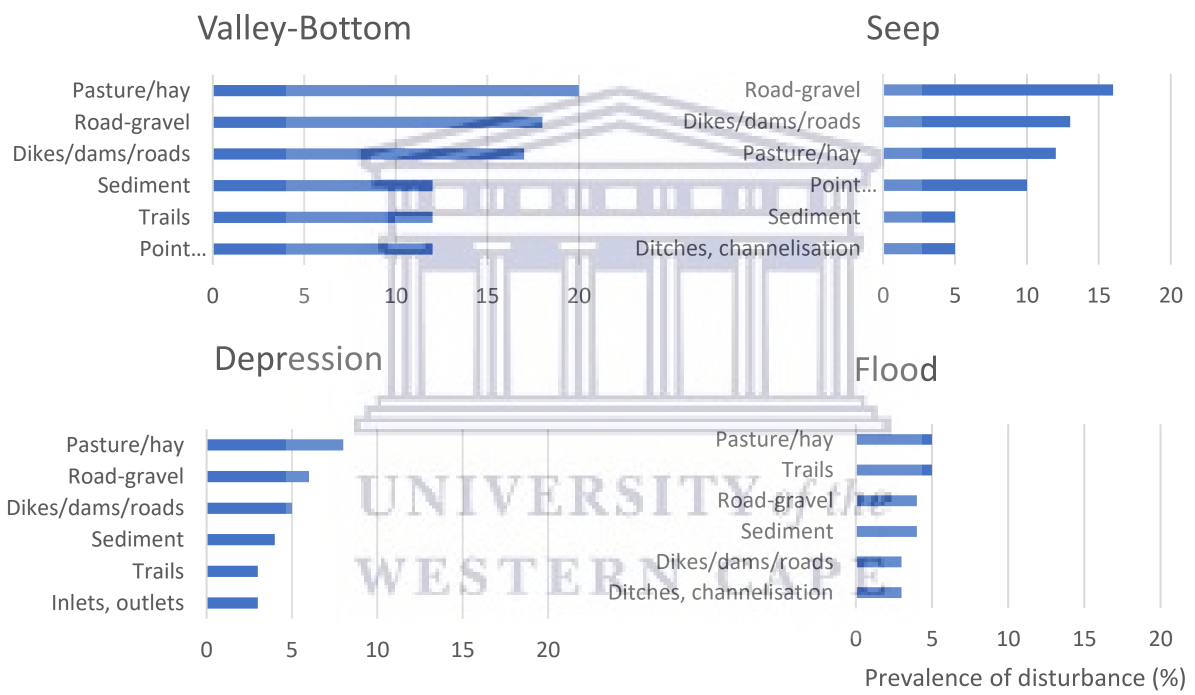
Depressions rank 3rd, with the highest percentage area of less than 10%, with pasture/hay as the highest disturbance activity.

Floodplains and flats ranked the lowest implying that the least number of disturbances was identified within their sampled buffers. Although, the highest percentage of disturbance in floodplains attributed to pasture/hay and trails, which both occupy 5%, and with pasture/hay ranking highest for flats with an area of 4.

However, the low rank for the floodplain is superficial as the percentage of the total area of the floodplain was not accounted for as only 5 sample points within a 500 m buffer each made up the area for floodplains for this analysis.

Table 6. 5: Total number of disturbance activities prevalent in the total area of the five wetland types. Rank* represents the highest to lowest disturbed wetland type.

Wetland type	Number of disturbance activities in the total wetland area	Rank*
Valley-Bottom	134	1
Seep	41	2
Depression	24	3
Floodplain	37	4
Flat	84	5



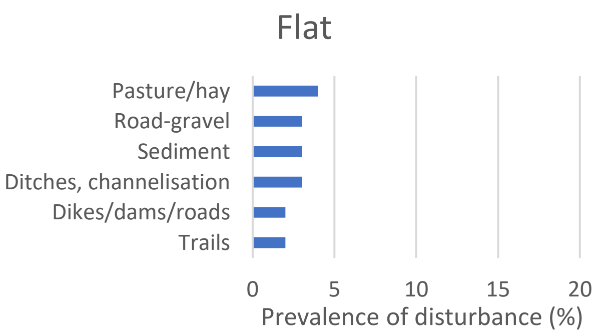


Figure 6. 4: Population estimates of the presence of the six most prevalent agriculture disturbance activities in each of the wetland types, expressed as the percentage of sample wetland area in each group.

6.3.2 Agricultural Stress Indices

The overall 500 m ASI and results for the two-component metrics; hydrologic modification and habitat modification summarise the extent of the general agricultural stress for the wetlands in the Nuwejaars catchment.

The impact weighted median population values of these agricultural stressor metric scores for the overall catchment were 0.1 for hydrologic modification and 0.2 for habitat modification indicating that they are highly modified. None of the metrics had a score of 0 (unmodified) (see Table 6.6).

Overall, the 95th percentiles for the metrics in the wetland buffers ranged from 0.2 for habitat modification to 0.3 habitat modification indicating high modification. Habitat modification also tended to have the highest or near highest 95th percentile values for each of the individual wetlands, with the 95th percentile of 0.3 for depressions, floodplains, and valley-bottoms and 0.2 for flats and seeps.

The 95th percentile for hydrologic modification was highest for flats, seeps, and valley-bottoms with a score of 0.2. 95th percentiles reflecting a score of 0.1 were quite rare amongst both groups but appear in the hydrologic modification for depressions and floodplains.

Among the wetland groups, the overall 500 m ASI showed the highest median value of 0.34 in valley-bottoms, the highest 75th percentile with a score of 0.38 in floodplains, with the highest 95th percentile value of 0.43 in seeps (Figure 6.5).

Table 6. 6: Agricultural stressor index metric (500 m – ASIm) population medians. Population 5th and 95th percentiles are shown in parenthesis.

Wetland types	Hydrologic modification	Habitat modification
Depression	0.1 (0.05-0.1)	0.1 (0.1-0.3)
Flat	0.1 (0-0.2)	0.1 (0.1 -0.2)
Floodplain	0.1 (0.1)	0.2 (0.2-0.3)
Seep	0.1 (0-0.2)	0.1 (0.05-0.2)
Valley-bottom (VB)	0.1 (0-0.2)	0.2 (0.05-0.3)
Total	0.1 (0-0.2)	0.2 (0.05-0.3)

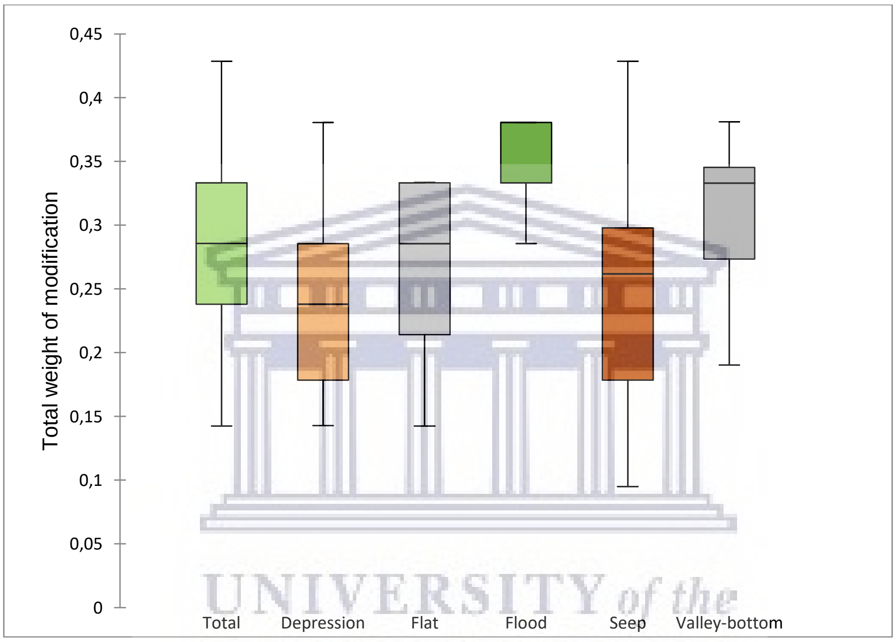


Figure 6. 5: Box and whiskers plots representing the Anthropogenic Stressor Index for the 500 m buffer for each wetland type. Boxes show the population-weighted 25th and 75th percentiles. The line in the box is the median, the whiskers show the 5th and 95th percentile and the lines at the end of the whiskers show the maximum and minimum weight.

6.3.2.1 Correlations among ASI

Correlations among the six 500 m-ASIs were mostly very weak (Table 6.7). Vegetation removal and damming were strongly correlated (r=0.38, p <0.0001).

The relationships of the other variables were positive but with a low Spearman correlation coefficient of 0.22 or less, except for ditching and hardening, vegetation removal and hardening, and filling/erosion and vegetation replacement which had negative correlation coefficients. However, because of the small sample size (*n*=53), all the negative correlations were not statistically significant.

Table 6. 7: Spearman rank-order correlations (n=53; p<0.0001 for all) among the six agricultural stressor indices (500 m -ASIs). Values in bold indicate that correlation is significant at 0.05.

Variables	Dam	Ditch	Hardening	Filling/erosion	Vegetation removal	Vegetation replacement
Damming	**1,00**	0,13	0,22	0,12	**0,38**	0,20
Ditching	0,13	**1,00**	-0,14	0,18	0,18	0,10
Hardening	0,22	-0,14	**1,00**	0,18	-0,05	0,02
Filling/erosion	0,12	0,18	0,18	**1,00**	0,06	-0,15
Vegetation removal	**0,38**	0,18	-0,05	0,06	**1,00**	0,14
Vegetation replacement	0,20	0,10	0,02	-0,15	0,14	**1,00**

The intensity of agricultural stress, as measured by the ASIs, across the wetland types was conveyed in levels of low, moderate, or high stress to make the results more generalisable (Table 6.4).

The population estimates of the percentage of agricultural stress for each stressor category are shown in Figure 6.6. Most of the sampled wetlands are subjected to high levels of stress for hardening which results from soil compaction, abandoned fields, and vegetation replacement as a result of conversion: a total percentage of 86% of wetlands have high levels of stress for hardening and a total of 83% for vegetation replacement. This is followed by damming (66%) and ditching (43%), which fall in the moderate stress level. Note that these percentages are estimations from the sample sites and not of the overall wetland extent in the catchment.

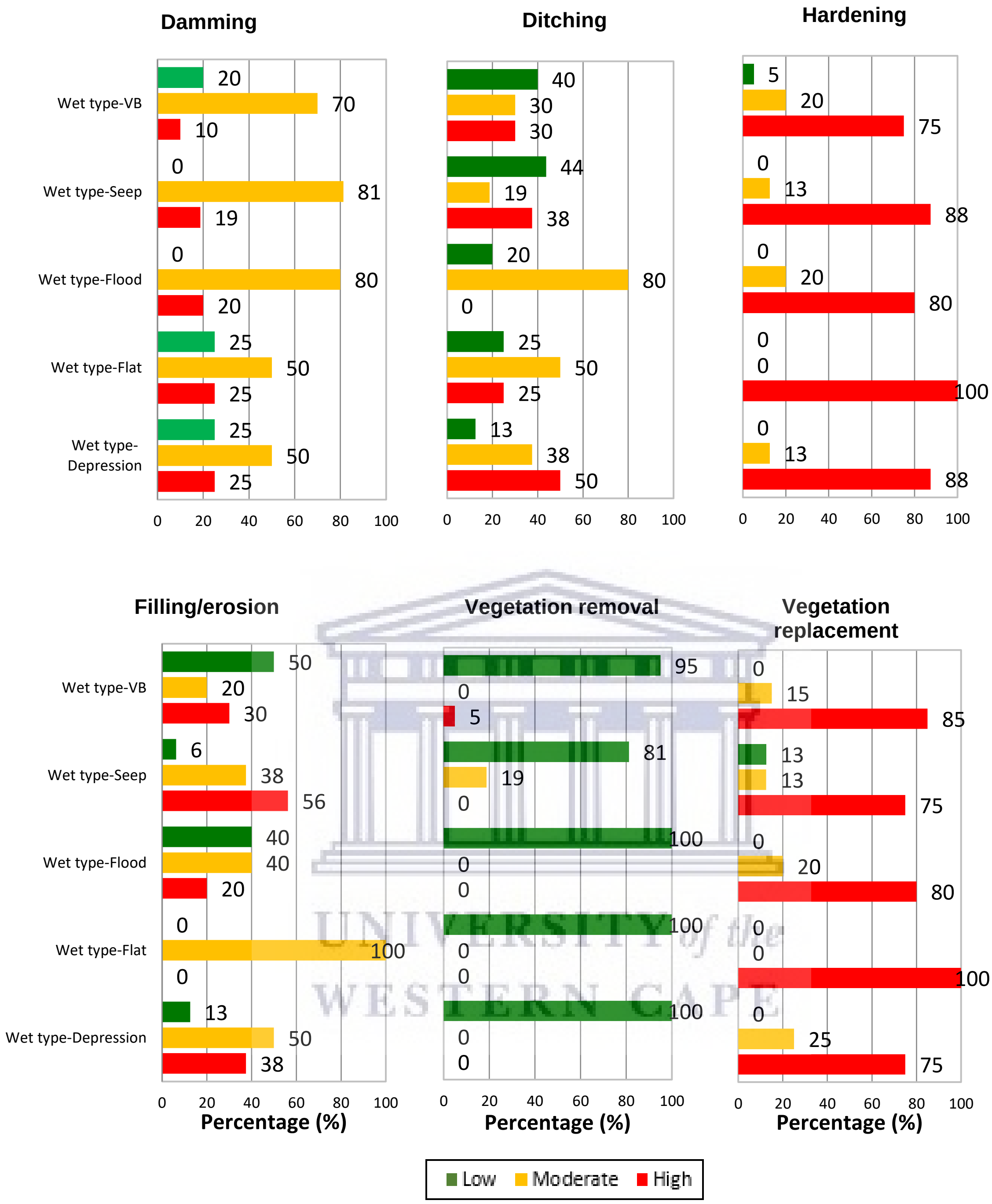


Figure 6. 6: Population estimates of the extent of wetland agricultural stress for each stressor category.

The estimates for the total stressor weights are shown in Table 6.8. The weights for hydrologic modification show that all wetlands that were impacted by damming, ditching, and hardening activities were subjected to moderate stress. The habitat modification shows high scores for each wetland type indicating that habitat modification has higher stress on all wetland types.

The total of hydrologic modification and habitat modification for each wetland indicates that the agricultural stressors for the wetland types have overall a high-stress level.

Table 6.9 confirms the total percentage of stress for each category and each wetland. High-stress levels are shown for depression, flat, floodplain, and seep wetlands, with all of them showing 100% high stress, while valley-bottom wetlands show only slightly lower levels, namely, 95% high stress and 5% moderate stress levels.

Table 6. 8: Estimate of the total stressor weight for the agricultural stress index.

Wet type	Hydrological weight	Habitat weight	Total weight
Depression	0,7	1,2	1,9
Flat	0,6	1,3	2
Floodplain	0,6	1,4	2
Seep	0,7	1,2	1,9
Valley Bottom	0,7	1,2	1,9
ALL	3,2	6,4	

Table 6. 9: Population estimates of the total weight of agricultural stress on wetlands.

	Stressor level (%)		
Wetland type	**Low**	**Moderate**	**High**
Depression	0	0	100
Flat	0	0	100
Floodplain	0	0	100
Seep	0	0	100
Valley bottom	0	5	95

6.3.3 Relationship between the agricultural stressor categories and wetland characteristics

The sum of the proportion of variance explained by the horizontal and vertical dimensions (axis labels) amounts to approximately 20% of the variance in the data. As the data set consists of a large amount of data of categorical variables, 15 factors were generated in total: thus, the variance was relatively low.

Factor 1 and factor 2 represented the highest variance. This means only 20% of the variance is considered in the correspondence summary map and due to the low variance, there is a greater probability that the correspondence summary map will be absent of other significant relationships that could be presented in other factors of lower variance.

In Figure 6.7, the lower left quadrant of the map shows that floodplains are associated with low-stress levels of hardening, filling/erosion, and moderate stress levels of ditching. Similarly, depressions show the same levels of stress.

Wetland vegetation types that are associated with low-stress levels for hardening, filling/erosion, and moderate stress levels are tall reed, restioid, muddy vlei, and black vlei. These are associated with wetlands that are found on plains where the slope is flat to gentle, and the relative relief is between 16 to 30 m, with Cape Bokkeveld Ceres geology, and are found to be associated with both stream orders of 4.

On the upper left quadrant, high-stress levels of hardening are found furthest away from the origin indicating that it is highly distinctive in the second factor and can be discriminating. It also shows a positive variation with high stressors of vegetation replacement where streams are absent in the landscape catchment (LandCat SO-0).

High levels of filling/erosion are also found in this quadrant showing positive variation with no presence of alien vegetation and are associated with wetlands present with the 2nd stream order. These high stressors show positive variation where the dominant geology is Bredasdorp and where wetland vegetation is dominated by short reeds.

High-stress levels of damming show some variation with the latter characteristics as well as with irregular plains where the slope is gently sloping, and relative relief is between 31 to 90 m.

High levels of vegetation removal and moderate levels of vegetation replacement along with wetland flats are distributed too close to the origin and therefore assumed to have no variation as they are indistinctive.

In the top-right quadrant, low levels of ditching and moderate levels of hardening represent a positive variation and are seen to be associated with stream order 3 in the low mountainous regions. Low levels of ditching and moderate levels of hardening also show a positive variation with valley-bottom wetlands and Palmiet where an association with Cape Table Mountain, Malmesbury Tygerberg, and Cape Granite are the dominant geology.

In the bottom-right quadrant, a high-stress level of ditching, moderate levels of filling/erosion and vegetation removal, and the presence of invasive alien vegetation showed positive variation with seep wetlands that show characteristics of sloping, wetlands associated with the 1st stream order, as well as with wetland vegetations such as Berzelia, and Elim riparian and where the geology is Cape Table Mountain Nardouw. Low levels of damming are shown to be associated with these characteristics as well.

The Figure showed that flats are indistinctive which is a result of the limited number of flats found in the Nuwejaars catchment of which only 4 flats were sampled for this analysis, which affected its spatial distribution on the correspondence summary map.

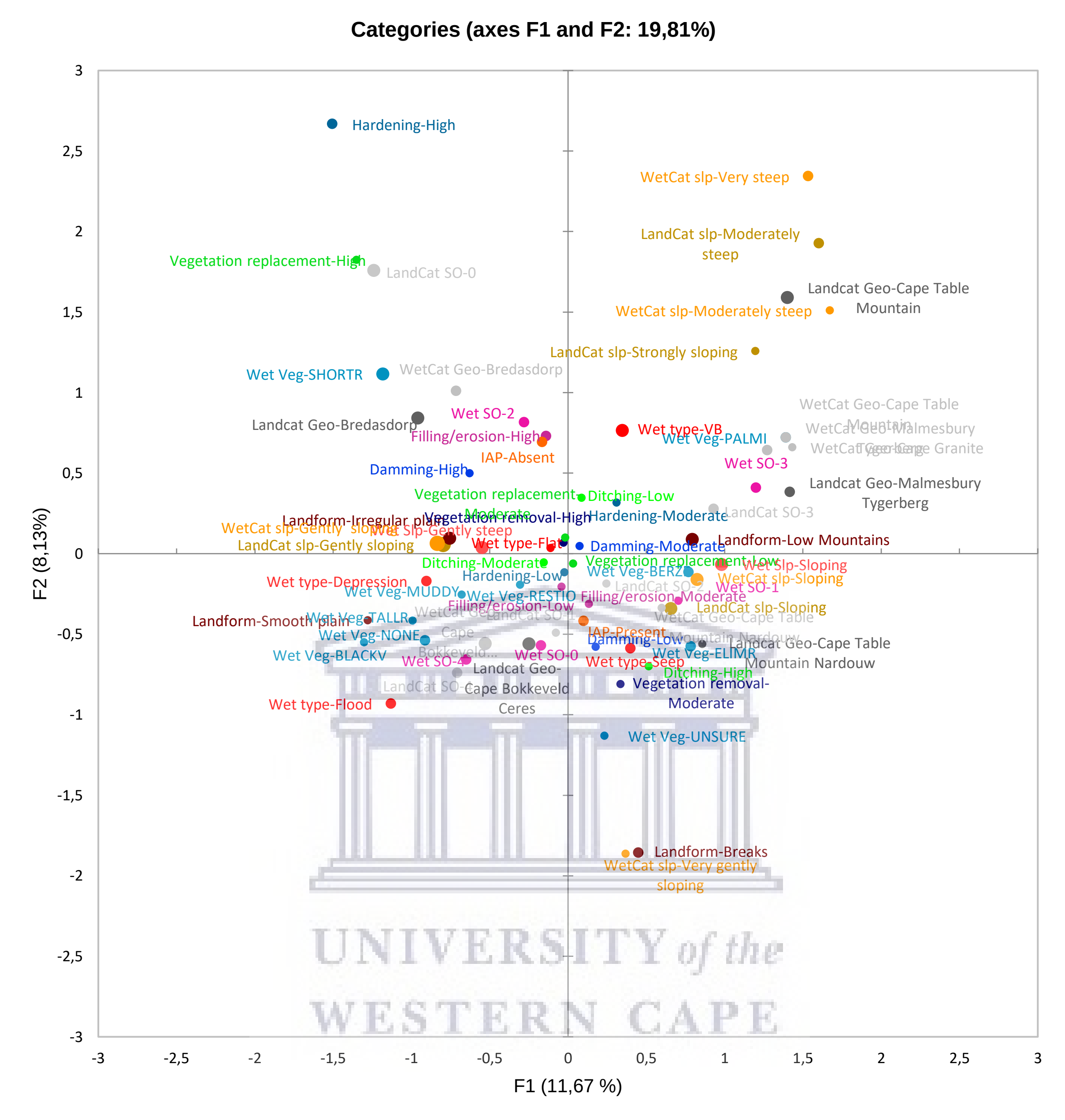


Figure 6.7: Multiple Correspondence Analysis summary map of the relationship of agricultural stressors with wetland, wetland catchment, and landscape catchment characteristics

6.4 Discussion

6.4.1 Agriculture disturbance activity and agricultural stressors in wetlands

The distributions of the 500 m-ADAI identified eight common disturbance impacts found in each of the wetland types sampled in the Nuwejaars catchment: pasture/hay, gravel roads, dams, sediment, culverts, pipes, trails, ditches, and soil compaction (Nieuwoudt et al., 2018). The extent of these activities varies quite considerably among the wetland types.

Valley-bottom wetlands have been identified as the wetland with the highest percentage of influence for each of these activities, followed by seeps, depressions, floodplain, and lastly flats. These activities have an extensive influence on the conditions of wetlands, and research (Jones et al., 2000; Cleaver & Brown, 2005) has shown that these activities have negative effects on wetlands.

The results showed that valley-bottom and seep wetlands are the most highly influenced by agricultural disturbance with many of the listed activities all being noted as occurring within and around these wetland sites (Nieuwoudt et al., 2018). This assessment provides useful information on what influences the vulnerability of wetlands in the Nuwejaars catchment.

The prevalence of the disturbance activities was highly consistent in terms of the percentage of wetlands with high agricultural stress. Agricultural stress as measured by the 500 m-ASIs were relatively consistent with the results of the disturbance activities prevalent. There were high levels of activities that "harden" the wetland's surface (soil compaction, and abandonment of fields), which influenced 86% of all the wetland types that were sampled.

Similarly, there were high levels of activity related to vegetation replacement (involving the conversion of wetland to agricultural fields for row crops, vineyards) which influenced 83% of the wetlands sampled.

Hydrology stressors such as damming, ditching, and hardening, affect the flow of water entering and exiting the wetland this has the potential of negatively impacting the nutrient cycle, the productivity of plants, and overall physical habitat of the wetland (Blann et al., 2009; Jackson et al., 2016; Hirpo, 2018).

The loss of vegetation, resulting from ploughing, overgrazing, and converting of wetlands may increase pollutant loads, sediment, and nutrients from entering the wetland and potentially remaining in a wetland initially influencing the habitat functions of a wetland (Dunne, 2011;

Morris & Reich, 2013; Pages et al., 2019). It is no surprise that the dominant types of agricultural stressors and their high percentage of stress on wetlands differ when assessing the stressor categories separately (Figure 6. 5). This is a result of the high density of agricultural land-use and diversity of geomorphology and water regimes in the catchment.

6.4.2 Relationship between stressor levels and wetland characteristics

The distribution of the stressors to the associated characteristics of the wetland types in the Nuwejaars catchment showed that high levels of hardening are very much prevalent in the catchment and are associated with high levels of stress from vegetation replacement (Jackson et al., 2016).

This entails that the disturbance activities of roads, confined feeding of animals, rural residentials that lead to soil compaction result in hardening stress, along with the conversion from wetland to agricultural land resulting in vegetation replacement within the catchment and have contributed to the loss and degradation of the wetlands, supporting the statement that stressors are unlikely to occur in isolation (Jackson et al., 2016). These stresses are commonly evident where streams are absent in the affected wetlands, which means they are more vulnerable to losing their structural and biological compositions.

High levels of filling/erosion which are associated with disturbance activities such as soil erosion, infilling, excavation, dredging, and sediment exposure are commonly found on irregular plains with sandy soils associated with the Bredasdorp geology, these areas are prone to erosion as soils are lost and a large amount of sediment is exposed to the wetlands through flow or run-off.

High-stress levels of damming show some variation with these characteristics as well as with irregular plains where the slope is gently sloping. High levels of vegetation removal and moderate levels of vegetation replacement along with wetland flats are distributed too close to the origin and are therefore assumed to have no variation as they are indistinctive. These characteristics are highly associated with valley-bottom wetlands and some of the lowland seeps, indicating that these wetlands are most vulnerable to damming, and vegetation removal which has been identified in the catchment and seen from the historical analysis as well as in historical literature where Cleaver and Brown (2005), identified that damming and ditching can greatly affect and modify the flow patterns of water in the wetlands, as well as Jones et al. (2000), highlighting that uncontrolled water abstraction from irrigation, bulldozing of wetlands and riparian zones, and damming are the greatest threat from agriculture.

The high-stress level of ditching is detected in association with seeps. These are evident in the historical analysis where drainage ditches have been identified from the aerial photographs indicating the presence of drainage ditches, culvert, and irrigation in the lowland seeps and as well as in flat wetlands.

The presence of invasive alien vegetation was highly associated with seep wetlands in the results despite its distribution affecting wetlands throughout the catchment (Jackson et al., 2016; Van Wilgen et al., 2016). In Chapter 4, Figure 4. 11 it is evident that the highest concentration of alien vegetation is found in the upper part of the Nuwejaars catchment in the mountainous region of the catchment where sloping, and 1st stream orders are present. The geology in this part of the catchment consists of sandstone, shale, and arenite which is favourable to Berzelia, and Elim riparian vegetation types. However, it is therefore susceptible to impacts of alien invasion because of heavy grazing, informal tracks, and damming (Van Wilgen et al., 2016).

The results have indicated that floodplains and depressions with the following vegetation present in the wetland tall reeds, restioid, muddy and Black vlei are under the least stress as only moderate levels of stress from ditching are shown in association to the two wetland types.

Jones et al. (2000) have identified some of the depressions and partial parts of the lower section of the Nuwejaars river to be in a good condition with fewer threats.

The findings, therefore, contradict the results of the stressors in the overall wetland where an overall high level of agricultural stress is found in all the wetland types.

6.5 Summary

In conclusion, agriculture disturbance activities have a major influence on the wetland types in the Nuwejaars catchment. They place high-stress levels on the wetlands, with valley bottom and seeps being vulnerable to these activities.

The results of this chapter have highlighted that the highest stress placed on wetlands in the catchment is habitat modification which has shown an overall high score on all the wetland types with hydrologic modification causing moderate amounts of stress.

The overall stressor level indicates that the sampled wetlands are highly stressed and should be considered for priority conservation; thus, activities should be monitored for their impact on these wetland types.

Chapter 7: Conclusion and Recommendations

This study has drawn together an analysis of historical change and a description of wetland characteristics to help understand the relationship between wetlands and their landscape. A catchment approach was used to investigate the impact of agricultural activities on the relationship between wetlands and their catchment. The benefits of a whole catchment approach to assessments are that they can aid in identifying which systems are suitable and which wetland systems, based on the functionality of the wetland types and their current conditions, are to be conserved. It can aid in determining suitable buffer zones between agricultural land-uses and associated activities, as well as other land-use types, and the wetland and wetlands catchment.

This study has found that the estimated historical wetland extent of 17 814 ha has diminished over the 78 years by approximately 3 5687 ha and that there has been an approximate overall 20% loss of total wetland extent in the Nuwejaars catchment. This is less than the commonly stated estimation that more than 50% of the country's wetlands have been lost (Kotze & Breen, 1995) and that only 15% of the country's wetlands remain in an unmodified or near-natural state (Van Deventer et al., 2019).

An in-depth analysis of the historical changes which occurred in the Nuwejaars catchment over three time periods has shown that the highest loss and degradation of wetlands were floodplains which lost a total of 39% of their historical extent, followed by flats with a total of 26%, and valley-bottoms which suffered a total loss of 20%. The historical analysis shows that the biggest threat to these wetlands was from ploughed and drained land.

The vulnerability indices that measured wetlands susceptibility towards agriculture and invasive alien species developed by Cole et al. (2000) showed a high score of threat potential. This supports the finding that the increase in agriculture has greatly affected the wetland vegetation type of which 12% is degraded This is a result of wetlands that have been drained and encroached by invasive alien vegetation, and by extensions of agricultural fields. The study found that a 14% change has occurred in the Nuwejaars catchment from 1938 to 2016, with an increase of 11 768.6 ha in agricultural fields.

Seven of the wetland vegetation types (Berzelia, Elim riparian, Palmiet, restioid, short reeds, and tall reeds) are highly threatened by agriculture, with an overall high threat weighting of 30.

Invasive species have become highly noticeable, and are a nuisance to both the wetland systems, as the indigenous wetland species are being threatened and in some parts of the catchment the native wetland plant species are non-existent.

This study identifies the reasons the Nuwejaars wetland ecosystems rapidly worsen are largely associated with the disturbance activities associated with agricultural practises including overgrazing, damming, ditching, and conversion. The environmental quality gradually deteriorates, and biotic diversity decreases in these habitats.

The Nuwejaars catchment, with its diversity of wetlands, is dominated by cereal crops and livestock agricultural practices that have been developing for decades. Although there is limited literature on the state of the wetlands in the catchment from the years 1936 to the early 2000s, recent literature, including this study, has reported many critical impacts that have and continue to negatively impact the wetlands in the catchment.

The major impacts identified are conversion, drainage, overgrazing, as well as invasive alien vegetation which has almost entirely claimed many of the wetlands in the upper parts of the catchment. The wetlands most affected by the alien vegetation are seeps and valley-bottom wetlands.

Conversion of wetland to agriculture is one of the biggest issues faced by the wetlands in the Nuwejaars catchment and is almost always associated with additional impacts from the drainage of the wetland to infrastructure diverting and or dividing the wetlands.

The agricultural land-use in the catchment is made up of wheat and canola cultivation, planted pastures, and livestock farming, among others. The area of vineyards has expanded to 144 ha as they become a more popular land-use in the catchment.

The characteristics of the wetland, associated wetland catchment, and landscape catchments were able to show that different wetlands respond differently to impacts derived from agricultural land-use practices.

Wetland types such as the valley-bottom located in the upper catchment associated with Palmiet showed greater levels of vulnerability to habitat modifications as a result of filling and erosion and removal of vegetation. Agricultural lands along the boundaries of these valley-bottom wetlands increase the intensity of the boundary to erode and result in gully erosion. Ellery et al. (2009) highlighted the vulnerability of a wetland to incision increases with increasing slope and area. Thus, valley-bottom wetlands are more vulnerable due to the relationship that exists between wetland slope and area, with wetland slope being the main controller of erosion.

Valley-bottoms are likely to alter in structure and hydrology functions under high stressors than the other wetland types extensively due to impacts. However, floodplains are more likely to show a decline in water quality instead of quantity as a result of their position on a flatter surface and are less suspectable of erosion as Ollis et al. (2013) indicated that the plants trap sediment.

The wetland systems from upstream of the floodplain release flow that is likely influenced by agriculture pollutants and enters and are dispersed throughout the floodplain. The floodplain is more likely to show some resilience to these impacts as their nature to flood out filters the water through as they retain the pollutants from entering the main river (Mereta et al., 2020).

The wetlands serve as vital water sources for many of these practices and in some areas found along the Nuwejaars River lower floodplain, Pietersielieskloof River valley-bottom wetland, and seeps located near the headwaters near Boskloofs River, overexploitation of the wetland is taking place.

The variation in the climate of the Nuwejaars catchment, and the drought that was experienced has resulted in many of the wetlands changing to seasonally inundated wetlands and during dry spells, they become more vulnerable as the land is seen as a potential for conversion.

Each of the wetland hydrogeomorphic types are unique in the Nuwejaars catchment, as their wetland and their associated catchments have a different topography in terms of size, slope, and geology. The size of the wetlands varies across the plain. However, the slope and the geology are highly correlated and can be linked with specific wetland types.

The average slope ranges for the wetlands highly associated with the Bredasdorp class range from 2 – 5% (gently sloping), predominantly in the floodplain, depressions, flats, and seeps located within the plain, a range of 5 – 10% (sloping) is associated with the Cape Bokkeveld Ceres class, primarily in the valley-bottoms, a range of 10 – 15% (strongly sloping) is associated with Cape Table Mountain and Malmesbury Tygerberg classes, and with the hillslope seeps.

The impacts in each catchment are quite similar, but they affect each wetland differently, with stressors mostly found to be due to hydrologic modifications from ditching and hardening, and habitat modifications caused by vegetation removal and replacement. This is supported by Jones et al. (2000), who mentioned that the greatest threats in the Agulhas Plain associated with agricultural practices are the results of damming, bulldozing wetlands and riparian zones, livestock farming, and abstraction for irrigation.

Despite satisfactory results for the overall outcome of the research finding, a major limitation to the study was presented by the challenge of collating and developing sufficient detail and trends from the extensive reach called for from the datasets for this study as it is based on a whole catchment approach and aims to provide a holistic understanding of each component of the wetlands to identify relationships.

The almost exclusive focus on desktop analysis of wetland response to impacts is largely limited to change in wetland extent and does not give a clear indication of hydrological functioning of the wetland. This, therefore, limits the ability of the study findings to fully answer the research question as to why certain wetland types are more vulnerable to others with regards to their geomorphological and hydrological functioning.

The study has also been limited to the understanding of wetlands according to the classifications by Ollis et al. (2013) and it is recommended to conduct the research using the generic wetland classifications by Grenfell et al. (2019) to assign wetlands to their appropriate class to improve the understanding of the formation of wetlands in drylands which will aid in better management of wetlands.

Further recommendations for future studies are to include both on-site level (fieldwork) sampling of soils, water, and vegetation traits and characteristics along with GIS landscape characteristics for desktop analysis as it will hold a complete variation in wetland response to impacts according to Herlihy et al. (2019).

The disturbance indices might not be true validations of impact as it measures stress by the presence of the number of activities within the buffer and does not measure the nature of the intensity of the activities as individual stressors. However, the results for this research are valuable in directing public attention, management, research, and restoration on probable causes of ecological damage to wetlands that are considerably widespread.

Additionally, these indices can be used to manage the design of future studies to explain processes and to substantiate the assumed relationships between agriculture activities and the condition and functions of wetlands (Lomnicky et al., 2018).

According to Mitsch and Gosselink (2015) wetlands are under constant threat globally and in South Africa regardless of their ecological sensitivity and significant services provided to the human population. Cole et al. (2000) suggested 8% of wetlands in the Agulhas Plain be protected or managed in a pristine condition, similarly, the NBA suggests 20% of a wetland type in South Africa remain natural or near-natural condition.

A conservation plan was developed by Cole et al. (2000). Since then, the Protected Area has expanded from 0 to 21 679 ha. However, this has included less than 15% of the wetlands of the Nuwejaars catchment. the wetland types are not represented, and the landscape components which ensure the wetlands will be resilient are not fully protected, thus leaving the wetlands within the Protected Area boundary highly vulnerable.

In light of the wetlands of the Nuwejaars catchment not being significantly protected under the Protected Area. The Nuwejaars Wetland Special Management Area (SMA) covering an area of 46 000 ha (62%) of the Nuwejaars River catchment, was implemented to protect these systems and aims to restore degraded wetlands through conservation measures.

To maintain the integrity and structure of wetlands to mitigate threats, appropriate management strategies for both short-term and long-term management and rehabilitation plans need to be put in place to the site-specific wetland types and their wetland catchment and landscape catchment characteristics.

The Nuwejaars SMA civil society contribution upstream of the Protected Area has great potential to contribute to the Protected Area's success. However, restoration appears limited to invasive alien vegetation clearing rather than pulling back out of wetlands to rehabilitate them (allow them to recover function and recruit natural vegetation).

To apply this in management, it is essential to keep track of the full extent of the wetland types and their conditions through wetland assessments that incorporate the holistic understanding of the condition and function the wetlands.

It is also recommended that adjacent land-use be included in the management of wetlands, not only the immediate buffer, especially to manage pollutants and direct loss, but also the management of water source recharge areas.

This study brought together many of the necessary components needed to manage a catchment holistically and started to answer questions about what makes a wetland favourable or suitable for different types of agricultural land-use types, as well as what wetland type is more vulnerable to agricultural land-use activities.

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APPENDIX A

Buffer sample plots					
Site ID					
Site Co-ordinates					
Stressor Presence/absence					
Residential & urban stressors					
Ranking : 1 - low impact, 2 - medium impact, 3 - high impact, flag - unsure of the level of impact					
Fill bubble if present at appropriate level	1	2	3	Flag	
Road-gravel					
Road-tar					
dumping					
Agricultural & Rural Stressors					
Fill bubble if present at appropriate level	1	2	3	Flag	
Pasture/Hay					
Row crops					
Fallow fields					
Old fields					
Dairy					
Vineyard					
Rural residential					
Irrigation					
Habitat/Vegetation stressors					
Fill bubble if present at appropriate level	1	2	3	Flag	
Trails					
Soil compaction					
Soil erosion					
Hydrology stressors					
Fill bubble if present at appropriate level	1	2	3	Flag	
Ditches, Channelisation					
Dike/Dam/Road					
Excavation, Dredging					
Sediment					
Soil loss					
Inlets, Outlets					
Point source/Pipe/culverts					
Additional notes					