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Vulnerability assessment of wetland ecosystems to water demand, climate variability and land-use/cover change: The case of Die Vlei wetland, Eastern Cape province, South Africa

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DECLARATION

By submitting this mini-dissertation electronically, I declare that the entirety of the work contained therein is my own, original work that I have not previously, in its entirety or part submitted this work for obtaining any qualification.

Signature:

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ABSTRACT

Water scarcity is a major challenge in many different countries, particularly arid and or semi-arid like South Africa. Wetlands are one of the freshwater ecosystems that may assist in alleviating water scarcity because they are valuable not only as a water source for humans but also as an ecosystem of animals and plant species. However, wetlands have been experiencing rapid rates of vulnerability/risk due to alterations by population growth leading to enhanced water demand, climate variability, and human activities leading to land cover/land-use changes. Geographical Information Systems (GIS) and Remote Sensing (RS) are less financially taxing methods useful in studying water scarcity, as shown in this study. The study begins with a literature review presentation based on a desk study from predominantly academic publications and additional municipal and consultancy reports on the wetland ecosystem's vulnerability/risk and focuses on applying GIS & RS in related studies. After that, the study conducts a vulnerability assessment using the Ramsar Convention's wetland vulnerability assessment using the theoretical framework stages using GIS and RS technologies. The study hypothesizes that water demand, climate variability, and land-use/cover changes (LULC) are the tri-factor responsible for wetland vulnerability. It begins the assessment by first quantifying wetland water demand using the wetland water budget, ecosystem services and the Penman-Montheith-FAO (ET_o) evapotranspiration index. Secondly, objectively representing climate variability on wetland vulnerability using trend analysis to measure rainfall and temperature variability. Thirdly, reconstructing LULC changes from multi-date remotely sensed SPOT imagery over ten years from 2007 to 2017 to identify and monitor impacts of trends. The vulnerability was assessed through a Principle Component Analysis (PCA) that identified relevant variables and Multi-Criteria Evaluation (MCE) to evaluate the wetland's exposure. The study concludes that there is evidence of a possible increase in water demand whilst climate variability, which is estimated to have a 39% contribution to the wetland dynamics, is characterised by a decrease in precipitation and an increase in temperatures. Lastly, LULC trends showed a marked increase in domestic and commercial farming, and farming has been identified as a wetland stressor of note.

KEYWORDS AND PHRASES

Wetland, Vulnerability, Vulnerability Assessment, GIS & Remote Sensing

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ACRONYMS AND ABBREVIATIONS

AADD	Average Annual Daily Demand
DPSIR	Drivers, Pressures, State, Impacts, and Responses
DWS	Department of Water and Sanitation
EC	Eastern Cape
ETo	Penman-Montheith evapotranspiration
EVI	Environmental Vulnerability Index
GAM	Generalized Additive Models
GIS	Geographical Information Systems
IWRM	Integrated Water Resource Management
LOESS	Local Estimated Scatterplot Smoothing
LULC	Land-use/ Land Cover change
MCE	Multi-Criteria Evaluation
NDVI	Normalized Difference Vegetation Index
PCA	Principle Component Analysis
QVAE	Quantification Vulnerability Assessment of Environment
RMLM	Raymond Mhlaba Local Municipality
RS	Remote Sensing
SA	South Africa
SANSA	South African National Space Agency
WO-test	The overall seasonality test
WSP	Water Safety Plan

CHAPTER 1: AN INTRODUCTION TO VULNERABILITY OF WETLAND ECOSYSTEMS

1.1 INTRODUCTION

Securitization of access to water has prompted most governments to invest heavily in the water management of both surface and sub-surface waters (Cech and Beebe, 2003; Stuart, 2017). These investments are meant to assist with sustainable access to and extraction of adequate water supply over the long term. However, new challenges have emerged in recent years that negatively influence sustainable access to water supply (Frame and Killick, 2004). Such challenges include, but are not limited to, population growth (Maharaj and Pietersen, 2004; Huo *et al.*, 2008), increase in water-intensive human activities (Zhang and Lu, 2009; Galli *et al.*, 2012), pollution of water bodies (Vörösmarty *et al.*, 2010; Hellawell, 2012) and climate variability/change (Elala, 2011; Intergovernmental Panel for Climate Change, 2014). The common denominator for all these challenges are rooted in population growth that affects Integrated Water Resource Management's (IWRM) three pillars of economic efficiency, environmental stability, and equity (Department of Environmental Affairs South Africa, 2011). This is because; population growth requires improved economic viability, pro-active management, and equitable distribution and sustainable use of water resources (Butterworth *et al.*, 2010). A logical analysis of these challenges draws a picture of a "destructive chain-of-events" from high rates of population growth leading to an increased demand on water availability, whilst providing the basis for large-scale water-based activities to cater for the larger population. This in turn leads to major land-use/cover changes (LULC) to facilitate the new activities all the while under the challenges already posed by climate variability and change. Therefore, the strain on the already limited water resources simultaneously increases with an increase in population growth (Galli *et al.*, 2012).

African countries have experienced different degrees of natural and anthropogenic water threats such as droughts and pollution (Department of Environmental Affairs South Africa, 2011). However, other authors argue that the "natural" water threats are, in fact, also a result of human influence (Vörösmarty *et al.*, 2010), for example, poor farming practices increasing the rate of climate change (Parry *et al.*, 2007; Laban, 2009). Nonetheless, threats against the continent's limited water resources have negatively impacted (Sullivan, 2011). The term "water threat/risk" was coined by Barry *et al.* (2008) to explain factors that negatively impact water availability, access, and provision within a given spatial extent. Inevitably, due to the resilience of fragile arid and semi-arid environments of Southern

Africa, water threats exacerbate during water extraction and provision (Loucks and van Beek, 2005). For example, during extraction of water resources, increased losses reduce the total supply value of the water resource (Naidoo *et al.*, 2008), whilst during provision, inadequate coping mechanisms of the water resources to external and inevitable variables such as anthropogenic activities and climate variability are worrisome (Schiermeier, 2014). Each of these concerns presents challenges to decision-makers who must achieve adequate, safe and dependable water supply in the future to improve human well-being in societies and to meet the requirements of future generations (Laban, 2009). The combination of population growth and variations in hydrological parameters increases uncertainty and complication in planning and management processes of the water sector (Lenton and Muller, 2012) more so because, unlike in other regions where sub-surface water can be used to supplement water supply, the dry areas such as the Eastern Cape (EC) have to rely heavily on surface water resources (Department of Environmental Affairs South Africa, 2011). Therefore, understanding the vulnerability of surface water resources in EC is vital in ensuring sustainable water management in the province. Surface water resources form three per cent of global freshwater, accessible for human consumption (Conservation Louisiana Coastal Wetlands Force and Restoration Task Force, 2009) and this includes wetlands that occupy about six per cent of the international land area, approximately seven to nine million km^2 (Mitsch and Gosselink, 2007).

1.2 WETLANDS

Wetlands are transitional regions between terrestrial and aquatic systems, where the water table is near the surface, or shallow water inundates land, seasonally, or permanently (Erwin, 2009; Tiner, 2016). They act as transport mediums for precipitation that is not lost to the atmosphere to the sea catchment (Frohn *et al.*, 2009) that have easily accessible water presenting permanent or occasionally seasonal natural assets and infrastructure that occur in a variety of locations and varied sizes able to provide a range of products, functions, and services free of charge (Mwita *et al.*, 2013; Youthed, 2014). Wetlands are valuable not only as a water source for humans but also as an ecosystem of animals and plant species (Millennium Ecosystem Assessment, 2005). Although wetlands provide an essential water source for human consumption and the sustenance of terrestrial ecosystems, they have unfortunately been experiencing rapid vulnerability rates (Fennessy, Jacobs and Kentula, 2007). Wetland vulnerability is a cause of concern in local communities due to the water provision services it offers for human activities and the functioning of ecosystems (Schuyt, 2005; Department of Environmental Affairs South Africa, 2011). This study attempts to assess the vulnerability of Die Vlei wetland to water demand, climate variability and LULC in and around the wetland objectively.

The study is premised on the need to enhance sustainable use of wetland water resources that are fast deteriorating and decreasing due to the combined influence of human activities and climate variability, as described in the problem below.

1.3 PROBLEM FORMULATION

The Department of Water and Sanitation (DWS) reported that freshwater levels are categorized as “critically low” due to the total water totals reducing notably. For example, Albert falls Dam dropped 26.1% from 2016 to 2017 (Govender, 2017). One freshwater resource that has shown potential to assist with water depletion in South Africa is wetlands (Fennessy, Jacobs and Kentula, 2007). Whilst some wetlands have been studied extensively and continue to be monitored, the wetlands in the EC, particularly the smaller ones, are a challenge as their vulnerability is primarily associated with inadequate management levels exacerbated by the effects of high water demand, population growth and climate variability (Amathole District Municipality, 2014). Population growth, which results in higher water demand and numerous LULC changes coupled with climate variability, will impose stress on the limited wetland resources in EC municipalities and intensify their vulnerability (Department of Environmental Affairs South Africa, 2011). Population growth in African countries is expected to double over the next decade, whilst climate variability is expected to alter local climates to a degree of 50% by 2050 (Laban, 2009; Urama and Ozor, 2010; Manase, n.d.). Assuming these predictions are accurate, by 2050, Raymond Mhlaba Local Municipality (RMLM) will have a population of 319 030 that depend on already depleting resources for freshwater (Statistics South Africa, 2011). Therefore, Die Vlei wetland will have to assist with water provision for a population of 1 029 (as of the 2011 census) plus heavy commercial uses. This is a cause of concern because the Die Vlei wetland is used for domestic and commercial purposes. Still, it would seem that there has not been a study conducted to quantify the water demand on the wetland and measure its vulnerability to increased water demand. Therefore, to cope with water scarcity and reduce Die Vlei’s vulnerability, studies are required to quantify the water demand and the possible impact climate variability and Land-use/ Land Cover change (LULC) have on water resources. This is significant to adopt measures to increase water use efficiency and conservation, described in detail below.

1.4 SIGNIFICANCE

The main water management challenge in South Africa is the increasing stresses and deterioration of the country’s limited natural water resources by increasing water demands and deteriorating water quality (Amathole District Municipality, 2014). This has significant implications for the future development of the country and the sustainability of their socio-economic viability (Elala, 2011). There is a broad consensus on the adverse effects of increasing the exploitation of wetland water resources as the population grows (Millennium Ecosystem Assessment, 2005). In African countries, the management of wetlands focuses on 'supply-side' management instead of 'demand-side management (Parry *et al.*, 2007). This means managers dedicate resources to measure the amount of water the wetland can produce instead of considering how much water is required from the wetland and how this need affects the wetland. Limited illustration of the vulnerability of wetlands from different variables is the central gap in water resource studies (Saha and Pal, 2019; Defne *et al.*, 2020). Other gaps, particularly for smaller wetlands, include the inadequate measure of the quantity of water demand from the wetland as a result of population growth dynamics (Laban, 2009; Vörösmarty *et al.*, 2010; Ghosh *et al.*, 2018; Fu *et al.*, 2019; Shi *et al.*, 2020; Sibanda and Ahmed, 2021) and, estimations and assessments of the impact of climate variability/change on wetlands (Urama and Ozor, 2010; United Nations Environment Programme, 2012). Therefore, this study will attempt to fill in the knowledge gap regarding how water demand on wetlands and land-use/cover changes in wetland ecosystems coupled with climate variability affect the functioning and life-supporting potentials of a wetland-used as a source of water for direct and indirect purposes. The vulnerability assessment will also provide decision-makers with possible options to evaluate and modify existing policies and implement measures to improve water resources management using an aim and four objectives described below (Turpie, Marais and Blignaut, 2008; Osland *et al.*, 2016).

1.5 AIM AND OBJECTIVES

The study aims to conduct a vulnerability assessment of the Die Vlei wetland by quantifying its water demand and using a hybrid approach that objectively reconstructs long-term changes in land use/cover and measures the sensitivity of the wetland to climate variability. The following objectives will satisfy the aim:

- To quantitatively represent water demand from the Die Vlei wetland;
- To measure rainfall and temperature variability from 2015-2020 using trend analysis;
- To systematically reconstruct trends in land-use and land cover (LULC) by classifying multi-date multi-spectral images of 2007 and 2017; and
- To conduct a vulnerability assessment of the wetland from water demand, LULC, and climate variability.

1.6 THESIS STRUCTURE

Chapter one is an introductory chapter to the whole study. It presents the background and focus of the research through the problem statement, significance, aims and objectives, and a detailed research design with the steps followed in conducting the research. Chapter two documents the simple four-pronged approach to the literature review, which includes assessing the literature on wetland ecosystems and their sustainable management thereof; three challenges of sustainable management: water demand, climate variability, and LULC and lastly, the vulnerability of wetland ecosystems. Reviewing the literature laid the foundation for the methodology and methods that were applied in the study. Chapter three comprises a detailed account of the methods used in the study of data collection, preparation, and processing. These included quantifying the water demand levels that Die Vlei has and temperature and rainfall fluctuations and reconstructing land cover/use changes. These three methods were done as feeders for the wetland vulnerability assessment, which was done using Principle Component Analysis (PCA), a Multi-Criteria Evaluation (MCE), and the Ramsar Convention's Wetland Vulnerability Assessment framework.

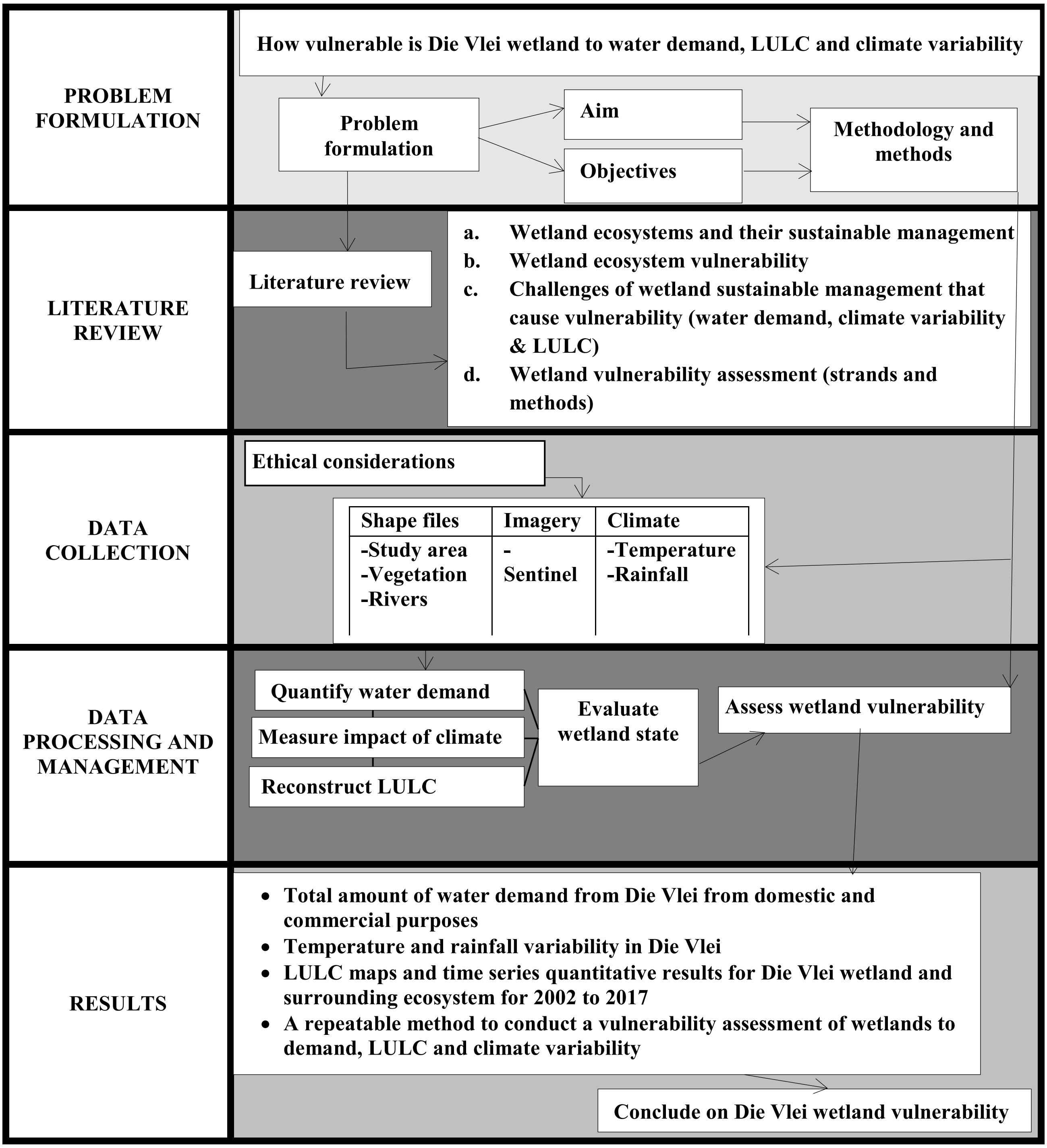
Chapter four outlines the study's results and discussions. Firstly, water demand is quantified based on evapotranspiration. Secondly, the impact of temperature and rainfall fluctuations on the wetland vulnerability is presented. Thirdly, the LULC is reconstructed for the wetland and its surrounding ecosystem. The quantified time series results from the reconstruction allow a statistical measure of the extent of wetland vulnerability. Lastly, the Ramsar Convention's Wetland Vulnerability Assessment framework is used to measure the wetland's overall vulnerability. Chapter five concludes the study by highlighting key observations, strengths, and shortcomings of the research and re-visiting the study's objectives. After that, the chapter evaluates the research and gives suitable recommendations to wetland managers and ecologists on the vulnerability level of Die Vlei wetland to water demand, climate variability, and LULC. A further description of the thesis structure is given below in the research design.

1.7 RESEARCH DESIGN

Table 1.1 presents all the steps to be followed in the study in chronological order to assess the vulnerability of Die Vlei wetland to water demand, LULC and climate variability. The design graphically explains the links between the different sections of the study from problem formulation.

It includes brief highlights of the content covered in the literature review, data requirements necessary for the study, and the methods used to achieve the results.

Table 1.1: Steps followed in chronological order to apply Geographical Information Systems (GIS) and Remote Sensing (RS) technology in a vulnerability assessment of Die Vlei wetland to water demand, climate variability and LULC.



1.8 CONCLUSION

Wetlands are valuable not only as a water source for humans but also as an ecosystem of animals and plant species (Millennium Ecosystem Assessment, 2005). However, wetlands are experiencing rapid rates of vulnerability (Fennessy, Jacobs and Kentula, 2007), which is concerning to local communities due to the water provision services it offers for human activities and the functioning of ecosystems (Schuyt, 2005; Department of Environmental Affairs South Africa, 2011). A combination of population growth, which results in higher water demand, variations in hydrological parameters due to climate variability and change, and LULC impose stress on the limited wetland resources in the Eastern Cape municipalities and intensify their vulnerability. This is unfortunate for decision-makers who may consider the use of wetlands to assist in achieving adequate, safe and dependable water supply to improve human well-being in societies and meet the requirements of future generations', particularly in dry regions like the Eastern Cape. To understand the approaches to wetland vulnerability assessments the following chapter reviews literature on three challenges of sustainable management, namely, water demand, climate variability, and LULC.

CHAPTER 2: A LITERATURE REVIEW ON WETLAND ECOSYSTEM'S VULNERABILITY/RISK

2.1 INTRODUCTION

Managing to satisfy current water needs and those of future generations requires an understanding of sustainable resource management (SRM), which is the management of natural resources that meets the needs of the present without compromising the ability of future generations to meet theirs (Smith, 2014). Water security is one of the core issues that governments worldwide dedicate significant financial resources to counter the alarming water depletion rates (Bakker, 2010). Sadly, this approach works primarily in first-world countries, whereas, in third-world countries, combating water scarcity is not as simple as dedicating government resources towards implementing solutions. This is because SRM is simple and easy to implement on paper but not strategically due to the complexity of resource availability and use. Also, some of these regions, such as South Africa, are semi-arid or arid, resulting in the need for expensive water-saving technologies and solutions that the governments cannot afford (Huitema *et al.*, 2009) or the lack of technical expertise to manage implementation (Pahl-Wostl *et al.*, 2010). Water's renewability is applicable only in the short-term as the sustainability of water renewal is questionable (Rast, Johannessen and Mauser, 2014). Reliance on the water is irreplaceable with alternative resources, such as using coal for energy, because water is not only essential for people's physical survival, personal hygiene and household uses (Loucks and van Beek, 2005; Alessa *et al.*, 2008; Smith, 2014) but, is also central to the development and is currently used for power generation, manufacturing, mining and agricultural industries (Cech and Beebe, 2003; Lenton and Muller, 2012).

Using categories of water resource availability and population growth, South Africa has several distinct sub-regions characterized by low levels of water availability. This is inadequate for the corresponding population growth rate that accelerates the extent and number of human activities (Huo *et al.*, 2008; Department of Environmental Affairs South Africa, 2011); as well as significant temporal and spatial variations in hydrological parameters that lead to increased rainfall and temperature fluctuations influenced by the hydrological cycle (Güntner *et al.*, 2007). The whole region is suffering from water scarcity, with certain parts of South Africa that are already dry facing the brunt of the effects of said scarcity. With the steady increase of water demand across the globe in recent years (Yates *et al.*, 2005), a decrease in freshwater availability(Hanasaki *et al.*, 2008), and success in managing vulnerabilities of surface water to aid water scarcity (Smit and Wandel, 2006); studies on different surface waters vulnerabilities – both artificial and natural is anticipated to be a central focus of water management. Although South Africa has large amounts of salty coastal water that require advanced desalinization technologies to convert it into freshwater (Glavovic, 2006), the country also lacks the corresponding financial muscle or political will necessary to manage such procedures (Turpie, Marais and Blignaut, 2008).

On the other hand, the majority of surface waters have been studied in great depth. However, due to improved treatment methods offered by technology, it is argued that there is potential in tapping into wetland water resources more than what is being done at present (Millennium Ecosystem Assessment, 2005; Mitsch and Gosselink, 2007; Voldseth *et al.*, 2009; Gopal, Shilpakar and Sharma, 2010). Wetlands currently account for about 0.006% of global surface freshwater (United States Geological Survey, 2018), 4.7% of Sub-Saharan Africa's surface water (Rebelo, McCartney and Finlayson, 2010) and 2.4% of South Africa's area (Department of Environmental Affairs South Africa, 2018). Assessment of wetland vulnerabilities using less financially taxing methods such as those offered by Geographical Information Systems (GIS) and Remote Sensing (RS) is a promising avenue to aid water scarcity as they allow the scope of the study to include both quantity and quality of water availability which is sensitive to its variation of use (Adam, Mutanga and Rugege, 2010). This review assesses the vulnerability of wetlands as a freshwater ecosystem focusing on the application of GIS and RS in related studies.

2.2 WETLAND ECOSYSTEMS

Wetland ecology looks at the interactions between organisms found in wetlands and aspects of their environment such as vegetation, soil, and climate (Holling, 1973; McCartney and de la Hera, 2004; Tiner, 2016). The majority of organisms found in wetlands evolved in a wet environment. The degree of dependency of the organisms on the wetland vegetation, soil and climate ranges from complete dependence for survival to partial dependency from organisms existing in different habitats but require wetlands for part of their life cycle (Finlayson *et al.*, 1999; Fennessy, Jacobs and Kentula, 2007). There are organisms whose occurrence can confirm wetland presence due to their reliance on the wetland. These organisms also influence hydrophytic vegetation and hydric soils in the wetland's climate (Erwin, 2009; Gopal, Shilpakar and Sharma, 2010; Sinha, 2011). Wetlands are not climate specific and exist in many climates except Antarctica (Erwin, 2009). Warmer climates mostly have swamps and marshes (McCartney and de la Hera, 2004; Tretin, 2008), whereas; fens and bogs are more common in cold or even Arctic climates (Morris *et al.*, 2002; Keddy, 2010). GIS and RS are useful in wetland studies due to GIS's ability to provide the basis for the analysis of data, including change detection and RS's ability to provide data during mapping (Spruce, Karsmizki and Giardino, 2004; Adam, Mutanga and Rugege, 2010; Mutanga, Adam and Cho, 2012). For example, a study mapped different types of wetlands in terms of their size, density, spatial distribution and use patterns in Usambara highlands and the Pangani floodplain in Tanzania, the Mount Kenya highlands and Laikipia floodplain in Kenya using RS techniques and field surveys (Mwita *et al.*, 2013). The multi-spectral resolution imagery, combined with field survey data and GIS, produced detailed maps of small wetlands and their uses that showed key information such as the intensity of wetland-use, which is useful in wetland monitoring and management.

Wetland vegetation is hydrophytic, meaning it is adapted for life in water, periodically flooded or saturated, and growing in wetlands and deep-water habitats (Tiner, 1999). Each wetland type has specific vegetation characteristics. A swamp is dominated by trees and developed leaf canopy (Rebelo, McCartney and Finlayson, 2010); marshes have predominantly herbaceous plants and a few others usually emergent through water (McCartney and de la Hera, 2004). Fens have mostly sedges and grasses (Morris *et al.*, 2002), and lastly, the bog has predominantly sphagnum moss, sedges, ericaceous shrubs, or evergreen trees (Keddy, 2010). Hydrophytic vegetation plays a role in the environmental function of the wetlands as an indicator for early signs of any physical or chemical vulnerability in a wetland environment (van Dam, Camilleri and Finlayson, 1998). In a study of mapping vegetation in Yellowstone National Park using spectral feature analysis of AVIRIS data, the results showed correspondence by precipitation and soil characteristics with strong relations to elevate the vegetation distribution (Kokaly *et al.*, 2003). In a Todd *et al.* (2010) study to link hydrological dynamics were with vegetation distribution across Everglades National Park (ENP), the results indicated that the percentage of time a location is inundated and its mean depth is the principal structuring variables that individual communities respond. In another study, wetland vegetation was mapped in the San Francisco Estuary using detailed vegetation field surveys and high spatial-resolution colour-infrared aerial photography. The results showed that supervised classification could map emergent wetland vegetation (Tuxen *et al.*, 2011). This highlighted the value of mapping wetland vegetation distribution to identify the influences of the vegetation condition; investigate ecosystem functioning; provide information about vegetation diversity and community structure; and the means for examining vegetation change over time (Kokaly *et al.*, 2003; Adam, Mutanga and Rugege, 2010; Todd *et al.*, 2010; Tuxen *et al.*, 2011; Mutanga, Adam and Cho, 2012).

Hydric soils (wet soils) are another ecological and statutory identifying characteristic of wetlands (Tiner, 1999). Hydric soils are saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions (Laanbroek, 2010). Anaerobic conditions allow soils to form adjacent uplands that favour the growth and regeneration of hydrophytic vegetation (Mitsch and Gosselink, 2007). In each wetland type, the soil characteristics reflect the physical processes such as special adaptations for the plant and microbial species occurring in the wetland (Laanbroek, 2010; Li *et al.*, 2010). Swamps have histic or histosols mineral soils that have a moderate to thick accumulation of surface organic matter (Tretin, 2008); marshes have hydric soils (McCartney and de la Hera, 2004), fens have mostly shallow peat, which allows considerable water movement through it (Morris *et al.*, 2002) and lastly, bogs have deep and sometimes uncompact peat (Keddy, 2010). Wetland soil types are powerful indicators of wetland conditions that directly impact other characteristics such as vegetation and water quality (Finlayson *et al.*, 1999). Grunwald, Thompson and Boettinger (2011) explain that significant advancements through GIS, incorporation of soil RS products, and advanced quantitative methods have produced novel digital soil mapping and soil properties prediction models. One such model is the geographically weighted regression kriging, which was used to examine the relationships between environmental variables and soil organic carbon stock. The results showed that GWRK enhances the precision for estimating the soil organic carbon stock (Kumar, Lal and Liu, 2012). Another application of GIS & RS was by Pennock *et al.* (2014) in nine freshwater ponds at Swift Current, St. Denis, and Melfort with an elevation threshold between wetland-recharge and wetland-discharge. The results showed the spatial distribution of wetland-recharge and wetland-discharge soils in freshwater ponds provides a record of pond hydrological conditions readily adapted to predictive soil mapping. This emphasized that wetland soils form a very dynamic soil environment that lowers oxygen concentrations due to the spatial and temporal differences (Laanbroek, 2010; Grunwald, Thompson and Boettinger, 2011) and have a predictable spatial pattern of distribution (Pennock *et al.*, 2014).

GIS and RS approaches are unreservedly useful in wetland studies. They can map physical characteristics such as sizes, densities, and spatial distributions and provide the basis for analysis of data and change detection in the wetland. The review above has also highlighted the value of GIS and RS to assess various aspects of wetland ecology aspects including hydrophytic vegetation and hydric soils that play a role in the environmental function of the wetlands. Besides, GIS and RS are useful in understanding wetland-uses - from the type and extent to the intensity of the use, which is important for wetland monitoring and management. The availability and use of satellite imagery (particularly multi-spectral high-resolution imagery) and field survey data are useful in studying wetland vulnerability. RS assists in studying even small or inaccessible ones. Wetland vulnerability is discussed further in the following section.

2.3 WETLAND ECOSYSTEM VULNERABILITY

The definition of vulnerability remains open for debate since systems are often dynamic and complex and so it cannot be a single definition. However, all the definitions concur that the state of the environment is the quantity of biological, physical and chemical features of an ecosystem and environmental functions that are vulnerable to the pressures in a specific area (Dow, 1992; Alwang, Siegel and Jorgensen, 2001; Peters, 2001; Brooks, 2003; Adger, 2006; Smit and Wandel, 2006; Parry *et al.*, 2007; Elala, 2011; United Nations Environment Programme, 2012). Turner *et al.* (2003) views vulnerability in terms of the degree to which a system is likely to experience harm due to exposure to a hazard, whilst Adger (2006) describes it negatively as the susceptibility to be harmed. Ecosystem vulnerability is related to the estimation of tolerance to stressors (Williams and Kapustka, 2000). As such, wetland vulnerability occurs after the wetland is degraded due to alterations by human activities and climate variations, resulting in modifying their biophysical form (van Dam, Camilleri and Finlayson, 1998). Wetland vulnerability describes a wetland area whose structure and function have degenerated and possibly vanished due to the effects of natural threats and human practices (Wang *et al.*, 2012). While wetlands are one of the most productive ecosystems, they are also the most threatened because several factors are known as stressors. Ecology stressors lead to wetland destruction and alteration, an advanced development mode, even at the government level (Keddy, 2010; Rebelo, McCartney and Finlayson, 2010). An estimated 65% of wetland stressors are a result of direct and indirect human influences. Of the 65%, approximately 73% constitutes direct influences such as LULC, whilst the remaining 27% constitutes indirect influences such as climate (Wright *et al.*, 2006). Schuyt (2005) conducted various case studies on wetlands, and the main types of wetland stressors have one aspect in common: a threat by human activities. This is because freshwater ecosystems are amongst the most heavily used, depended upon, and exploited ecosystems for the sustainability and well-being of humans (Hellawell, 2012; United Nations Environment Programme, 2012; Hitt *et al.*, 2015). Due to this reliance, there are various strands of wetland vulnerability, and these are discussed below.

2.3.1 Strands of wetland vulnerability

Wetland vulnerability is a direct result of the widespread unsustainable use of wetlands due to the lack of recognition of the traditional values of these wetlands, desire for their modernization, and failure to appreciate their ecological role, particularly in developing countries (Osland *et al.*, 2016). Finlayson *et al.* (1999) argue that wetland vulnerability refers to the relationship between wetland exposure, resilience, and adaptation. The exposure of the wetland to a particular risk, the resilience of the wetland to the impact of the risk, and the adaptation of the wetland to cope with the efforts required to minimize the risk's impacts will be discussed or described in the following sections.

2.3.1.1 Wetlands exposure

Crowell, Webster and O'driscoll (2011) argue that currently, the communities living in wetlands are exposed to a wide range of hazards and several vulnerability conditions, which frustrates people's livelihoods and lowers the quality of life. However, the wetlands themselves have also been exposed to a wide range of threats such as the release of chemicals, physical and biological agents, extraction and use of resources, and creation of invasion corridors (Omann, Stocker and Jäger, 2009). However, the main threats are the increase in population growth, climate variability, or change and changes in patterns of LULC. Population growth exposes the wetlands to an increased demand for the wetlands' ecological services, climate variability exposes the wetland environment for strained resources for the ecological functions that make them viable, and LULC exposes the wetlands to shifts in the ecosystem balance (Schuyt, 2005; Erwin, 2009; Laban, 2009; Omann, Stocker and Jäger, 2009; Patel *et al.*, 2009). Studies predict that as more areas get developed, the degree of imperviousness and surface runoff will increase, resulting in more flooding (Oelofse, 2003). For example, Miguez‐Macho and Fan (2012) state that the exposure to frequent flooding and waterlogging has gradually increased as human activities advance further into the wetlands. The degree of the wetland's past exposure to risk and ability to recover from the impacts is directly linked to the wetland's level of resilience, which is discussed in the next section.

2.3.1.2 Wetland resilience

Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb the change of state, driving variables, and parameters (Alessa *et al.*, 2008; Zhang *et al.*, 2019). Resilience is a property of the natural system. Natural vulnerability is conditional and is increasingly referred to as a desirable attribute of wetland systems, especially in the face of uncertain future changes in wetland processes (Thorne *et al.*, 2018). Many wetlands are confronted with a range of environmental and socio-economic pressures such as urbanisation, pollution, and resource depletion. These pressures increase wetland vulnerability to longer-term developments such as increased water demand, climate variability or change, and LULC, all of which interact within both short- and long-time scales. The resilience of wetland systems has been suggested as an appropriate pro-active adaptive response to reduce this vulnerability (Bijlsma *et al.*, 1996; Zhang *et al.*, 2019).

However, academic studies and policy documents that have stressed the importance of wetland resilience did not give a clear definition of the term, nor have they indicated directions of the procedure (Zhang *et al.*, 2019). Nonetheless, three types of resilience wetlands worldwide are shaped and defined by interacting morphological, ecological and socio-economic processes, each of which plays a part in determining overall wetland resilience (Osland *et al.*, 2016; Stagg *et al.*, 2016). While the wetland's resilience determines how it will deal with the impacts of being exposed to risk, the adaptation determines its ability to recover, which is discussed below.

2.3.1.3 Wetland adaptation

McCauley *et al.* (2015) explain that water levels in wetlands are bordered by managed grasslands that are significantly greater than those surrounded by unmanaged grasslands. Wetland management reduces both the proportion of years the wetland goes dry and the regularity of dry periods, which produces the most active vegetation cycle (Janssen *et al.*, 2005; Euliss *et al.*, 2008). Parolin *et al.* (2010) suggest that plants in wetlands with strongly shifting water tables, in particular, need adaptations to changes such as the shortage of oxygen in the root zone and also to extended periods of dry conditions with low water availability. However, Verhoeven and Setter (2010) condemn water levels in wetlands to promote agricultural use; their focus is on the difference between sustainable and non-sustainable wetlands of farming practices. They claim that the peatlands drainage has led to intense soil collapsing and greenhouse gas emissions, whereas floodplains and rice fields are suitable for sustainable agricultural use. This is complemented by the Millennium Ecosystem Assessment (2005)'s outline of the severe effects of agricultural use on wetlands' ecological character and secondary biodiversity protection from agents such as fertilizer and pesticide.

Heedless of the variations of definitions and descriptions of wetland vulnerability, it is clear that wetland vulnerability occurs after the wetland is degraded due to alterations by human activities and impacts and climate variations resulting in modifying their biophysical form. The vulnerability occurs due to stressors/risk, which the literature emphasizes are a result of direct and indirect human activities such as farming, infrastructure and recreation. The size of stressors and the duration that they last is known as the exposure and relationship to how resilient it is to the impact of the stressor and the adaptation to the risk determine wetland vulnerability. In wetlands, human activities lead to increased water demands, LULC and climate variability/change discussed below.

2.3.2 Challenges in wetland ecosystems, causing vulnerability

No one cause can be singled out for wetland vulnerability, but rather a combination of a large number of drivers, which include pollution, reclamation, excessive exploitation of biological resources and bio-invasion (van Dam, Camilleri and Finlayson, 1998; Osland *et al.*, 2016; Thorne *et al.*, 2018). However, the main drivers of wetland vulnerability include human activities pressure on wetland resources for domestic and commercial activities (Huo *et al.*, 2008; Zhang and Lu, 2009); climate variability and change (Laban, 2009; Zhang *et al.*, 2019); and land conversions mainly for agricultural lands, urban settlements, and infrastructure construction (McCauley *et al.*, 2015; Osland *et al.*, 2020). This review envisions a scenario where the wetland is first used for water provision to satisfy demand. Secondly, climate variability sensitizes the wetland to the demand. It enhances the extent of the human activates that continue to alter the wetland's LULC, causing alterations to the wetland's biophysical form viz. vulnerability (van Dam, Camilleri and Finlayson, 1998). The way that water demand, LULC and climate variability are challenges for wetlands are expanded on below.

2.3.2.1 Water demand

Water demand for freshwater resources requires consideration of ecosystem services (Yates *et al.*, 2005). Ecosystem services are the benefits derived from natural and managed ecosystems and biodiversity provided to people, both directly and indirectly (Millennium Ecosystem Assessment, 2005). Generally, freshwater in itself is a provisioning service that refers to the use of freshwater for domestic and commercial purposes, including crop and livestock management, irrigation, power generation, and transportation (Raneesh, 2014). Inland water ecosystems such as wetlands provide cultural, regulating, and supporting services that contribute directly and indirectly to human well-being (Fetter, 2018). As a result, there has been a marked increase in the exploitation of wetland resources, which exerts pressure on the wetlands to cater for the influx of population growth and related LULC from human activities exacerbated by climate variability. For example, between 1951 and 2011, there was an increase in India's population from 0.4 billion to 1.2 billion. During the 90 years from 1901 to 1991, the number of urban centres had doubled while the urban population had increased. This led to pressure on wetlands to meet the water and food demands of the growing population and economic activities (Bassi and Kumar, 2012). Also, Patel *et al.* (2009) explained the increased sensitivity in wetland ecosystems' resilience to degradation factors such as population growth and LULC had a marked increase with the added pressure from climate variability. Therefore, with a growing population, water demand, changing climate and LULC on the wetlands is likely to increase.

Ideally, water input should be equal to or greater than water output so that there is water balance in the wetlands (Fetter, 2018). Unfortunately, water outputs (the water demands) are significantly higher than water inputs (precipitation) (Neuhaus, 2013). As a result, estimation of water demand from wetlands is critical in understanding their vulnerability. The majority of water-governing authorities' measure water demand using the Annual Average Daily Demand (AADD) formula. This is the total volume of water sold in a given year divided by capita, dwelling, area, or combinations of all three in a service area (Yates *et al.*, 2005). However, this method works solely for systems where records of the volume of water provided are available or easily calculated, which is different in wetlands where there are variations in the water budgets and the irregular shapes of the systems (Neuhaus, 2013). Water demand occurs as evapotranspiration, an interaction between climate and water resources or as human water extraction for domestic and commercial purposes (Intergovernmental Panel for Climate Change, 2008; Vörösmarty *et al.*, 2010; Raneesh, 2014). Therefore, water demand can be estimated in surface water resources by calculating wetland specific yield or using the Penman-Montheith (ET_o) evapotranspiration index and associated hydrological modelling assumptions (Sumner, 2007; Naipal, Naipal and Samson, 2013). For example, (Sumner, 2007) noted how wetland specific yield conceptualisation was highly inaccurate if it did not consider the effects of soil capillarity and land surface microtopography as is standard practice even though this data is challenging to get especially in under-studied wetlands. Another example is that there wasn't a study to quantify the contribution of water removal from Nani Swamp even though it is the major irrigation source for about 25 000 hectares of rice polders until Naipal, Naipal and Samson (2013) used the ET_o and found that evapotranspiration did contribute significantly to the swamps water loss making it a more viable approach in data limited wetlands. ET_o is also useful given the impact of climate variability on wetland's as discussed below.

2.3.2.2 Climate variability

Wetlands vulnerability to climate refers to the relationship between a particular climate-related event's impact on a wetland, the risk associated with that impact, and the efforts to manage that risk. It occurs when the degree to which a wetland is sensitive to and unable to adapt to or moderate the consequences of climate change and other (anthropogenic) pressures on its ecological character (Intergovernmental Panel on Climate Change Coastal Zone Management Subgroup, 1990). Temperature, evaporation, the amount of humidity and seasonality of rainfall are critical drivers for wetlands. They play a vital role in determining water quantity and the overall water system of the wetland (Raneesh, 2014). Wetlands exist in different climates, but rising temperatures and decreasing precipitation due to climate change present a potential danger to already shrinking wetlands (Sinha, 2011). Whilst a temperature rise can aggravate the problem of eutrophication, leading to algal blooms, kill fish and create dead zones in the wetland (Gopal, Shilpakar and Sharma, 2010), decreased precipitation will elevate already growing water demands and alter the freshwater inflows to wetland ecosystems (Bates, Kundzewicz and Wu, 2008; Erwin, 2009). The increase in temperature and a decrease in precipitation will eventually affect the balance between water demand and supply within the wetlands resulting in further impacts of climate change on the wetland ecosystems (Raneesh, 2014).

Climate-induced disturbances are expected to increase in frequency and intensity and affect wetland ecology by altering its hydrology. Zhang *et al.* (2019), for example, developed a set of quantitative metrics to quantify wetland hydrologic resilience in coastal-forested and herbaceous wetlands in North Carolina that measure this impact with satisfactory accuracy. Wetlands are also vulnerable to a rise in water levels together with the projected increase in storm activity in zones of significant human use (Stagg *et al.*, 2016) and, evaluation of climate change impacts on the wetland vegetation community structure and distribution (Todd *et al.*, 2010). In coastal wetlands, a changing climate increases rates of sea-level rise that magnifies and adds stress on the wetlands due to increased salinity from saltwater intrusion, extreme precipitation, and drought (Bradford, 2016). A limited analysis of wetlands in India suggests that high altitude coastal wetlands will be one of the most sensitive classes affected by climate change (Patel *et al.*, 2009). For example, based on simulations from five numerical models, (Kirwan *et al.*, 2010) concluded that coastal marshes would likely survive conservative projections of sea-level rise but would be vulnerable under scenarios of rapid sea-level rise linked to ice sheet melting. Overall, future efforts to manage and restore wetlands will be difficult due to climate change as wetland systems are vulnerable to change in the quantity and quality of their water supply (Erwin, 2009). This is aggravated by LULC, which is discussed below.

2.3.2.3 Land-use/cover changes (LULC)

LULC is the alteration to the landscape that occurs because of human activities (Osland *et al.*, 2020). For example, the clearing of land for a building or the change of purpose of a building from one use to another. Part of wetland vulnerability is because of their loss due to LULC. Wetland loss is a global concern because they are highly diverse ecosystems that provide essential goods and services, thus threatening both biodiversity and human well-being (Sica *et al.*, 2016). There are various reasons why wetlands are being converted across the globe, including fertile soils, abundant nutrients, and freely available water, which leads to deforestation, over-grazing, agriculture, pastures and forestry (Schuyt, 2005). Such conversions lead to the wetlands spatial extent reducing and alteration of hydrological regimes. Also, transformations of the wetland's surrounding ecosystems for urbanisation and infrastructure, construction, reclamations, development projects such as dams, water diversions, and industrial expansions lead to large amounts of industrial wastewater and domestic sewage being discharged into the wetlands as well as pollution from pesticides and fertilizers, which affects the water quality of the wetland (Patel *et al.*, 2009).

Assessing LULC in wetlands is useful to improve understanding of change processes in wetlands and contribute to decision support for sustainable use of wetland ecosystems (Franke *et al.*, 2009). This is because LULC applications are often identified to establish the models from which monitoring activities such as change detection can be performed. After all, they include both baseline mapping and monitoring (Berakhi, Oyana and Adu-Prah, 2015; McCauley *et al.*, 2015). Various studies have assessed LULC in wetlands. For example, Li *et al.* (2007) performed numerical simulations of idealised deforestation and overgrazing for the Niger and Lake Chad basins of West Africa with a terrestrial integrated biosphere simulator and an aquatic transport model terrestrial hydrology model with biogeochemistry, which is an illustration of how LULC affect hydrological regimes. Berakhi, Oyana and Adu-Prah (2015), a study in East Africa on land-use changes, pointed out that agriculture is the leading cause of wetland vulnerability because of the vigorous processes such as land clearing and use of the wetland for different agricultural activities. This is complemented by Franke *et al.* (2009), who found an intensification in the agricultural use of East African wetlands by mapping land cover and monitoring land-use changes with remote sensing. Sica *et al.* (2016) developed land cover maps using Landsat images from 1999 and 2013 and identified main land cover changes for Paraná River Delta and found that one-third of the freshwater marshes of the Lower Delta (163 000 ha) was replaced by pastures (70%) and forestry (18%) in only 14 years.

The challenges that wetlands are exposed to are the cultural, regulating, and supporting services that the wetlands provide that directly and indirectly support human well-being. First, a high population growth rate is simultaneous with an increase in the demand for the wetlands' water resources and ecological services that the wetland can seldom handle. High demand pressure causes a strain on wetland resources, which is exacerbated by climate variability that exposes the wetland environment to increasing temperatures and decreasing precipitation that alter wetland hydrology. This is particularly concerning because climate-induced disturbances are expected to increase in both frequency and intensity, which will increase the shifts in the ecosystem balance caused by LULC. In wetlands, land conversions are mainly from land clearing and infrastructure constructions to create urban settlements and agricultural lands when humans move to the wetlands to benefit from the fertile soils, abundant nutrients, and freely available water. The vulnerability of wetlands from the tri-factor of water demand, climate variability and LULC require assessments as described below.

2.3.3 Wetland vulnerability assessment

Several elements are necessary for inclusion in any vulnerability assessment[1], derived from the interactions between human and biophysical subsystems. They are affected by processes operating at different spatiotemporal and functional scales (Turner *et al.*, 2003). These elements include multiple interacting stressors, the sensitivity of the coupled system to the exposure, system resilience, and system adaptation. This is to say; a vulnerability assessment should focus on assessing the vulnerability of selected variables of concern and to specific sets of stressors as opposed to attempting to quantify the vulnerability of a system (Alwang, Siegel and Jorgensen, 2001; Brooks, 2003; Smit and Wandel, 2006). More specifically, climate-related vulnerability assessments focus on the characteristics of the vulnerable system, the kind and quantity of stressors and their origins, their effects on the system, and the time horizon of the assessment (Elala, 2011; United Nations Environment Programme, 2012; Osland *et al.*, 2016).

Accurate wetland mapping is challenging, especially on a large scale, given their heterogeneous and fragmented landscape (Mahdianpari *et al.*, 2019). Fortunately, with the aid of GIS & RS's three primary techniques, namely, on-site evaluations; aerial photography, digital image processing and vulnerability indices (Spruce, Karsmizki and Giardino, 2004), wetland vulnerability assessments may be undertaken at any spatial extent or temporal scale (Turner *et al.*, 2003). On-site evaluations manage to provide highly detailed data. However, it cannot study remote and inaccessible areas, and its results do not rationalize the additional expenses incurred for personnel, equipment, and time when mapping at a landscape scale (Harvey and Hill, 2001). Similarly, aerial photography provides a synoptic view of the study area, allowing a generalized understanding of hydrology and vegetation patterns. Modern aerial photography offers high spatial resolution and advancements in technology such as drones that provide real time data. However, traditional methods had a large time gap between imagery production and map production. In both conventional and modern techniques, it is costly, time-

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[1] Vulnerability assessment is used interchangeably with risk assessment in the literature therefore, although this study mostly mentions vulnerability assessment, risk assessment is considered to mean the same thing

consuming, subject to human interpretation errors, and repeatability is a challenge because it was a human-induced photo interpretation product (Wentz *et al.*, 2006). Therefore, only satellite imagery selection and vulnerability indices are discussed further below.

2.3.3.1 Satellite imagery selection

Processing of satellite imagery is one of the major steps in wetland vulnerability assessments using GIS & RS. There are various types of satellite imagery, each with specific pros and cons, making imagery selection particular to the research and study area (Ozesmi and Bauer, 2002; Frohn *et al.*, 2009). The two main types of imagery are either hyperspectral or multi-spectral. Hyperspectral sensors offer detailed and maximised spatial resolution data, whilst multi-spectral sensors provide data that maximizes spectral and radiometric resolution and decreased spatial resolution. Both types are used for wetland studies but have been criticized for their difficulty in identifying small, long, or narrow wetlands due to the spatial resolution mostly ranging between 20 to 30m and the need to match imagery with dates when the wetland areas were at their highest water levels to separate the wetlands from uplands (Ozesmi and Bauer, 2002). It is also difficult to differentiate between the various types of wetlands due to an overlap of spectral signatures (Frohn *et al.*, 2009), which can confuse classes of wetlands and upland land cover classes (Mwita *et al.*, 2013; Amani *et al.*, 2018). Generally, five measures evaluate satellite imagery for a study: spatial resolution, spectral resolution, temporal resolution, cost, and study area coverage Table 2.1.

Table 2.1: Satellite imagery evaluation for studies.

Imagery characteristic	Description
Spatial resolution	A measure of the smallest object that the sensor or the ground area can resolve imaged in the sensor's instantaneous field of view (IFOV) or the linear dimension on the ground represented by each pixel.
Spectral resolution	The ability of a sensor to define acceptable wavelength intervals. The finer the spectral resolution, the narrower the wavelength range for a particular channel or band.
Temporal resolution	The amount of time needed to revisit and acquire data for the same location depends on the orbital characteristics of the sensor platform and sensor characteristics.
Cost considerations	The total amount of money required to both purchase and process the satellite imagery.
Coverage	The geographical area covered by the sensor to collect data and the period during which the sensor collected data.

Remote sensing technology has long been used in wetland inventory and monitoring. However, the accuracy and detail level of wetland maps derived with moderate resolution imagery and traditional techniques is limited and often unsatisfactory (Lane *et al.*, 2014). Therefore, effective image selection would require a comparison of the imagery to select the best-suited imagery. For example, Harvey and Hill (2001) compared 1m aerial photos, 2m SPOT, and 30m Landsat images to determine the accuracy and applicability of these data sources in wetland classification. The study found that the sensitivity of Landsat band 2 (green), band 3 (red), band 4 (near-infrared), and band 5 (middle infrared) provided a more accurate classification compared to SPOT and the overall accuracy is comparable to that of aerial photographs. In a study conducted at the Maputaland Coastal Plain, north-eastern KwaZulu-Natal in South Africa, satellite imagery was used to assess the distribution of wetlands over wet and dry periods and land-use change. Grundling (2014) also found that Landsat imagery and wetland vegetation maps, cultivation, and urban classes from high spatial and spectral resolution imagery can be employed in similar habitats. Therefore, it would seem that Landsat is the preferred imagery for studies.

However, the capabilities of Sentinel 2 for mapping and monitoring wetlands using pixel-based, object-based, and index-based classification and the results showed successful mapping and monitoring of wetlands with a kappa coefficient of 0.95 (Kaplan and Avdan, 2017). Therefore, Amani *et al.* (2017) analysed the spectral characteristics of five wetland types in a pilot site in Newfoundland using data from Sentinel 2A and Landsat 8, and according to the analyses, the overall classification accuracy was 84% with a Kappa Coefficient of 0.77 with Sentinel 2A having higher accuracies. In a follow-up study, Landsat 8 was compared to RapidEye, Sentinel 2A, and ASTER to investigate the spectral separability of wetland classes in Newfoundland and Labrador, Canada by Amani *et al.* (2018). The results indicated that the Near Infrared band, Red Edge band, and red band in chronological order were the most valuable bands for the discrimination of wetland class pairs. The accuracy in Sentinel 2A was the highest. This supported the notion that Sentinel is the most suitable sensor for the wetland studies because it mends the bridge between hyperspectral and multispectral sensors through its optimization of the number of potential applications thanks to numerous narrow bands spanning on a significant range of the spectrum at a high spatial resolution (Muro *et al.*, 2016; Yesou *et al.*, 2016).

Another comparison followed a study by Lane *et al.* (2014) where Worldview-2 was explored and evaluated for identifying and classifying freshwater deltaic wetland vegetation and aquatic habitats in the Selenga River Delta of Lake Baikal, Russia. The study demonstrated that including Worldview-

2’s additional four spectral bands from parts of the spectrum less commonly used in remote sensing analyses was beneficial in providing the first spatially explicit mapping of a large and heterogeneous wetland system. However, a study that followed and evaluated the potential of Worldview-2 and Sentinel 2 sensors to identify and map Andean wetlands using the one-class classifier Bias support vector machines. The results showed that the combination of remote sensing data and a small sample of ground reference measurements enables one to map the Andean high altitude wetlands with high accuracies with both sensors, particularly Sentinel 2 (Araya-López *et al.*, 2018).

Additional studies that support Sentinel sensors in wetland mapping studies include Mahdianpari *et al.* (2019) study that leveraged Synthetic Aperture Radar and optical Sentinel-1 and -2 data composites to produce a detailed, provincial-scale wetland inventory map. The results revealed the superiority of the object-based approach for wetland mapping. The classification using multi-year optical data was more accurate than that of SAR in the classification accuracy of wetland classes. In another study, the synergistic use of Sentinel 1 and 2 combined with the System for Automated Geoscientific Analyses Wetness Index in the content of LULC mapping in the highly vulnerable iSimangaliso Wetland Park. Results showed that the SAGA wetness index combined with Sentinel-1 and 2 synergies could successfully produce a LULC classification in a location where both wetland and non-wetland classes exist (Whyte, Ferentinos and Petropoulos, 2018). This was complemented by Chatziantoniou, Psomiadis and Petropoulos (2017), who also evaluated the synergistic use of Sentinel 1 and Sentinel 2 data combined with the Support Vector Machines machine learning classifier for mapping LULC in National Park of Koronia and Volvi, Greece. The study findings exemplified the appropriateness of the spatial and spectral resolution of Sentinel data in obtaining a rapid and cost-effective LULC and the suitability of the Sentinel 1 and 2 data for improving the ability to map a complex area containing wetland and non-wetland LULC classes for wetlands as required in geospatial vulnerability assessments that are described below.

2.3.3.2 Geospatial vulnerability assessment approaches

The primary framework for freshwater vulnerability assessments is the driver-pressure-state-impact-response (DPSIR) framework, which discusses wetland vulnerability in terms of analysis of human and environmental systems. For example, Malekmohammadi and Jahanishakib (2017) used a combined method of the hydro-geomorphic approach to estimate vulnerability indicators through Multi-Criteria Decision Making (MCDM) and DPSIR analysis to assess the vulnerability of Choghakhor wetland, Iran. The assessment showed that the DPSIR is useful in determining a management strategy to reduce the vulnerability of ecosystem services. Another framework often used is the Water Safety Plan (WSP) which was used by Parker and Summerill (2013) to identify barriers for WSP implementation in this region, as well as potential motivating factors, which is achieved through 20 semi-structured interviews with utilities, regulators, and international agencies. The results showed that smaller or weaker utilities might struggle to implement a WSP as they are constantly engaged in their day-to-day problems and cannot plan for the longer term. Both frameworks place value on the use of expert knowledge acquired through questionnaires or interviews. This has been proven in a study by (Mutisi, 2014), where the expert judgement was applicable in Harare, Zimbabwe, to verify that mitigation measures associated with the challenges of wetland degradation were in place.

There are different approaches used to assess wetland vulnerability, which involves identifying the status of, and threats to, wetlands as a basis for the collection of more specific information through monitoring activities (Gitay, Finlayson and Davidson, 2011). One method is to use a landscape-scale geospatial assessment of wetlands such as the study by Copeland *et al.* (2010) in Wyoming to map areas with high densities of wetlands and quantify wetland complexes as a function of their biological diversity, protection status, susceptibility to climate change, and proximity to sources of impairment. The results gave an inventory of wetlands, their size, and wetland complexes, which is basic information that will allow decision-makers to allocate limited resources to conserve, manage, and restore wetlands effectively. Another method is to use a methodology that gives a structure to data collection and analysis that leads the user to produce a vulnerability assessment. This was tested on three wetland sites in Nepal by Stratford, Acreman and Rees (2011). The results showed that the method provided a prioritized table of values and threats, which helped develop a site management plan straightforward.

Geospatial vulnerability assessment approaches also use vulnerability indices such as the Environmental Vulnerability Index (EVI) and the Quantification Vulnerability Assessment of Environment (QVAE). EVI was used by a technical report produced by the South Pacific Applied Geoscience Commission (2004) based on a series of 50 as smart indicators and countries' environmental vulnerabilities categorized into one of five categories, namely, extremely vulnerable, highly vulnerable, vulnerable, at-risk, and resilient for 253 countries. The results show that EVI is a holistic framework for assessing vulnerability would be one that quantifies the impact of humans on the environment and then considers how changes in the environment would increase human vulnerability (Kaly, Pratt and Mitchell, 2004). QVAE was used by Metzger and Schröter (2006) to assess vulnerability with a view of the services, which ecosystems provide to human dynamics such as carbon storage, food production, biodiversity, and scenic beauty. The study successfully produced spatially explicit maps of vulnerability per ecosystem service for multiple scenarios and time slices within the next century.

van Dam, Finlayson and Humphrey (1999) propose that wetland risk assessment is a form of vulnerability assessment whose framework encompasses six basic steps. These are identifying the problem, the effects, the extent of the problem, the risk, risk management and reduction, and monitoring. GIS and RS are useful in these risk/vulnerability assessments and are used in different studies to assess wetland vulnerability to various stressors. For example, Pittock, Finlayson and Howitt (2013) assessed other programs to see whether micro engineering works to manage the hydrology of wetlands for effective adaptation to water scarcity and climate change. The study recommended that trade-offs between alternative strategies are assessed as the basis for minimizing perverse impacts under changing climatic and hydrological conditions. In another study, a systematic methodology for risk assessment and zoning of Shadegan International Wetland, Iran, uses a process of ecological risk assessment to identify stress factors and responses within the framework of an ecosystem-based approach. Malekmohammadi and Blouchi (2014)'s results showed that high-ranking potential risks and areas with different levels of risk and management strategies were proposed for this wetland.

Other studies include land cover dynamics linked to the spatial changes in wetlands fringing lagoons are comprehensively assessed with remote sensing data, and GIS uses topographic maps as baseline data (Obiefuna *et al.*, 2013). Results show that as wetlands, water bodies, and vegetation decreased, built-up areas and bare land increased. Most of the growth in built-up areas occurred in previous wetland areas and some vegetated areas. Sarkar, Parihar and Dutta (2016) presented a Fuzzy-based Risk Assessment Model using GIS and RS tools to identify the areas with varying intensity of wetland conversion risk within the East Kolkata Wetland Area. The validation showed that the Fuzzy-based Risk Assessment Model has efficiently modelled and mapped the various levels of wetland risk zones of EKWA. Lastly, Wright and Wimberly (2013) used LULC data to assess grassland conversion from 2006 to 2011 in the Western Corn Belt, and their results were able to identify areas with elevated rates of grass-to-corn/soy conversion, a net decline in grass-dominated land cover and that grassland conversion is concentrated close to wetlands. Each of these studies confirms that early warning indicators for the major types and causes of wetland vulnerability include changes to the exploitation, physical modification and loss of production (van Dam, Finlayson and Humphrey, 1999).

A wetland vulnerability assessment to climate requires the inclusion of multiple interacting stressors and consideration of the effects of the stressors on the system and the time horizon of the evaluation. Mapping wetlands accurately is challenging due to their heterogeneous and fragmented physical landscape that changes over time. However, GIS & RS – exceptionally high-resolution satellite imagery such as Sentinel - assist with accurately mapping wetlands at any spatial and temporal scale. This has proven helpful for geospatial vulnerability assessments that can be done by a landscape-scale geospatial assessment of wetlands; or a structure to data collection and analysis that leads the user through an evaluation; or vulnerability indices. All three methods highlight that early warning indicators for the major types and causes of wetland vulnerability include changes to the exploitation, physical modification and loss of production.

2.4 CONCLUSION

Water scarcity is a major challenge in most countries, particularly those that are arid/semi-arid, like South Africa. One viable freshwater ecosystem that may assist in alleviating the water scarcity is wetlands. Heedless of the benefits they offer, wetlands have experienced rapid vulnerability rates (Fennessy, Jacobs and Kentula, 2007). Assessment of wetland vulnerabilities requires less financially taxing methods such as those offered by GIS & RS, which will aid water scarcity as they allow the scope of the study to include both quantity and quality of water available, which is sensitive to its variation of use (Adam, Mutanga and Rugege, 2010). The three main issues of wetland vulnerability addressed in the review are alterations by human activities and climate variations resulting in modifying their biophysical form (van Dam, Camilleri and Finlayson, 1998). The review shows that GIS's ability to provide the basis for analysis of data, including change detection and RS's ability to provide data during mapping, helps assess wetland's vulnerability to water demand, climate variability and LULC (Spruce, Karsmizki and Giardino, 2004; Adam, Mutanga and Rugege, 2010; Mutanga, Adam and Cho, 2012).

CHAPTER 3: METHODOLOGY & METHODS TO ASSESS WETLAND VULNERABILITY

3.1 INTRODUCTION

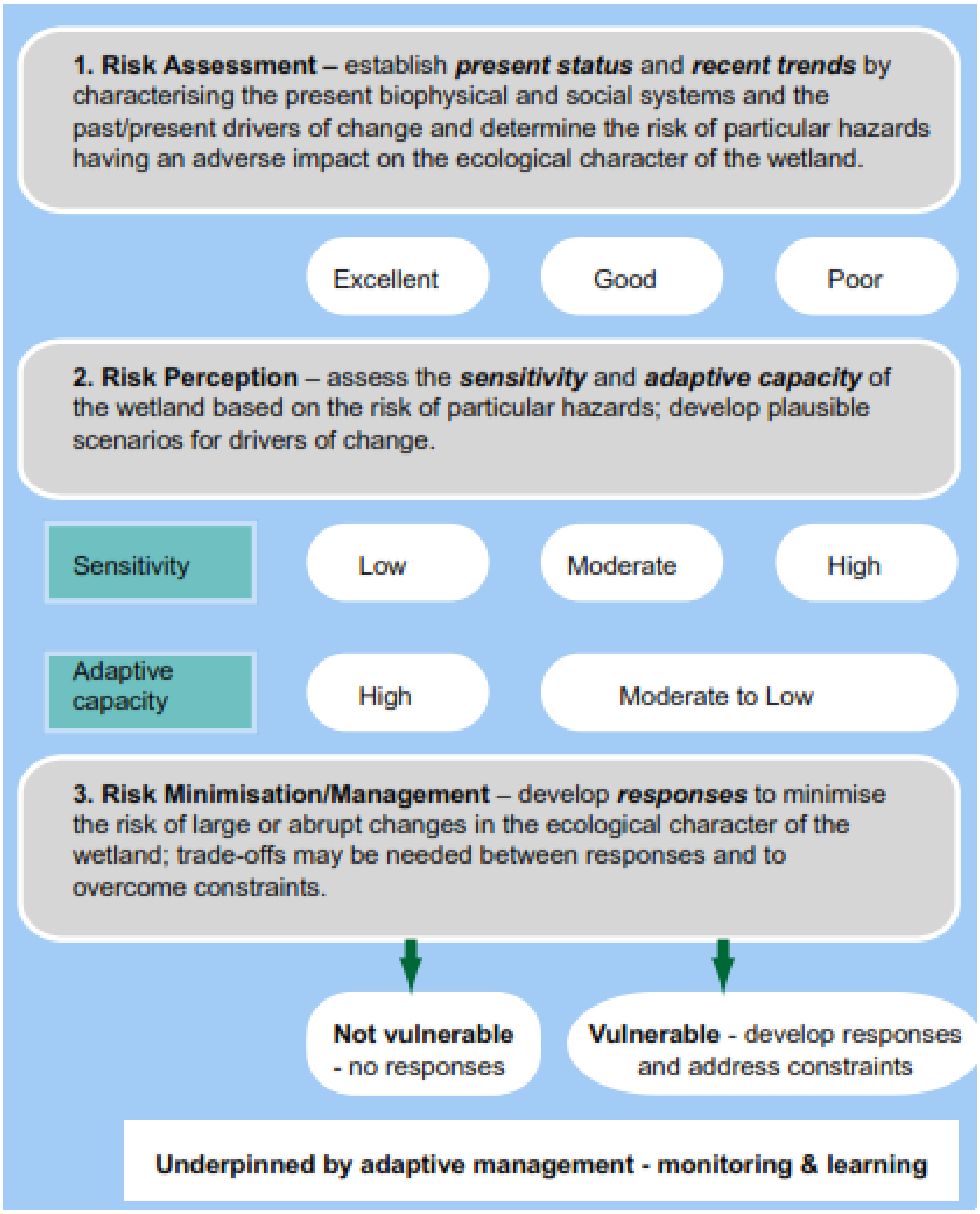
Chapter three comprises a detailed account of the methods used in the study from data collection, preparation, and processing. As part of the methodology, the study adopts the Ramsar Convention's Wetland Vulnerability Assessment to develop a framework for wetland vulnerability monitoring. Thereafter, the study uses tools derived from GIS and RS to assess the vulnerability of a wetland because of water demand, land cover/use changes and temperature and rainfall fluctuations.

3.2 METHODOLOGY

Measuring wetland vulnerability requires defining the wetland's condition, functions, and values where the condition is the wetland's "state" that reflects a combination of physical, chemical, and biological characteristics (van Dam, Camilleri and Finlayson, 1998; Copeland *et al.*, 2010; Gitay, Finlayson and Davidson, 2011; Stratford, Acreman and Rees, 2011; Osland *et al.*, 2016; Malekmohammadi and Jahanishakib, 2017; Thorne *et al.*, 2018). Functions include the ecological processes or services a wetland performs (Fennessy, Jacobs and Kentula, 2007; Galli *et al.*, 2012), and values include education, recreation, and aesthetics (Mitsch and Gosselink, 2007). Due to the wetland vulnerability being primarily due to human influences manipulating or using the wetland ecosystem, the study advances the wetland vulnerability assessment adapted from Gitay, Finlayson and Davidson (2011) Ramsar Convention Secretariat. This framework considers the wetland vulnerability in three stages, namely, risk assessment, risk perception, and risk minimization/management (Gitay, Finlayson and Davidson, 2011).

Risk assessment requires delimiting the spatial and temporal boundaries of the wetland's hydrology, identifying the past and present drivers of change and existing hazards, and assessing the present condition of the wetland ecosystem services. Risk perception requires an assessment of both sensitivity and adaptive capacity concerning a particular hazard. This will result in the development of plausible scenarios delineating changes and their drivers. Risk management requires developing responses to hazards to reduce intense changes within the ecology of the wetland. The Ramsar Convention is a broad method that is inclusive of qualitative information and an extensive evaluation.

However, the model infrastructure is well laid out to accommodate a quantitative approach to identify still and measure the vulnerability of a wetland. In this study, risk assessment is addressed by applying GIS and remote sensing that uses spatial data to delimit the spatial extent or variations of the wetland's component over time. Risk perception accommodates the development of a definition of sensitivity and adaptive capacity that can be adapted to quantitative data from which hazardous variables can be identified, which is the case of the current study. Then, an index defining criticality can be used to describe the vulnerability of the wetland.



1. Risk Assessment – establish ***present status*** and ***recent trends*** by characterising the present biophysical and social systems and the past/present drivers of change and determine the risk of particular hazards having an adverse impact on the ecological character of the wetland.

2. Risk Perception – assess the ***sensitivity*** and ***adaptive capacity*** of the wetland based on the risk of particular hazards; develop plausible scenarios for drivers of change.

3. Risk Minimisation/Management – develop ***responses*** to minimise the risk of large or abrupt changes in the ecological character of the wetland; trade-offs may be needed between responses and to overcome constraints.

Underpinned by adaptive management - monitoring & learning

Figure 3.1: Wetland vulnerability assessment adapted from Gitay, Finlayson and Davidson (2011).

3.3 DATA DESCRIPTION, COLLECTION AND MANAGEMENT

The study was conducted using various software, including ArcGIS 10.4, R version 4.0.0 in the Visual Studio IDE, and eCognition. As a geographical study, correct projected and geographic coordinate systems determine the exact locations of different objects on the earth's surface. Therefore, all data were projected to Universal Transverse Mercator (UTM) Zone 36S and geographic coordinate system WGS 1984. This study required various secondary data sets such as climate data for evapotranspiration estimation and trend analysis; Sentinel 2 satellite images to compute land-use and land cover change. This was necessary because appropriate data collection techniques ensure the validity and reliability of data used in research (Mouton, 2001). The data collection and description of each of these data sets are described below.

3.3.1 Climate Data

The rule of thumb with climate studies is that the climatic data should ideally have corresponding dates with the satellite imagery (Ozesmi and Bauer, 2002). This is to understand correlations between what is observed on satellite imagery and what is highlighted by the climate data. Unfortunately, the data made available by South Africa Weather Services (SAWS) had gaps lasting as long as three weeks in some instances. They were from a weather station over 96km away from the study area. Climate data of the Hogsback area from 02-06-2015 to 03-02-2020 were obtained from the Meteoblue weather service (https://www.meteoblue.com/en/weather/) which is a weather service that offers weather prediction in a graphical synopsis for any arbitrarily chosen location on earth. The variables Meteoblue provided included rainfall (mm), temperature (ºC), wind speed at 10 (km/h), sunshine (minutes), solar radiation (w/m^2), and relative humidity (%) measured as daily accumulation (Digital Attachment 1 and Appendix B). However, it is essential to note here that the Meteoblue data is from a consistent weather simulation model, which means challenges from modelling such as data availability constraints (Redhead *et al.*, 2016; Jafarzadeh *et al.*, 2019) as well as pre-existing modelling assumptions (Vaze *et al.*, 2011; Haque *et al.*, 2015). Therefore, it may lead to over generalisations in the climate predicted for small study areas such as Die Vlei. Nonetheless, it offers consistent data, which was crucial for the study. Furthermore, Meteoblue provides high-resolution precipitation and low-value precipitation, but the study used the high resolution to present better climatic differences.

3.3.2 Satellite images

Satellite technology facilitates the recording of data measurements made at a distance (D'eon and Delparte, 2006) and has since been adapted to freshwater ecosystems monitoring (Hitt *et al.*, 2015). Particularly for monitoring small wetlands, which requires spatially high-resolution remote sensing data to account for the prevailing small-scale diversity in land use (Franke *et al.*, 2009). In this study, a comparison of different multispectral satellite imagery currently freely available for South Africa either through the South African National Space Agency (SANSA) or various accessible online sources whose coverage included the study area was used to establish the appropriate imagery to use for the study. Table 3.1 shows that each imagery type has disadvantages such as low spatial, horizontal, and vertical resolution, high spatial inaccuracies, and partial coverage of the study area. The list was created using input from (Ozesmi and Bauer, 2002; Shuman and Ambrose, 2003; Klemas, 2011; Amani *et al.*, 2018).

Table 3.1: Comparison of resolution and description of different satellite imagery available for South Africa.

Sensor	Spatial resolution (m)	Spectral resolution (nm)	Temporal resolution (days)	Launch year
CBERS-4	20	450 to 890	26	2014
Landsat 8	30	435 to 1 384	16	2013
Modis - Terra	250, 500, and 1000	400 to 14 400	~2	1999
- Aqua				2002
RadarSAT-2	-1:Spotlight mode -3:UltraFine mode -100:ScanSAR Wide Beam mode		24	2007
Sentinel 2	-10: visible & NIR bands -20: red edge & SWIR bands - 60: atmospheric correction bands	443 to 2 190	5	2014
SPOT 7	Panchromatic: 2 Multispectral: 8	450 to 890	~ 3	2014

Of the compared imagery, SPOT and Sentinel 2 had the best spatial resolution and better horizontal accuracies. Although Sentinel has higher vertical accuracy, SPOT has a larger temporal scale.

Therefore, they were both used to systematically reconstruct LULC, the SPOT for long-term changes, and the Sentinel for a "current assessment" of the wetland. The study downloaded SPOT from the United States Geological Survey (USGS) platform at the following website: https://earthexplorer.usgs.gov/. SPOT data have a revisiting period of 1 to 4 days and a constellation period of 26 days. The data were downloaded for ten years between the dates 2007 and 2017. On the other hand, the Sentinel 2 dataset was downloaded from the science hub of Copernicus at the following website: https://scihub.copernicus.eu/dhus/#/home. This data revisits ten days and a constellation period of 5 days between the two satellites, A and B.

3.4 STUDY LIMITATIONS

One of the significant shortcomings of the study is data availability. First, the quantification of water demand would have benefited from a well-recorded log of metered water use to serve as a baseline to model additional demand in areas that are not metered. Therefore, the study uses evapotranspiration as a proxy for water demand. The climate data posed a challenge because the study failed to secure data from a local weather station. The SAWS weather data was from a station over 90km away and inconsistent with gaps lasting over three weeks at times. This made the SAWS weather data inefficient, and the study resorted to using Meteoblue data.

Furthermore, the Ramsar Convention requires expert knowledge; however, the study could not conduct interviews, which limited the data collection. However, the extensive literature review compensated for this. The study also would have benefited from site visits independent of the pilot survey. While satellite imagery was used for visual assessment, its value is not the same. This is because Die Vlei is a small wetland. The spatial resolution of imagery with sufficient temporal resolution imagery such as SPOT is coarse. The temporal resolution of imagery with adequate spatial resolution such as Sentinel is too short. Therefore, the study uses both imageries, the SPOT to reconstruct LULC in 2007 and 2017, and the Sentinel to assess the current LULC.

3.5 JUSTIFICATION OF SELECTION STUDY AREA

Die Vlei (Figure 3.2) is a wetland located in the Hogsback area, North-East of Raymond Mhlaba Local Municipality in the Eastern Cape Province of South Africa. Heedless of the Eastern Cape's aridity where rainfall distribution shows that 72% of the region receives on average less than 100mm mainly in the provinces' towns, 18% of its area receives 100-300mm, and only 10% receives more than 300 mm (Hay *et al.*, 2012; Ngaka, 2012; Amathole District Municipality, 2014; Mahlalela *et al.*, 2020). The temperature range is between –6ºC and 32ºC with an annual average of 16ºC, which complements the arid climate (Lechmere-Oertel, 2010). However, Hogsback has an altitude range between 1200m and 1963m and receives over 900mm of rainfall per annum. This emphasizes the unique capability of Die Vlei to offer support to the general water-scarce province. Die Vlei is in quaternary catchment S32D, coordinates 32.55°S, 26.97°E a total of about 8 000 ha is characterized by open water and heavily saturated soils and has attributed to the low-land river section running through it. The wetland occurs on the steep to low gradient slopes as well as the valley bottom. Criss-crossing dolerite dykes impede flow, resulting in constriction and backing up of the river, forming a large wetland on either side of the river in the valley. Interflow from hillslope seeps drain through valley bottoms towards the main floodplain system, with all wetlands predominantly palustrine (van Deventer *et al.*, 2020).

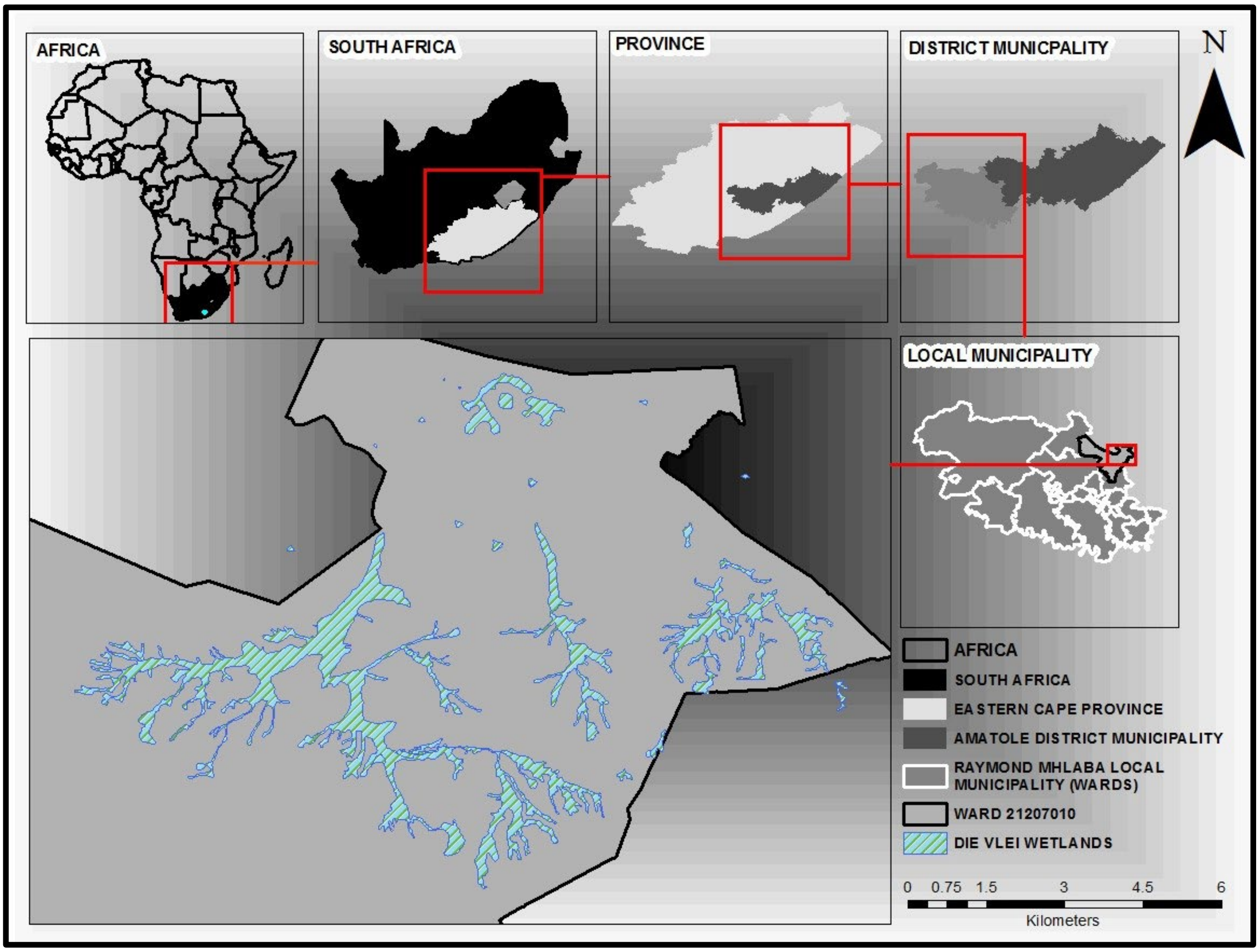


Figure 3.2: Representation of the study area: Die Vlei wetland, that lies to the North-East of the nearest village – Hogsback in Nkonkobe Local Municipality, Eastern Cape Province.

The Working for Wetlands program identified it as viable for rehabilitation after reporting that it is exposed to extensive pressure from a growing population, climate-induced and numerous LULC that have led to persistent vulnerability and limited the wetland's ability to sustainably provide water for human use (Department of Environmental Affairs South Africa, 2011; Youthed, 2014). For the study, Die Vlei was delineated via desktop following the guidelines for delineating a wetland set out by the Department of Water Affairs and Forestry. As a small but productive wetland, Die Vlei is the most suitable wetland for the study because firstly, between census 2001 and 2011, the Hogsback population almost doubled from 645 to 1 029 due to both immigration and growth of businesses (Statistics South Africa, 2011), whilst the water bodies have continuously shrunk over time. A spike in population growth correlates with increased demand on domestic and commercial water requirements, which is assumed to be the case in Die Vlei (Youthed, 2014). An estimation of the actual demand heedless of the sector is invaluable in assessing the wetland. Secondly, Mhangara (2011) reported trends showing increasing land degradation in that area, which is likely to continue in wetlands as water bodies and vegetation decrease whilst built-up areas and bare land increase (Obiefuna *et al.*, 2013). It is essential to assess if this is the case with Die Vlei and what impact LULC has on the wetland's vulnerability. Lastly, both population growth and LULC are exacerbated by climate variability/change and increase wetland vulnerability (Patel *et al.*, 2009). Climate variability in semi-arid or arid areas leads to an increase in temperatures and a decrease in rainfall totals, which reduce the productivity of the wetland (Voldseth *et al.*, 2009; Gopal, Shilpakar and Sharma, 2010). As both population growth and LULC are present in Die Vlei whilst there is evidence of climate variability the world over, this study is best suited to show the combination of these factors on wetland vulnerability.

3.6 METHODS: RAMSAR CONVENTION'S VULNERABILITY ASSESSMENT

The methodology used in the study was based on the Ramsar Convention's Vulnerability Assessment. The study presents the methodological framework created, shown in Figure 3.3, as the methods to be followed to suit the theory's first step to analyse wetland vulnerability to water demand, climate variability, and LULC towards a complete vulnerability assessment wetland.

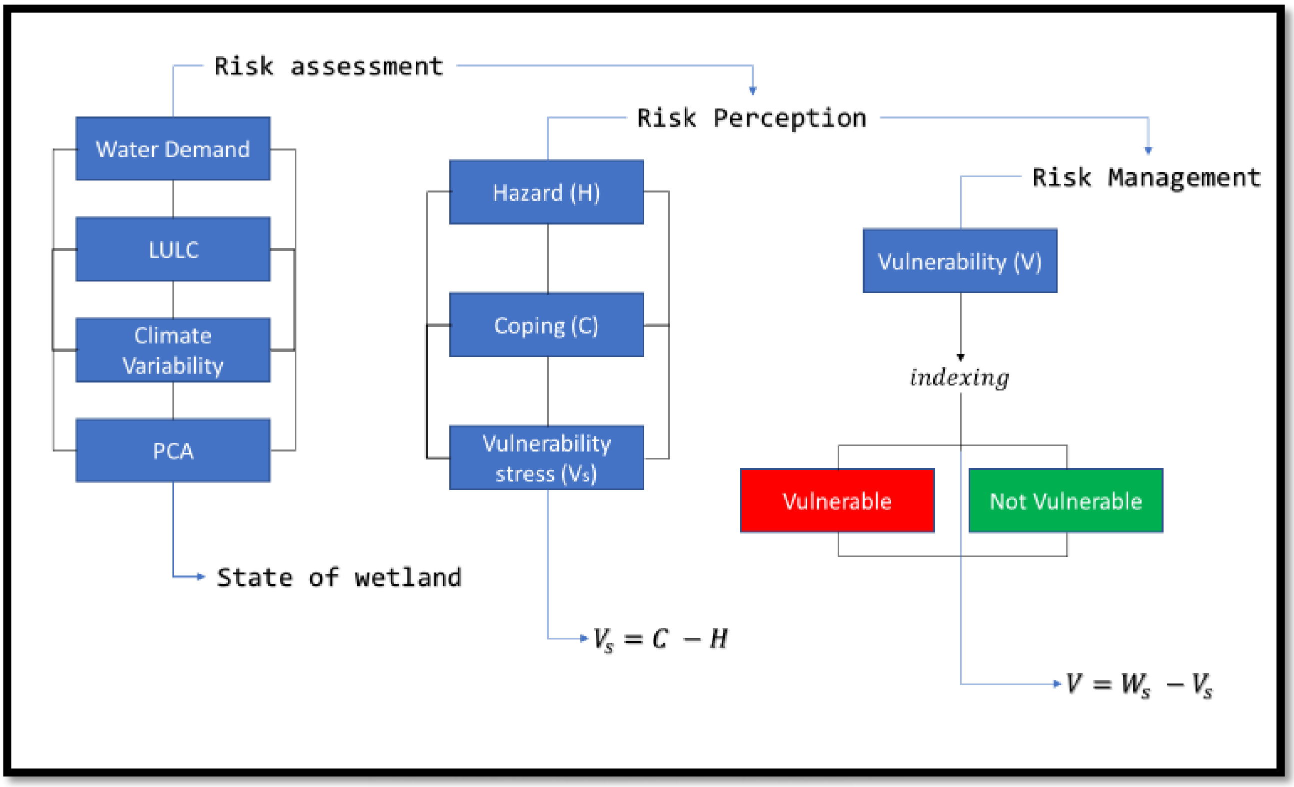


Figure 3.3: Experimental design giving systematic detail of the methods used in the study in their chronological order.

The study was conducted in Die Vlei wetland and had four objectives that each method was designed to achieve. The vulnerability assessment is conducted using water demand is quantified from evapotranspiration, trend analysis results of temperature and rainfall, and reconstructed LULC change. The risk assessment and perception and each of the corresponding methods is discussed in detail below.

3.7 RISK ASSESSMENT

This study focuses on water demand, climate variability, and LULC as the main combination of factors that affect the Die Vlei wetland's physical state. Water demand (represented by water balance and evapotranspiration) and climate variability (characterised by monthly rainfall and temperature) were considered "individual" factors. For LULC, due to the variation in land-uses and land covers, the study followed to identify water, bare soil, and vegetation (dry grass and healthy grass) as three LULC's of interest using the Normalized Difference Vegetation Index (NDVI) to evaluate the wetland's state. Firstly, the vulnerability assessment used a statistical package R to run a Principal Component Analysis (PCA) in the factoextra package to identify the main contributing variables to the wetland’s physical state. Secondly, from the PCA, the study was able to estimate each variable’s contributions to the physical variations in the wetland.

3.7.1 Quantitative representation of water demand

To measure water demand, this study used Penman-Montheith-FAO (ET_o) evapotranspiration index. The index estimates the potential amount of water loss occurring in the wetland and the surrounding ecosystem (Sumner, 2007; Naipal, Naipal and Samson, 2013). The ET_o is calculated using the following relationship:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

Where:

R_n (mj/m^2) is the net radiation on the surface, which balances incoming and outgoing energy at the top of the atmosphere. It can also be estimated as follows:

$$R_n = RG * 0.419 * 0.8$$

RG is the solar radiation, the radiant energy emitted by the sun from a nuclear fusion reaction that creates electromagnetic energy expressed in cal/cm^2. It has two factors, Factor 0.0419 converts cal/cm^2 day into MJ/m^2 day, and Factor 0.8 is the R_n/RG quotient for a vegetated area with a good water supply. The air vapour pressure at saturation, es (kPa) is calculated as:

$$es = 0.707 * e^{(0.05979 * Ta)}$$

Ta is the average air temperature (°C), which describes the kinetic energy, energy of motion, and the gases that makeup air. The air saturation shortage Ds (kPa) is the amount by which the water vapour in the air must be increased to achieve saturation without changing the environmental temperature, and pressure is calculated as follows:

$$Ds = es * (1 - \frac{HR}{100})$$

HR is the relative humidity, which is the amount of water vapour present in air expressed as a percentage of the amount needed for saturation at the same temperature. The saturation vapour pressure is a measure of when the pressure of vapour is in equilibrium with the liquid phase. The saturation vapour pressure curve slope, Δ (kPa/°C), is solely dependent on the temperature and has a symbiotic relationship where the saturation vapour pressure rises when the temperature rises. Δ (kPa/°C) is calculated as:

$$TETA = (Ta + 237.3)^2$$

$$ALFA = 17.27 * \frac{Ta}{Ta + 237.3}$$

$$\Delta = 4098 * (0.6108 * e^{ALFA}) / TETA$$

Advection is the transport of some property of the atmosphere or ocean, such as heat, humidity, and salinity, which is important for forming orographic clouds and water precipitation from the clouds hydrological cycle. To calculate the advective contribution in ET_o, the following equation is used:

$$Adv = \frac{(\gamma * 900 * U * Ds)}{Ta + 273}$$

With $\gamma = .066\ (kPa/°C)$; U= wind speed in m/s; Ds = saturation shortage (kPa)

The radioactive contribution:

$$Rad = 0.408 * \Delta * Rn$$

The resistance to vapour diffusion in the limit layer:

$$Dn = \Delta + 0.066 * (1 + 0.34 * U)$$

The radioactive component of ET_o:

$$ETRAD = \frac{Rad}{Dn}$$

The advective component of ET_o:

$$ETADV = \frac{Adv}{Dn}$$

Finally, the water demand (ET_o) is broken down as:

$$ETo = ETRAD + ETADV$$

Therefore, water shortage was evaluated using the relation between supply-demand calculated as:

$$DH = P - ETo$$

3.7.2 Measuring climate variables variability using trend analysis

All climate variables were first restructured into decadal accumulation values to complement the temporal resolution of Sentinel 2 imagery, which is also ten days. This was done to facilitate synchronising the climate events with variabilities detected within the wetland surface area following (Ozesmi and Bauer, 2002). Following the decadal accumulation, the data was reduced to 171-time point data. Trend analysis was done by testing specific components of the time series, namely, periodic fluctuations to detect seasonality and trend detection is used to evaluate the general changes in the variables of a dataset that increase or decrease following specific trends (Cheng *et al.*, 2011; Zhi and Ji, 2012). Seasonality detection was done using a time series plot to evaluate seasonality and the WO-test developed by Webel and Ollech (2018). The WO-test gives out a “TRUE” if the series is seasonal and “FALSE” otherwise. Given that a dataset may not be seasonal in some cases but contain a seasonal component, the study used the Exponential smoothing state-space model function in R to detect possible seasonal components and used the chi-square test to validate if the seasonal components are significant.

A final test was done to evaluate whether all possible seasonality or trends observed could be considered a variant or stationary. Essentially, a stationary time series differs from a variant time series in that it is devoid of trend or seasonal patterns, which makes it present like random white noise irrespective of the observed time interval (Webel and Ollech, 2018). Therefore, the three main properties of a stationary time series are, firstly, the mean value of time series is constant over time, meaning that the trend component is nullified. Secondly, the variance does not increase over time, and lastly, the seasonality effect is minimal, if at all present (Zhi and Ji, 2012). The study used the time series function (ts ()) in the R package to evaluate trends (see Appendix A). The trend of the given series was fitted to four models: the moving average, the parametric regression, the Local Estimated Scatterplot Smoothing (LOESS), and the splines trends estimation that fits the Generalized Additive Models (GAM) to the data (Bodnar and Schmid, 2010). LOESS is also known as the non-parametric regression. All four regressions were compared together in a line plot to conduct a visual model fit test to identify the best-suited model to the trend.

3.7.3 LULC change impact on wetland vulnerability

This study employed the use of object-based classification to classify and map the LULC of the wetland ecosystem. Both the segmentation and classification were done in eCognition, an object-based classification software using a three-tier classification approach that divided the classes based on their definitions and spectral signatures (Definiens Developer 8, 2020). SPOT-5 imagery for the years 2007 and 2017 was used in the study with only three visible bands and excluding the infrared bands, and their spatial resolution was already resampled to 2.5 meters.

3.7.4 Principal Component Analysis (PCA) method

Numerous factors affect the wetland either physically or chemically. This study focuses only on the physical state of the wetland and the impact of water demand, climate variables, and LULC. Therefore, there was a need for the study to identify which of the variables was the most influential for the wetland. Three features were considered to be of interest for the wetland: vegetation, water, and bare soil. The study extracted the wetland boundary from LULC and used it as the border in monitoring spatial changes in the three variables mentioned above. These changes were quantified in terms of surface area by variable. After that, the study used statistical package R in factoextra packages to run a PCA.

3.7.5 Defining the state of the wetland

The first step in a wetland risk assessment is to classify the wetland health (state). In this study, this was done by identifying variables of the wetland that constitute a healthy wetland as defined by Gitay, Finlayson and Davidson (2011). After that, the study measured the surface area of each variable as the basis to classify the wetland based on predominance. The study did this following the steps that are described below:

1. Measure the total surface area of the wetland, which is 100% of the wetland physical extent.
2. Supposing the wetland has four variables: water, soil, dry grass, and healthy grass, then the wetland is considered healthy if there is more vegetation and water than bare soil.
3. Calculate the surface area of each variable's physical extent and then balance the spatial extent among the variables to facilitate classification. The study expressed this by expressing occupancy in percentage.
4. Occupancy then allows the study to identify the state of the wetland as either excellent, good, or poor.

3.8 RISK PERCEPTION

Given that this study solely focuses on the influence of water demand, climate variables and LULC, risk perception have to be modified to have its scope extended to include how it should be viewed in respect of how the variables relate to each other rather than seeking solely expert knowledge, which is a good addition. Therefore, in this study, using correlation and regression analysis, statistical methods, risk perception was used to identify climate variables and the LULC that poses a risk and those that contribute to the sustainability of the wetland based on their respective relations to the wetland.

3.8.1 Identify the hazardous variable/s of the wetland

In this study, variables that cause essential factors of the physical wetland to change negatively are identified using correlation. The interpretation of this is that those that negatively affect elements such as vegetation were considered sensitivity variables that are hazards to the wetland amongst all climate variables. A simple regression model was used to measure the correlation and test the significance of predictability of climate variability on the wetland.

3.8.2 Compute vulnerability stress

Many studies have employed the use of various techniques to quantify vulnerability. These techniques include fuzzy modelling, statistical analysis, or GIS-based techniques (Wilhelmi and Wilhite, 2002;

Acosta-Michlik *et al.*, 2005; Shewmake, 2008; Azadi *et al.*, 2009). Some studies have advocated for indices to measure vulnerability (Adger, 2006; Zakieldeen, 2009; Patnaik and Narayanan, 2015), a similar approach adopted in this study combined with a GIS-based method. Various vulnerability indices are used for a variety of purposes, including measuring vulnerability to population resilience to drought, famine; wetland state, and other disasters (Webb and Harinarayan, 1999; Luers *et al.*, 2003; Deressa, Hassan and Ringler, 2008; Zarafshani *et al.*, 2012; Davis, 2013; Wisner, 2013). These indices can be adapted and adjusted to suit a quantitative framework even though they are predominantly used within qualitative frameworks. This study adopted the vulnerability index proposed by Webb and Harinarayan (1999) and similar to Alwang, Siegel and Jorgensen (2001) that consist of balancing between hazard and coping expressed as follows:

$$\text{Vulnerability (V)} = \text{Hazard (H)} - \text{Coping (C)}$$

However, to suit this study, it is more suitable to evaluate the effect of hazardous variables on the wetland rather than balancing coping abilities to hazards. This is in response to the model's selection of assessing the ability to manage a disaster given an initial bad condition (Zarafshani *et al.*, 2016). In this study, the intention is only to evaluate the effect of a hazard on the wetland as a take-off point for conducting a complete vulnerability assessment. Therefore, the study cannot give a comprehensive view of the vulnerability of the wetland but can highlight the perspective of the impact of climate variability on the wetland and explain the general exposure to risk from water demand and LULC. A logical deduction is that to assess vulnerability stress, the hazard should be subtracted from coping as shown below:

$$V_s = C - H$$

Where V_s is vulnerability stress, C is coping, and H is a Hazard. Wetland vulnerability stress refers to a quantitative estimation of risk that determines whether the wetland is likely to be stressed or not.

3.9 RISK MANAGEMENT: WETLAND VULNERABILITY ASSESSMENT

This study defined wetland vulnerability in the context of climate variability if the wetland is exposed to a changing climate with negative impacts on the wetland's ecological system and functioning.

Therefore, this study developed an index to determine wetland vulnerability, which was done using an equation proposed by Burg (2008). This equation estimates that vulnerability is a sum of exposure to risk and the inability to cope. These selected variables were substituted with vulnerability risk wetland state, respectively. The former is essentially risk exposure, and the latter determines the ability to cope with harsh climates. Therefore, the study expresses the wetland vulnerability using the equation given below:

$$V = W_s * W_w + V_s * W_v$$

V is vulnerability, Ws is wetland state, Ww is the weight for wetland state, Vs are vulnerability stress, and W_v weight for vulnerability stress. Therefore, the study compared the long-term average of all input variables. The variables were indexed to equate "bad conditions" having negative values and "good conditions" having positive values to facilitate comparison. Interpretation of the vulnerability score is that if the score is below 0, it suggests that, on average, the wetland is likely vulnerable due to harsh climatic conditions, which is exacerbated by water demand and LULC occurring in and around the wetland ecosystem. To identify the most influential variable in the wetland's vulnerability, the study conducted a Multi-Criteria Evaluation (MCE). The MCE allowed the study to use only the relevant variables to compute wetland vulnerability; from its results, the contribution of each variable to the model was determined and used as weights. Eigenvalues determined the MCE weights in a widely used method for a weighted combination of various layers (Kourgialas and Karatzas, 2011; Pramanik, 2016; Owusu *et al.*, 2017; Buruso, 2018; Muhsin, Ahamed and Noguchi, 2018; Nag and Kundu, 2018; Akther *et al.*, 2019; Purnamasari, Ahamed and Noguchi, 2019).

3.10 CONCLUSION

In conclusion, the calculations for the index and the classification of the variables follow a three-step process:

a) Each variable is first estimated in terms of probabilities,
b) The variable scores in percentage are indexed using the SPEI, and
c) The combined indices to assess either vulnerability stress or wetland state, the vulnerability will be converted back to percentages then classified.

Essentially, the study used the index for calculations and probabilities for classifications.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 INTRODUCTION

Chapter four presents the study's results and discusses them in line with the literature. The chapter begins by discussing the results of the estimated water demand when ET_o is used to delimit the spatial and temporal boundaries of the hydrology of the wetland. Thereafter, the results of the temperature and rainfall trend analysis and results of the LULC are presented. Lastly, the vulnerability assessment results using PCA and MCE are presented and discussed to conclude on the condition of the wetland's vulnerability.

4.2 RISK ASSESSMENT

Wetlands are affected by a combination of physical, chemical, and biological characteristics that, although they are interrelated, may have different degrees of influence on the resulting physical state of the wetland. These variables influence the wetland differently in other areas. For example, where temperatures may be an influential variable in a humid wetland, it may not be so influential in an arid wetland. Such differences are evident in the water demand estimation done using ET_o described below.

4.2.1 Water demand estimation

The wetlands are, in most cases, vulnerable to reduced water availability as a result of population growth and the resultant increase in human activities that exert pressure on water resources (Schuyt, 2005; Hanasaki *et al.*, 2008). Climate variability/change exerts added pressure on the water resources and the growing population itself, leading to extreme pressure on the limited resources to be viable over time (Erwin, 2009; Sinha, 2011). Wetland condition largely depends on the amount of rainfall occurring and temperature range in the wetland ecosystem's surrounding area that contributes to the biomass structure of the wetland (Mutanga, Adam and Cho, 2012). Therefore, it is logical that water requirements are expressed in climate variables such as ETo, serving as a proxy for domestic and commercial water demand and hydrological processes within the wetland requiring water.

Rainfall is usually higher than ET_o, as represented in Figure 4.1, which displays a time series plot of rainfall and evapotranspiration compiled from decadal rainfall for 02-06-2015 03-02-2020. The plot confirms that rainfall truly is usually more significant than ET_o. This suggests that, even though occasionally and in some instances for extended periods, ET_o may be higher than rainfall. This is primarily due to the enhanced amount of precipitation intercepted and evaporated by different land cover types (Obiefuna *et al.*, 2013). In other words, if rainfall is considered as the wetland's water supply, then evapotranspiration can be a representation of the wetland water demand.

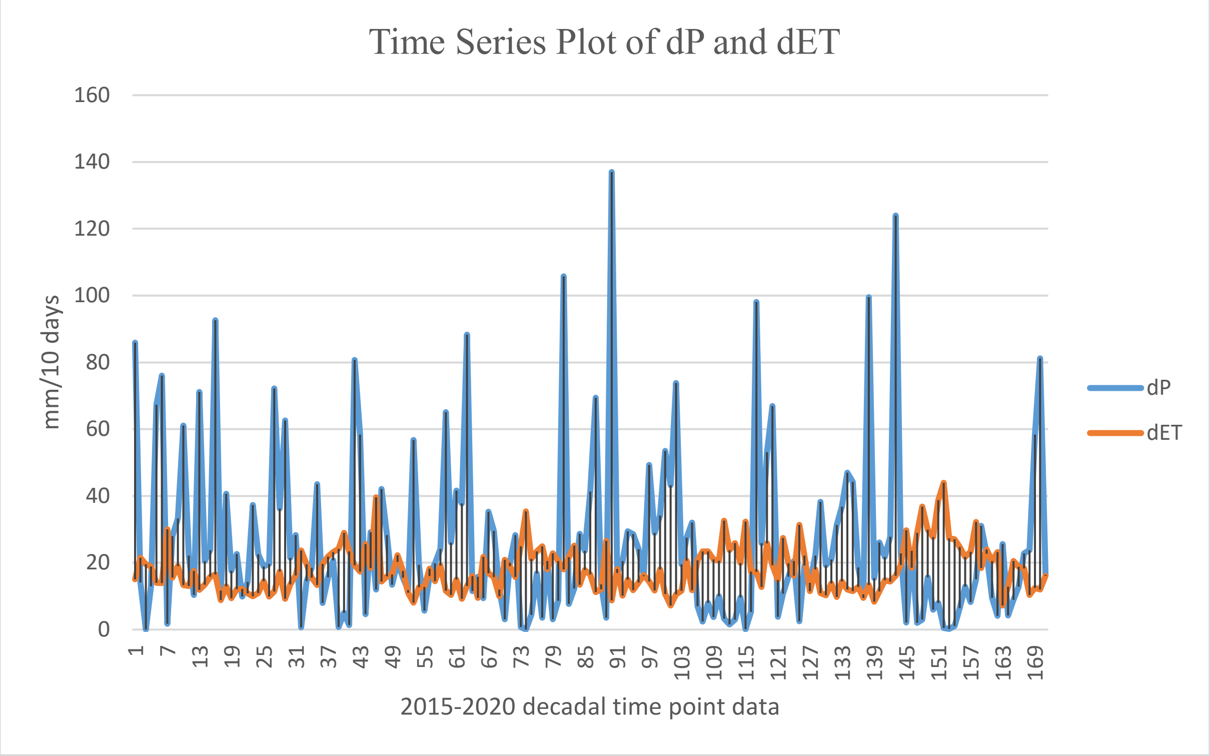


Figure 4.1: Time series plot of decadal precipitation (dP) and evapotranspiration - ET_o (dET).

The plot shows that from 2015 to 2020, the amount of rainfall occurring in the Hogsback is peaking at approximately 14mm, representing the balance between rainfall and ETo, sufficient to sustain wetland ecosystem services. However, that estimation does not explicitly consider other variables that could significantly affect the wetland, and inevitably the representation of the relationship between rainfall and $ET_{o.}$ in summary is presented in Table 4.1. The table shows that approximately 75% of the climatic events are expected to be wet "conditions" such as floods instead of dry "conditions" such as a drought. This may happen when the water balance is low; however, the fact that it is positive shows that there will be a considerable amount of water supply to the wetland (Rouse, 2000), as is complemented by the high rainfall totals of the Hogsback area.

Table 4.1: Summary of Evapotranspiration, Rainfall and Water balance.

	Min	1st Qu.	Median	Mean	3rd Qu.	Max
Evapotranspiration	7.21	12.70	16.54	17.89	21.70	43.95
Rainfall	0.00	9.45	19.70	26.33	31.70	137.00
Water Balance (R – ET)	-43.45	-11.77	4.45	8.44	17.83	128.30

Using the Hampel filter, an outlier detection algorithm, Table 4.1 gives a clear representation that the rainfall data seemingly has outliers as it identified 13 rainfall outliers. The outliers may have influenced the data to have a higher mean as the values do not seem isolated. Their frequency may have a genuine impact on the resulting rainfall totals for the wetland. Heedless of these outliers presence, any trends or seasonality identified in the data are discussed in detail in section 4.3.1. What is relevant to the water demand is that an average of 17.89 mm is the amount of water demand from the wetland against 26.33 mm of water supply within this time series. This would suggest a relatively stable balance sustain the wetland from a water balance between rainfall and evapotranspiration point of view. However, it is important to note that this is only applicable when ET_o is used to measure water demand and is likely to differ if quantified demand from domestic and commercial uses is included.

The study's evaluation of trend models used to measure seasonality or likely identifiable trends in the ET_o is plotted in Figure 4.2, where it appears the ET_o follows a GAM. This means that hypothetically if there is any need for predictions, the GAM's predictions of ET_o will likely be more accurate. However, there is also a barely noticeable component of seasonality in this plot. Unfortunately, the data does not confirm this hypothesis with this type of analysis as the pattern could be a cyclic variation that follows no regular periods.

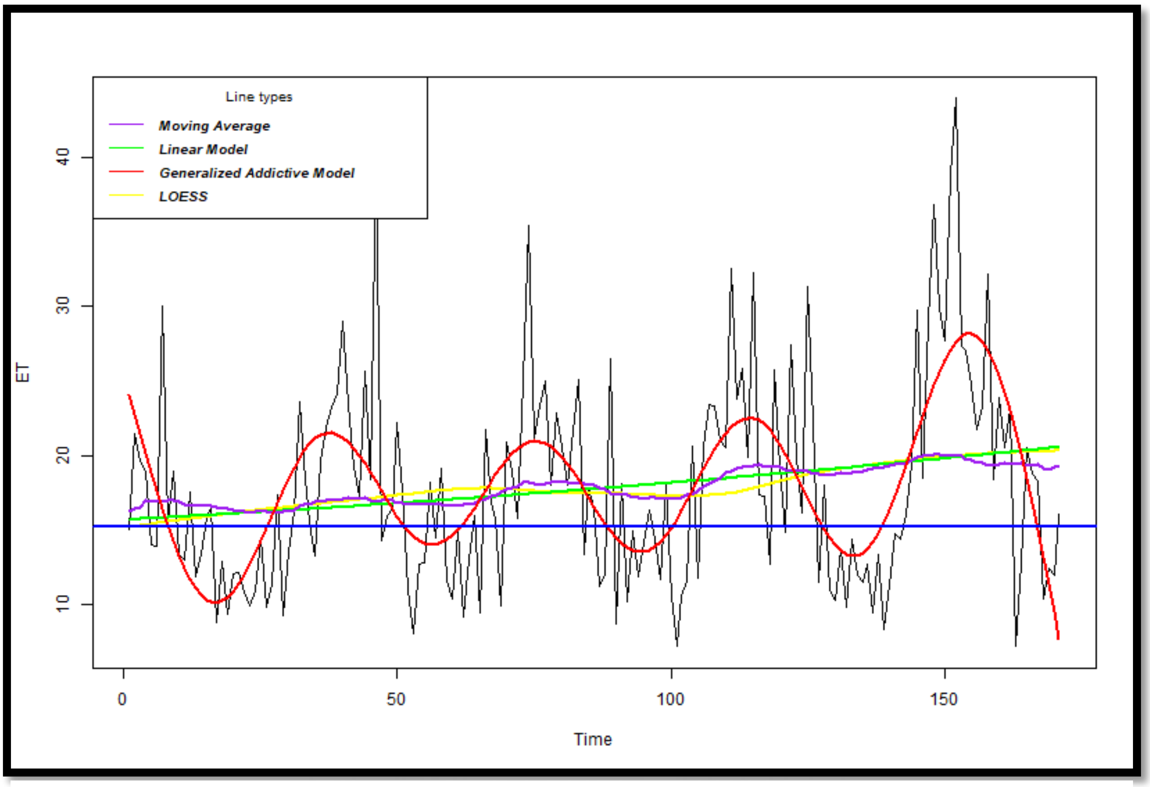


Figure 4.2: Time series plot of evapotranspiration (ETo) represented using four forecasting models (1) The moving average, (2) Linear Model, (3) Generalized Addictive Model (GAM and), (4) Local estimated scatterplot smoothing (LOESS) fitted to the evapotranspiration data.

The barely noticeable component of seasonality was investigated further to ascertain if the seasonal component is significant. This was done using Webel and Ollech (2018) WO-test, which tests for overall seasonality, and the results are presented in Table 4.2. The WO-test results show that the data does not follow a seasonal pattern, although; it appears there is a cyclic variation. Nonetheless, because any seasonality is not verified, it would be challenging to forecast the wetland's data.

Table 4.2: The WO-test of seasonality for the decadal evapotranspiration (ET$_o$).

Test used: WO
Test statistic: 0
P-value: 1 1 1
The WO - test does not identify seasonality

The Augmented Dickey-Fuller Test tests a null hypothesis that a unit root is present in a time series sample. The alternative hypothesis differs depending on the version of the test used, which in this study was stationarity or trend-stationarity. The Augmented Dickey-Fuller Test results showed that the variations detected in ET$_o$ are not stationary, as presented in Table 4.3, which means that over time, it is expected that the ET$_o$ will change from its current mean (Withey and van Kooten, 2011).

Table 4.3: The Augmented Dickey-Fuller test of seasonal stationarity for evapotranspiration (ET_o) with an added Chis-squared test of significance of the seasonal component.

Augmented Dickey-Fuller Test		
Data: decadal ET		
Dickey-Fuller = -3.0822	Lag order = 5	p-value = 0.1244
Alternative hypothesis: stationary		
Added a chi-squared test p-value: 1		

The data's expected direction of change might be either increasing or decreasing. This study determined the desired direction of change was evaluated by plotting the moving average, Linear Model, GAM, and LOESS (Figure 4.3).

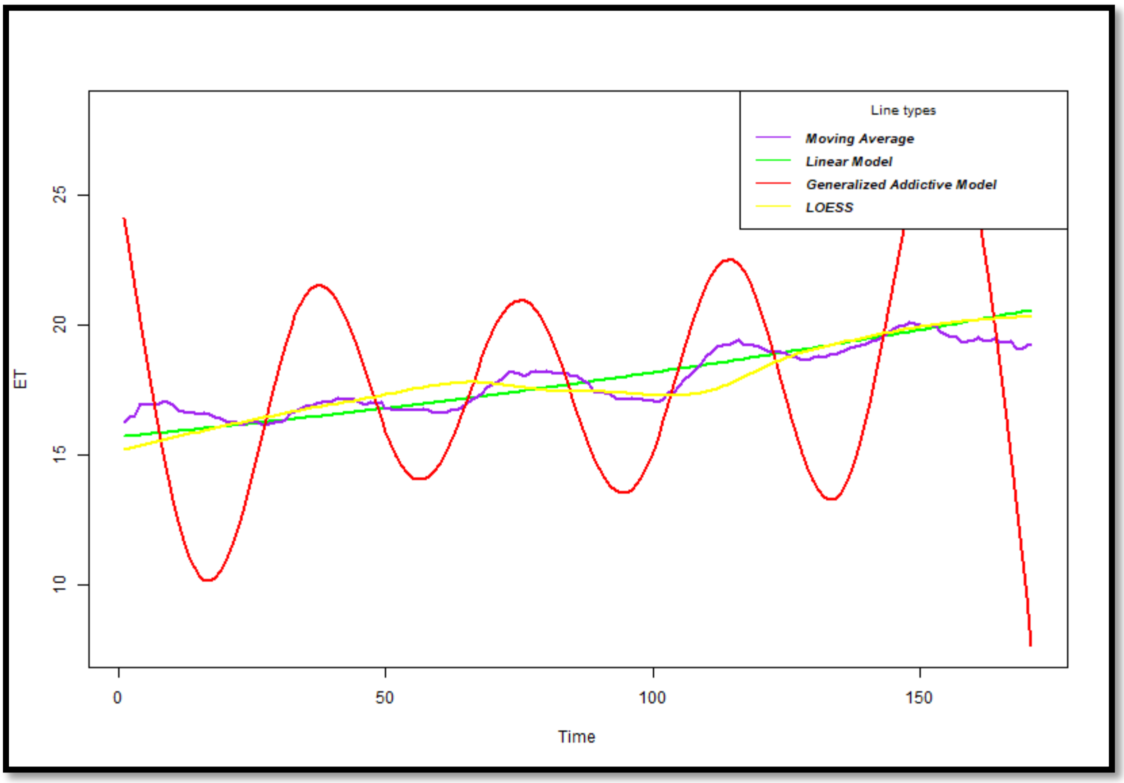


Figure 4.3: Expected changes in evapotranspiration (ET_o) over time-based on the evapotranspiration data run on (1) The moving average, (2) Linear Model, (3) Generalized Addictive Model (GAM), and (4) Local Estimated Scatterplot Smoothing (LOESS)

In the plot, it is noticeable that there is a minuscule adjustment in the magnitude of the trend, indicating an increase over time of the overall mean. Therefore, it should be expected that future occurrences of ET_o over Die Vlei would most likely be higher than the current ones causing increased water supply. However, this is also dependent on the rainfall and temperature that are discussed below.

4.2.2 Temperature and rainfall trend analysis

The rainfall and temperature variability results are broken down into detecting seasonality and trends in decal temperature, the stationary of seasonality test, and the results of detecting seasonality and trends in decal temperature.

4.2.2.1 Detecting seasonality for temperature

The test results show that the decadal temperature has no seasonality. However, a seasonal plot of decadal temperature plotted as decomposition of additive time series presented in Figure 4.4 shows a possible trend in temperature. The plot gives additive decomposition results of random, seasonal, trend, and observed plots that seasonality should not be expected given that the trend patterns do not seem to follow any fixed time intervals.

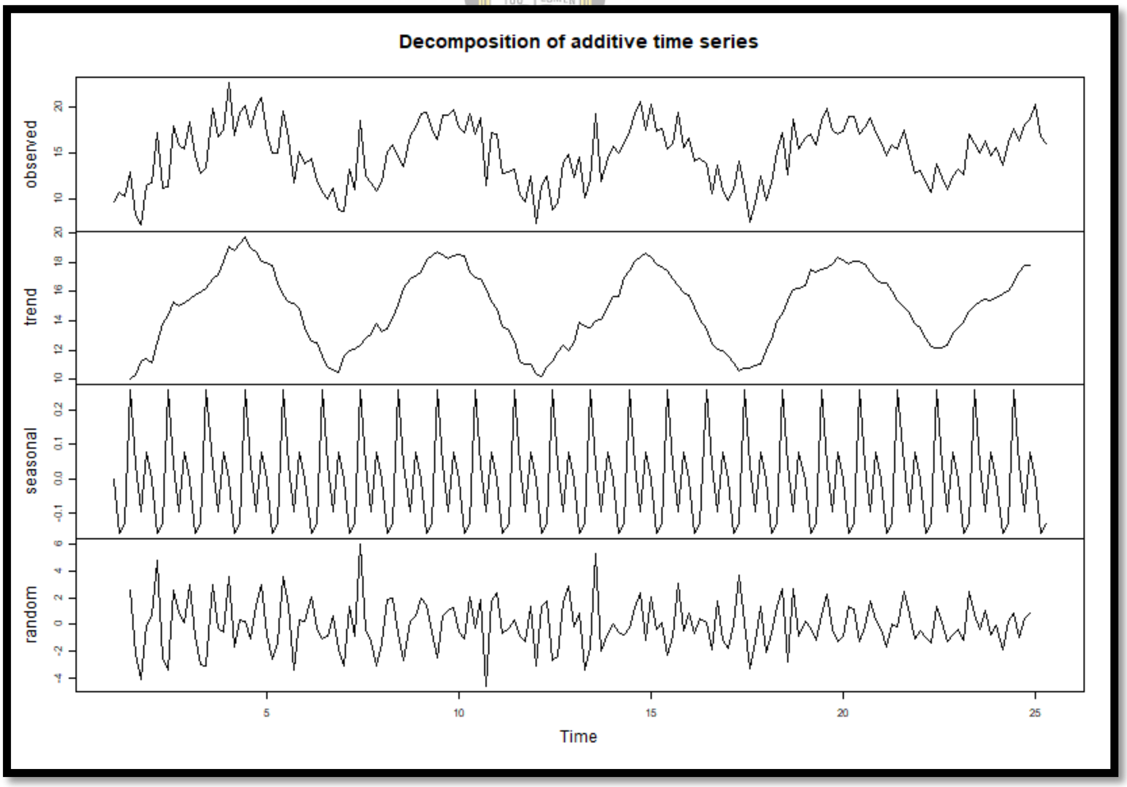


Figure 4.4: Seasonality plot for decadal temperature (°C) plotted as decomposition of additive time series from 02-06-2015 to 03-02-2020.

It is most likely that the decadal temperature may exhibit a fixed non-seasonal pattern. These can be verified using additional statistical tests such as the WO-test by Webel and Ollech (2018). In the decadal temperature, it was expected that the WO-test would not detect seasonality, and Table 4.4 shows that this was the case. The interpretation of this result means that seasonality is not a reliable measure for forecasting future temperature scenarios when the input data are decadal temperature. Suggesting that if, for example, the input data were average daily temperature, the results of the WO-test would likely present differently. Therefore, it would be helpful to identify a model that can provide accurate predictions or a weather station with consistent readings for daily temperature readings to evaluate trends.

Table 4.4: The WO-test of seasonality for the decadal temperature (°C).

Test used: WO
Test statistic: 0
P-value: 1 1 1
The WO - test does not identify seasonality

4.2.2.2 Trend analysis on decadal temperature

This study fitted the moving average, Linear Model, GAM, and LOESS on ET_o to the temperature data to evaluate trends. The results presented in Figure 4.5 show that the GAM, similar to the ET_o, seemingly fits the data better than the other three models. This is most likely due to the initial results that indicated there was no seasonality in the dataset. It is more likely that the detected trend is mostly irregular cyclic variations that may or may not have a seasonal component. However, that seasonal component is expected to be insignificant for forecasting.

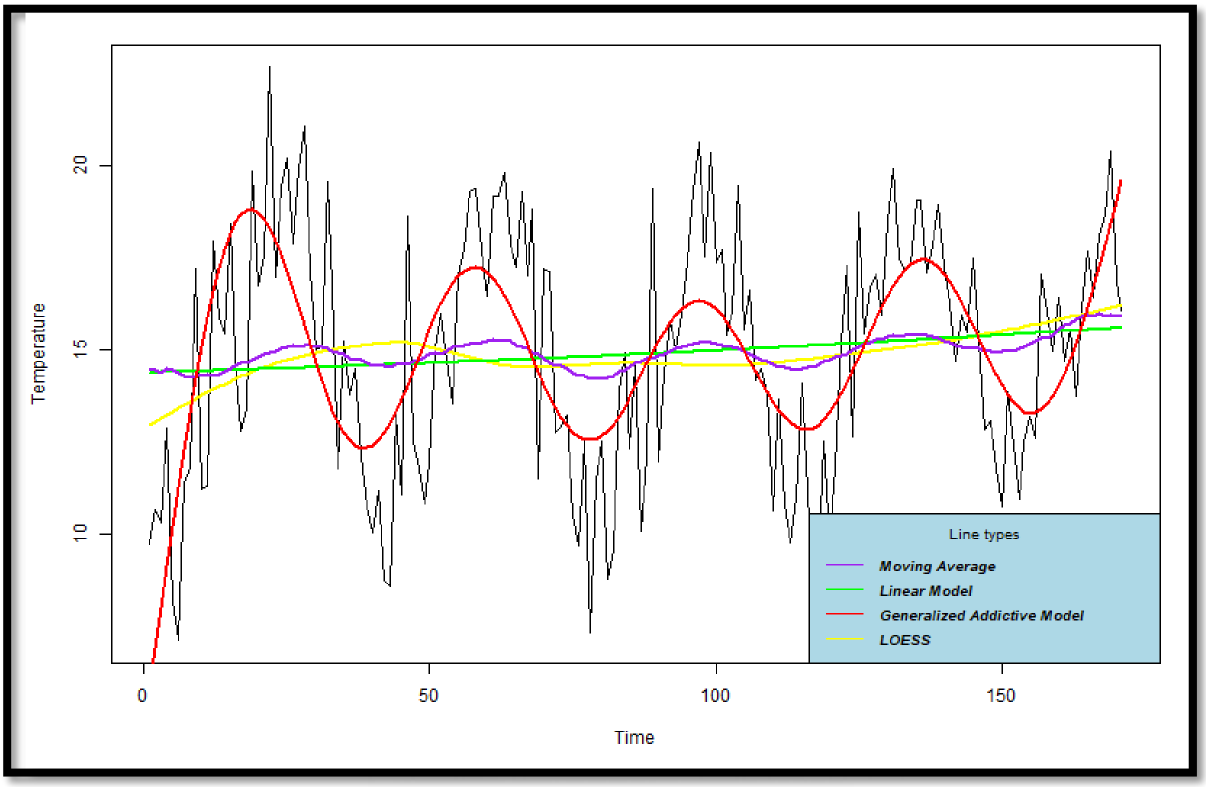


Figure 4.5: Time series plot from 02-06-2015 to 03-02-2020 of temperature (°C) represented using four forecasting models. (1) The moving average, (2) Linear Model, (3) Generalized Addictive Model (GAM), (4) Local Estimated Scatterplot Smoothing (LOESS) fitted to the temperature data.

4.2.2.3 Stationarity of seasonality (decadal temperature)

The Augmented Dickey-Fuller's test results presented in Table 4.5 show that the data is stationary. Decadal temperature Augmented Dickey-Fuller's test had a null hypothesis (H_0). Data assumed to have an increasing trend over time, and an alternative hypothesis (H_1) that data does not have a rising trend over time. The test output p-value of "1" confirmed stationarity; however, if this p-value were rounded to two decimal places, the null hypothesis would be accepted. All the same, it is sensible to conclude that there is a possibility that the temperature will expectedly rise in the long run.

Table 4.5: The Augmented Dickey-Fuller test of seasonal stationarity for decadal temperature (°C) with an added Chis-squared test of significance of the seasonal component.

Augmented Dickey-Fuller Test		
Data: decadal Temperature		
Dickey-Fuller = -3.456	Lag order = 5	p-value = 0.04858
Alternative hypothesis: stationary		
Added a chi-squared test p-value: 1		

Studies have investigated the impact of temperature and rainfall on wetlands, and there is consensus that temperature plays a significant role in the state of wetlands. Kadlec (2006) highlighted three essential factors concerning temperature in wetlands: it modifies the rates of several key biological processes. It sometimes regulates the water quality and is a prime determinant of evaporative water loss processes. Also, there is a noted strong relationship between temperature and biomass (Feher *et al.*, 2017). For example, Kadlec and Reddy (2001), explained that the temperature on wetlands affects processes regulating organic matter decomposition, all nitrogen cycling reactions, including mineralization, nitrification, and denitrification. This was complemented by El-Refaie (2010), who explained that temperature plays a significant role in nutrient removal. More specifically, high temperatures hinder the process of proper nutrients removal. This means, with the expected increase in temperature as identified in this study, the Die Vlei wetland could experience serious nutrient removal challenges that would affect the wetland's water quality, but it is also a major contributor to its water demand. Regardless, the decadal temperature results for Die Vlei showed that changes within the ecosystem induced by temperature are expected to be small.

4.2.2.4 Detecting seasonality for rainfall

It is most likely that the decadal rainfall similar to the decadal temperature will portray a stationary non-seasonal pattern. Using the WO-test by Webel and Ollech (2018). In the decadal rainfall, the WO-test did not detect seasonality, as is presented in Table 4.6. The interpretation of these results initially means that seasonality is not a reliable measure for forecasting future rainfall estimates. However, given that the data contains no seasonality, it will be essential to evaluate any traceable cycles with a seasonal component, especially since rainfall totals differ with seasons. Therefore, if the input was daily rainfall totals, the results may have been different. Consequently, it would be useful to identify a model that can provide accurate predictions for the temperature to evaluate trends.

Table 4.6: The WO-test of seasonality for the decadal rainfall (ml).

Test used: WO
Test statistic: 0
P-value: 1 1 1
The WO - test does not identify seasonality

The test results show that the decadal rainfall does not show any form of seasonality. The corresponding additive time series plot shown in Figure 4.6 gives additive decomposition results of random, seasonal, trend, and observed plots show that there are no particular trends detectable from the data. On the contrary, it would appear that the data are more random and not following any meaningful patterns that are useful in predicting rainfall seasonality. Regardless of the observations, it is still useful to test these indicators to validate all suspicions.

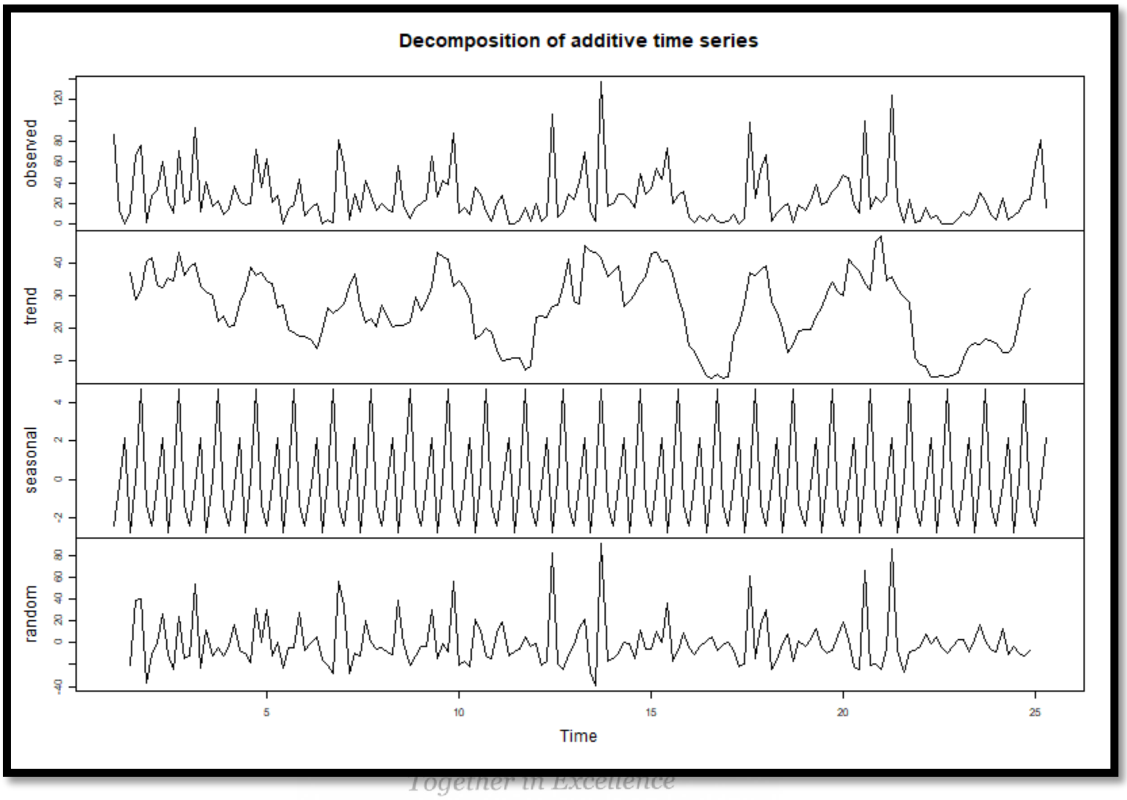


Figure 4.6 Seasonality plot for decadal rainfall (ml) plotted as decomposition of additive time series from 02-06-2015 to 03-02-2020.

4.2.2.5 Trend analysis on decadal rainfall

As expected, the decadal rainfall data show no trends and follow no particular model from the moving average, Linear Model, GAM, and LOESS models used in this study. However, there is a noticeable decrease over time in rainfall, as shown in Figure 4.7, suggesting that it is most likely that over time, rainfall will decrease.

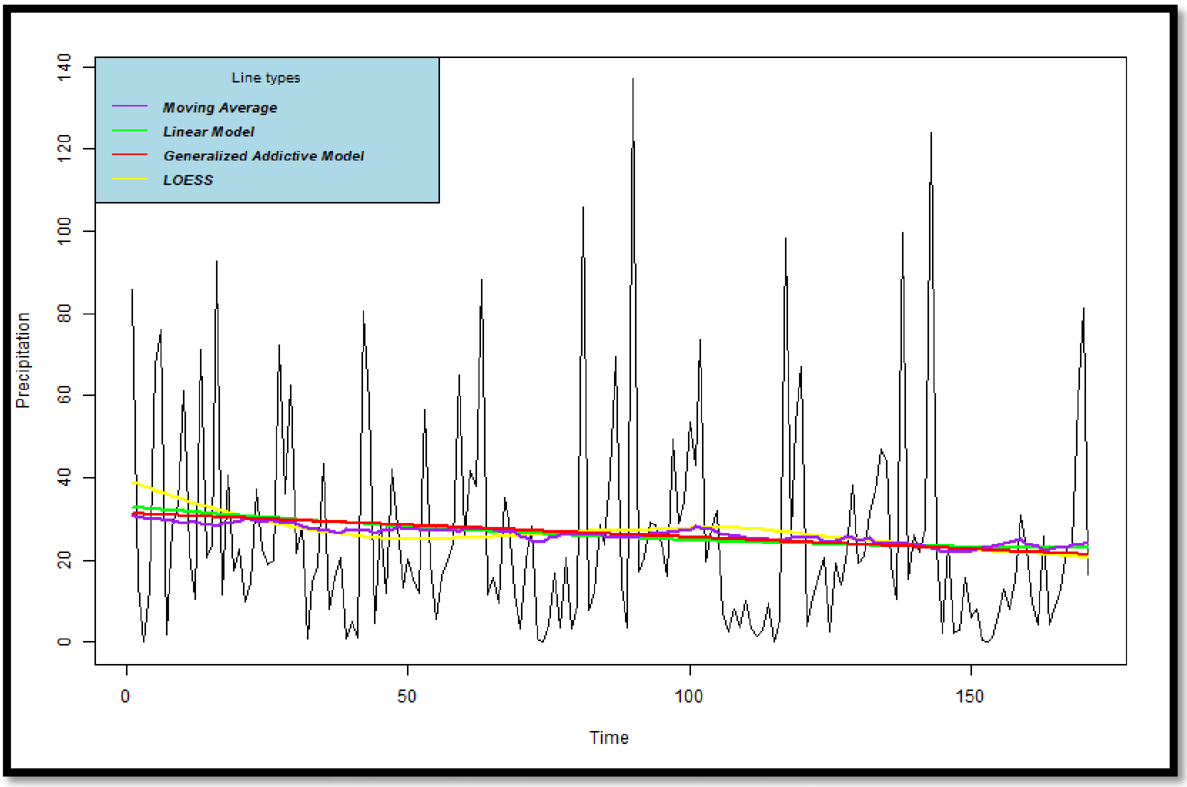


Figure 4.7: Time series plot from 02-06-2015 to 03-02-2020 of rainfall (ml) represented using four forecasting models. (1) The moving average, (2) Linear Model, (3) Generalized Addictive Model (GAM), (4) Local Estimated Scatterplot Smoothing (LOESS) fitted to the rainfall data.

4.2.2.6 Stationarity of seasonality (decadal rainfall)

As shown in the Augmented Dickey-Fuller test presented in Table 4.7, the data is stationary based on the p-value. Decadal rainfall Augmented Dickey-Fuller's test had a null hypothesis (H_0). Data assumed to have an increasing trend over time, and an alternative hypothesis (H_1) that data does not have an increasing trend over time. It is a fair conclusion that there will most likely be a decrease in rainfall in the long run. The output presented in Figure 4.7 also noted that the moving average, Linear Model, GAM, and LOESS models show a hint of an expected decrease in rainfall. Although, since these models do not fit the data, that indication may be insignificant.

Table 4.7: The Augmented Dickey-Fuller test of seasonal stationarity for decadal rainfall (ml) with an added Chis-squared test of significance of the seasonal component.

Augmented Dickey-Fuller Test		
Data: decadal rainfall		
Dickey-Fuller = -4.5796	Lag order = 5	p-value = 0.01
Alternative hypothesis: stationary		
Added a chi-squared test p-value: 1		

Chu and Han (2015) investigated multiple factors, including ecosystem respiration, net ecosystem CO_2 exchange, ecosystem respiration, and gross primary productivity in China. Their findings show that precipitation only correlated to these factors at an annual rate and the only factor that correlates well with precipitation was maximum photosynthesis. Also, rainfall correlates strongly with canopy heights within wetlands (Feher *et al.*, 2017). Since rainfall is the main water supply, an increase of rainfall will increase water to the wetland and, consequently, facilitate the process of wetland purification and nutrients removal (Taylor, Prigent and Dad-son, 2018). Rainfall is also responsible for the concentration of biomass in the wetlands and serves as the main contributor to the sustenance of the wetland (Kadlec, 2006). This makes it a very important variable to closely evaluate the preservation of the wetland even though many studies find little or no correlation to some of the physiochemical properties of the wetland. Therefore, it is appropriate to assume that Die Vlei wetland could struggle with such processes as the time series analysis showed that there are chances of rainfall decrease.

One of the questions that will need to be addressed is "if there are no changes in rainfall, what will the impact of changes in temperature measure like on water availability in the catchment?" The increase in temperature foretells that water demand is most likely going to increase. Another question is that "if the rainfall is to remain constant, what should the expected water supply be to sustain water balance?" or "how long will it take under these same conditions for the wetland to completely dry out due to the imbalance between supply and demand?" The plot presented in Figure 4.8 below shows that the moving average, Linear Model, GAM, and LOESS models show that water balance is expected to reduce over time. This expected decrease in water balance over time will most likely have a complementary reduction of both water quality and quantity in the wetland. For example, the increase in temperature will reduce nutrient removal efficiency (El-Refaie, 2010). The decrease in rainfall will eventually affect overall water availability, including flow rates that will considerably minimise water quality and affect the biomass of the wetland to subsequently increase water demand (Taylor, Prigent and Dad-son, 2018).

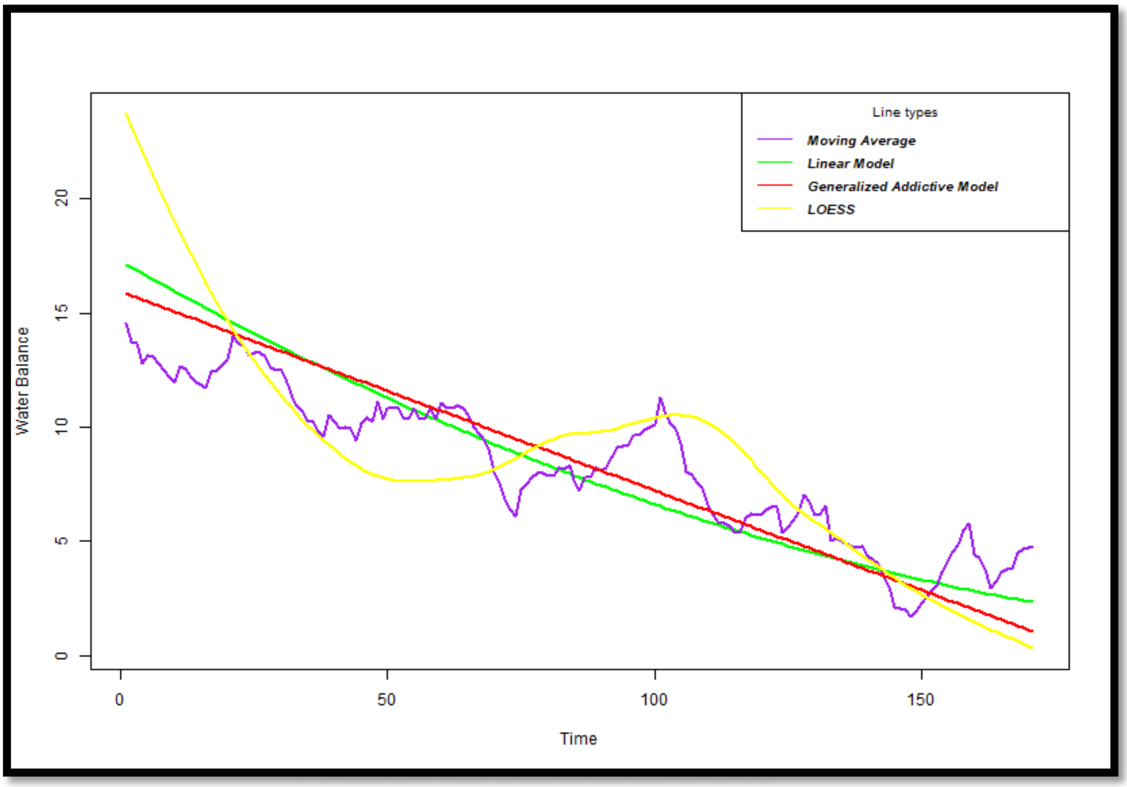


Figure 4.8: Expected changes in water balance over time-based on (1) The moving average, (2) Linear Model, (3) Generalized Addictive Model (GAM), and (4) Local Estimated Scatterplot Smoothing (LOESS).

This study has evaluated three climate variables and managed to identify possible future expected changes. However, within the scope of this study, it is difficult to determine how these changes can be controlled to minimize or maximize their effects on the wetland. The time series findings evaluated in this study concluded that ET_o and temperature are expected to increase, rainfall is expected to decrease, affecting the overall water balance over the wetland (Barros and Albernaz, 2014). Die Vlei has a serious challenge as these changes within temperature and rainfall will cause an increase in the imbalance between supply and demand and eventually result in a shortage of water in the wetland. The results highlight two main issues; firstly, none of the climate variables evaluated in this study exhibit any seasonality. Even though some of them, such as temperature and ET_o have trends, it was established that this trend does not have a significant seasonal component. Secondly, the estimation of temperature and rainfall trends indicate a possible increase over time in temperature, while rainfall is expected to decrease. Also, given that the behaviour also influences the estimated ETo in both temperature and rainfall, it could be expected that water balance will decrease over time as well (Chu and Han, 2015). Lastly, as previously mentioned, there is still a serious limitation caused by the data shortage, which is necessary to answer most of the questions about the contribution of climate to the sustainability of a wetland, mainly related to LULC discussed below.

4.2.3 Land cover/ land-use reconstruction

Land cover dynamics linked to the spatial changes in wetlands fringing lagoons are comprehensively assessed with remote sensing data and GIS (Obiefuna *et al.*, 2013). Therefore, this study used a GIS technique for image evaluation to identify eight possible classes. These classes are water, bare soil (BS), wet soil (WS), dry grass (DG), grass, built-up areas (BA), commercial forest (CF), and indigenous forest (IF). An illustration for the LULC computed for 2007 and 2017 is shown in Figure 4.9, whilst the complimentary accuracy assessments are presented in Table 4.8 for 2007 and 2017.

Table 4.8: Accuracy assessment of Die Vlei's 2007 and 2017 supervised maximum likelihood classification.

	Classes	**WS**	**Water**	**Grass**	**CF**	**IF**	**DG**	**BS**	**BA**	**Total**	**Omission**	**Mapping accuracy**
2007	WS	128	0	0	2	0	0	4	1	135	5.19	84.77
	Water	0	40	0	2	3	0	0	1	46	13.04	86.96
	Grass	0	0	68	1	2	0	0	1	72	5.56	83.95
	CF	2	0	5	105	38	1	0	0	151	30.46	62.13
	IF	0	0	3	5	68	0	0	0	76	10.53	57.14
	DG	7	0	0	1	0	36	1	2	47	23.40	69.23
	BS	5	0	0	0	0	0	32	7	44	27.27	62.75
	BA	2	0	1	7	0	4	2	38	54	29.63	57.58
	Total	144	40	77	123	111	41	39	50	625	Accuracy	82.40
	Commission	11.85	0.00	12.50	11.92	56.58	10.64	15.91	22.22		Kappa	79.19
2017	**Classes**	**Grass**	**IF**	**CF**	**BS**	**WS**	**DG**	**Water**	**BA**	**Total**	**Omission**	**Mapping accuracy**
	Grass	223	0	2	4	0	3	1	7	240	7.08	79.93
	IF	1	117	21	0	0	0	0	0	139	15.83	73.58
	CF	0	11	274	1	1	0	53	1	341	19.65	70.44
	Bare Soil	4	0	2	150	8	4	0	6	174	13.79	65.50
	Wet Soil	5	1	15	19	68	4	0	1	113	39.82	54.40
	Dry Grass	0	0	0	0	0	31	0	0	31	0.00	73.81
	Water	15	0	2	20	3	0	50	2	92	45.65	34.25
	BA	14	8	6	11	0	0	0	19	58	67.24	25.33
	Total	262	137	322	205	80	42	104	36	1188	Accuracy	78.45
	Commission	16.25	14.39	14.08	31.61	10.62	35.48	55.43	29.31		Kappa	73.83

Figure 4.9 shows that built-up areas are not as extensive as the study assumed. Their geographical location is seemingly concentrated in the southern part of the wetland and covered mainly by indigenous forest trees. In 2007, a large percentage of bare land was misclassified as built-up in the northern part of the wetland, surrounded by farmlands probably due to spectral mixing. However, classification accuracies both had high kappa values, with the 2007 image having a classification accuracy of 82%, whilst the 2017 image had a classification accuracy of 78%.

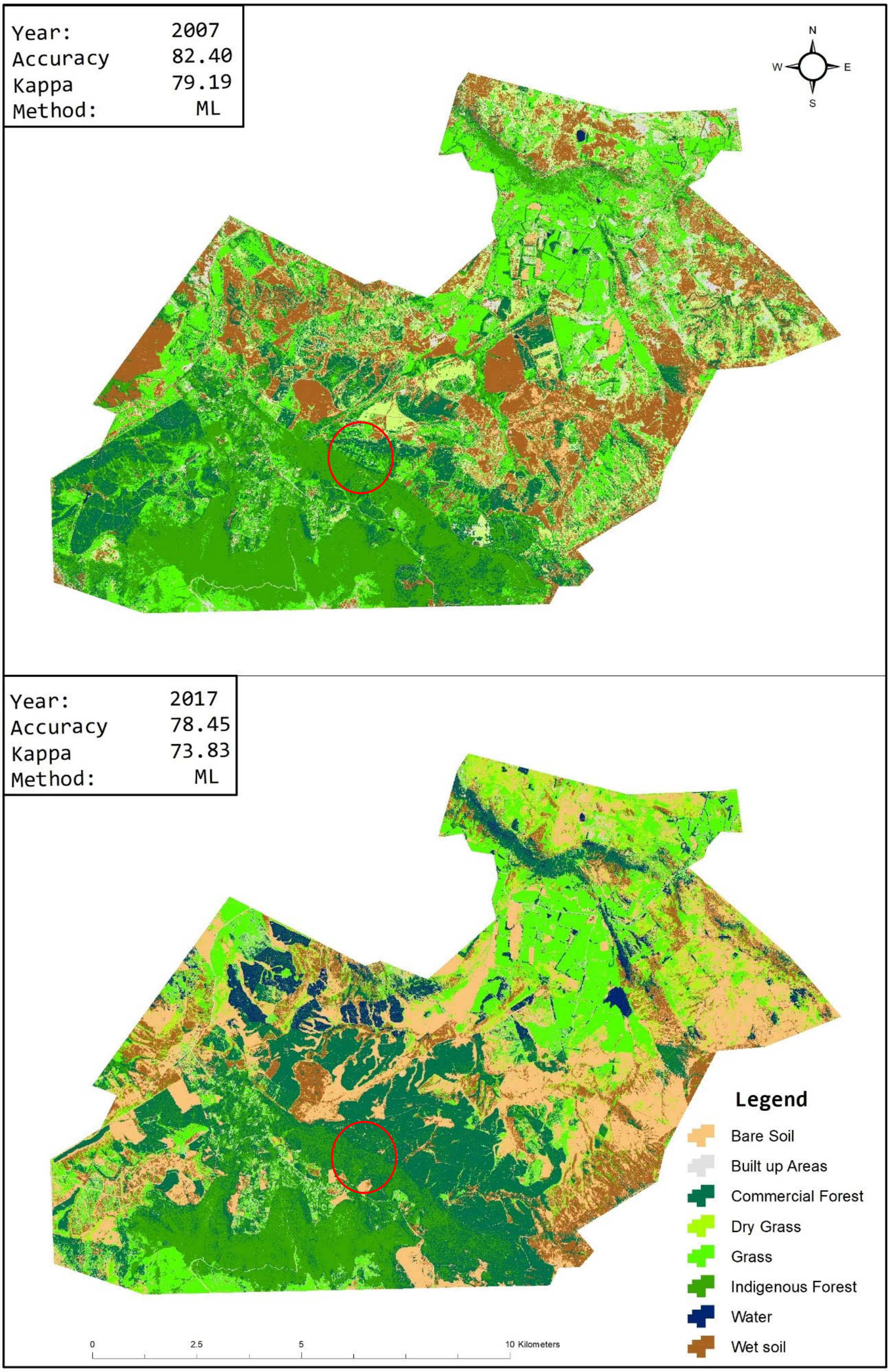


Figure 4.9: Land cover/land-use change for 2007 and 2017, computed using the maximum likelihood supervised classification. The red circled areas show that an increase in dryland accompanies an increase in a commercial forest.

Visual interpretation of the images shows that the wetland boundary is demarcated due to the growth of the commercial forest, which was complimented by a site visit where Figure 4.10 was taken. The main class that seems to have significantly increased in surface area between 2007 and 2017 is the commercial forest. It is fair to assume that there was a significant presence of commercial forest even in 2007, but it may have been recently planted and may have had mixed spectral signatures with grassland. Nonetheless, it is still clear that commercial forest has expanded into the wetland. Consideration of the 2017 image shows that the largest concentration of commercial forest is in the central region of Hogsback, which complements the large-scale intensive commercial logging activities (Lechmere-Oertel, 2010). Interestingly, the spatial pattern that is shown in the 2017 classification indicates that the commercial forest was built around the wetland, which was most likely to avoid physical impacts on the wetland's ecosystem whilst it was used for irrigation (Youthed, 2014). However, the increase in the commercial forest is accompanied by an increase in bare land. Even a visual inspection of the two images clearly shows as highlighted by the red circled areas in Figure 4.9.

Figure 4.10: Visual representation of evidence of commercial forest in Die Vlei wetland where the picture (A) shows a marked commercial plot and picture (B) shows a plot that is being harvested.

Post-processing of the Sentinel 2 image captured in 2019 July show that a significant part of the wetland has already been degraded and can barely be discerned at the satellite's high resolution. The wetland presented in Figure 4.11 was extracted and carefully adjusted enough to include extents that are still detectable in 2007. The results show that there are five main sections to the wetland, which are labelled on the map as “1”, “2”, “3”, “4” and “5”. These five sections are supposed to be interconnected; however, supposedly, due to intense exposure to external factors, parts of the wetland’s channels could not be successfully reconstructed using the images employed in this study. It is most likely that images from pre-2007 would be useful in retracing the lost channels except for the fourth section of the wetland that has dried out and is now an informal settlement. From visual interpretation, it would seem that most of what constitutes a direct impact on the wetland is predominantly from the commercial forest. However, the wetland would benefit from further studies that investigate the commercial forest to find out if there is any irrigation from the wetland as the sole source of watering or there are additional sources such as dams that would alter the hydrology of the largest wetland ecosystem (Stratford, Acreman and Rees, 2011; Bassi *et al.*, 2014). Another factor that seems to have contributed to the breaking down of the wetland are farmlands, which seem to be strategically distributed around the wetland to most probably benefit from its water through irrigation. Commercial forest and farmlands require large amounts of water for sustenance. With the irregularities expected from climate and low water quantities in the area, it is logical to deduce that they contribute to the wetland’s vulnerability. The degree that they contribute is discussed below in the results of the PCA.

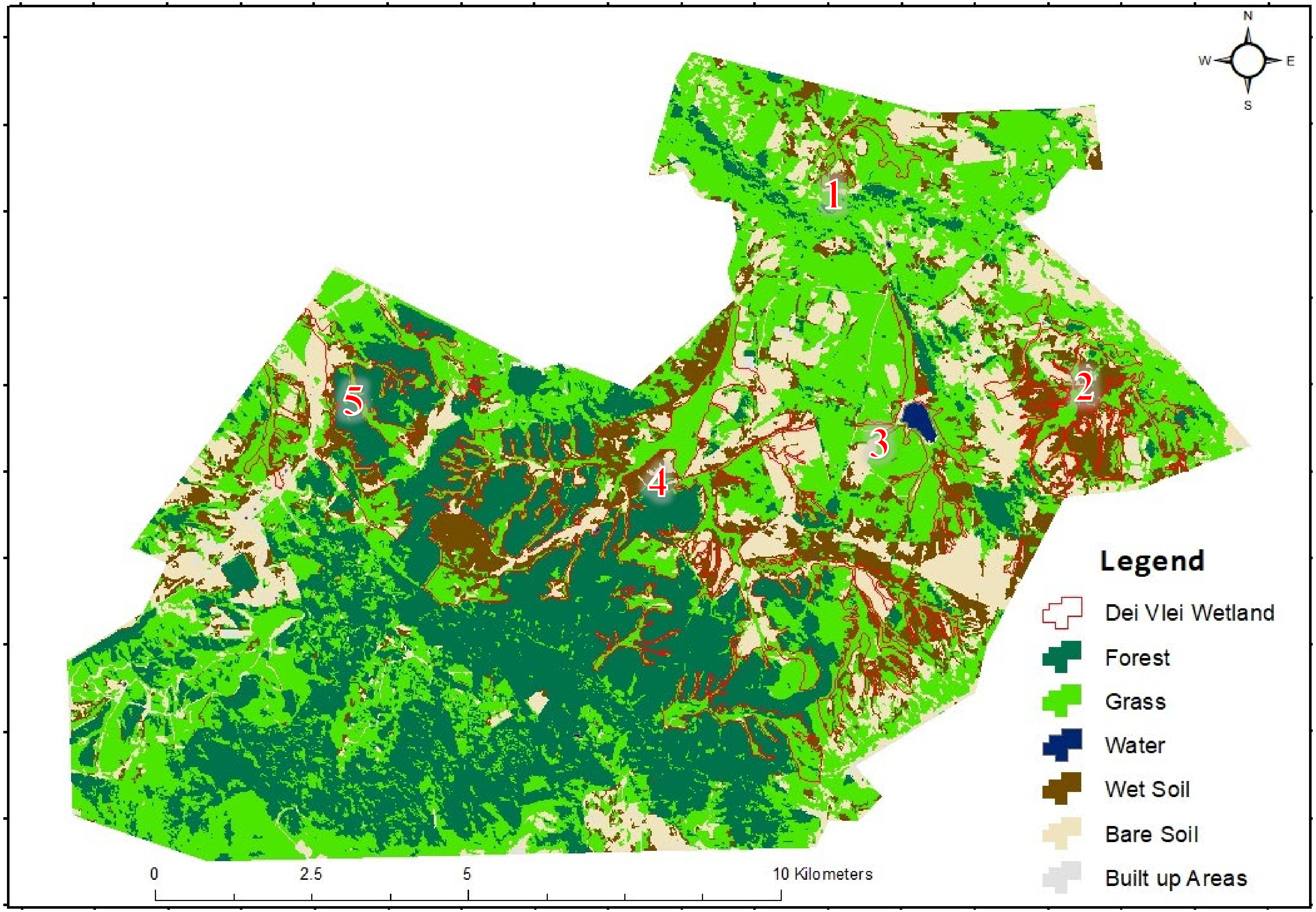


Figure 4.11: The Die Vlei wetland LULC as extracted from the 2019-07 Sentinel 2 image showing the five main channels of the wetland as labelled.

4.2.4 Principal component analysis

This study measured the impact of water demand, climate variability, and LULC as individual factors that were both independently operating on the wetland. The impact of the water demand was measured using water balance and evapotranspiration; the impact of climate variability was measured by monitoring monthly temperature and rainfall variability across the wetland surface area; and for LULC, vegetation, water, and bare soil were considered to be the influential measurable variables in the PCA as presented in Table 4.9. The LULC variables are all interrelated. A symbiotic relationship was noted between bare soil and vegetation and bare soil and water, where an increase in bare soil has a simultaneous decrease in both vegetation and water. Also, generally, vegetation density and cover have a positive relationship with water, where an increase in water also leads to an increase in vegetation. Therefore, assessing the vegetation concentration in the wetland can be considered a good indicator of water availability. This study used Normalized Difference Vegetation Index (NDVI) to quantify the wetland's vegetation density whilst making use of the classes from the LULC to compute surface area. All NDVI values less than 0 were assigned to the water class; values between 0 - 0.58 were assigned to the bare soil class and included wet soil and built-up areas. Values between 0.58 and 1 were assigned to the grass class, including healthy grass and unhealthy grass.

Table 4.9: Summary of the PCA data consisting of water demand: water balance and evapotranspiration; for climate variability: monthly rainfall and temperature; and LULC: water, soil (wet soil, dry soil, built-up areas) and vegetation (in the "grass" and "healthy" classes) used for Die Vlei wetland's vulnerability assessment.

1	1	2	Grass	ETo	DH	Rainfall	Tam
20170711	8110	167152	951	68.80	-41.40	27.40	10.53
20181223	1214	103005	71994	38.23	37.97	76.20	18.04
20190127	1492	162779	11942	39.04	81.16	120.20	17.50
20190206	1844	59510	114859	32.71	39.79	72.50	18.40
20190313	1924	27927	146362	33.35	104.75	138.10	18.12
20190427	2169	16334	157710	45.25	132.05	177.30	15.46
20190522	2120	17582	156511	68.39	-19.89	48.50	16.02
20190626	1521	97628	77064	95.71	-75.11	20.60	12.54
20190726	1886	115486	58841	112.07	-94.87	17.20	12.16
20190815	1917	126391	47905	79.39	-70.19	9.20	12.12
20190909	1543	154187	20483	78.24	-25.94	52.30	15.42
20191029	1379	150710	24124	65.70	-19.40	46.30	15.00
20191128	874	151219	24120	45.63	-7.63	38.00	16.43
20191228	637	165524	4753	54.83	0.87	55.70	16.98
20200117	652	143434	32127	39.40	111.70	151.10	18.63

Evaluation of the PCA results was meant to identify the significant variables in the computation of vulnerability. Also, the PCA was included in the study to measure each variable's contribution to the overall model. Figure 4.12 presents a bar graph of the percentage of explained variances by dimensions in PCA. The first dimension represents approximately 56% of all variances explained in the dataset, whilst the second dimension represents about 33.5% of all variances. This illustrates that even without considering any of the other sizes in the dataset, the first- and double dimensions account for about 89.5% of all explained variances, which is a high percentage of variances described and sufficiently used.

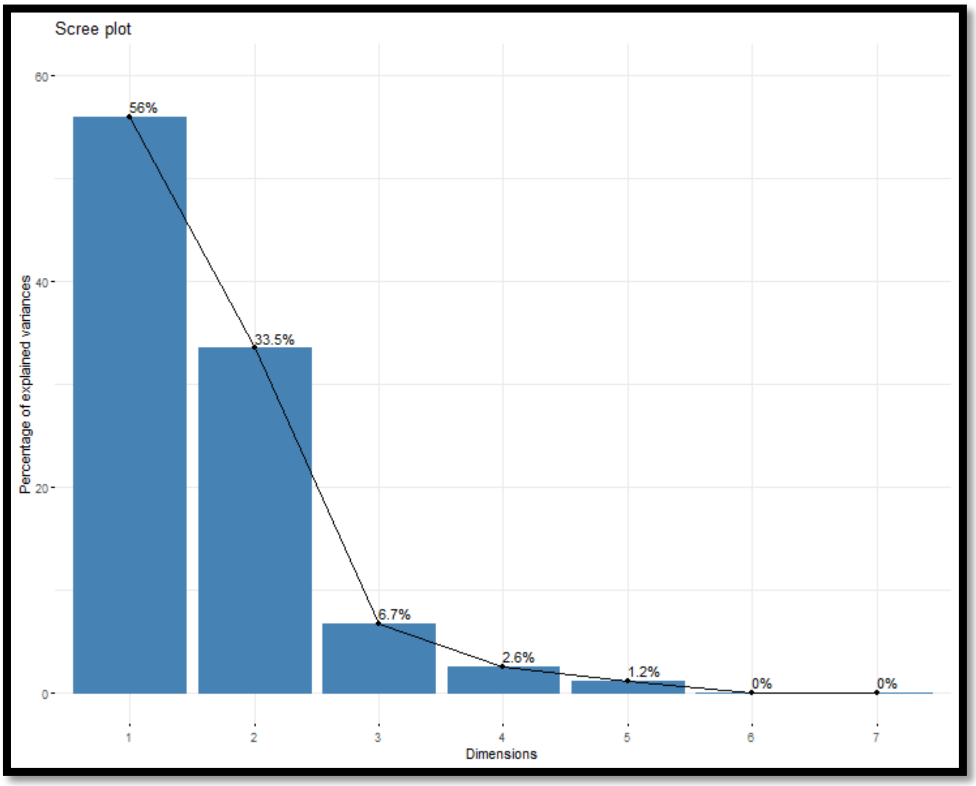


Figure 4.12: Percentage of explained variances by dimensions in the PCA.

The data from dimension one and dimension two follow predominantly two different directions. ET_o, Tam, DH, and rainfall from the first dimension are presented on the x-axis, and all follow a similar direction. On the other hand, water, soil, and grass from the second dimension are shown on the y-axis and follow a similar direction. Within each dimension, specific variables have more influence than others do, as presented in Figure 4.13, where the colour code represents which variable contributes more within a dimension. Figure 4.13 it is fair to predict that soil, for example, has a contrasting relationship with grass and water as they present in opposite directions. This is logical because it is expected that a reduction in grass and water is accompanied by an increase in bare soil/land. An additional relationship that should be noted from the data includes a noticeable negative impact of ET_o on temperature, rain, and DH in the first dimension.

Given that the majority of the variables tested by this study in the PCA fall into the first dimension, it can be deduced that hypothetically, more changes within the wetland should be explainable using the same variables provided that this study adapts the first dimension. A similar synopsis can also be made for the second dimension with the LULC variables. Therefore, both the dimensions seem to present the highest weights of influence in the model, thereby explaining the variance.

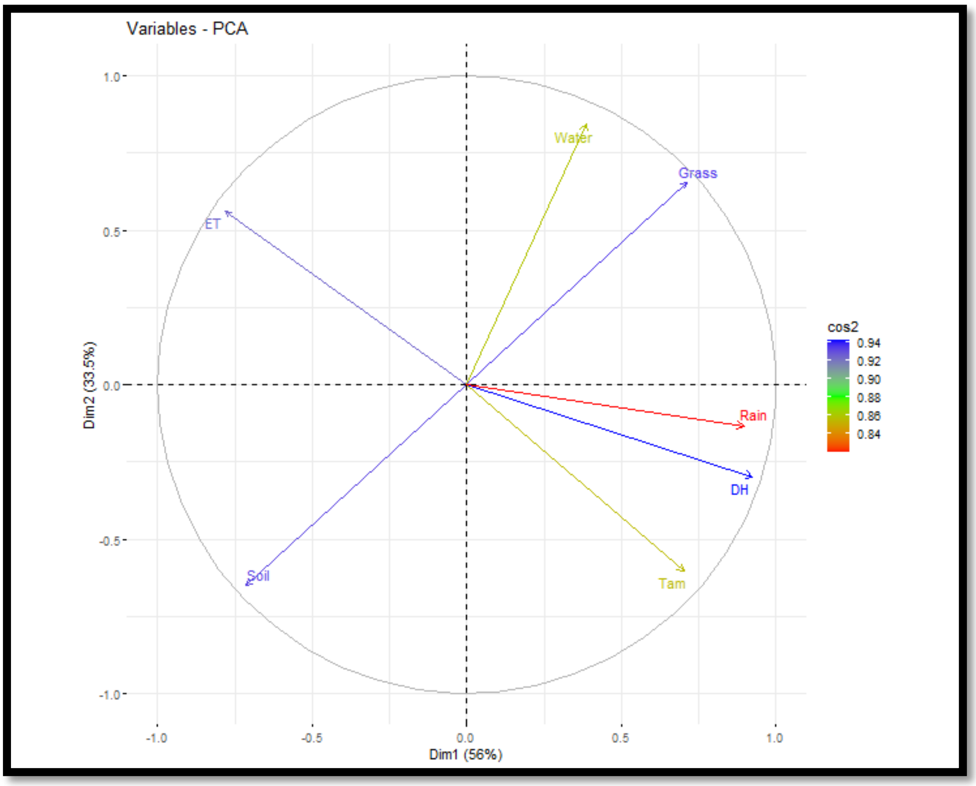


Figure 4.13: A plot of significant dimensions results in a PCA of water balance, evapotranspiration, monthly rainfall, water, mean temperature, soil, and vegetation in the Die Vlei wetland.

Interestingly, it would seem that soil and grass are present in both the first and second dimensions. Consider Figure 4.14 that presents the contribution of each variable to the model by their respective dimensions. It is clear that where both soil and grass have almost equal contributions to both dimensions, however, their contribution is more significant in the second dimension. This is also complemented in Table 4.10, which presents a quantified contribution of each variable within each dimension. Soil contributes 12.96 to the first dimension and 18.05 to the second dimension. In contrast, grass contributes 12.93 to the first dimension and 18.24 to the second dimension, an approximate 5% more influence in both variables.

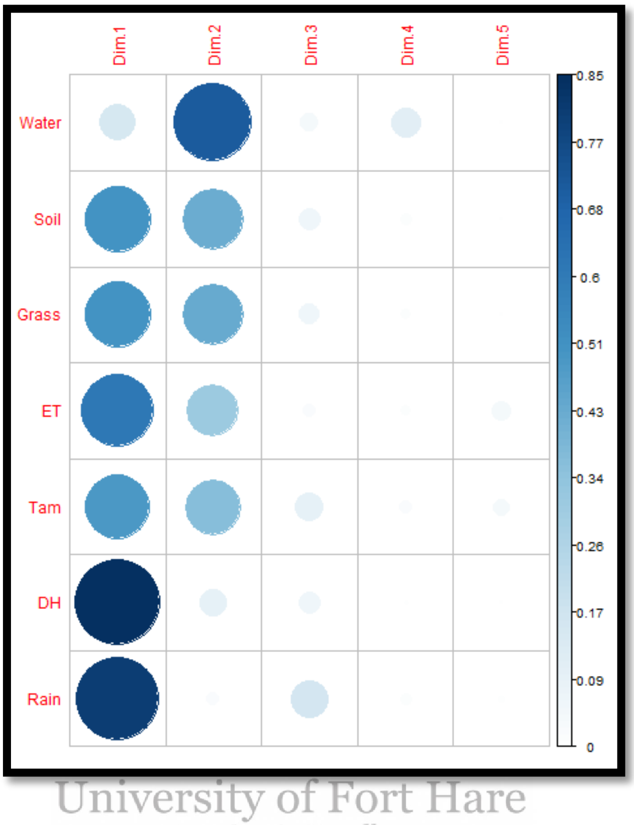


Figure 4.14: Contribution of each variable to the model by their respective dimensions.

Table 4.10: Contributions of each variable within each dimension.

Dimension/Variable	Dim.1	Dim.2	Dim.3	Dim.4	Dim.5
Water	3.81	30.25	7.83	57.92	0.17
Soil	12.96	18.05	11.35	8.14	0.05
Grass	12.93	18.24	11.15	7.02	0.13
ET	15.54	13.42	4.33	7.77	51.03
Tam	12.55	15.50	19.38	10.26	42.31
DH	21.75	3.78	11.82	1.01	0.80
Rain	20.46	0.76	34.13	7.88	5.50

The fact that water demand, climate, and LULC variables are significant in two different dimensions suggests that climate variables may not have as strong an influence on the wetland’s variables as the study assumed. This can be verified by computing a correlation matrix of all variables, as shown in the R output presented in Table 4.11.

A positive correlation is interpreted to mean that an increase in one variable will cause an increase in the other variable. In contrast, a negative correlation is interpreted to mean the alternative. As expected, the soil has a negative correlation to grass and water, which implies that the increase in surface area in one results in a decrease in surface area in the other. The other relationships of interest to the study are presented in Table 4.11 as green coloured cells that represent a relationship between water demand, climate, and LULC wetland variables. Although some of these relationships are close to zero (meaning there is no relationship, positive or negative), the correlation scores give insight into how climate influences LULC variables within the wetland. It is important to note here that low correlations do not imply that the variables' influence is not significant. On the contrary, it means there are additional aspects within the wetland ecosystem that have a comparably greater influence on the physical changes of the wetland. The following relationships are observed:

a) Rainfall decreases bare soil/land's surface area within the wetland whilst it increased grass' surface area, and
b) ET_o and temperature seemingly increase water content within the wetland.

The relationship between rainfall, bare soil and grass is expected as rainfall is that vegetation affects rainfall through transpiration. Through photosynthesis, plants convert carbon dioxide and sunlight into carbohydrates and lose water through their leaves. However, the plant's roots allow them to extract water from below the Earth's surface and continue photosynthesising, which is why increased rainfall leads to increased vegetation growth. Similarly, the relationship between ET_o and temperature is also expected as higher temperatures provide a higher amount of energy available to convert the liquid water to water vapour viz. increased water. However, it is interesting that the results show only a slight increase, which may be due to climate change, but that is a mere assumption that would benefit from the further in-depth investigation.

Table 4.11: Correlation Matrix of water balance, evapotranspiration; monthly rainfall, water, bare soil and vegetation used in the PCA for Die Vlei wetland.

R	Rain	Water	Soil	Grass	ETo	Tam	DH
Rain	1.00						
Water	0.27	1.00					
Soil	-0.47	-0.74	1.00				
Grass	0.47	0.75	-1	1.00			
ETo	-0.69	0.16	0.21	-0.21	1.00		
Tam	0.58	-0.24	-0.16	0.15	-0.91	1.00	
DH	0.97	0.14	-0.42	0.41	-0.85	0.74	1.00

The two main dimensions, i.e. dimension one and dimension two, are identified in the study as containing all relevant variables necessary for a good model. To decide which variable should be included in the model, the study plotted the variable contribution plot assuming they were combined with a uniform contribution weight as presented in Figure 4.15. The plot draws a dashed line called the reference line corresponding to the expected value if the contributions were uniform. Ideally, if all variables are plotted to be higher than the reference line, they are essential contributors to the dimension. However, in Figure 4.15, only grass, soil, ET_o, and DH surpass the reference line and are, therefore, the most important variables. This is a logical result given that that DH is based on the balance between rainfall and ET_o, while ET_o itself is estimated using temperature. Therefore, DH contains all the effects of the climate variables investigated in this study. Lastly, even though water is not presented as influential in the model, the study used the deductive reasoning around the wetland being used for water and the fact that its plot is almost close to the reference line to include it as a variable consideration in the study.

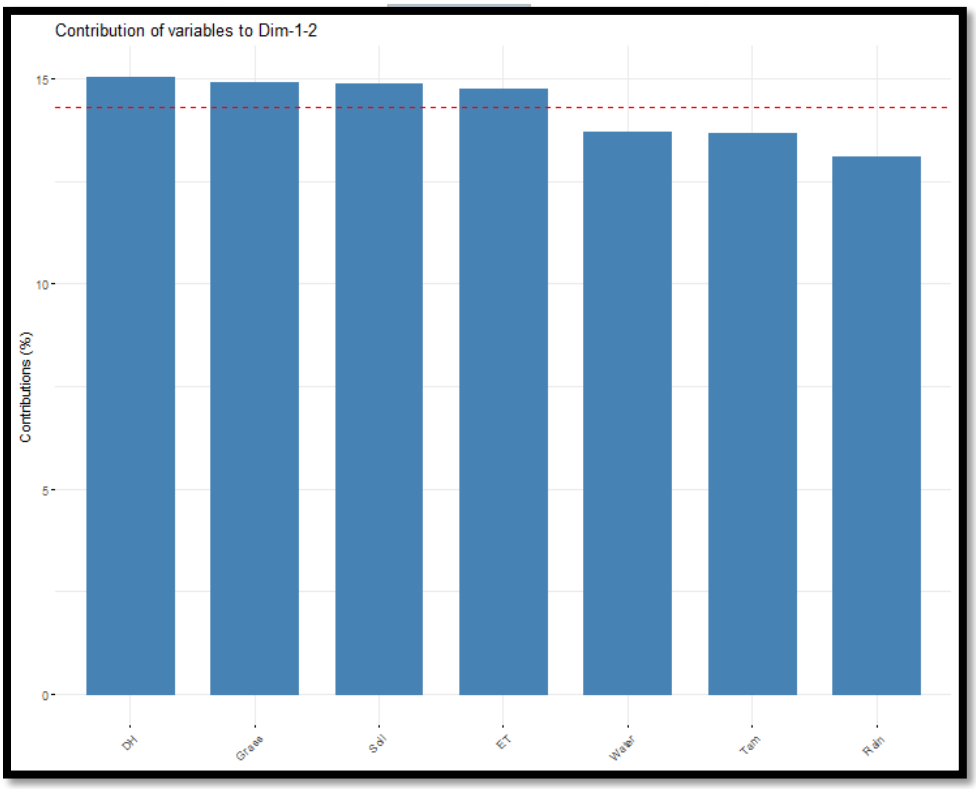


Figure 4.15: Evaluation of individual variable's contribution if they were combined under the assumption their contribution is uniform.

The findings from the PCA agree with multiple studies that have investigated wetlands in various regions, particularly in its identification of water balance as one of the main variables that play a crucial role in determining wetland state in addition to ET_o, soil, and vegetation. This is because water balance is a good indicator and input variable in modelling for drought monitoring, and it accounts for water balance that affects soil moisture, vegetation greenness and could cause severe agricultural drought (Adams and Peck, 2008; Raneesh, 2014; Etter *et al.*, 2017; Mo *et al.*, 2017). Therefore, a key question based on the study's findings is if climate variability is known to impact wetlands significantly. It is clear that the impact of climate on physical aspects such as farmlands and water resources, as well as social aspects such as the drastic changes in population dynamics, affect the wetland (Zarafshani *et al.*, 2016; Zheng *et al.*, 2019). The dynamics of climate that lead to these negative impacts have also been identified in this study and, therefore, prove the assumption that the climate variability in the region is responsible for a low adaptive capacity to drought, which has an indirect impact on the wetland (Turpie and Visser, 2013; Manyevere *et al.*, 2014; Chari, Hamandawana and Zhou, 2018). Therefore, based on the high significance of the relation between climate variability and the physical state of the wetland as analysed in this study, it is important to question how much climate variability contributes to the wetland's state of vulnerability. Also, additional variables undoubtedly have a considerable impact on the physical state of the wetland. For example, studies have shown that human dynamics have contributed to the physical degradation of wetlands through population growth (Adeleke, 2017) or anthropogenic activities. Tan *et al.* (2017), supported by Xu *et al.* (2020), concluded in their studies that population dynamics play a predominant role of about 89.67% over natural factors in wetland degradation. This shows a shared responsibility for variables affecting a wetland; analysing the contribution of each variable is an important consideration in wetland vulnerability studies when planning for mitigation.

There is no evidence to support that it is useful to measure contributions of variables to estimate vulnerability without defining what is considered a "good physical wetland state" and a "bad physical wetland state". This study used three key definitions to build a profile for the definitions of a good and bad wetland state:

a) Keddy *et al.* (2009), page 35: "*A wetland is an ecosystem that arises when inundation by water produces soils dominated by anaerobic processes and forces the biota, particularly rooted plants, to exhibit adaptations to tolerate flooding*".

b) Batzer and Sharitz (2014): advanced that wetlands are saturated by surface or groundwater long enough to support vegetation adapted to water-saturated soils.

c) Döll *et al.* (2020): Wetlands should include swamps, marches, and other areas similar to these.

From these three definitions, a wetland in a good physical state should be covered in water and show sustainable capacity for different types of vegetation species as long as they are adapted to saturated soils. This study then queried the best-suited methodology to assess wetlands' physical states (i.e. classify if the wetland was in a good state or a bad state) through a vulnerability assessment (i.e. how much risk a wetland is exposed to for it to be considered as a wetland that is in a "bad state"). Although various methods exist, this study opted to index its findings for a better description of wetland state and vulnerability as it has been proven that the use of indices is both flexible and adaptable (Gitay, Finlayson and Davidson, 2011; Nhamo, Magidi and Dickens, 2017; Papathoma-Köhle *et al.*, 2019). These indices allow the definition of the state of the wetland, which is described below.

4.2.5 Defining the state of the wetland

Due to the notion put forward by the study that a wetland in a good state should have the majority of the surface area covered in water and grass. It follows that the presence of dry soils would indicate degradation of the wetland, similar to what can be seen in Die Vlei as presented in Figure 4.16. Following this logic, the study computed surface area occupied by each wetland variable over time as a percentage and compared the output percentages of the different variables to identify the predominant variable.

Figure 4.16: Evidence of degradation in Die Vlei wetland with picture (A) showing evidence of what could be degradation from cutting down of trees for domestic purposes such as firewood and picture (B) showing evidence of what could be degradation from commercial clearing to harvest logs.

Using the PCA results, the study assigned weights to the different wetland classes: 0.2 for water, 0.49 Soil, and 0.49 for grass. Vegetation and water were added together and had a contribution weight of

0.51, and soil had 0.49. This was done to separate "good conditions" from "bad conditions", following the logic that good conditions were denoted by positive values, while negative values indicated bad conditions. Given that the classes are presented in percentage values, it is common practice to use the inverse normal to derive a spatial score. Therefore, the study took the negative of the inverse normal applied on soil, and the equation of the state of the wetland was given as follows:

$$Balance = (Vegetation\% + Water\%) * 0.51 - Soil\% * 0.49$$

Thereafter, the scores were transformed back to percentages to find the appropriate class. The study's index had values of 0 and 1. Therefore, the classification ranges and cut-offs were proposed: between 0 and 0.33 inclusive - bad conditions; between 0.33 and 0.67 inclusive - good conditions; and any value above 0.67 is classified as excellent condition. Even if the study chose to focus on vegetation alone and the index using its estimated spatial extent, the same idea could have been achieved. Table 4.12 shows that, on average, the current states of the wetland are "average". This is concerning as the conditions are mostly closer to the cut-off for bad conditions (0.33) than they are to the starting values for excellent conditions (0.67) and, the frequency of the bad condition is alarming as in most of these cases, the spatial index score is below 20. However, response actions to address the wetland state depends on the risk's perception as described below.

Table 4.12: Wetland state index, based on the surface area occupied by soil against water and vegetation.

Year	Soil	Score	Vegetation	Score	Balance	Index	State
20170711	0.95	1.63	0.05	-1.63	-1.63	0.05	Bad
20181223	0.58	0.21	0.42	-0.21	-0.21	0.42	Good
20190107	0.92	1.43	0.08	-1.43	-1.43	0.08	Bad
20190206	0.34	-0.42	0.66	0.42	0.42	0.66	Good
20190313	0.16	-1.00	0.84	1.00	1.00	0.84	Excellent
20190427	0.09	-1.32	0.91	1.32	1.32	0.91	Excellent
20190522	0.10	-1.28	0.90	1.28	1.28	0.90	Excellent
20190626	0.55	0.14	0.45	-0.14	-0.14	0.45	Good
20190726	0.66	0.40	0.34	-0.40	-0.40	0.34	Good
20190815	0.72	0.57	0.28	-0.57	-0.57	0.28	Bad
20190909	0.88	1.15	0.12	-1.15	-1.15	0.12	Bad
20191029	0.86	1.06	0.14	-1.06	-1.06	0.14	Bad
20191128	0.86	1.07	0.14	-1.07	-1.07	0.14	Bad
20191228	0.97	1.86	0.03	-1.86	-1.86	0.03	Bad
20200117	0.81	0.89	0.19	-0.89	-0.89	0.19	Bad
Mean	0.63	0.33	0.37	-0.33	-0.33	0.37	Good

4.3 RISK PERCEPTION

Risk perception is often viewed as a combination of hazard and coping abilities, which are usually based on probability and value shock. The latter is based on the time elapsed from previous occurrences or how predictable these occurrences are. These values also include the ability to prevent, mitigate, or manage an inevitable disaster (Alwang, Siegel and Jorgensen, 2001; de Groot *et al.*, 2006). These definitions are helpful when assessing risk in vulnerability, particularly in connection to humans and their responses to disasters. In the section below, the risk perception is discussed, beginning with identifying the hazardous variable of the wetland.

4.3.1 Identifying the hazardous variable of the wetland

The selection of hazardous variables was based on the climate variable that negatively influences vegetation and water. The correlation, which was presented in Table 4.11, supports the conclusion that, in as much as Et_o has a positive influence on water, this can be overlooked given that the surface area of the wetland covered in water is not only small but is also mixed with grass. Therefore, Et_o should be considered a hazardous variable as it can have a negative effect on the grass variable. On the other hand, it is unnecessary to evaluate both Et_o and temperature as Et_o is already a factor of weather and the two variables have a symbiotic relationship. Also, the use of Et_o is strongly supported in the literature where authors such as (Sehmi and Kundzewicz, 1997; Raneesh, 2014; Etter *et al.*, 2017; Mo *et al.*, 2017) advocate that Et_o reduces moisture content in any ecosystem and the ability of the wetland to cope with the reduction of moisture is discussed next.

4.3.2 Identifying coping strength of the wetland

The wetland's ability to cope was measured based on the climate variables as they play a pivotal role in sustaining the state of the wetland. The study chose to follow the rationale that selecting a variable that positively contributes to the wetland is useful in promoting vegetation growth and density (National Research Council, 1992). In this case, by correlation, rainfall seemed to contribute the most to the wetland. This was expected as it is justified and explained in studies that offer evidence of how rainfall variability is a pivotal component in the maintenance of wetlands ecosystems balance (Parry *et al.*, 2004; Simelton *et al.*, 2009; van Loon and van Lanen, 2013; Kumar *et al.*, 2016). When the wetland ecosystem is unbalanced, then the wetland is stressed, and the computation of that stress is described below.

4.3.3 Computing vulnerability stress

Application of the identification of the hazardous variable in the wetland and measurement of the coping strength of the wetland was used to develop a method for the computation of vulnerability stress. This computation was based on long-term data of ET_o as the hazardous variable and rainfall as the coping variable between 2015 and 2019. The results presented in Table 4.13 show that the maximum amount of water balance amounts to 132.05 mm, while the min was -94.87 mm, and the long-term mean was a positive value of 25.40 mm. A positive mean illustrates how on average, more water is being supplied to the wetland than the water that is being negatively affected (and therefore reduced) by climate variables.

Table 4.13: Summary of long-term decadal water balance.

Min	Q1	Median	Mean	Q2	Max
-94.87	-14.91	26.27	25.40	71.17	132.05

The justification of estimating vulnerability stress as water balance is that water balance describes the contribution of climate variables to the wetland as it accounts for climate water withdrawal and climate water supply. Unfortunately, given the study's results, it is difficult to conclude the values' implications unless they are indexed. Post indexing, the study could justify using the Standardized Precipitation and Evapotranspiration Index (SPEI) due to it being widely used to explain stress similar to that identified in Die Vlei (Beguería *et al.*, 2011; Beguería *et al.*, 2014; Vicente-Serrano *et al.*, 2015). The study uses the 3-parameter gamma distribution (Table 4.14) to estimate the probability of each monthly water balance, and the inverse normal distribution was used to obtain each index.

Table 4.14: 3-parameter gamma distribution used to compute the probability of water balance.

Distribution	Location	Shape	Scale	Threshold
3-Parameter	Gamma	211.30231	3.94644	-812.43670

Table 4.15 presents SPEI scores for the main summary statistics for the monthly water balance, which shows the probability and index scores for the minimum, the mean, and the maximum possible water balance in the dataset used. From the table, it is clear that normal water balance conditions are optimum for interpretation when they are closer to zero. If the scores have less than zero values, then there is a record of increased stress, while if the scores are higher than zero, then there is a record of decreasing stress.

Table 4.15: SPEI scores for main summary statistics for the monthly water balance.

Min	Mean	Max
-94.87	25.8	132.1
0.02	0.53	0.97
-2.12	0.07	1.87
High	Low	No Stress

SPEI is only applicable when assessing stress using individual cases of water balance instead of assessing long-term water balance. This is because one major challenge with the method used in this study is that, regardless of the type of data one is using, the standardized value for the mean will always have a score of zero or close to zero when standardized, regardless of whether the mean value is negative or positive. This then defeats the purpose of this study to attempt to identify stress, which occurs when water balance is low. There is a need here to have an index that will identify negative values found in water balance and account for a reduction in water balance that might not necessarily be negative, considering that negative values in water balance mean shortage of water. This study proposes that a better way to approach this, to account for both negative values and reduced water balance, is by following a two-step method. Firstly, computing SPEI and secondly, counting the number of times the model produces negative values, dividing it by the sample size, and then calculating stress based on that probability. For example, if in a sample of ten, the negative values appear six times, the vulnerability stress is estimated to be approximately 30%. The SPEI method can further be used for classification where if negative values are between 50 and 69%, then the stress is low. If values are between 69% and 84%, then the stress is severe, and if above 84%, then stress is considered drastic. From the vulnerability stress index results presented in Table 4.16, it appears that within 56 months, Die Vlei and its surrounding areas were wet for approximately half that period. This may mean that the stress from climate variables on the wetland is average as there is evidence of water supply which is assumed to be sufficient to sustain the wetland in a good state.

Table 4.16: Vulnerability stress index computed on the long-term average.

	Sample size	Result output	Stress index indicator
Sample Size	56	56	N/A
Negative	28	0.5	Normal
Positive	28	0.5	Normal

It should be noted that, at this juncture, these results do not illustrate whether or not the wetland is vulnerable; instead, they represent the potential risk that the wetland is under from climate variables. The probability of a risk event and its likely impact on the subject matter is defined as a risk factor

(Gitay, Finlayson and Davidson, 2011). It is not abstract that climate variability is considered one of the risk factors. Some authors even argue that it is the leading risk factor due to its documented impact on water resources (Erwin, 2009; Romieu *et al.*, 2010; Barros and Albernaz, 2014). In fact, within the concept of vulnerability, the risk from climate variability is usually considered using both slow changes and extreme events (Gitay, Finlayson and Davidson, 2011). Another issue the study considered was the two different probabilities that the study computed. The first one estimated the probability of a given water balance amount to occur, and the second one estimated the risk as presented in Table 4.17. The individual probability was estimated using a 3-parameter gamma distribution, which estimates the likelihood that a single event contributes to the occurrence of the risk to an area of interest. This means 90% of the water balance in Die Vlei is likely to bring more water to the wetland than to pose a risk making it an unlikely promoter of risk impact.

Table 4.17: Probability estimation for water balance (DH) amount from December 2018 to January 2020 and their corresponding classes.

Year	DH	Score	Stress	
20181223	37.97	0.62	Normal	Risk occurrence likelihood (ROL)
20190107	81.16	0.85	Unlikely	
20190206	39.79	0.63	Normal	
20190313	104.75	0.92	Unlikely	
20190427	132.05	0.97	Unlikely	
20190522	-19.89	0.24	Severe	
20190626	-75.11	0.04	Drastic	
20190726	-94.87	0.02	Drastic	
20190815	-70.19	0.05	Drastic	
20190909	-25.94	0.21	Severe	
20191029	-19.40	0.24	Severe	
20191128	-7.63	0.31	Normal	
20191228	0.87	0.37	Normal	
20200117	111.70	0.94	Unlikely	
Risk impact likelihood (RIL) - Exposure to Risk				
Mean	10.26	0.46	Normal	
Negative	7.00	0.50	Normal	
Sample	14			

Meanwhile, a water balance of 20% would suggest there is more withdrawal than the addition of water to the wetland. Therefore, its contribution to risk impact is severe. The long-term probability score explains the contributions of water balance to the wetland, accounting for dryness and times of wetness. It delineates in percentage how much exposure the wetland faces concerning climate and, therefore, is the risk impact likelihood. The two methods do not classify risk the same way; for Risk Occurrence Likelihood (ROL), good conditions are characterized by high probabilities.

On the other hand, for Risk Impact Likelihood (RIL), since the probabilities are estimated based on the number of times negative values occurred, high probabilities mean high frequency of dry conditions such as drought. Whilst it is fair to argue that the observations presented in Table 4.17 are more likely a seasonality effect than a drought, it is also important to note that seasons with lower temperatures are meant to have corresponding low evapotranspiration. Therefore, the general reduction in rainfall should be accompanied by a reduction in evapotranspiration. It might be higher than the expected rainfall, which was the case for Die Vlei during the selected period due to the country's drought (Lefebvre et al., 2019). Viz. the occurrence of drought during the data period chosen could affect the obtained results. Also, Table 4.18 showing water balance within the cold season for Die Vlei from 2015 to 2019 complement the idea that the result presented in Table 4.17 is more likely due to the drought than being a result of seasonality.

Table 4.18: Water balance between May and October from 2015 to 2019.

Months	2015	2016	2017	2018	2019
May	-20.56	3.43	-13.41	-52.34	-19.89
June	44.82	-32.52	-58.76	-63.49	-75.11
July	108.39	71.12	-41.40	-64.93	-94.87
August	11.22	-47.28	66.57	71.30	-70.19
September	63.75	46.41	1.92	65.63	-25.94
October	52.71	-4.39	79.13	-24.96	-19.40

It is argued that the survival of a wetland and its rehabilitation is dependant mostly on its water content. Erwin (2009) stated that the climate's contributions to both the quality and amount of water a wetland receives are considerably high. This was explained further by Barros and Albernaz (2014), whose paper highlights that the effects of climate variabilities are not limited to hydrological cycles in the wetlands and extend to the reduction of vegetation species, physical degradation, including the decrease in productivity of certain species. In that same paper, it is argued that increased rainfall may cause disruptions in the ecosystem, including flooding and alien species invasion, which is likely the case in Die Vlei as it was selected for wetland rehabilitation that requires observation of mitigation measures (Youthed, 2014). Questions that should be answered to address Barros and Albernaz (2014) that are relevant to Die Vlei are:

a) What conditions of the climate are likely to cause flooding?
b) What are the relevant activities of the wetland? and
c) How much water is the wetland capable of absorbing without causing drastic changes?

For example, the Dei Vlei wetland is surrounded by sizeable commercial forest and farmlands that are likely sustained by its water flow. Therefore, further investigations should offer insight into the quantification of the amount of water considered to be "too much" for a wetland to be subjected to. Essentially, the human impact includes afforestation groundwater-uptake after planting and actual extraction (domestic/irrigation) taking place. For example, Lefebvre *et al.* (2019) found that some wetlands within the Mediterranean can survive past a 400 mm decrease in annual rainfall. This resilience is attributed to their ability to store water, low evapotranspiration, and winter rainfalls. However, this is not likely representative of wetlands in all the world regions (Lamsal *et al.*, 2017). For example, wetlands found in semi-arid and arid regions such as the Eastern Cape receive scarce rainfall during the rainy season, let alone winter rainfall. This is why Die Vlei is a unique resource for the province as it is in Hogsback, which receives high rainfall totals that are key to alleviate the pressure on the province as a whole. Besides, the Mediterranean region can receive over 1 000 mm rainfall per year such that the 400 mm decrease is a mere 40% reduction, which hydrological storage systems may compensate. Nonetheless, this study postulates that for wetland systems like Die Vlei, a 40% reduction of its usual rainfall range allows the wetland to maintain a good state only provided that it does not receive reduced rainfall for long periods. These results are discussed further in the vulnerability assessment described below.

4.4 RISK MANAGEMENT: VULNERABILITY ASSESSMENT

The study proposes that only two variables are needed to compute the vulnerability assessment: wetland state and vulnerability stress (risk exposure). Wetland state can be calculated using a combination of the grass and water variables, whilst wetland risk can be computed using only water balance (DH). Therefore, the study calculated the MCE using these two variables and estimated their weights to be 0.61 for wetland state and 0.39 for water balance (Table 4.19). Each Risk Occurrence Likelihood (ROL) demonstrates how climate variability can contribute to the vulnerability of the wetland. Interpretation of the model is that when both the wetland state and vulnerability stress are "bad", then the wetland is likely to be highly vulnerable to climatic dynamics. In this case, the long-term average should be a sufficient estimation of vulnerability because it documents the long-term change in climate and historical scenarios of how wetland's variables have changed. For example, from December 2018 to January 2020, Table 4.19 shows that the wetland has been in bad condition, likely due to the wetland recovering from the drought. These are historical scenarios based on changes observed in the grass, water, and soil. Therefore, it is acceptable to assume that the wetland was not in a good state due to the experienced drought during that period, which exacerbated the effects of human activities on the wetland viz. it is exposed to a "drastic level of risk". This is further supported by how the wetland state was based on long-term averages, and the risk impact was assessed based on the frequency of dry conditions, which again are prevalent during a drought. Therefore, it would seem that Die Vlei is unable to persist through dry climate conditions and will likely face a reduction of vegetation cover or an increase in alien species (Lefebvre *et al.*, 2019).

Table 4.19: Vulnerability index of the Dei Vlei wetland evaluated based on individual risk occurrence likelihood.

Year	Wetland	State	V_s	Stress	Score	Vulnerability	Class
20181223	0.42	Good	0.62	Normal	-0,01	0,50	Medium
20190107	0.08	Bad	0.85	Unlikely	-0,47	0,32	High
20190206	0.66	Good	0.63	Normal	0,39	0,65	Medium
20190313	0.84	Excellent	0.92	Unlikely	1,17	0,88	Low
20190427	0.91	Excellent	0.97	Unlikely	1,54	0,94	Low
20190522	0.90	Excellent	0.24	Severe	0,51	0,69	Low
20190626	0.45	Good	0.04	Drastic	-0,76	0,22	High
20190726	0.34	Good	0.02	Drastic	-1,07	0,14	High
20190815	0.28	Bad	0.05	Drastic	-0,99	0,16	High
20190909	0.12	Bad	0.21	Severe	-1,02	0,15	High
20191029	0.14	Bad	0.24	Severe	-0,92	0,18	High
20191128	0.14	Bad	0.31	Normal	-0,85	0,20	High
20191228	0.03	Bad	0.37	Normal	-1,27	0,10	High
20200117	0.19	Bad	0.94	Unlikely	0,06	0,52	Medium
Mean	0.37	Good	0.46	Normal	-0,24	0,40	Medium
Drought count		8	0.43	Normal	-0.27	0.39	Medium

From the study results, Die Vlei is in a "bad state." Although this is likely due to the drought which was ongoing in the selected period, it does illustrate that the challenges with wetland vulnerability are not only restricted to methodological challenges or classification challenges. For example, the impacts of climate change are difficult to manage, let alone reverse and in most cases, it is more strategic to develop adaptive capacity instead to increase resilience (van Loon and van Lanen, 2013). This is notable as the PCA highlighted that climate is responsible for about 39% of the negative changes observed in Die Vlei. Also, whilst the majority of wetland studies have in one way or another measured wetland vulnerability to different factors, there were previously limited studies that addressed either adaptation or rehabilitation of the wetland in response to climate variability/change over the long term (Erwin, 2009). Therefore, the identification of the wetland for rehabilitation is logical as the results highlight the vulnerability of Die Vlei.

4.5 CONCLUSION

This study established that a wholesome vulnerability assessment requires considering how both long-term effects and inter-annual changes affect the wetland. This can be addressed by considering cases when the wetland is both at risk and in a degraded state or condition coupled with the total duration of these conditions. This can be summarised by employing a risk impact method, which counts occurrences over time. In the Die Vlei wetland case, Table 4.20 illustrates that 8 out of 14 times, 57%, the region is subjected to dry conditions whilst 11 out of 14 times, 79% of the wetland is in a bad or degraded state. Table 4.20 shows that Die Vlei is already at high risk without considering the intensity and other descriptive issues.

Table 4.20: Summary of the Dei Vlei climate effects using the frequency of dry conditions and a bad state of the wetland as a judgment tool.

Sample	Drought count	Probability	Class
14	11	0.214286	Bad
14	8	0.428571	Normal
		0.290096	High

It is clear that with the current condition of Die Vlei, climate variability poses a threat to the wetland's ecosystem. It concerns that land cover practices such as farming continue to use the wetland's groundwater, hydrological infrastructure (such as dams), and rainfall. In contrast, climate variability negatively affects them, as the drought has shown. Proactive measures that support water storage would be useful, including policy formulation and sensitization of stakeholders to increase awareness so that exploitations of the wetland can be optimized.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

Chapter five concludes the study by highlighting key observations, strengths, and shortcomings of the research and re-visiting the study's objectives. Thereafter, the chapter evaluates the research and makes recommendations to wetland managers and ecologists on the vulnerability level of Die Vlei to water demand, climate variability, and LULC.

5.2 RE-VISITING OBJECTIVES

Whether a seasonal component is significant within the data or not is irrelevant. The fact that the data itself does not exhibit any seasonality makes it challenging to assess the predictability of the data. It is only evident that we can expect evapotranspiration to increase but cannot tell to what extent the expected increase will be. Therefore, it could be concluded that, in the long run, water demand from the wetland is going to increase. To sustain the wetland from a climate point of view, it will be necessary for the expected future rainfall scenarios to also increase, otherwise with time, it won't be easy to sustain the wetland.

Given that the water balance shows trends expected to decrease over time, it should also be expected that the wetland will reduce in both water quality and quantity. Since all these changes are climate-related, it should also be noted that it may not be as easy to control their changes or effects. At this point, the study has evaluated three climate variables and managed to identify possible future expected changes. However, within the scope of this objective, it is difficult to determine how these changes can be controlled to minimize their effects on the wetland.

The results show that the ET_o follows a GAM trend and is expected to increase with time. The changes in the long-term average are expected to be small. However, the statistical measurement indicates that these changes have a non-seasonal component, making it difficult to predict them. It also appears that the amount of rain accumulated within this region is sufficient enough to supply enough water to the wetland for sustenance. This means, from a climate point of view, it might be considered that the wetland is not exposed to any intensive vulnerability. However, possible stress might be accounted for by other variables. Based on the findings from the time series evaluated in this study, it was discovered that temperature is expected to increase, rainfall is expected to decrease, affecting the overall water balance of the wetland region. Based on the highlighted literature, it can be expected that the wetland's water quality is affected since the increase in temperature will reduce the efficiency of the nutrients removal process. The decrease in rainfall will eventually affect the overall water availability, including flow rates that will also considerably reduce water quality and affect the biomass of the wetland to increase water demand subsequently. Therefore, water-intensive practices such as commercial logging and farming in the area would benefit from further investigation of their water demand. However, in this case, it is fair to speculate that the wetland is degrading, and farming practices in the area should be investigated closely as they require a lot of water.

5.3 CONCLUSIONS

The study conducted a vulnerability assessment of the wetland using the Ramsar Convention (Gitay, Finlayson and Davidson, 2011). This required three main steps: conducting a risk assessment and establishing a risk perception ending with risk management. Part of the methods this convention requires is to use extensive knowledge of experts through interviews to understand dynamics within the subject being investigated in a wetland. This study first adapted the Ramsar model to suit the limitations of this study that could not include expert knowledge. Through literature review, climate variability was identified as a risk factor to be used in this study (Adams and Peck, 2008; Turpie and Visser, 2013; Manyevere *et al.*, 2014; Raneesh, 2014; Zarafshani *et al.*, 2016; Etter *et al.*, 2017; Mo *et al.*, 2017; Chari, Hamandawana and Zhou, 2018; Zheng *et al.*, 2019; Xu *et al.*, 2020). Therefore, the assessment of risk was done in four main steps. The study computed water demand from a climate perspective, expressed as a water balance between supply (Rainfall) and demand (Evapotranspiration).

The study performed trend analysis on the variables and discovered that although there was no seasonality detected and the data was said to be stationary, it was noticed that there were hints of a possible increase in water balance through graphical plots. This implied an expected reduction in water demand, and spelling, expected good conditions of water supply. The study went further to analyse land use and land cover through systematic reconstruction of the wetland spatial extent between 2007 and 2017 using one area for accounting for long-term changes. The study also assessed current conditions of the wetland using Sentinel 2 for the period starting from December 2018 to January 2020. The estimated full extent of the wetland was extracted through Sentinel and corrected using historical spot data. The study identified an intensive activity in farming. Two types of farming occur around the Die Vlei, including commercial farming of timber and agricultural farming of citrus and farms that have been identified as a wetland stressor (Zhang *et al.*, 2019). Through image analysis and the results of the WRC project, it was concluded that there must be a high demand for water from the wetland from these farming activities due to their strategic design around the wetland(van Deventer *et al.*, 2020). However, this can be confirmed through other studies that can add to this using qualitative analysis that should include expert knowledge and information concerning land reclamations, reformations, and exploitation. Through LULC analysis, it was discovered that the Die Vlei wetland has three main variables: soil, vegetation, and water, which became the wetland variables constantly mentioned throughout the study.

This study's trend analysis also included an assessment of changes in rainfall and temperature over time. Therefore, Temperature, Rainfall, ET_o, and DH are the climate variables considered. Ultimately, a PCA was conducted on these eight variables, and it was identified that vegetation, soil, ET_o, and DH are sufficient variables to explain dynamics within the wetland. The study evaluated the wetland state on the premise that a healthy wetland should contain more water and vegetation over soil (Batzer and Sharitz, 2014; Döll *et al.*, 2020). The soil was regarded as a negative indicator of the wetland state by this alone, while water and vegetation became positive indicators. Results had shown that, on average, the wetland is in a good state. However, concern was over the frequency in which soil is predominant over vegetation and water combined. These realities showed intensive inter-seasonal and inter-variable exchanges that should be evaluated more closely to obtain more explanations that climate alone cannot provide. Even though water balance was not so critical in some cases, the wetland tends to be less of water and vegetation. The second step was to evaluate risk perception. In this step, the study identified variables that constitute a risk for the wetland and those that comprise coping promoters of the wetland. Rainfall was identified as coping. Then, vulnerability stress was calculated as coping minus hazard following, which was later used together with wetland state as input to compute vulnerability index during risk management.

5.4 STUDY EVALUATION

Key findings from this study are that the increase of commercial forest between 2007 and 2017 contributes to the wetland dynamics. Expect an increase in water balance that can contribute to the future sustenance of the wetland if the growth happens over a more extended period. However, to produce conclusive evidence, one should use climate projections to establish robust future scenarios (Lefebvre *et al.*, 2019). Climate was estimated to have a 39% contribution to the wetland dynamics. However, within a study that includes multiple variables, this might increase or decrease. Finally, the wetland was found to be under stress and vulnerable to climate variability since it was identified that there are more frequent drought occurrences.

It should be noted that this is based on an analysis of current dynamics and not on a long-range period. However, literature has it that the region is a drought-prone area and experience a frequent lowering of rainfall, although it receives winter rainfalls (Turpie and Visser, 2013; Manyevere *et al.*, 2014). This study concluded that climate variability on its own is a significant contributing variable to the wetland's vulnerability (Erwin, 2009; Barros and Albernaz, 2014; Lamsal *et al.*, 2017; Lefebvre *et al.*, 2019). The only way to address issues related to climate variability is to invest in Policy formulation and sensitization of stakeholders to increase awareness so that exploitations of the wetland can be optimized for preservation purposes. The commercial land found in the region hint that exploitation of this wetland is mainly economically driven, and thought, ecosystem preservation may not be a concern for stakeholders. It should also be noted that, because the area is covered by forest, it was difficult to measure the increase of over the study period accurately. It will be more advantageous to conduct an onsite exploration to measure this effect. Finally, the fact that soil occupies about 60% of the wetland suggests that the wetland has reduced to 40% of its estimated full extent. This shows that a few years from now, the wetland is at risk of further degradation if current identified trends continue. The use of evapotranspiration to represent water demand whilst suitable in this study's context is a weakness that could have been remedied by proper estimation of specific domestic and commercial water demand on the wetland through advanced data collection and records from the local municipality. Besides, up to date climate data may also provide more insight into the vulnerability of wetlands from climate variability. Although the study had to use the Meteoblue data because of the lack of consistent daily data for the study area and the distance from the nearest weather station, the decadal temperature and rainfall averaged Meteoblue data is a compound average.

5.5 RECOMMENDATIONS

Heedless of the limitations of the data used in this study, it is a fairly reasonable conclusion that Die Vlei is vulnerable to demand, climate variability and land-use/cover change. However, these said limitations have highlighted various recommendations that would assist in developing policy, for example, the 1998 National Environmental Management Act and practices such as Working for Wetlands that protect and rehabilitee wetlands and these are discussed further here. Regarding the challenges posed by data, the quantification of water demand would have benefited from the quantification of domestic and commercial needs using AADD, for example, as opposed to using evapotranspiration. The climate data was also key in the study, and it would have been favourable to use complete daily recordings from a local weather station if possible. Lastly, a key piece of data that would have provided invaluable qualitative data was the inclusion of expert knowledge and its exclusion negatively affected the results, particularly the risk perception.

Regarding the study area, it would be useful to conduct a full land exploration of the Hogsback area as this would allow an assessment of domestic and commercial human activities and their impact on the wetland. For example, farming activities should be investigated to know the quantities of water from the wetland they use through extraction/pumping for irrigation and measures to relieve/manage drought stress. Furthermore, as a tourist attraction, numerous recreational activities may affect the wetland through pollution. Therefore, it is recommended to assess the impact of all the recreational areas such as The Hobbiton camping site on the wetland. Lastly, a lot of the land in Hogsback is protected. Most of its water resources are privatized; however, there is evidence of informal settlements within the wetland ecosystem, presumably due to land reforms reclamations. Their effect needs to be investigated. Regarding the study's methodology, it is recommended that including forecasting tools for the variables viz. water demand from estimated population growth trends; climate variability from IPCC's Representative Concentration Pathways and LULC from current changes.

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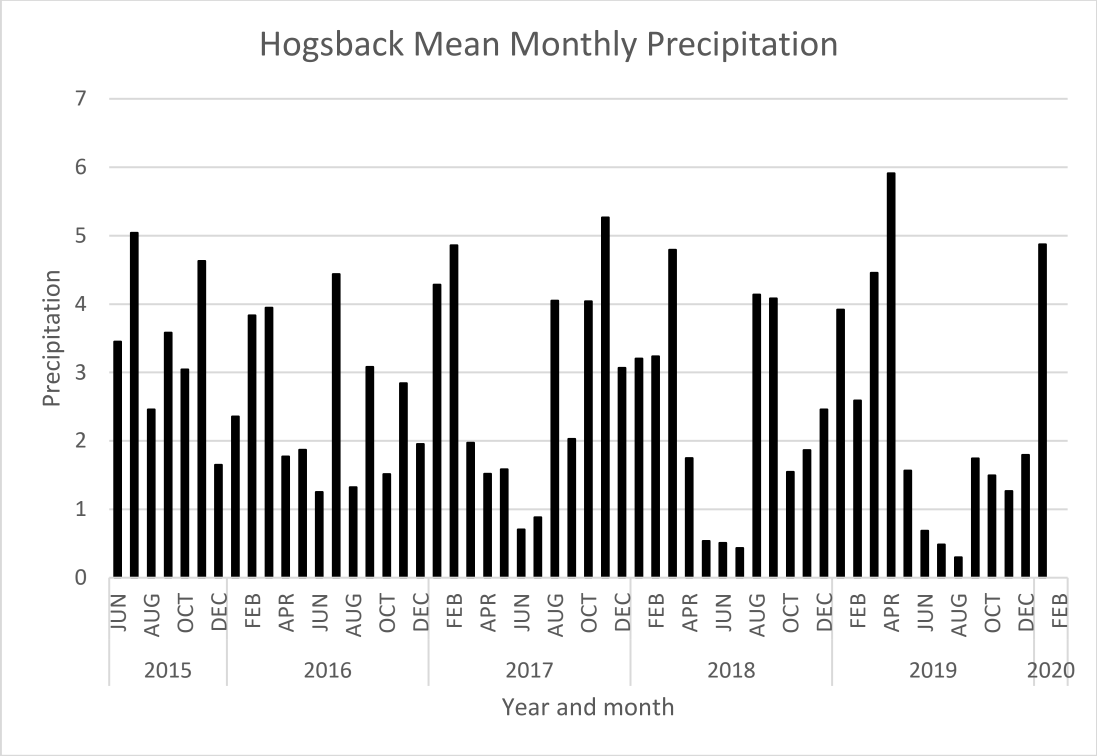
APPENDICES

APPENDIX A: TIME SERIES FUNCTION ts() IN THE R PACKAGE TO EVALUATE TRENDS

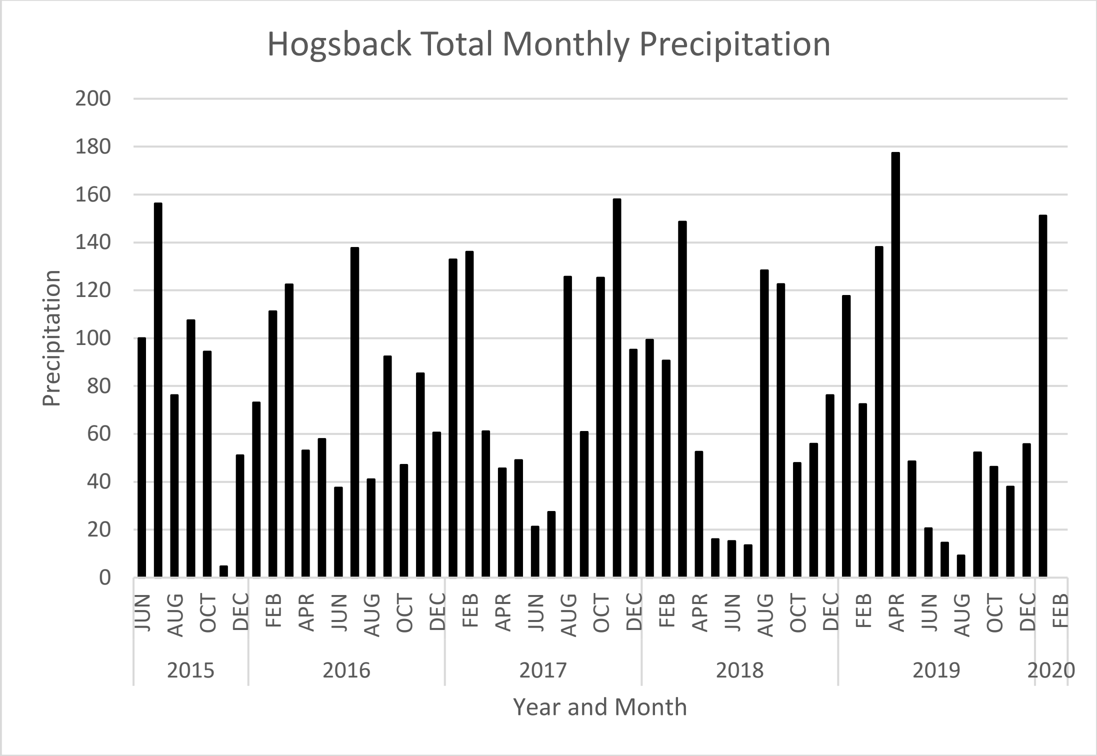
```
library(fpp2)
library(seastests)
library(mgcv)
library(tseries)

attach(data)
birthstimeseries <- ts(dP, frequency = 7, start = 1)
birthstimeseriescomponents <- decompose(birthstimeseries)
plot(birthstimeseriescomponents)


time.pts = c(1:length(dP))
time.pts = c(time.pts - min(time.pts)) / max(time.pts)
dP = ts(dP, start = 1, frequency = 1)
ts.plot(dP, ylab = "Precipitation")
x = rnorm(1000, 0, 1)
y = rnorm(1000, 0, .02) + sin(x)
plot(x, y)
ysmooth = ksmooth(x, y, kernel = "normal")
lines(ysmooth, col = "red")

mav.fit = ksmooth(time.pts, dP, kernel = "box")
dP.fit.mav = ts(mav.fit$y, start = 1, frequency = 1)

ts.plot(dP, ylab = "Precipitation")
lines(dP.fit.mav, lwd = 2, col = "purple")
abline(dP.fit.mav[1], 0, lwd = 2, col = "blue")

x1 = time.pts
x2 = time.pts ^ 2
lm.fit = lm(dP ~ x1 + x2)
summary(lm.fit)

dP.fit.lm = ts(fitted(lm.fit), start = 1, frequency = 1)
ts.plot(dP, ylab = "Precipitation")
lines(dP.fit.lm, lwd = 2, col = "green")

abline(dP.fit.lm[1], 0, lwd = 2, col = "blue")

loc.fit = loess(dP ~ time.pts)
dP.fit.loc = ts(fitted(loc.fit), start = 1, frequency = 1)


gam.fit = gam(dP ~ s(time.pts))
dP.fit.gam = ts(fitted(gam.fit), start = 1, frequency = 1)

ts.plot(dP, ylab = "Precipitation")
lines(dP.fit.loc, lwd = 2, col = "yellow")
lines(dP.fit.lm, lwd = 2, col = "green")
lines(dP.fit.mav, lwd = 2, col = "purple")
lines(dP.fit.gam, lwd = 2, col = "red")
#abline(dP.fit.loc[1], 0, lwd = 2, col = "blue")
legend("topright", legend = c("Moving Average", "Linear Model", "Generalized Addictive Model", "LOESS"), lty = 1, col = c("purple", "green", "red", "Yellow"), cex = 0.8, title = "Line types", text.font = 4, bg = "lightblue")

all.val = c(dP.fit.mav, dP.fit.lm, dP.fit.gam,  dP.fit.loc)
ylim = c(min(all.val), max(all.val))
```

```
ts.plot(dP.fit.lm, lwd = 2, col = "green", ylim = ylim, ylab = "Precipitation")
lines(dP.fit.mav, lwd = 2, col = "purple")
lines(dP.fit.gam, lwd = 2, col = "red")
lines(dP.fit.loc, lwd = 2, col = "yellow")
legend("topright", legend = c("Moving Average", "Linear Model", "Generalized Addictive Model", "LOESS"), lty = 1, col = c("purple", "green", "red", "Yellow"), cex = 0.8, title = "Line types", text.font = 4)

#testing seasonal component significance

fit1 <- ets(dP)
fit2 <- ets(dP, model = "ANN")

deviance <- 2 * c(logLik(fit1) - logLik(fit2))
df <- attributes(logLik(fit1))$df - attributes(logLik(fit2))$df
#P value
1 - pchisq(deviance, df)
Adf.test(dP)
```

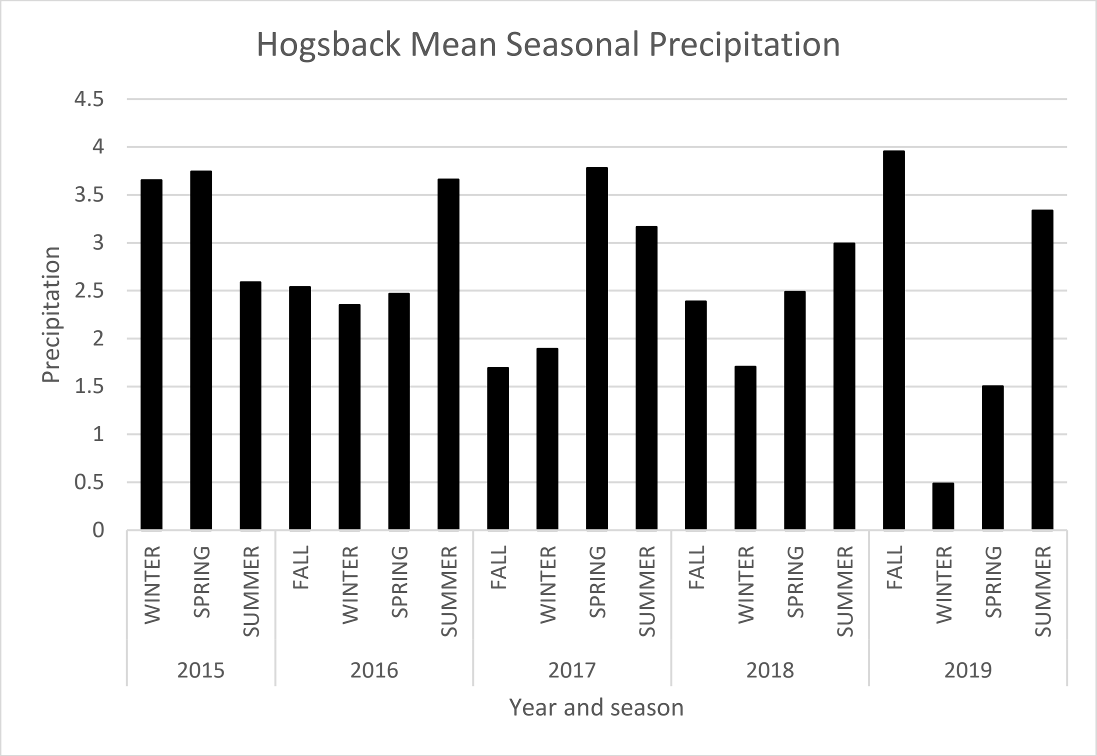
APPENDIX B: METEOBLUE CLIMATE DATA



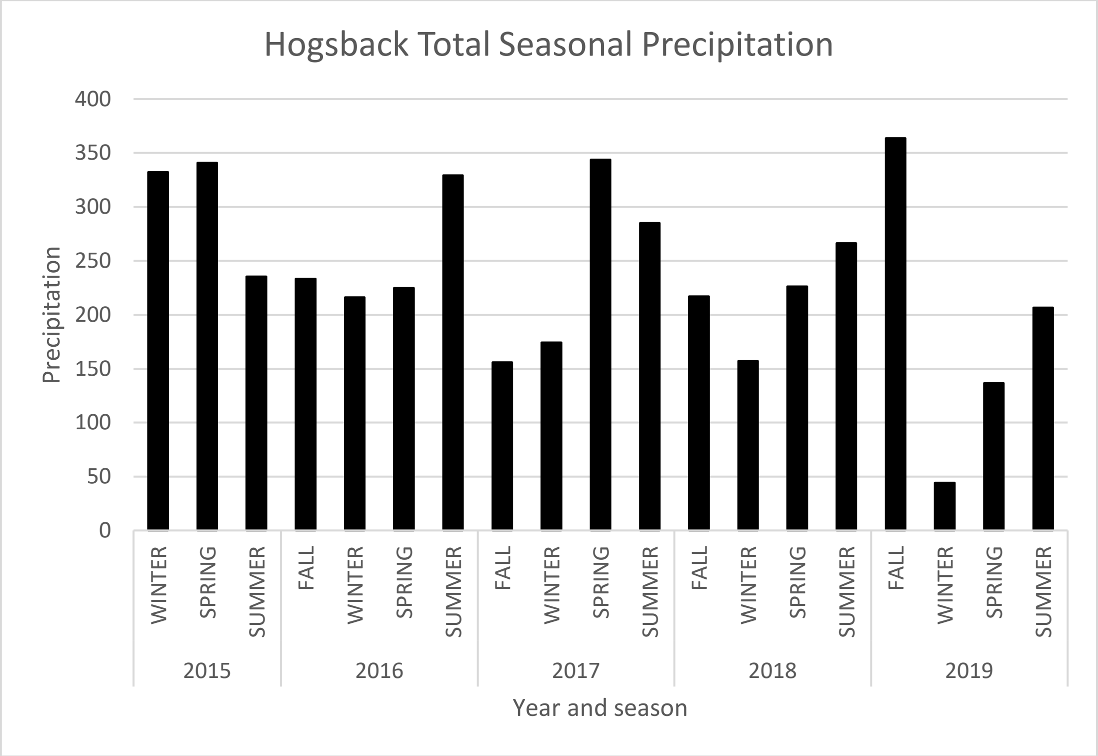
Appendix B 5.1: Hogsback mean monthly precipitation compiled from the Meteoblue climate data.



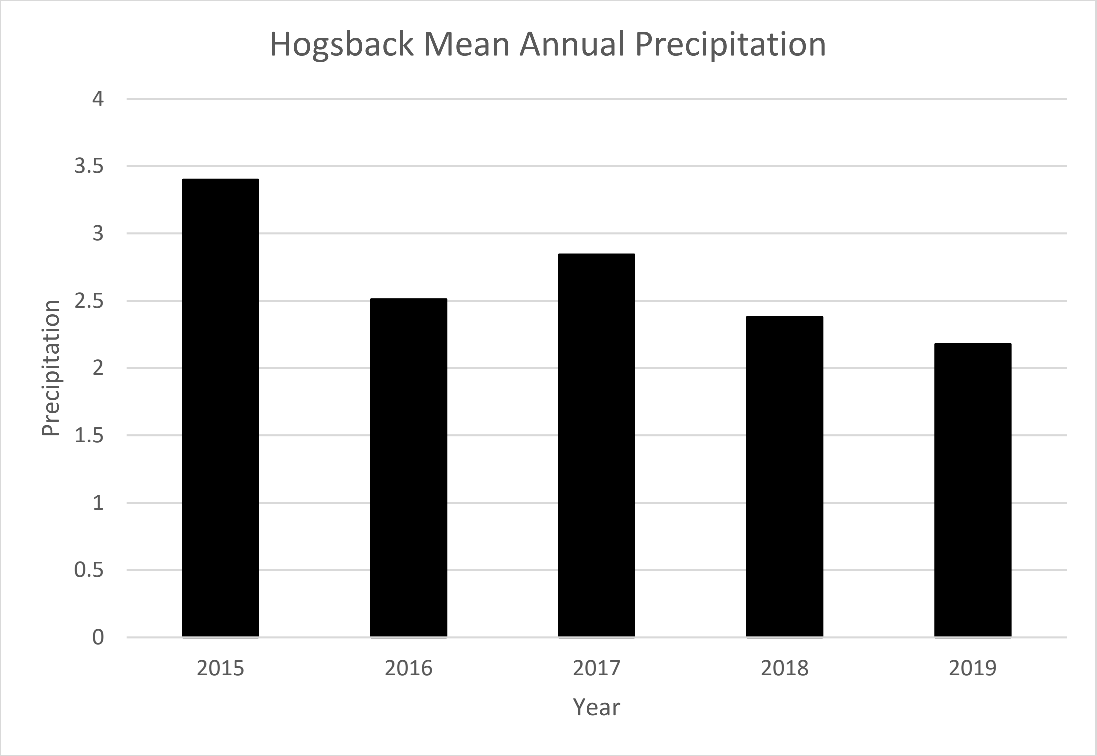
Appendix B 5.2: Hogsback total monthly precipitation compiled from the Meteoblue climate data.



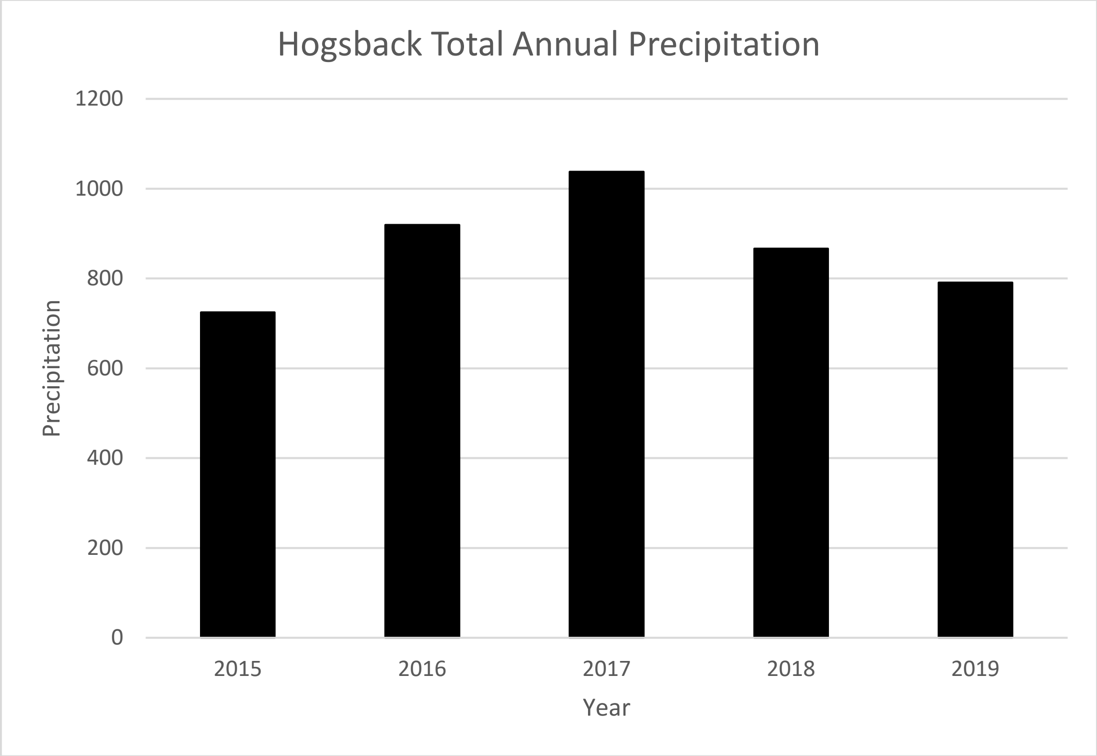
Appendix B 5.3: Hogsback mean seasonal precipitation compiled from the Meteoblue climate data.



Appendix B 5.4:Hogsback total seasonal precipitation compiled from the Meteoblue climate data.



Appendix B 5.5: Hogsback mean annual precipitation compiled from the Meteoblue climate data.



Appendix B 5.6: Hogsback total annual precipitation compiled from the Meteoblue climate data.

APPENDIX C: ETHICAL CLEARANCE

University of Fort Hare
Together in Excellence

ETHICAL CLEARANCE CERTIFICATE
REC-270710-028-RA Level 01

Certificate Reference Number:	CHI021SMAR01
Project title:	**Vulnerability assessment of wetland ecosystems to land use change and climate variability, the case of Die Vlei wetland, Eastern Cape Province, South Africa.**
Nature of Project:	Masters
Principal Researcher:	Kudzanai Rosebud Marembo
Sub-Investigator:	N/A
Supervisor:	Dr W Chingombe
Co-supervisor:	N/A

On behalf of the University of Fort Hare's Research Ethics Committee (UREC) I hereby give ethical approval in respect of the undertakings contained in the above-mentioned project and research instrument(s). Should any other instruments be used, these require separate authorization. The Researcher may therefore commence with the research as from the date of this certificate, using the reference number indicated above.

Please note that the UREC must be informed immediately of

- Any material change in the conditions or undertakings mentioned in the document
- Any material breaches of ethical undertakings or events that impact upon the ethical conduct of the research

The Principal Researcher must report to the UREC in the prescribed format, where applicable, annually, and at the end of the project, in respect of ethical compliance.

Special conditions: Research that includes children as per the official regulations of the act must take the following into account:

Note: The UREC is aware of the provisions of s71 of the National Health Act 61 of 2003 and that matters pertaining to obtaining the Minister's consent are under discussion and remain unresolved. Nonetheless, as was decided at a meeting between the National Health Research Ethics Committee and stakeholders on 6 June 2013, university ethics committees may continue to grant ethical clearance for research involving children without the Minister's consent, provided that the prescripts of the previous rules have been met. This certificate is granted in terms of this agreement.

The UREC retains the right to

- Withdraw or amend this Ethical Clearance Certificate if
    - Any unethical principal or practices are revealed or suspected
    - Relevant information has been withheld or misrepresented
    - Regulatory changes of whatsoever nature so require
    - The conditions contained in the Certificate have not been adhered to

- Request access to any information or data at any time during the course or after completion of the project.

- In addition to the need to comply with the highest level of ethical conduct principle investigators must report back annually as an evaluation and monitoring mechanism on the progress being made by the research. Such a report must be sent to the Dean of Research's office

The Ethics Committee wished you well in your research.

Yours sincerely

Professor Gideon de Wet
Dean of Research

20 July 2016