Spatial and temporal variations of inundation and their influence on ecosystem services from a shallow coastal lake. A case study of Soetendalsvlei in the Nuwejaars catchment, South Africa

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DECLARATION

I declare that the thesis entitled: "*Spatial and temporal variations of inundation and their influence on ecosystem services from a shallow coastal lake. A case study of Soetendalsvlei in the Nuwejaars catchment, South Africa*" is my own work, that it has not been submitted for any degree of examination in any other university, and that all sources I have used or quoted have been indicated and acknowledged by complete references.

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ABSTRACT

Enhancing our understanding of wetland properties and the ecosystem services provided by wetlands within a dynamic landscape, is fundamental to ensuring appropriate management strategies for enhanced biodiversity and ecosystem benefits. With increased anthropogenic activities and the impacts of climatic variability, a better understanding of the factors influencing the water balance dynamics of wetlands can provide insight into how wetlands respond to change. The main aim of the research was to improve the understanding of the spatial and temporal availability of water and storage of a depression wetland in a semi-arid climate, and to relate these to ecosystem functions. As ecosystems are intricately connected to society, a secondary aim of the research was to gain insight to how wetland ecosystems, within a changing climate and landscape, provide benefits to society, and add value to human-wellbeing. Soetendalsvlei, a shallow freshwater depression, and one of the few coastal freshwater lakes of South Africa, was the focus of the research.

The availability and storage of water was explored over different temporal scales using aerial photographs (1938 – 2014), satellite-derived images (1989 – 2019) and *in situ* data (2015 – 2017). Within-wetland change of Soetendalsvlei and the land use and land cover surrounding Soetendalsvlei was assessed for 1938, 1961, 1973, 1989 and 2014. It is evident that the natural land cover of vegetation and wetlands have been transformed for agricultural land use from 1938 to 1989. The consequent impacts on Soetendalsvlei is evident with the decrease in open water and increased growth of macrophytes along the shoreline. Between 1989 and 2014, with the proclamation of the Agulhas National Park and the establishment of the Nuwejaars Wetlands Special Management Area (NWSMA), conservation planning and initiatives had direct impacts on the natural land cover and the use and management of water resources.

To evaluate the influence of rainfall variation within the Nuwejaars catchment on wetland cover/dynamics, the monthly rainfall data from 1930 to 2018 for three stations in the catchment were assessed. The analysis of long-term rainfall data using the Mann-Kendall test shows no evidence of trends in the lower Nuwejaars catchment, although increasing rainfall in the upper catchment was detected. The Standard Precipitation Index (SPI) was useful in identifying the variable seasonal and inter-annual rainfall in the Nuwejaars catchment, and the occurrence of *very wet* and *very dry* periods. Extreme meteorological and agricultural drought has occurred three times within the last 93 years (i.e. 1925 to 2018), with a significant impact on water resources. The intensity and duration of the 24-month SPI is a good indicator of the impacts of

hydrological drought on Soetendalsvlei. Hydrological droughts have historically caused desiccation of Soetendalsvlei.

With no access to *in situ* hydrological data prior to 2015, high resolution aerial photographs and an *in situ* survey were used in identifying the optimal threshold for extracting surface water, using the Landsat satellite archive. A 30-year time series of the extent of surface water inundation derived from Landsat imagery shows no significant trend of flooding, but displays significant monthly, seasonal and annual variation that is influenced by rainfall variability. The time series of surface water inundation allowed the characterization of the hydroperiod into permanent, seasonal and intermittently flooded areas within the depression wetland. To assess the water dynamics of the depression, a bathymetric survey of the depression was conducted, and weather stations, rainfall gauges and water levels for the lake and river were installed in the catchment. As groundwater level data was not available, net groundwater flow was assumed as zero when investigating the water balance of the lake. The available data was used to develop a daily conceptual model to estimate the daily variation of water storage for Soetendalsvlei at the outlet of the Nuwejaars catchment from 2015 to 2017. Soetendalsvlei has a storage capacity of approximately 20 Mm^3. Results show that surface runoff from the Nuwejaars catchment is the dominant inflow of water storage in Soetendalsvlei. Surface outflow will only occur when the threshold water storage of 9.5 Mm^3 is exceeded, after which the pattern of surface outflow closely simulates the inflows. Evaporation is the dominant outflow during summer and when lake storage is below the threshold for surface outflow. The results of this study demonstrates the importance of shallow depression wetlands, such as coastal lakes, in water storage and in regulating flow to the downstream catchment.

To assess wetland benefits, and the value of wetlands to society, habitat provision, scientific value and the social value of wetlands were assessed for the Nuwejaars catchment. Results show that multiple complex social-ecological factors enable dynamic conditions that affect wetland properties and functions, and the capacity to provide benefits. Habitat provision provides insight to the environmental conditions of the Nuwejaars catchment, and was assessed using available avifauna data. On a landscape scale the lower Nuwejaars catchment, which consists of a mosaic of wetlands, agricultural fields and protected landscapes, supports a higher number of bird species than the upper catchment. The integration of bird counts with wetland inundation for Voëlvlei and Soetendalsvlei demonstrated the importance of the hydroperiod in influencing bird richness and diversity. The scientific value of the Nuwejaars catchment was assessed for the period 2014 to 2019, to coincide with the establishment of the "Living Laboratory". The scientific value of wetlands was assessed by reviewing the number of publications related to functions, processes, benefits and values of wetlands, and the spatial distribution of study sites within the Nuwejaars catchment. Enabling conditions, such as financial support, stakeholder engagement and collaboration, clear protocols and accessibility, are important consideration in realizing opportunities for scientific value of ecosystems. Given that most wetlands are located on private property, the scientific value varies spatially, with the Nuwejaars Wetlands Special Management Area (NWSMA) contributing significantly to scientific knowledge. Participatory mapping and interviews were conducted to assess the cultural value of wetlands. Floodplain, valley-bottom and depression wetlands provide multiple benefits related to regulating and cultural ecosystem services. The regulating benefits identified by stakeholders were related to water storage, flow regulation and water quality amelioration. The cultural benefits most commonly mapped in this research were related to wildlife, recreation and aesthetic beauty.

The diverse wetlands in the Nuwejaars catchment provide bundles of ecosystem services. Ecosystem services are enhanced through adaptive management strategies. Protecting the natural environment within an agricultural landscape, is important for biodiversity conservation and increased farming productivity. In a landscape where wetlands are protected by various management authorities, the collaboration and interaction of stakeholders to promote monitoring, co-create knowledge and collectively identify and enforce appropriate management strategies, is essential for wetland conservation.

KEY WORDS

Bathymetry

Morphometric properties

Water balance model

Modified Normalized Difference Water Index

Hydroperiod

Land use and land cover change

Ecosystem services

Living Laboratory

Spatiotemporal

Wetland Value

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With God all things are possible.

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ABI	Agulhas Biodiversity Initiative
ANP	Agulhas National Park
AOI	Area Of Interest
API	Antecedent Precipitation Index
ARC	Agricultural Research Council
BGCMA	Breede Gouritz Catchment Management Agency
BOCMA	Breede Overberg Catchment Management Agency
CAPE	Cape Action for People and the Environment
CD:NGI	Chief Directorate: National Geo-Spatial Information
CPUT	Cape Peninsula University of Technology
CV	Coefficient of Variation
CWAC	Coordinated Waterbird Counts
DEM	Digital Elevation Model
DN	Digital Numbers
DWS	Department of Water and Sanitation
ES	Ecosystem Services
ET	Evapotranspiration
ETM+	Enhanced Thematic Mapper Plus
FEPA	Freshwater Ecosystems Priority Areas
GIS	Geographic Information Systems
GPS	Global Positioning Systems
HGM	Hydrogeomorphic
IDW	Inverse Distance Weighting
IWRM	Integrated Water Resources Management
IWS-UWC	Institute for Water Studies at the University of the Western Cape
LGI	Lake Geometry Index

MEA	Millennium Ecosystem Assessment
MK	Mann-Kendall
MNDWI	Modified Normalized Difference Water Index
MOU	Memorandum Of Understanding
NDWI	Normalized Difference Water Index
NFEPA	National Freshwater Ecosystems Priority Areas
NRF	National Research Foundation
NUFFIC	Netherlands Organisation for International Cooperation in Higher Education
NWSMA	Nuwejaars Wetland Special Management Area
OLI	Operational Land Imager
RMSE	Root Mean Square Error
SABAP	Southern African Bird Atlas Project
SAEON	South African Environmental Observation Network
SANBI	South African National Biodiversity Institute
SANParks	South African National Parks
SHNT	Standard Normal Homogeneity Test
SPI	Standardized Precipitation Index
SRTM	Shuttle Radar Topography Mission
SWIR	Shortwave Infrared
TIRS	Thermal Infrared Sensor
TM	Thematic Mapper
TMG	Table Mountain Group
TOA	Top Of Atmosphere
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WMO	World Meteorological Organization

WRC	Water Research Commission
WWF	World Wildlife Fund

CHAPTER 1

INTRODUCTION AND CONTEXT

1.1 General background of the study

Wetlands cover approximately 8% of the Earth's land surface (Davidson *et al*., 2018) and provide a wide range of benefits for humans (MEA, 2005; Zedler & Kercher, 2005; Ramsar Convention Secretariat, 2018). Wetland ecosystem services include a wide range of goods such as water, fish and plants (Mitsch & Gosselink, 2007; Kotze *et al.,* 2009). In many communities, the provisioning services of wetlands contribute to household income, and are vital in contributing to poverty alleviation (Shackleton *et al*., 2000; Sharma *et al*., 2015). Wetlands may, depending on the wetland type, ecological properties, size and location within the catchment, provide regulating ecosystem services such as flood mitigation, streamflow regulation, sediment control and the removal of pollutants (Schallenberg *et al*., 2013), and are commonly referred to as valued ecological infrastructure. Wetlands are also places of cultural heritage, sites for tourism, education and research. Many of these cultural ecosystem services are intangible by nature and provide benefits such as aesthetic value, sense of place and inspiration. The significance and dependence on wetlands for livelihoods and well-being highlights just how important it is to maintain healthy and functioning wetlands (Ramsar Convention Secretariat, 2018).

Despite the global recognition of the importance of wetlands, the nature, extent and healthy functioning of many wetlands are threatened by anthropogenic activities and climate change (Erwin, 2009; Davidson, 2014; Gardner *et al*., 2015). Wetlands that are hydrologically connected to rivers are vulnerable to modification of river flows due to human activities as well as invasive vegetation (Vale & Holman, 2009; Schallenberg *et al*., 2013). In a global assessment of natural wetland loss during the 20th century, Davidson (2014) estimated that the area covered by inland wetlands has declined by 69 to 75%, while the area of coastal wetlands has declined by between 62 to 63%. The loss of wetland area was more significant from 1970 to 2015, with the global extent of wetlands decreasing by almost 35% (Ramsar Convention Secretariat, 2018). According to the National Biodiversity Assessment of South Africa in 2018, wetlands are the most threatened and least protected ecosystems in South Africa (Skowno *et al*., 2019). Without a national assessment of wetland loss, assumed wetland loss in South Africa varies geographically from less than 20% to 50% within the interior plateau zone to greater than 50% of wetland loss along the inland margin and coastal belt (Kotze *et al*., 1995).

The successful conservation of wetlands requires a comprehensive understanding of the complex factors and processes affecting wetland functions. How the wetland functions, and its ability to provide particular ecosystem services, is primarily determined by the geomorphology and hydrology of the wetland (Mitsch & Gosselink, 2007; Ollis *et al*., 2013). The geomorphology describes the landscape setting and overall physical structure of the wetland, which affects the hydrology of the wetland. The hydrology of the wetland describes the movement of water into and from the wetland, and can be characterized by the spatial coverage, frequency and the duration the wetland is flooded. The water level of wetlands is an important control on the physical and chemical characteristics of water and sediment within a wetland, which in turn determine the development of biota (Mitsch & Gosselink, 2007). The water level regime and spatial variation of inundation is a critical determinant of vegetation patterns (Casanova & Brock 2000; Kolada, 2014); habitats of migratory birds (Pickens & King, 2014) as well as the structure and functioning of littoral zones (Evtimova & Donohue, 2016).

With hydrology identified as one of the main drivers in the functioning of wetlands (Mitsch & Gosselink, 2007), an estimation of the water balance is critical, not only in contributing to the scientific literature, but also in improving the management of water resources (Dessie *et al*., 2015; Politi *et al*., 2016) and the conservation of water-dependent ecosystems. The balance between inflows and outflows, geometry of the wetland and characteristics of the catchment, influence water level fluctuations (Kebede *et al*., 2006). Water level fluctuations in wetlands are seasonal or longer-term (Sacks *et al*., 1998; Schwerdtfeger *et al*., 2014). The seasonal pattern of water levels, also known as the hydroperiod, depends on climatic variations, and is especially prominent in Mediterranean, arid and semi-arid regions. The knowledge of the hydroperiod provides information relevant for the improved understanding of ecosystems (Mitsch & Gosselink, 2007) as the frequency with which emergent vegetation is submersed and exposed by water provides for varying habitats in wetlands (Coops *et al*., 2003). Longer-term fluctuations of water levels are linked to climatic variability and change (Mercier *et al*., 2002), although human interventions have significantly altered the hydrological response of wetland systems (Niedda *et al*., 2014). The progressive and long-term change in wetland water levels and patterns of inundation due to climate change and/or anthropogenic influences have a significant influence on wetland productivity and resilience (Kolding & van Zwieten, 2012). The complex and dynamic role of human influences on different components of the water budget of wetlands should thus be incorporated when assessing the drivers of wetland function (Sivapalan *et al*., 2012; Di Baldassarre *et al*., 2013; Evers *et al*., 2017).

1.2 Wetlands and other aquatic ecosystems

The diversity of wetland types is very broadly reflected by the Ramsar Convention (Ramsar Convention Secretariat, 2016, p9) as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres", and as such, shallow lakes and the littoral zones of deep lakes are classified as wetlands. The legal definition of a wetland in South Africa is "land which is in transition between terrestrial and aquatic systems, where the water table is usually at or near the surface, or land that is periodically covered with shallow water, where the land in normal circumstances would support vegetation typically adapted to life in saturated soil" (National Water Act No 36 of 1998). The definition of the National Water Act clearly excludes rivers, lakes and artificial wetlands, except for the transition zone from the river/lake and the terrestrial ecosystem (Ollis *et al*., 2013).

Worldwide, various classification methods have been developed to describe and categorize wetlands based on characteristics related to the hydrology, geomorphology and/or ecology, with each classification influenced by different disciplines. In an overview of classification methods, Mitsch & Gosselink (2007) describe, amongst others, the well-known Cowardin Classification, and the hydro-geomorphic approach developed by Brinson (1993), each of which have been adapted to reflect the properties of wetlands in South Africa. Ollis *et al*., (2015, p732) provide a review of these and other classification systems that have been applied to the South African context, and highlights the need for a wetland classification system to "provide a common language and consistent terminology", and that incorporates the diverse wetlands in South Africa. The theoretical considerations for the development and the implementation of "The Classification System for inland Wetlands and other Aquatic Ecosystems in South Africa" is summarized in Ollis *et al*., (2015). The classification system considers inland wetlands as having no direct connectivity to the ocean. Fundamental to the classification system by Ollis *et al*., (2015) is the recognition that the hydrology and geomorphology are key variables in determining wetland occurrence, type and function (Brinson, 1993; Ewart-Smith *et al*., 2006; Ellery *et al*., 2009; Zaharescu *et al*., 2016). "The Classification System for Wetlands and other Aquatic Ecosystems in South Africa" identifies seven major hydrogeomorphic (HGM) units or wetland types, namely river, floodplain wetland, channelled valley-bottom wetland, unchannelled valley-bottom wetland, seep, wetland flat and depression (Figure 1.1). Each HGM unit influences the storage and movement of water through the wetland, with a conceptual hydrological model depicting water inflows, storage, and outflows for each wetland type (Ollis *et al*., 2013).

According to “The Classification System for Wetlands and other Aquatic Ecosystems in South Africa”, a depression is a “wetland or aquatic ecosystem with closed or near-closed elevation contours, which increases in depth from the perimeter to a central area of greatest depth and within which water typically accumulates” (Ollis *et al*., 2013, p29). The varied shape, size, substrate, vegetation type, water quality, location of the depression within a wider regional/catchment landscape and the nature of water flow and storage in and from the depression, creates a diversity of depressions, vernacularly known in South Africa as pans, vleis and/or lakes (lacustrine wetland). Grenfell *et al*., (2019) proposes a complementary genetic approach to “The Classification System for Wetlands and other Aquatic Ecosystems in South Africa” and futher classifies depressions based on geomorphic processes which shape(d) the wetland. Depressions are considered as aeolian (shaped by wind action) and geochemical (shaped by *in situ* weathering), and considers the influence of both water and sediment fluxes over different spatial and temporal scales.

The origin and development of coastal depressions have been shaped by geomorphic and climatic processes since the Late Pleistocene (Hart, 1995; Smith & Compton, 2004; Carr *et al*., 2006). Palaeoenvironmental research along the South African coastline provide descriptions of the complex geomorphic, climatic and fluvial influences of the relative sea level change through marine regression and transgression (Hattingh, 1996; Gordon *et al*., 2012); and alternating periods of aridity and high humidity over the past 70 million years in shaping the contemporary landscapes (Carr *at al*., 2006). The extent of these influences were determined from sediment cores from within the basins of depressions such as coastal lakes and pans; and from the lunette dunes found along the shore of these depressions. The underlying geology, characteristics of the landscape, climate, connectivity of the depression to the fluvial network and ocean, surface and groundwater flow, as well as anthropogenic influences are important properties and characteristics which influence the hydrology, soils, water quality and vegetation characteristics of depressions (Silberbauer & King, 1991; Hart, 1995; Semeniuk & Semeniuk, 1995; Smith & Compton, 2004; Carr *et al*., 2006). Given the diverse geomorphic processes and variable climate along the coastline of southern Africa, the coastal depressions display varied morphology and hydrologic attributes (Hart, 1995). Noble & Hemens (1978, p39) classified coastal lakes into three types based on the degree of marine influence, “brackish with seepage outflow only; freshwater or brackish with outflow to sea but no tidal exchange and freshwater or brackish with outflow to sea, and occasional seawater input”. Soetendalsvlei and Zeekoevlei are two coastal lakes in the Western Cape, South Africa that are classified as “freshwater or brackish with outflow to sea but no tidal exchange" (Noble & Hemens, 1978, p39). The freshwater outflow from these depressions that are hydrologically connected to the sea, but without tidal influence, are vital to the ecological flow requirements of estuarine environments (Adams, 2014; Whitfield *et al*., 2017). Coastal lakes/depressions and rivers, that contribute to the ecosystem functioning of estuaries, are delineated as part of the estuarine functional zone and are mapped within the 5 m topographic contour of the estuary (Cilliers & Adams, 2016). Coastal depressions where freshwater overflow to the downstream estuary is naturally regulated due to a change in storage, are known as barrier lakes (Allanson, 2001). Examples of barrier lakes in South Africa include Soetendalsvlei (Gordon, 2012), Swartvlei (south Western Cape) and Kosi lake systems (KwaZulu-Natal) (Allanson, 2001). Noble & Hemens (1978) reported on available scientific knowledge of coastal lakes in South Africa, and at that time recommended monitoring to better understand, conserve and manage the aquatic ecosystems. The need for monitoring is presently still recommended particularly due to the impact of freshwater flow reduction due to increasing effects of anthropogenic influences and climatic variability, and the consequent impacts on the functioning and ecosystem health of coastal lakes and estuaries (Nel *et al*., 2009; Dallas *et al*., 2014; Whitfield *et al*., 2017; Skowno *et al*., 2019).

1.3 Wetlands as complex social-ecological systems

Given the diverse structure and function of wetlands, and the influence over time of dynamic complex interactions of biotic and abiotic components at various spatial scales, wetlands are regarded as complex systems (Liu *et al*., 2007; Kotze *et al*., 2009; Parrott & Quinn, 2016). Integral to the conservation of coastal lakes is an understanding of this complexity, and the capacity to predict how these systems will respond to change. The observation of gradual change and "catastrophic shifts in ecosystems" have highlighted that ecosystem response may be complex and nonlinear (Sheffer *et al*., 2001, p592; Liu *et al*., 2007). The response of the ecosystem depends on the "state of the ecosystems" which Larsen & Alp (2015, p1) defines as "structure and function, including its populations and communities and their relationship with each other and the environment". Depending on the state of the ecosystem, the lake ecosystem may exhibit "resilience" to change, defined as "the ability of a system to maintain its state by absorbing both internal and external change and disturbances" (Özkundakci & Lehman, 2019, p481).

Özkundakci & Lehman (2019, p482) illustrates this lake resilience using a 'marble in a cup diagram' where the marble represents the lake's current ecosystem state (Figure 1.1). Thus any change (depicted as black arrow) may cause a shift in the lake ecosystem (i.e. marble will move within the cup/depression), but the change is reversible, and the ecosystem will, once the disturbance is removed, maintain a state at equilibrium. A lake may exist at multiple ecosystem states (shaded marbles), which influences the resilience (depth of the depression to the ecosystem state). A degraded lake will have a lower resistance (depth of resilience at 3), and is thus more "susceptible" to exceeding the threshold, i.e. the transition from one state to another (white marble in the ecosystem state at new equilibrium) due to change (Özkundakci & Lehman, 2019).

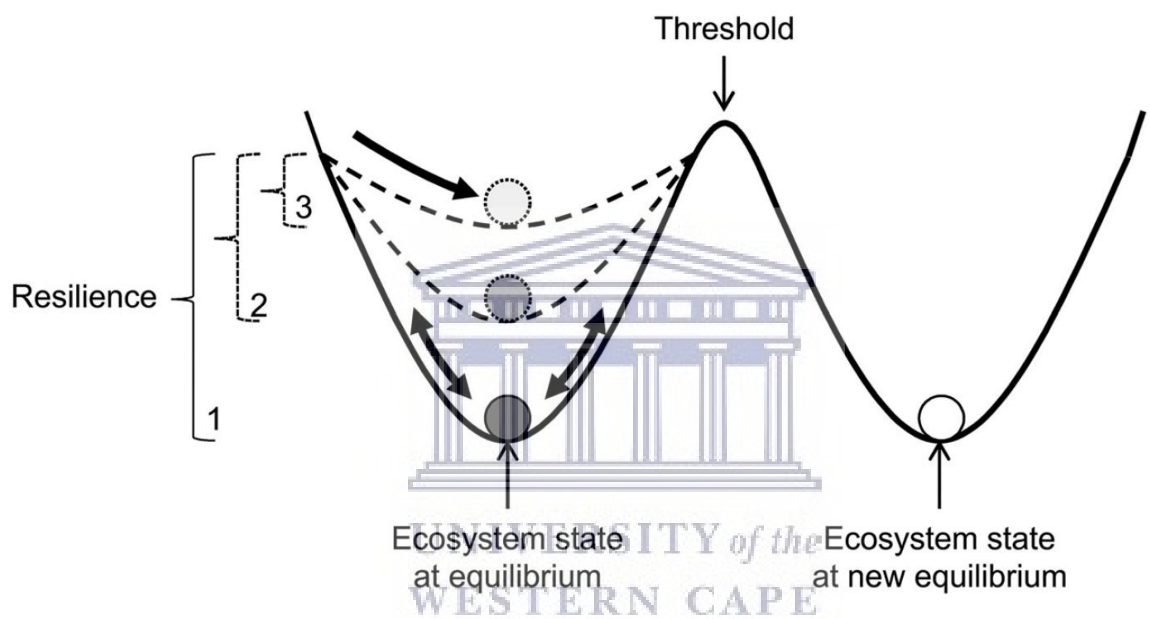


Figure 1.1 Lake resilience ('marble in a cup diagram') (source Özkundakci & Lehman, 2019)

The variable and natural fluctuation, over time, of water levels in wetlands and lakes create conditions that support species adapted to these variable states (Coops & Hosper, 2002). However, due to extreme climatic events and/or anthropogenic influences, "changes in the hydrological regime often represent the trigger that cause abrupt shifts" (Larsen & Alp, 2015, p1). Zohary & Ostrovsky (2011, p47) provide insight on how altered fluctuations in lake levels influences the ecology of the littoral zone, where excessive changes may "impair ecosystem functioning". To ensure adequate management strategies to maintain or enhance ecosystem functioning and resilience, requires data of the variable water level and ecological properties of the ecosystem, and knowledge of how these changes influence the littoral habitat (Crisman *et al*., 2005; Zohary & Ostrovsky, 2011; Wu & Liu, 2015a; Evtimova & Donohue, 2016; Özkundakci & Lehman, 2019). For many lakes and wetlands, the lack of data and information on lakes, particularly data which provides information on ecosystem services is lacking (Xu *et al*., 2018).

Wetland ecosystems are also intricately linked to human livelihoods and well-being. With connections and interactions between the ecological and human components, wetlands have been described as social-ecological systems (Parrott & Quinn, 2016; Cumming *et al*., 2017) and coupled human and natural systems (Liu *et al*., 2007). To capture the complexity of social-ecological systems, and strengthen the sustainable development, management, conservation and rehabilitation of wetlands, resource-based frameworks such as integrated water resources management (IWRM) (Global Water Partnership, 2000, Dickens *et al*., 2003; Leendertse *et al*., 2008; Biggs *et al*., 2017), social-hydrologic frameworks (Elshafei *et al*., 2014), community based natural resource management and ecosystem-based frameworks such as the ecosystem services (ES) and ES cascade (MEA, 2005; Potschin & Haines-Young, 2011; Boerema *et al*., 2017) have been developed. The adoption of any one, or a combination of frameworks are dependent on the aim, nature and scale of the study and the complexity of the social-ecological system.

As wetlands are integrally connected to water resources within a basin, the conservation of wetlands have commonly been integrated into a catchment or basin framework such as IWRM, through water allocation and resource directed measures (Leendertse *et al*., 2008). IWRM is "a process which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Global Water Partnership, 2000, p2). While the utility of the IWRM framework offers an approach for resource protection, efficient water use and good governance, the approach has not been widely adopted (Jonker, 2007). Critique of IWRM include the lack of clear definitions, the failure to connect environmental and human wellbeing and the challenge of "integrating social and ethical factors alongside the environmental sciences into environmental management" (Cook & Spray, 2012, p98). One of the obstacles of implementing IWRM for wetland conservation is not recognizing the various ecosystem services provided by wetlands (Rebelo *et al*., 2013).

The ecosystem services (ES) cascade (Figure 1.2) which has been adapted over time provides a broad, but useful framework to understand the intricate and dynamic link between the biophysical properties, processes and functions of ecosystems and the benefits and value to humans (MEA, 2005; Le Maitre *et al*., 2007; Kotze *et al*., 2009; Potschin & Haines-Young, 2011; Boerema *et al*., 2017). With regards to wetlands, the framework considers the structure and properties of wetlands (i.e. biotic and abiotic components) and how these properties interact over time and space to provide wetland functions and processes (i.e. ES supply) which in turn, provides goods and benefits that may be of value to society (i.e. ES demand) (Haines-Young & Potschin, 2018). Wetland ecosystem services which are defined as the "benefits derived from wetland functions/processes" bridges the knowledge/understanding between the ecological and socio-economic systems related to wetlands (Boerema *et al*., 2017).

In assessing water-related ecosystem services Brauman *et al*., (2007, p88) states that the ES framework makes "explicit the complex feedbacks and tradeoffs among services and human beneficiaries". The varied "reconstructions" of the ecosystem services framework has thus added various human feedback loops to reflect this complex linkages between society and the human environment (Fish *et al*., 2016). The challenge for the conservation of lake and wetland ecosystems, is not only the lack of data and information on these aquatic ecosystems, but also incorporating the knowledge of ecosystem services in evaluating the complex feedbacks and tradeoffs (Xu *et al*., 2018).

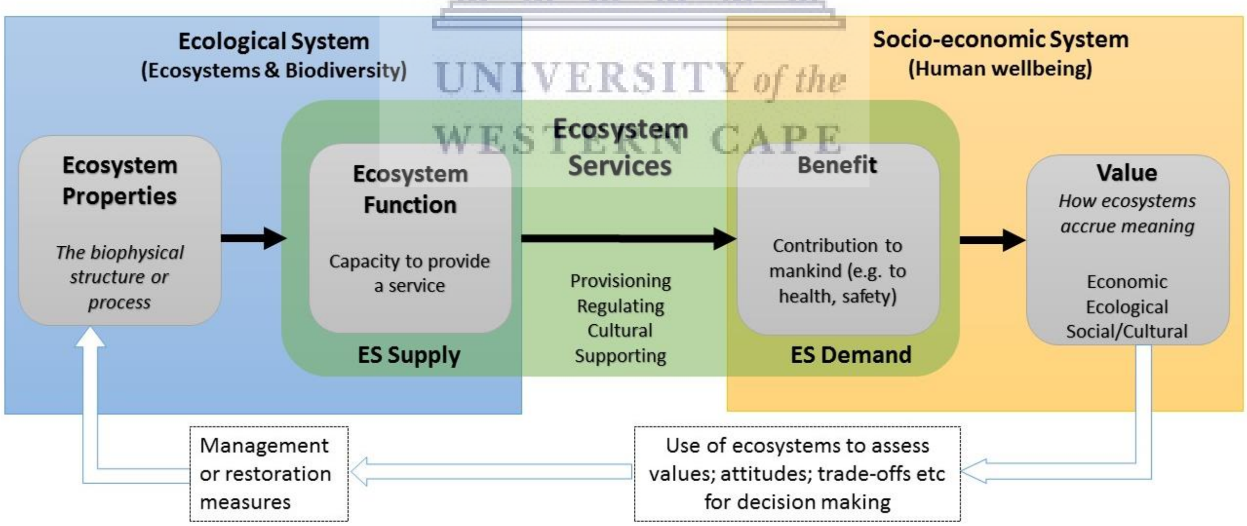


Figure 1.2 Conceptual framework for ecosystem services, adapted from de Groot *et al*., (2010); Boerema *et al*., (2017) and Scholte *et al*., (2016)

The ES framework, and adaptations of this framework, has been widely adopted in wetland management as it provides a platform which brings together knowledge and methodological approaches from various disciplines, where the ultimate aim is to integrate ES with 'landscape planning, management and decision making' (de Groot *et al*., 2010, p260). Each discipline brings a wealth of knowledge relevant to the different components of the ES cascade, with scientific ES measures and indicators developed (Kandziora *et al*., 2013) to ensure that research findings are comparable and transferable (de Groot *et al*., 2010; Boerema *et al*., 2017). While much research has focussed on measures and indicators for provisioning and regulating ecosystem services, the 'intangible benefits' of cultural ecosystem services (with the exception of recreation and tourism) has not been easy to measure or quantify. How does one accurately reflect the "contributions ecosystems makes to human well-being in terms of the identities they help frame, the experiences they help enable and the capabilities they help equip"? (Fish *et al*., 2016, p212). According to Chan *et al*., (2012) and Fish *et al*., (2016, p214) a combination of methodologies that clearly defines concepts and "provides a varied but consistent and robust evidence base" is needed to understand and quantify cultural ecosystem services.

Critique of the ES approach includes the lack of clear definitions, measures and indicators for various components of the cascade (Boerema *et al*., 2017) and the implementation of the ES concept in the sustainable management of ecosystems (de Groot *et al*., 2010). Research has mainly focused on the ecological component of the ES framework, while the socio-economic component has been dominated by research emphasising the economic value of ecosystems (Conradie & Garcia, 2013; Plieninger *et al*., 2013; Fish *et al*., 2016). Chan *et al*., (2012) strongly argues for an explicit characterization of cultural values within the ES framework. Cultural values include underlying ideals and the relative importance of "what matters to people". "Values", as defined by Chan *et al*., (2012), are important to consider as they influence beliefs, norms and behavior and provide insight into the "contribution of ecosystem services to human well-being" (Plieninger *et al*., 2013, p119). Only in developing and integrating the linkages between the ecological, socio-economic and cultural components of the ES cascade can the sustainable development of wetlands resources, well-being of society and maintenance of biodiversity be effectively established (Le Maitre *et al*., 2007; Evers *et al*., 2017).

1.4 Rationale for the study

The unique morphometry and nature of wetlands, together with the variations in climatic conditions, is a challenge when generalizing and modelling wetland hydrology (Ellery *et al*., 2009). The different geomorphological and climatic settings within southern Africa has meant that explanations of wetland processes based on northern temperate wetland systems, for which detailed hydrological studies exists, cannot always be applied in understanding wetland hydrology in arid landscapes, neither can wetland processes be generalized within southern Africa (Tooth & McCarthy, 2007; Ellery *et al*., 2009). With the development of the classification system for inland aquatic ecosystems in South Africa, Ollis *et al*., (2015, p742), highlighted the need for further biophysical and hydrological monitoring at national level to test whether the wetland types "adequately reflect ecosystem functioning". Given the diversity of wetland types, the geomorphology of a wetland is one of the key features that determine how the wetland functions (Tooth & McCarthy, 2007; Ollis *et al*., 2013; Grenfell *et al*., 2019). The geometry, size and shape (i.e. morphometric properties) of the wetland have an influence on water level fluctuations (Mitsch & Gosselink, 2007), water storage capacity (Haghighi *et al*., 2016; Yao *et al*., 2018), macrophyte distribution (Janssen *et al*., 2014), sediment accretion, and wetland productivity (Håkanson, 2005). Despite the significance of wetland morphometry in understanding ecosystem functioning (Håkanson, 2005), there is a global dearth of morphometric studies due to time and budgetary constraints (Politi *et al*., 2016; Cael *et al*., 2017).

In refining conceptual hydrological models of the different wetland types in South Africa developed by Ollis *et al*., (2013), Maherry *et al*., (2016) recommends further monitoring (specifically on a daily basis) to improve our understanding of the hydrological processes of the different wetland types. Wetlands have the potential to influence streamflow regulation; however, the effect of different wetland types and wetland morphometry on regulating ecosystem services in not clear (Kadykalo & Findlay, 2016). In arid environments, the influence of hydrological connectivity, or lack thereof, between non-perennial rivers, lakes and wetlands will affect the functioning of aquatic ecosystems (Garbin *et al*., 2019). An improved understanding of wetland processes within arid environments, will provide greater insight to the impact of wetlands on flow regimes and catchment hydrology, and so improve the representation of wetlands in hydrological models used in South Africa (Maherry *et al*., 2016). The need for site-specific and detailed data of wetland characteristics and hydrological processes are also required to assess the ecosystem services provided by wetlands (Kadykalo & Findlay, 2016). Long-term *in situ* data and hydrological studies are available for select catchments with large coastal lakes in South Africa, particularly where lakes provide ecosystem services such as water provision. Bathymetric data and lake water levels are documented for various coastal lakes along the KwaZulu-Natal coastal plain, from Lake Sibayi (Weitz & Demlie, 2014; Smithers *et al*., 2017) to the lakes in the Richards Bay area in the Mhlathuze catchment (Kelbe, 2010) and the Wilderness Lakes along the southern coast of South Africa (Parsons & Vermeulen, 2017; Petersen *et al*., 2017). Limited bathymetric and hydrological studies on the urban lakes on the Cape Flats coastal plain along the south-western coast of South

Africa provide insight to the current ecological conditions of the water resources (Harding, 1992; Harding & Quick, 1992; Kirsten & Meadows, 2016). Where bathymetric data is available, the data needs to be updated to reflect the dynamic processes which shape the coastal lakes.

With many catchments ungauged, specifically in developing countries such as South Africa, the lack of hydrological data is an impediment to understanding wetland and catchment hydrology (Pan *et al*., 2013; Gal *et al*., 2016; Maherry *et al*., 2016). The availability, analysis and interpretation of remotely sensed data can enhance our knowledge of the spatial and temporal availability of water and wetland inundation (van Deventer *et al*., 2018; Bredin *et al*., 2019) and the potential of these wetlands to provide ecosystem services (Brauman *et al*., 2007). A time-series of historical remotely sensed data provides a description of how ecosystems have changed over time, and allows greater insight into how systems will change in the future (Ellery *et al*., 2009; Hoffman, 2014; Guo *et al*., 2017), particularly where climatic factors and anthropogenic activities may influence wetland processes. Although there is general consensus that climate change will influence wetland processes, uncertainty exists on the magnitude and frequency of change (Dallas and Rivers-Moore, 2014) and the potential effects of climate change on wetland ecosystem services (Chang & Bonnette, 2016).

With many wetlands located on private property, understanding the dynamic relationship between the human and natural environment is an important consideration if we are to ensure the continued and healthy functioning of wetlands (Myers *et al*., 2013). Furthering our understanding of wetlands as complex social-ecological systems thus requires an integrated approach. With an increased demand by society for water and wetland-related ecosystem services, and the potential impacts of multiple environmental stressors on ecosystem services, the ES framework provides measures and indicators useful in assessing the supply of ecosystem services provided by wetlands and the value to society of the wetland ecosystem services (MEA, 2005; Potschin & Haines-Young, 2011; Grizzetti *et al*., 2016; Jackson *et al*., 2016). According to Comberti *et al*., (2015, p249), cultural ecosystem services are of “foundational importance to ecosystem conservation”, and understanding the public awareness and the value assigned to wetland ecosystems provides an understanding of their willingness to support wetlands protection and restoration (Scholte *et al*., 2016).

1.5 Research problem

Enhancing our hydrological understanding of wetlands, and appreciating the ecosystem services provided by wetlands within a landscape, is fundamental in ensuring appropriate conservation strategies (Reis *et al*., 2017), particularly where anthropogenic activities and climatic factors may influence wetland processes. Given the lack of site-specific biophysical data, limited hydrological and meteorological data; and a poor understanding of wetland processes, the overall aim of the thesis is to answer the following question:

How does the availability of water and storage in a depression wetland vary over time, and how does this variability influence ecosystem services?

1.6 Aim and research objectives

The main aim of the research is to improve the understanding of the spatial and temporal availability of water and storage of a depression wetland in a semi-arid climate, and to relate these to ecosystem functions. A secondary aim is to understand how wetland ecosystem functions, within a changing climate/landscape, provide benefits to society, and add value to human wellbeing.

Research objectives:

1. To assess the influence of rainfall variability and anthropogenic activities on wetland dynamics/properties.
2. To characterize the spatial and temporal variation of flooding of a depression wetland.
3. To determine how wetland morphology influences wetland functions and processes.
4. To establish the seasonal variation of storage and influences on wetland functions and processes.
5. To understand how wetlands, within a variable landscape and climate, provide ecosystem services and benefits to society.

1.7 Rationale for the selection of the study area

The Heuningnes catchment is located in the southern most region of the Western Cape, South Africa and covers an area of 1401 km^2 (Figure 1.3). The rationale for the selection of the Heuningnes catchment in the Western Cape, South Africa, was primarily driven by a lack of understanding of factors influencing the protection and sustainable use of aquatic ecosystems (including lakes, rivers, groundwater and wetlands). Based on the Classification System for Wetlands and other Aquatic Ecosystems in South Africa (Ollis *et al*., 2013), aquatic ecosystems in the lower Heuningnes consists of rivers and diverse wetlands (such as pans, lakes, floodplain wetlands, flats and seeps) (Figure 1.4) which support a great diversity of fauna and flora (Jones *et al.,* 2000). As a signatory to the Convention on Wetlands of International Importance especially as Waterfowl Habitat 1971 (RAMSAR convention) in 1975, and the Convention on Biological Diversity in 1995, South Africa is obligated to ensure the conservation of wetlands and biological diversity. With the Heuningnes Estuary declared a RAMSAR site on 2 October 1986 (RAMSAR site no 342), there was increasing concern on the loss and fragmentation of ecosystems in the lower Nuwejaars catchment (Barham, 1968; Cole *et al*., 2000). The Heuningnes estuarine functional zone is within the 5 m topographical contour level, and includes freshwater flow from the Kars and the Nuwejaars River (Figure 1.4). The Nuwejaars River drains an area of 760 km^2, and flows into Soetendalsvlei, the largest southernmost lake in Africa (Cleaver and Brown, 2005). Surface outflow from Soetendalsvlei is via the Heuningnes River. The Kars River drains an area of 885 km^2, with the confluence of the Kars and Heuningnes Rivers approximately 15 km upstream of the estuary.

At the interface where freshwater from the Nuwejaars catchment flows into the Heuningnes River, is Soetendalsvlei, a depression wetland (Figure 1.3), known as the second largest freshwater lake (also referred to as *lacustrine wetland*) in South Africa (River Health Programme, 2011). Soetendalsvlei and Voëlvlei are considered as "rare wetland types since so few coastal lakes exist" and "represent five percent of the significant South African standing water" (Jones *et al*., 2000, p18). Although Soetendalsvlei shows historic evidence of marine influence, at present the coastal lake is a fresh-water lake, with surface outflow to the sea, but with no marine influence (Hart, 1995; Gordon *et al*., 2012). Midgley *et al*., (2005) classified Soetendalsvlei as a blind estuary, created by a barrier system of sand dunes. Using sediment cores from the basin of the Soetendalsvlei for radiocarbon dating and diatom distribution, Gordon *et al*., (2012) concluded that this coastal lake was influenced by marine intrusion, which influenced the trophic status and organic matter content of the lake. Although outflow from Soetendalsvlei contributes significantly to freshwater flow to the estuary, there is uncertainty on the timing and volume of surface outflow from the lake. The Nuwejaars catchment which drains into the Soetendalsvlei is ungauged. There is no information on surface flows from the Nuwejaars catchment, and the extent to which the wetlands and lake regulates flows to the downstream catchment.

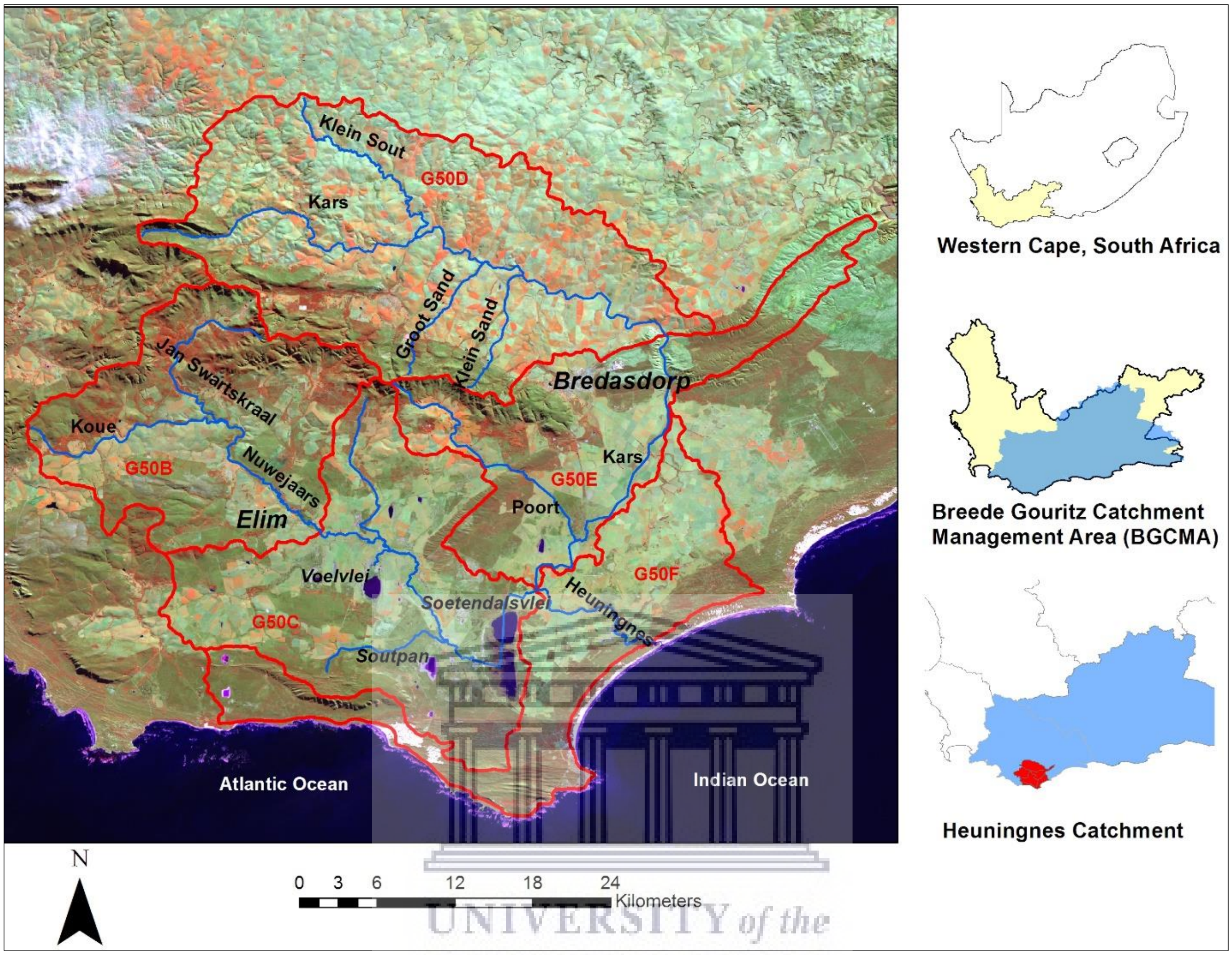


Figure 1.3 Location of the Heuningnes catchment (study area)

Soetendalsvlei, which has a maximum depth of about 3 m, and is about 20 km^2 when flooded (Hart, 1995; Cleaver & Brown, 2005), attracts the highest number of bird species in the Nuwejaars catchment. Soetendalsvlei and Voëlvlei are important sites for waterbirds species such as Purple gallinules, Moorhens, Rednobbed Coot and rallids (Heydenrych, 1999; Kraaij *et al*., 2009; Malan *et al*., 2015). Estuarine fishes such as the Estuarine round herring (*Gilchristella aestuaria*), Cape moony (*Monodactylus falciformus*), Flathead mullet (*Mugil cephalus*), Southern mullet (*Liza richarsoni*) and White steenbras (*Lithognathus lithognathus*) migrate from the Heuningnes estuary to Soetendalsvlei, and remain there, until the species reaches adulthood, whereafter they return to the sea to spawn (Hoekstra & Waller, 2014). According to Bickerton (1984), the estuarine fish may be landlocked until freshwater outflow from the Soetendalsvlei connects the shallow lake to the Heuningnes estuary.

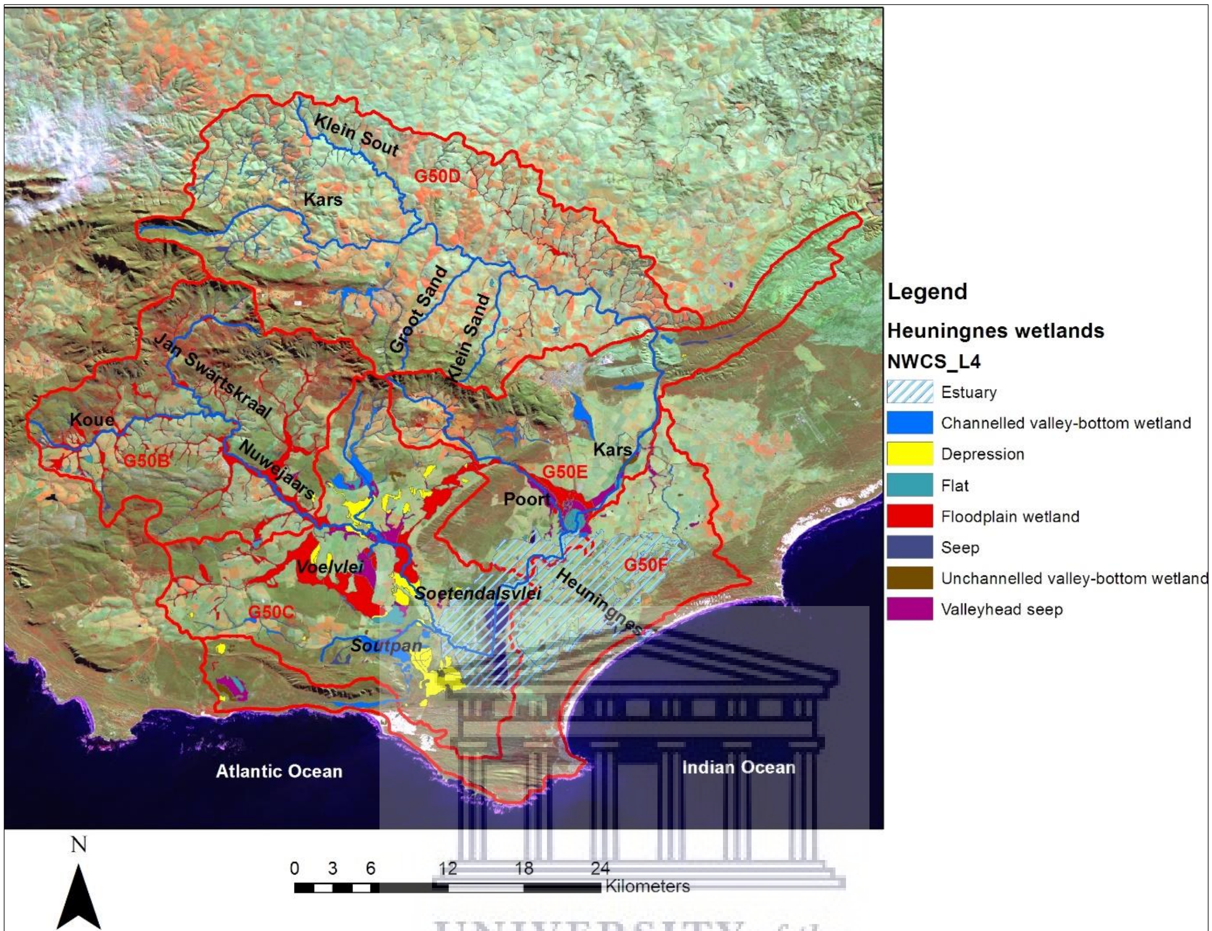


Figure 1.4 Wetland types in the Heuningnes catchment

Despite the significance of coastal lakes, such as Soetendalsvlei, in providing various water-related ecosystem services, there is a need for "monitoring programmes suitable for each system" (Malherbe, 2018, p1). There is limited data on the morphology or *in situ* hydrological data for the lake and the upstream catchment. To ensure the conservation of lakes and the aquatic ecosystems they support, *in situ* monitoring and research of individual lakes and their catchment is important as it allows insights to processes and responses that affects their functioning (Özkundakci & Lehman, 2019).

1.7.1 The living laboratory

The concept of a 'living laboratory' in hydrology can to some extent be equated to a 'research' or 'experimental' catchment where the primary aim is to develop a monitoring network to improve the hydrological understanding of a particular unit/wetland or catchment (Toucher *et al*., 2016). Zingraff-Hamed *et al*., (2019, p21) offers a general definition of a "Living Laboratory", not only as a place, but as an "approach supporting collaborative and open innovation through user stakeholder involvement in order to address environmental, economic and societal challenges". Core characteristics of a "living laboratory" is a real-life setting, diverse stakeholder engagement, co-creators of ideas, beneficial learning amongst stakeholders and co-production of knowledge (Zingraff-Hamed *et al*., 2019). The establishment of a 'living laboratory' in a catchment with varied land use, private land ownership and diverse stakeholders requires substantial stakeholder engagement, collaboration and communication, to ensure the timeous collection of relevant and diverse data, and the co-development and sharing of information and knowledge. The selection of the Nuwejaars catchment, within the larger Heuningnes catchment, as the "living laboratory" was motivated by the Breede-Gouritz Catchment Management Agency (formerly known as the Breede-Overberg Catchment Management Agency, BOCMA) and various stakeholders in the catchment. The selection was motivated by the need for monitoring of hydrological data and information for informed decision-making.

The Breede-Gouritz Catchment Management Agency (BGCMA), established by the Minister of Water Affairs and Forestry in 2005, has core functions which entail water resource planning, water use management and regulation, institutional engagement and water resource protection within the Breede-Gouritz water management area, which includes the Nuwejaars catchment (Figure 1.2). Agriculture and conservation are the two dominant land uses in the Nuwejaars catchment. With current agricultural and domestic water use, and the increasing need by emerging farmers for access to water resources for sustainable livelihoods and economic development in the upper Nuwejaars catchment (Ncube, 2018), the lack of hydrological data is an impediment to the core functions of the BGCMA. Engagement with the emerging farmers were largely facilitated by the BGCMA.

Wetlands, found predominantly in the lower Nuwejaars catchment are formally protected by the South African National Parks (SANParks) and CapeNature (provincial authority), with informal protection by the Nuwejaars Wetlands Special Management Area (NWSMA). The NWSMA, which covers more than 46 000 hectares of privately owned land and the town of Elim, is committed to sustainable farming and the conservation of wetlands (Germishuys, 2007a). The 23 private landowners of the NWSMA have title deed restrictions which ensures the continued conservation and sustainable development of wetlands. The vision of the NWSMA is "to create a sustainable ecology, which ensures the protection of the Nuwejaars Wetland Ecosystem, enhances the heritage and culture of the sub-region, generates benefit for all stakeholders, helps meet social and environmental requirements, and encourages community lifestyles compatible with environmental sustainability" (Cleaver and Brown, 2005, p20). A representative of the NWSMA attended a workshop in December 2013 where all relevant stakeholders of the "living laboratory" discussed data and information needs to address water resource management (Mazvimavi, 2014). To support sustainable agricultural activities, the NWSMA has a "renewed focus on supporting research in the agricultural sector" that will also inform adaptive management strategies to "support a better-functioning natural world and buffer area" (NWSMA, 2019, p 14). Through a consultative process a memorandum of understanding (MOU) was developed between the NWSMA and the Institute for Water Studies at the University of the Western Cape (IWS-UWC) which addressed responsibilities of each of the organizations. The term of the MOU was 5 years, with the signing by the Chairperson of the NWSMA by 27 June 2014. The contract was revised and edited in November 2019, with the MOU extended to 30 November 2024. The IWS-UWC were contractually required to provide details of all equipment installed, adhere to guidelines relating to access to private property, provide identification when conducting fieldwork, provide annual interim reports and share reports and theses emanating from the study within the NWSMA.

"Trust is at the heart of all successful negotiations" (Germishuys, 2007b, p12). Engagement with the commercial farmers in the Nuwejaars catchment was largely facilitated by the Department of Agriculture in Bredasdorp, through the LandCare: Area Wide Planning Programme. In a landscape dominated by agricultural land use, the LandCare progamme "aims to maintain and restore healthy, productive agricultural land through integrated natural resource management, capacity building and partnerships" (Germishuys, 2007b, p12). A LandCare representative, familiar with the area and known to the farmers, introduced the research team from the Institute for Water Studies, University of the Western Cape (IWS-UWC) to individual landowners. The LandCare representative also facilitated meetings and feedback sessions with various stakeholders (such as the Department of Water Affairs and Sanitation and local authorities) at the Bredasdorp Multipurpose Centre.

The acquisition of relevant monitoring equipment and the installation of the monitoring network in the Heuningnes catchment required substantial financial investment. Research funding was jointly awarded to the Institute for Water Studies at the University of the Western Cape (IWS-UWC) and the Centre for Water and Sanitation Research at the Cape Peninsula University of Technology (CPUT) by the Netherlands Organisation for International Cooperation in Higher Education (NUFFIC) in 2012. Funding was aimed at 'capacity building for integrated water resources management in South Africa', and financial support was available for postgraduate studies. In 2014, the Water Research Commission (WRC) provided further funding for "Finding 'new' water to address conflicting and competing water demands in the Nuwejaars catchment, Cape Agulhas" (WRC Report No 2324/1/18). The hydrological monitoring network was mainly focused on the Nuwejaars catchment, within the larger Heuningnes catchment. The identification of monitoring sites, required equipment and financial investments for the catchment instrumentation plan was informed through a collaborative process with various stakeholders and partners. A data management system is facilitated by the Institute for Water Studies at the University of the Western Cape (IWS-UWC), with agreement of data sharing with the South African Environment Observation Network (SAEON). The location of the monitoring network in the Nuwejaars catchment is illustrated in Section 2.6. The establishment of the Nuwejaars catchment as a "living laboratory" by the Institute for Water Studies at the University of the Western Cape (IWS-UWC) was facilitated by formal agreements between the IWS-UWC with the Breede-Gouritz Catchment Management Agency (BGCMA), the Nuwejaars Wetlands Special Management Area (NWSMA) and the South African National Parks (SANParks). From the conceptualization of the "living laboratory" in September 2012, and the process of engagement and formalizing these engagements with the relevant stakeholders (Mazvimavi, 2014), the installation of monitoring equipment, mostly on private land, started in October 2014.

The importance of this background information is to highlight the very integrated, but complex and dynamic personalities/factors/processes/drivers that shape(d) the "living laboratory".

1.8 Structure of the thesis

The thesis is divided into nine chapters with a synopsis of each chapter given below. Each of Chapters 3 to 8 include an introduction, methodology, results and discussion.

Chapter 1: Introduction

A general background to the study is presented, followed by the rationale, aim and objectives. The rationale for the selection of the study area is presented.

Chapter 2: Study Area

This chapter provides a general overview of the Nuwejaars catchment. Details of the hydro-meteorological network in the “living laboratory” of the Nuwejaars catchment by the Institute for Water Studies at the University of the Western Cape in 2014 is presented.

Chapter 3: The influence of land cover change and rainfall variability on wetland dynamics (Objective 1)

The main aim of this chapter is to understand the historic land cover dynamics of the Soetendalsvlei and to assess the relative impacts of rainfall variability and surrounding anthropogenic influences on wetland properties and land cover. The analysis of available historical aerial photographs from 1938 to 2014 aim to assess how wetland properties have changed due to surrounding land cover change. With limited official climatic data, the incorporation of long-term monthly rainfall data from private landowners is analyzed to understand the temporal and spatial variation of rainfall in the catchment, and the influence on wetland cover.

Chapter 4: Long-term variation of inundation: Case study of Soetendalsvlei (Objective 2)

The use of remote sensing is used to establish the spatial and temporal variation of flooding/inundation for Soetendalsvlei from 1989 to 2019. Inundation is estimated using the Modified Normalized Difference Water Index (MNDWI), a multi-band spectral index, which uses a band-ratio approach for extracting surface water features. The utility of using remotely sensed data as a proxy for *in-situ* lake level is explored.

Chapter 5: Morphometric properties of Soetendalsvlei (Objective 3)

The morphometric properties of Soetendalsvlei is derived through a bathymetric and terrestrial survey of the wetland, and a desktop analysis of relevant primary and secondary data. Knowledge of wetland morphometry provides knowledge of the storage capacity of the depression, and is important in understanding how inundation/water levels vary spatially.

Chapter 6: The water balance dynamics of Soetendalsvlei in the Nuwejaars catchment (Objective 4)

The establishment of a hydro-meteorological monitoring network in the Nuwejaars catchment, and knowledge of the depth-area-volume relationship derived from the bathymetric survey is used to estimate the inflows, outflows and variation of water storage for Soetendalsvlei from 2015 to 2017. The chapter aims to understand the hydrological response of the lake to rainfall events and dry periods within the year. With the development of a daily water balance model, the chapter further explores the possible impacts of a change of surface inflows on water storage through scenario analysis.

Objective 5 of the thesis was explored in two separate chapters:

Chapter 7: Wetland ecosystem services: Habitat provision for birds in the Nuwejaars catchment (Objective 5)

The integration of wetland inundation and avifauna data was assessed to explore how wetlands influenced habitat provision. With birds often used as indicators of ecosystem health, data collected by citizen scientists and managed by the Coordinated Waterbird Counts (CWAC), Animal Demography Unit at the University of Cape Town were assessed. The temporal and spatial variation of species richness were explored by assessing the number of birds within the pentads in the Nuwejaars catchment. With available bird counts for the depression wetlands of Soetendalsvlei and Voëlvlei, this chapter also evaluates how wetland inundation influences bird abundance, richness and diversity.

Chapter 8: Wetland ecosystem services: Cultural value of wetlands in the Nuwejaars catchment (Objective 5)

The main aim of this chapter is to understand which wetland ecosystems provide benefits to, and add value to society. Based on a synthesis of research conducted in the "living laboratory" between 2014 and 2019, one of the objectives of this chapter is to assess the scientific value of wetlands in the Nuwejaars catchment. Interviews, participatory mapping and informal discussions with relevant stakeholders in the Nuwejaars catchment were also conducted to understand which wetlands society regard as providing benefits.

Chapter 9: General summary, discussion and recommendations

An overview and synthesis of all the chapters are provided, as well as key recommendations.

CHAPTER 2

STUDY AREA

The chapter provides a general description of the Nuwejaars catchment based on secondary data and information and details of the monitoring sites in the “living laboratory”.

2.1 Topography, hydrogeology and soils

The topography of the Nuwejaars catchment varies from the high lying mountain ranges, the undulating hills in the upper catchment and the relatively flat landscape of the Agulhas Plain in the lower catchment (Figure 2.1). The Bredasdorp, Koueberg and Soetanys Mountain ranges serve as the watershed for the Nuwejaars catchment. The Bredasdorp Mountains along the northern boundary of the catchment have maximum elevations of 650 m and consist of the folded and fractured Table Mountain Group (TMG) and the Malmesbury Group. The TMG consists predominantly of sandstone but also quartzite and shales, with the resistant sandstone forming the more prominent high lying areas (Toens *et al*., 1988). These mountainous areas are important recharge zones due to intense fractures and high porosity of the weathered mantle which allows the infiltration of rain (Toens *et al*., 1988). The Malmesbury Group consists of sheared shale and fine-grained greywacke (Bickerton, 1984). Outcrops of Post Malmesbury, pre Cape granite occur on the south-facing slopes of the Bredasdorp Mountains (Bickerton, 1984). The Jan Swartskraal River draining the Bredasdorp Mountains is one of the main tributaries of the Nuwejaars River, with a relatively steep gradient before confluence with the Koue River (Figure 2.1). The Koueberg and Soetanys Mountains which form the respective northwesterly and southerly boundary of the Nuwejaars catchment, is also dominated by the resistant sandstone of the TMG. The south facing slopes of the Koueberg Mountain form the north-westerly Nuwejaars catchment boundary, with a maximum height of 407 m. The main tributary from this area is the Koue River (Figure 2.1). The north facing slopes of the Soetanys mountain ranges form the southerly boundary of the catchment with a maximum height of 254 m. The rivers draining into Soutpan have a relatively gentle gradient.

The hilly character of the upper Nuwejaars catchment is due to the weathering of the less resistant Bokkeveld shales. According to Bickerton (1984) from the town of Elim to the Soetendalsvlei, the Nuwejaars River flows over shale and sandy shale of the Bokkeveld Group. Once the river flows from the Soetendalsvlei, the Heuningnes flows over calcified dune sand and coastal limestone of the Bredasdorp Beds until it reaches the unconsolidated sands of the mouth of the estuary Bickerton (1984).

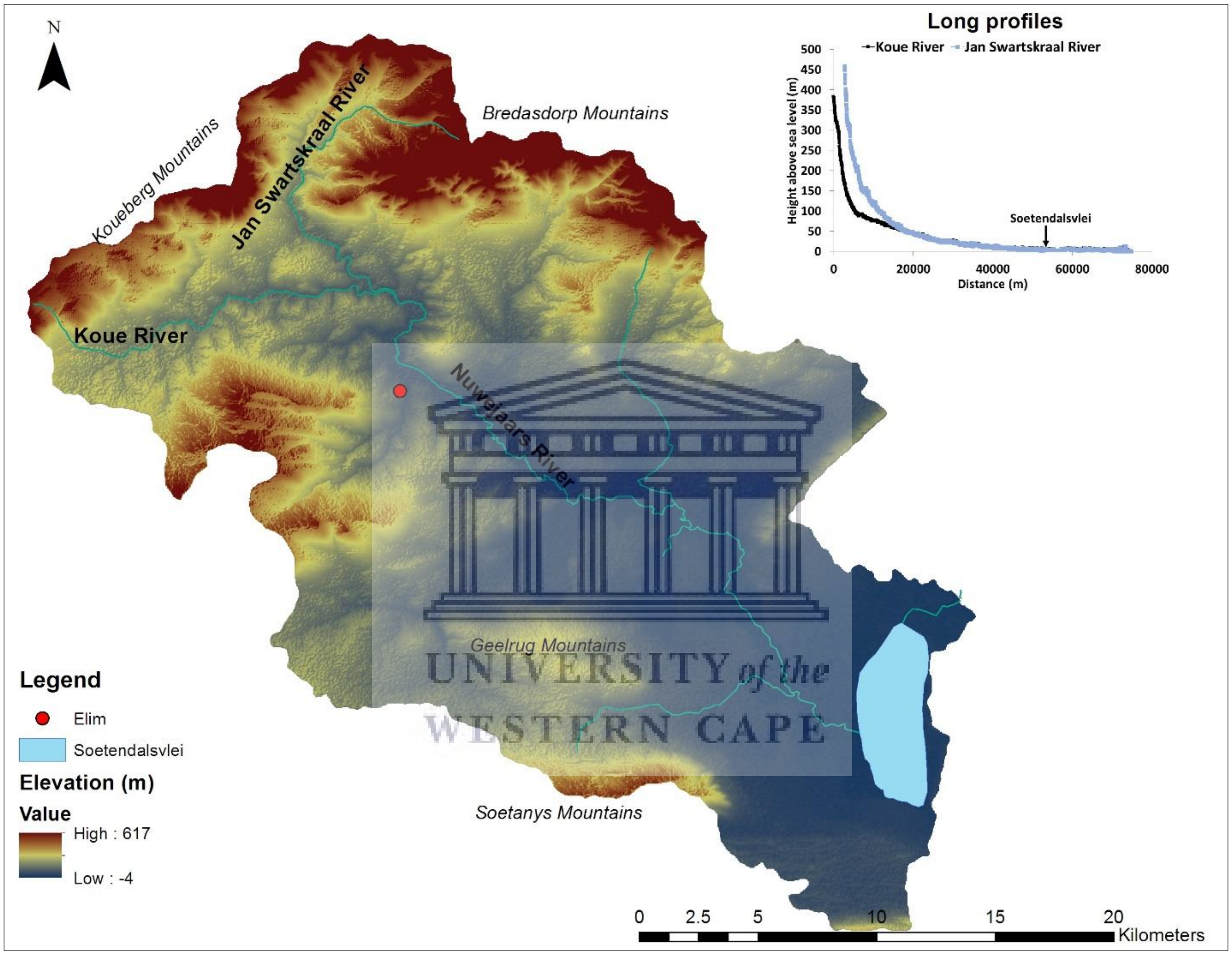


Figure 2.1 Topography of the Nuwejaars catchment

The secondary aquifer systems are associated with fractures in TMG and fractured rock aquifers of the Malmesbury and Bokkeveld sediments (Visser, 2001). Primary aquifers are mainly associated with unconsolidated alluvial sands on the floodplains and banks of the fluvial system (Visser, 2001).

2.2 Climatic conditions

The Nuwejaars catchment experiences a Mediterranean climate with warm dry summers from December to February and mild wet winters from June to August (Bickerton, 1984; Cleaver and Brown, 2005). Rainfall is the main form of precipitation in this area during winter (Figure 2.2) with fog occurrence for approximately 20 days per annum (Bickerton, 1984). According to Bickerton (1984, p7) rainfall is mainly cyclonic with some orographic rainfall occurring in the upper reaches of the catchment. Cut-off-low weather systems which are prominent in winter and autumn, are associated with flood events (Pharoah *et al*., 2016). There is a gradual decrease in precipitation from the western to the eastern catchment boundary (Toens *et al*., 1998). Rain-bearing winds are mainly from the west or south-west. During summer, southeasterly winds dominate (Kruger *et al*., 2010).

The average maximum temperatures during the summer months (October – April) vary between 21 and 26 ^{o}C and 18 to 21 ^{o}C in winter (May to September), while the average minimum temperatures during the summer months vary between 11 and 17^{o}C and 7 and 10^{o}C in winter (Cleaver and Brown, 2005). Monthly S-pan evaporation data measured at station G5E001 in Bredasdorp (1965 to 2017) reflects a temporal variation (Figure 2.2) with high evaporation rates during the summer and lower rates during the winter months. Evaporation is generally higher than rainfall during the summer months.

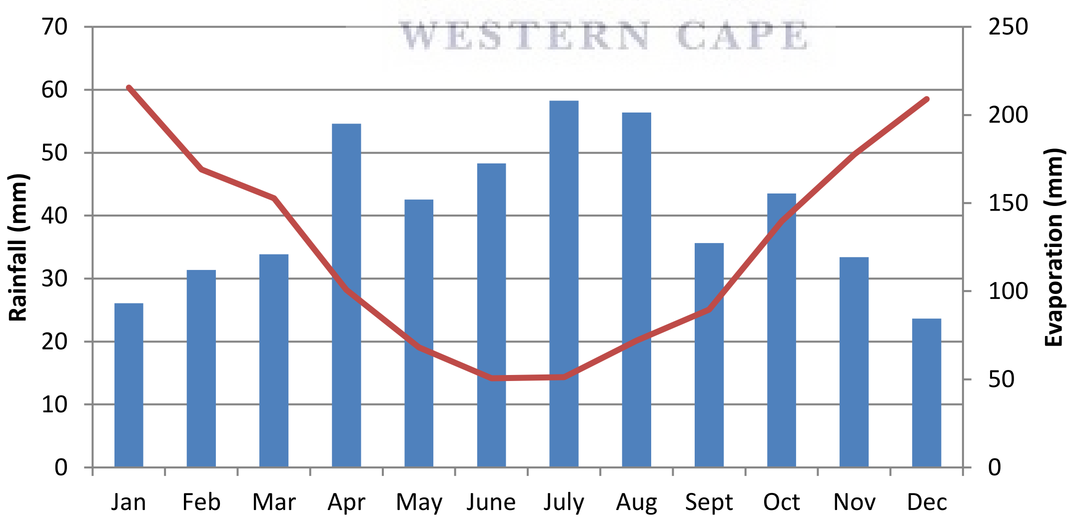


Figure 2.2 Average monthly rainfall and evaporation (S pan data) for Bredasdorp, G5E001 (1965 – 2017) (data source: Department of Water and Sanitation)

2.3 Vegetation

The Nuwejaars catchment is located within the Cape Floristic Region of South Africa, and is known for its floristic diversity (Cole *et al*., 2000). Overberg Dune Strandveld, Central Ruens Shale Renosterveld and different Fynbos species are found within the Nuwejaars catchment (Figure 2.3). Fynbos is the dominant vegetation biome, with the distribution of the species influenced by the climate, but particularly the geology and characteristics of the soils (Cole *et al*., 2000). The coastal renosterveld and lowland fynbos have high priority conservation status but are threatened due to fragmentation as a result of roads, agricultural development and particularly by invasive alien infestation (Cleaver & Brown, 2005).

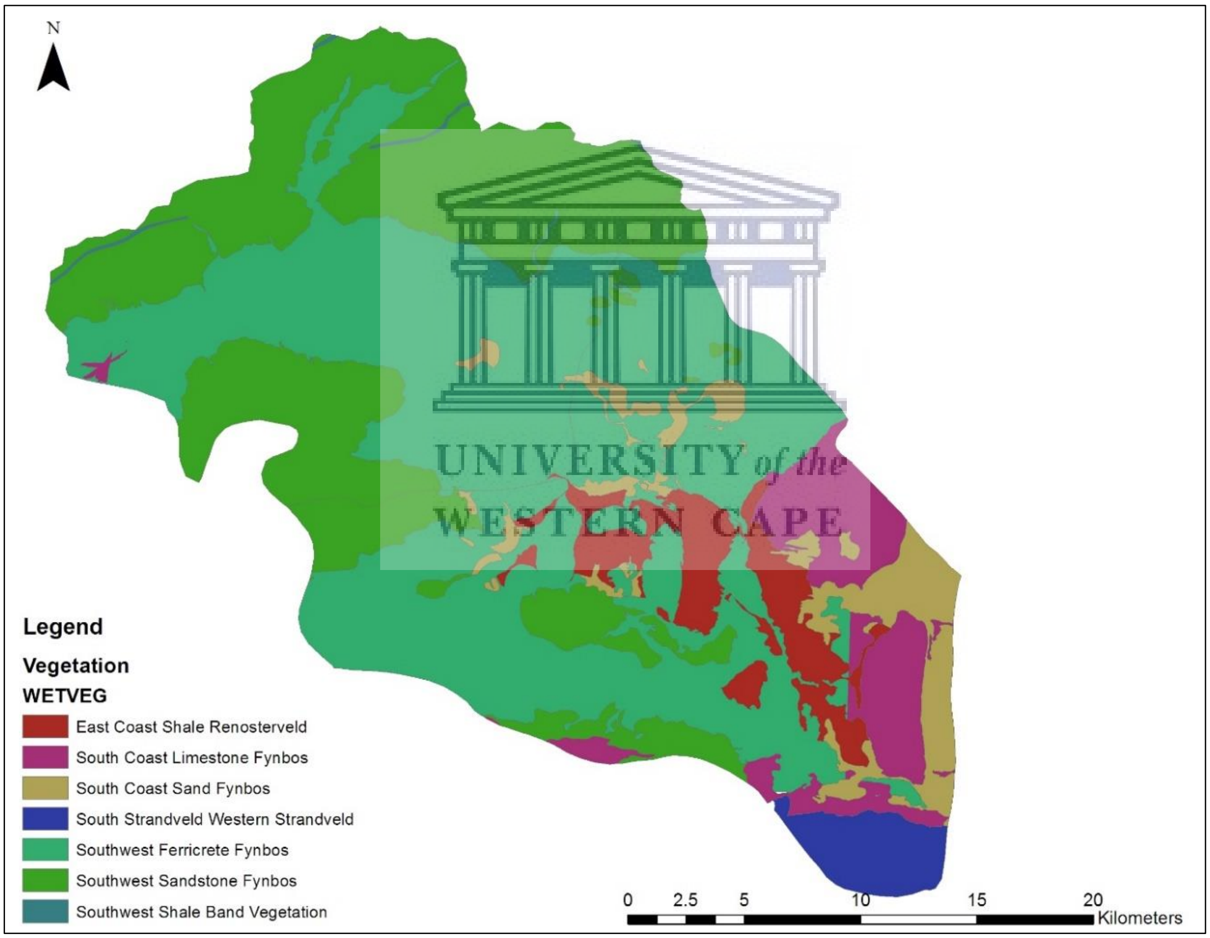


Figure 2.3 Vegetation in the Heuningnes catchment (data source: SANBI, 2018)

Dense stands of *Acacia saligna* and *Acacia Cyclops* are the main threats to the wetlands on the Agulhas Plain (Jones *et al*., 2000). The *Acacia*, *Pinus* and *Hakea* are invasive vegetation introduced to the fynbos biomes during European settlement (Richardson *et al*., 1992), and was used for dune stabilization in the Heuningnes catchment (Bickerton, 1984). The spread of the invasives are also attributed to environmental factors such as the dispersal of seed through wind, water and fauna (Richardson *et al*., 1992).

2.4 Land use, land cover and the cultural landscape

Sparse and dense shrublands, woodlands and wetlands dominate the natural land cover in the Nuwejaars catchment (Figure 2.4). The natural environment in the Nuwejaars catchment has largely been transformed into cultivated land for agricultural activities, with Elim the only major settlement in the catchment. Elim, is a Moravian missionary station, established in 1824 as a refuge for slaves (Conradie, 2010) and according to the Census 2011, has a population of approximately 1412. Land ownership within the Nuwejaars catchment, is dominated by privately owned farms with the exception of Elim, which still has a communal land system (Conradie, 2010).

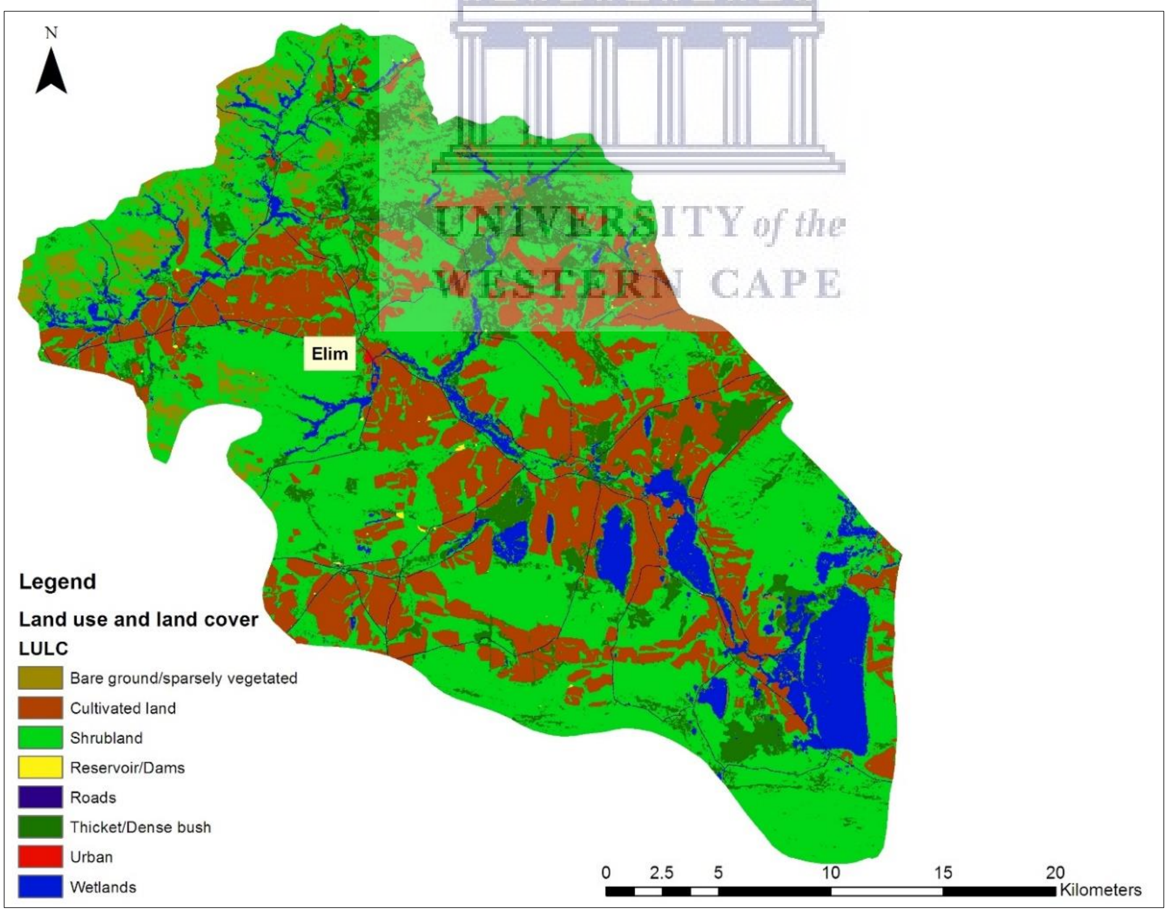


Figure 2.4 Land use and land cover in the Nuwejaars catchment

2.5 Rivers and wetlands

The Nuwejaars and Kars River are the main rivers in the Heuningnes catchment (Figure 1.3). Runoff data is only available for the Kars River (G5M05) from February 1953 to September 1960. With this 7 year flow data, Bickerton (1984) estimated a mean annual runoff of 42,5 x 10^6 m^3 for the Heuningnes catchment. Simulated mean annual runoff figures for the Heuningnes catchment are given by Midgely and Pitman (1969 in Bickerton, 1984) as 78,3 x 10^6 m^3 while Pitman *et al*., (1982 in Bickerton, 1984) provides a figure of 37,6 x 10^6 m^3. Based on the Water Resources Assessment for South Africa (2005), the mean annual runoff for the Heuningnes is 137 mm/year (Table 2.1). The Nuwejaars catchment, consisting of G50B and G50C, thus contributes significant surface flow to the Heuningnes River.

Table 2.1 Mean annual precipitation, evaporation and runoff for quaternary catchments in the Heuningnes catchment (source: Water Resources Assessment, 2005)

	Quaternary catchment	Area (km^2)	Mean Annual Rainfall (mm/yr)	Mean Annual Evaporation (mm/yr)	Mean Annual Runoff (mm/yr)
Nuwejaars River	G50B	339	492	1445	45
	G50C	421	362	1440	35
Kars River	G50D	572	439	1465	27
	G50E	313	394	1465	30

The National Wetland Map for South Africa is based on the hydrogeomorphic classification system for wetlands in South Africa (Ewart-Smith *et al*., 2006; Ollis *et al*., 2013; van Deventer *et al*., 2018). A subset of the National Wetland Map (Version 4) from for the Nuwejaars catchment is illustrated in Figure 2.5 and shows all the hydrogeomorphic units, excluding all artificial wetlands (data available from the SANBI BGIS website: http://bgis.sanbi.org) . The areal extent of the inland wetland systems in the Nuwejaars catchment amount to 180.4 km^2, a coverage of approximately 23.8% of the Nuwejaars catchment. The occurrence of inland wetlands is greatly influenced by the drainage, topography and soils of the catchment (Silberbauer and King, 1991; Ellery *et al*., 2009). The upper catchment of the Nuwejaars River (G50B) is dominated by floodplain wetlands and the occurrence of seeps, while the lower catchment (G50C) has a combination of floodplain wetlands, depressions, valleyhead seeps and channelled valley-bottom wetlands. Soetendalsvlei is delineated as part of the estuarine functional zone.

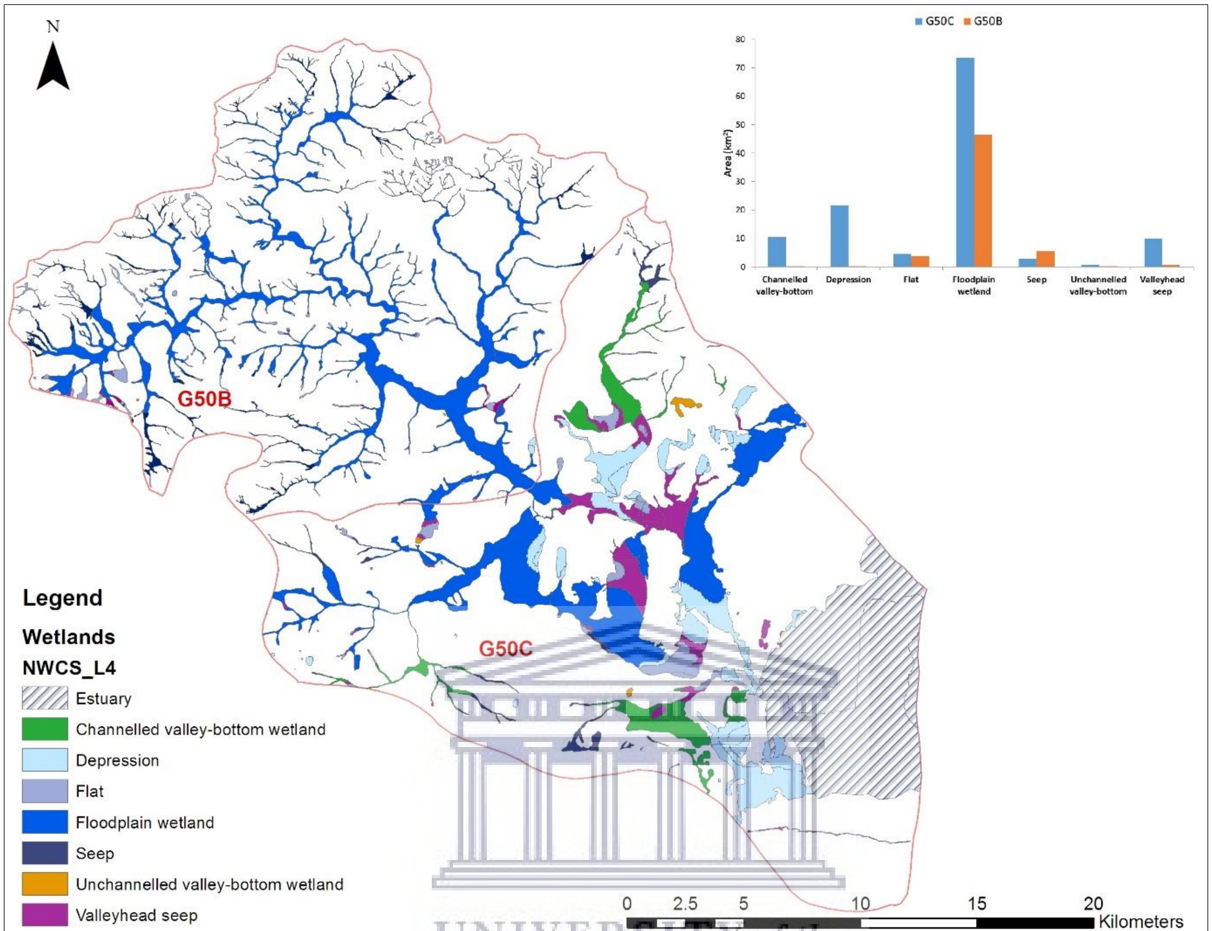


Figure 2.5 Wetland types in the Nuwejaars catchment (data source: SANBI)

2.6 The living laboratory - instrumentation

The establishment of the hydrological monitoring system in the “Living Laboratory” of the Nuwejaars catchment, included the installation of weather stations, rainfall gauges and water levels for rivers, groundwater and Soetendalsvlei (Figure 2.6). The installation of equipment was completed between December 2014 and June 2016, with details of the equipment and date of installation available from Mazvimavi (2018). Flow monitoring sites were established along the Nuwejaars and Heuningnes River at road crossings and bridges from October 2014. The Department of Water and Sanitation (Worcester, Western Cape) installed gauge plates at selected flow monitoring sites. Two lake level monitoring sites on the eastern shoreline of Soetendalsvlei were installed with the permission of the landowner in March 2015. All water level data loggers record data at hourly intervals. For the purpose of this research, select data from the “living laboratory” will be used for analysis, and included within the relevant chapter.

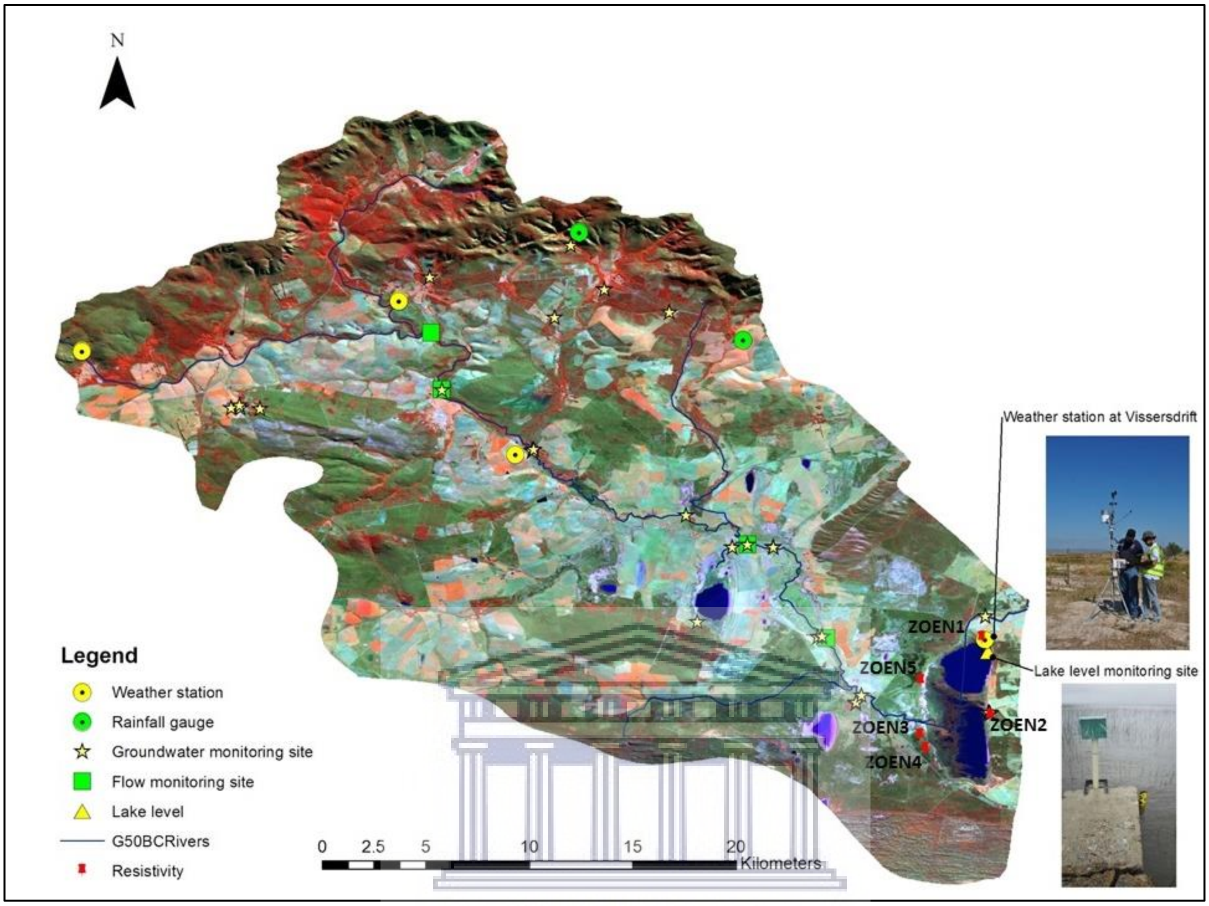


Figure 2.6 Monitoring sites in the Living Laboratory

To inform a better understanding of the interaction between groundwater and surface water resources, a geophysical survey was conducted between September and October 2014 at select sites in the Nuwejaars River to assess locations for groundwater monitoring. Resistivity surveys were conducted at the two largest depressions of Soetendalsvlei and Voëlvlei, as well as along the Nuwejaars River. Low resistivity at all transects indicate the "presence of shallow saline water" (Mazvimavi *et al*., 2014, p28). Resistivity sites along Soetendalsvlei are illustrated in Figure 2.6 with each transect line starting at the edge of the lake. Resistivity varied at the sites around Soetendalsvlei (Figure 2.7), with ZOEN1 submaterial values varied from less than 3 ohm-metres, to values between 20 and 60 ohm-metre within the surface layers. ZOEN2, with values less than 5 ohm-metres, was likely due to saline water throughout the submaterial layer. ZOEN3 and ZOEN5, located on the western shore of Soetendalsvlei had values less than 3 ohm-metres. ZOEN4, also on the western shore of Soetendalsvlei had values of approximately 100 ohm-metres, which may be due to the occurrence of freshwater (Mazvimavi *et al*., 2014, p24).

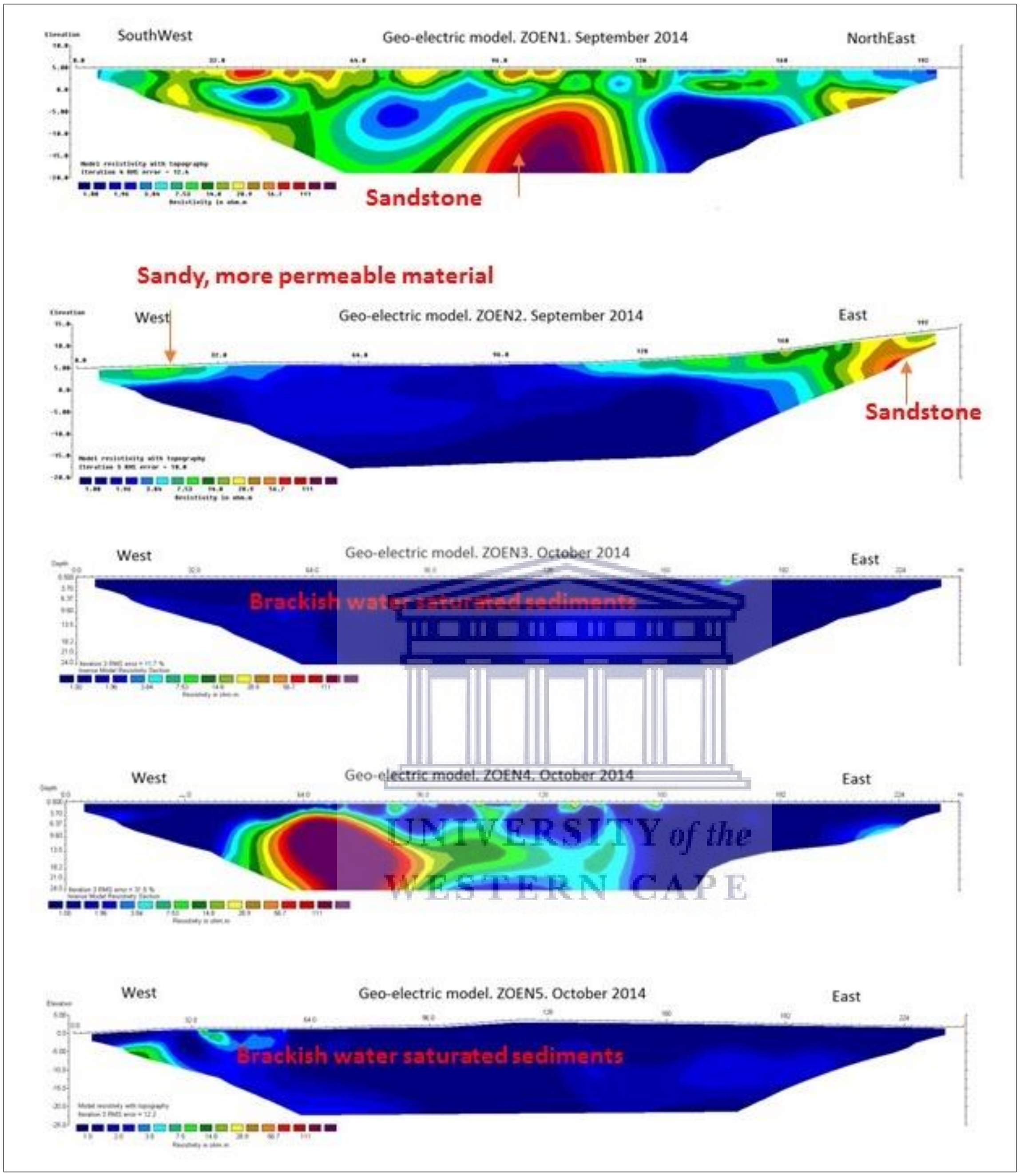


Figure 2.7 Resistivity along select sites at Soetendalsvlei (source Mazvimavi *et al*., 2014)

Based on the interpretation of the resistivity results, the installation of piezometers using the water jetting method was initiated from October 2014. However, due to *in-situ* and logistical challenges relating to the installation of the piezometers and the data collection process, groundwater data was not included in this study.

CHAPTER 3

THE INFLUENCE OF LAND COVER CHANGE AND RAINFALL VARIABILITY ON WETLAND DYNAMICS

3.1 Introduction

The spatial extent and ecological functioning of the world's natural freshwater coastal lakes and wetlands have undergone a significant decline due to anthropogenic influences on catchment hydrology and climate change (Davidson, 2014). Global climate models predict significant change in rainfall and air temperature, with an increase in the frequency of extreme events such as floods and droughts (MacKellar *et al*., 2014). The potential impacts of climate change on freshwater ecosystems such as shallow lakes include change to physical habitats and water regime (Dallas and Rivers-Moore, 2014). In tropical climates, closed lakes such as Laguna Mar Chiquita, Argentina (Troin *et al*., 2010) and the closed lakes of Lake Rotorua, Lake Rotoiti and Lake Rotoma in New Zealand (Healy, 1975) reflect rising lake levels associated with increased rainfall. The increasing water levels of lakes on the Tibetan Plateau (China) have been attributed to an increase in precipitation (Wu *et al*., 2014) and glacier runoff due to increased annual air temperature (Li *et al*., 2017). In arid and semi-arid regions where rainfall is naturally variable, water levels of shallow lakes will likely decline due to reduced precipitation and groundwater inputs, as well as increased temperatures (Coops *et al*., 2003). Declining lake levels associated with a decrease in rainfall have been documented for Lake Sibayi, a coastal lake in KwaZulu Natal, South Africa (Weitz & Demlie, 2014) and Lake Baratz in northern Italy (Niedda *et al*., 2014). Extreme drought events within the Poyang Lake basin China from 1956 to 2009 was quantified using the Standardized Precipitation Index (SPI), which analyzes droughts at different time scales (Zhang *et al*., 2015). The inundation of Poyang Lake showed significant correlation with inter-annual rainfall (Wang *et al*., 2019) and with the 24-month SPI (Zhang *et al*., 2015). The effect of extreme drought conditions on 28 groundwater-dependent lakes in South-East Australia, between 1997 and 2008, caused a 60% reduction of inundation. Local groundwater levels sensitive to rainfall caused hydraulic gradient reversal, affecting lake inundation (Tweed *et al*., 2009). With lake water levels sensitive to climatic variation an understanding of long-term climatic patterns are important (Odongo *et al*., 2015).

Notwithstanding the impacts of climate change, it is the human impact on the water regime (quantity, quality and timing) which is regarded as a key driver in terms of lake and wetland function/degradation. Land-use intensification such as cultivation; afforestation; as well as residential, industrial and infrastructure developments, have markedly changed the flow regime of lake catchments (Schallenberg *et al*., 2013; Van Asselen *et al*., 2013), with consequent impacts on the ecosystem functioning of shallow lakes. In an assessment of global surface inundation, Prigent *et al*., (2012) suggests a 6% decline in surface water inundation since the 1990s due to the draining of wetlands and increased water abstraction. In assessing the variability and trends of water balance components for the Lake Naivasha Basin, Kenya, Odongo *et al*., (2015) found no evidence of climate change to explain the decline of lake volumes, and attributed land cover change and infrastructure development as the main anthropogenic causes. While abstraction of water for human use and irrigation has also caused lake level declines for Lake Abiyata, Ethiopia (Ayenew, 2002), increased runoff due to land use change has resulted in increased inundation of lakes and wetlands in the Chaobai River basin, China (Yang *et al*., 2016). The "Sahelian Paradox", where a decline in rainfall is accompanied with increased water inflow to the Agoufou lake and the endorheic ponds in North Africa, is mostly due to land use change and increased runoff from shallow soils (Gal *et al*., 2016) with increased groundwater recharge affecting pond regimes (Favreau *et al*., 2009). The conclusion from these, and many similar studies, is that the response of lakes to change is unique, and linked to intricate and interrelated factors.

Along the coast of South Africa, coastal lakes have been subject to intense anthropogenic influences (Hart, 1995). Verlorenvlei, a coastal lake and Ramsar site along the west coast of South Africa, is subject to flow modification due to influences such as invasive alien infestation, water abstraction and agricultural return flows. Increased irrigation during the wet cycle is regarded as a threat to the ecological recovery of the lake system (Watson *et al*., 2019). Although a decrease in precipitation was attributed to declining lake levels in Lake Sibayi, along the east coast of KwaZulu Natal (Weitz & Demlie, 2014), the 4 metre decline in the lake level, between 2001 and 2014, was mainly due to afforestation and increased water abstraction in the catchment (Smithers *et al*., 2017). Along the south coast of South Africa, in-channel dams and agricultural pressures are the main drivers in the reduced river flows to the Wilderness Lakes (Petersen *et al*., 2017). The altered hydrology, change in water chemistry and the cessation of the trampling effects of large herbivores of the Wilderness Lakes have resulted in a change in the distribution of emergent vegetation in the lakes, with a decline of wetland species such as *Juncus Kraussii* and *Schoenoplectus,* and a proliferation of *Phragmites Australis* (Russell, 2003). Although *Phragmites Australis* provide ecosystem services in terms of water quality amelioration, it is an aggressive species that may lead to reduced local plant coverage and diversity and changes in ecosystem functions. With the cumulative impacts of anthropogenic activities and potential impacts of climate change significantly threatening the ecological functioning of coastal lakes and wetlands, there is a call for an increased understanding of wetland systems (Dallas and Rivers-Moore, 2014).

With many catchments poorly gauged, the use of secondary documents and historical maps provide information that offers an account of system processes and changes over time (Ballanti *et al*., 2017). A time series of historical aerial photographs provide an important source of visual information from which to assess the conditions and dynamics of a landscape (Necsoiu *et al*., 2013; Guo *et al*., 2017; Mahdavi *et al*., 2017), to understand the drivers of change and the influence of human activities and decisions (Ihse, 1995; Bürgi *et al*., 2004; Al-Tahir *et al*., 2005). Direct drivers of change in lakes and wetlands include land use intensification, invasive species, modification of the hydrological regime and climate change (Schallenberg *et al*., 2013). A global meta-analysis of drivers of wetland change has noted that in most cases, change is due to a combination of two or more direct drivers that interact over time (Van Asselen *et al*., 2013). Direct drivers may change over space and time due to population and economic growth, technological innovations, institutional factors and cultural values (Van Asselen *et al*., 2013).

Coastal lakes have been coined “mirrors of the landscape” and “sentinels of environmental change” as they reflect the dynamic processes and changes occurring within the lake catchment (Kortmann & Dickenson, 1990). Assessing and understanding how lake ecosystems have been influenced, in the context of both climate variability, land use and land cover change, is of great importance for water resources management and the conservation of aquatic ecosystems and the biodiversity it supports (Brinson & Malvárez, 2002; Vale & Holman, 2009; Yuan *et al*., 2015; van Deventer *et al*., 2018). Assessments of land cover change in the Nuwejaars catchment, South Africa, have highlighted the occurrence of anthropogenic activities, such as dam and road construction, intensification of agricultural activities and invasive alien vegetation, with negative impacts on aquatic and terrestrial environments (Cleaver and Brown, 2005; Sampson, 2021). What is lacking of the assessments, particularly for the Nuwejaars catchment, is how the wetland(s) have responded and/or changed over time. Of particular interest is Soetendalsvlei at the outflow to the Heuningnes River and the “mirror of Nuwejaars landscape”.

There is a general perception that climate change is, and will be, a significant driver of the functioning of ecosystems in the Nuwejaars catchment (Child, 2010). Although there is general consensus that the Western Cape will become drier, uncertainty exists on the magnitude and frequency of change (Dallas and Rivers-Moore, 2014). At this stage, with Soetendalsvlei effectively divided into nine farm portions, there is no understanding of the environmental changes to this lake, or the major driving forces directly influencing the land cover and inundation immediately surrounding the lake. The main aim of this chapter is to understand the historic land cover dynamics of the Soetendalsvlei and to assess the relative impacts/importance of rainfall variability and anthropogenic influences on the lake.

The key objectives of this chapter are:

1. To investigate the land use and land cover change in and around Soetendalsvlei from 1938 to 2014, and
2. To assess the influence of rainfall variation within the Nuwejaars catchment on wetland cover/dynamics.

3.2 Methods

3.2.1 Analysis of historic climatic data

An understanding of trends and variations of climatic data is pertinent in understanding the impact on water resources (Zhang *et al*., 2015) and in the adaptation of effective livelihood strategies (Asfaw *et al*., 2018). Although an analysis of all climatic variables, particularly temperature, are important in understanding climate change and variability, in most cases historical precipitation data is the only data available in a region. Historic monthly rainfall data is available from the Agricultural Research Council (ARC) and two farmers, respectively in, and in close proximity to, the Nuwejaars catchment (Table 3.1 and Figure 3.1). Rainfall data from Zeekoevlei has been incorporated into the South African Environmental Observation Network (SAEON) database. Rainfall data from Kosierskraal was captured from written records. Daily and monthly meteorological data is available from Prinskraal; however, with the weather station relocated in 2006, the historical data is only available from 1973 to October 2006. The Pearson Correlation Coefficients between the stations were determined.

Table 3.1 Characteristics of rainfall stations

Station Name	Station managed by	Co-ordinates Latitude	Longitude	Altitude (m)	Period of observation
Zeekoevlei	Landowner	-34.65819	19.76496	9	1909 - 2018
Kosierskraal	Landowner	-34.5725	19.875	94	1981 - 2018
Prinskraal	ARC	-34.6274	20.11616	12	1973 - 2005

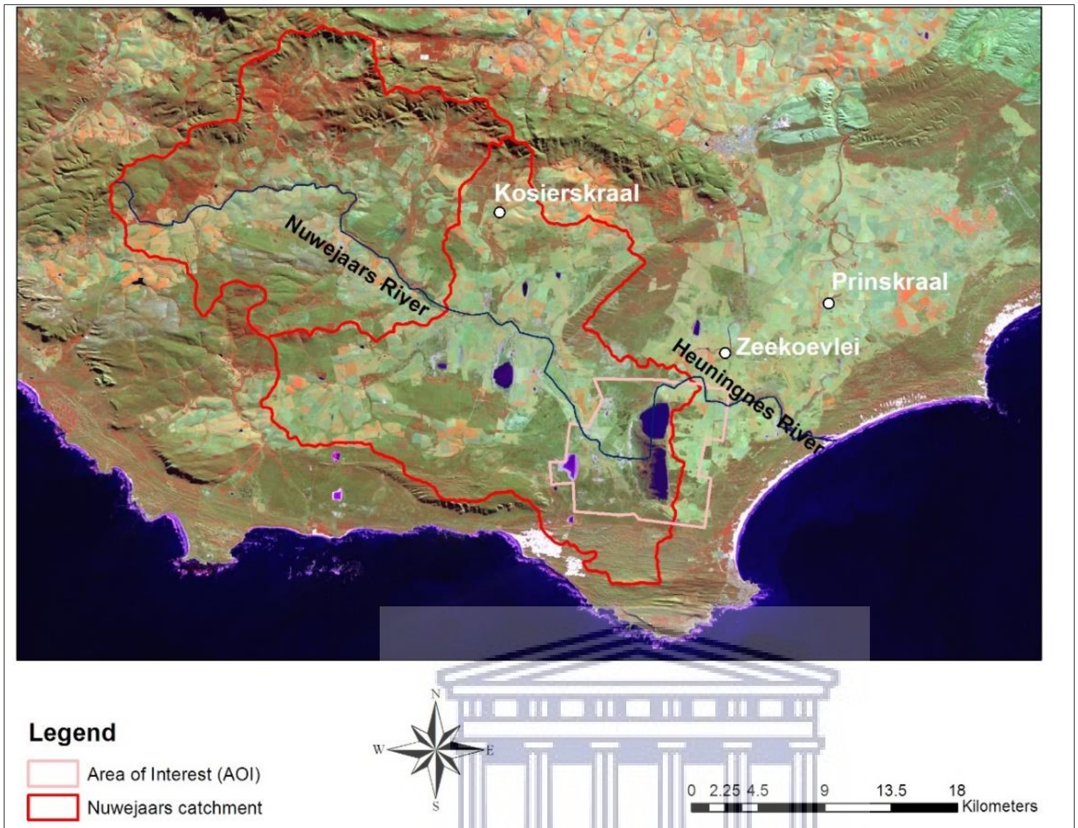


Figure 3.1 Geographic location of the Area of Interest (AOI) and the climate stations in the Nuwejaars catchment

3.2.1.1 Homogeneity and trend detection

Homogeneity tests, such as the Pettitt test; Standard Normal Homogeneity Test (SHNT) and the Buishand test, are commonly applied to a time series to detect if the data are homogenous or whether there is an abrupt change in the data series (Javari, 2016). The Pettitt test (Pettitt, 1979) is a non-parametric test, where no assumptions are made about the distribution of the data. The SHNT (Alexandersson, 1986) developed for change detection in data series, is a likelihood ratio test where the mean of the first observation is compared with the mean of the remaining observations. The Buishand test can be applied to a time series with any type of distribution. Ahmed *et al* (2018) suggests the use of multiple methods in assessing homogeneity of a time series. The significance of homogeneity tests in detecting abrupt changes in data series can highlight a regime shift in the data series, although any change in the location or properties of the rainfall instrument or method of recording may cause the abrupt change in the data series (Villarini *et al*., 2009). The Pettitt test, Standard Normal Homogeneity Test (SHNT) and the Buishand tests were applied to the annual rainfall series to detect if the data are homogenous.

The purpose of trend tests is to determine if a data series has changed over time, and to determine the rate of change (Helsel & Hirsch, 2002). The Mann-Kendall trend test is a common non-parametric test applied to hydrological, environmental and climate data. The Mann-Kendall test was applied to the monthly, seasonal and annual rainfall series to assess whether any trend can be discerned.

3.2.1.2 Standard Precipitation Index and drought characterization

The main objective of using a drought index is to understand how rainfall variability, specifically extreme events, influences the availability of surface water resources (Nsubuga *et al*., 2019). The Standard Precipitation Index (SPI) is a normalized indicator that classifies wet and dry periods by determining the probability that observed rainfall deviates from the long-term average (McKee *et al*., 1993). A major advantage of the SPI, specifically for data-poor regions, is that only long-term precipitation data (i.e. more than 30 years) is required for analysis. The functional definition of the SPI developed by McKee *et al*., (1993), is:

$$SPI = \frac{x - \bar{x}}{s} \quad (3.1)$$

Where:

SPI = Standard Precipitation Index

x = monthly rainfall

$\bar{x}$ = mean rainfall calculated for 1, 3, 6, and 24-month period

s = standard deviation of monthly rainfall for the time series

Positive SPI values indicate above average rainfall, while negative values show rainfall below the long-term average. The SPI has been adopted by the World Meteorological Organization (WMO) to monitor and analyze drought events (WMO, 2012). The SPI program is available for analysis at http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx, with a user guide developed by the WMO (2012). The classification of SPI values according to the WMO (2012), indicate categories of wetness and dryness (Table 3.2).

Table 3.2 Standard Precipitation Index (SPI) values (WMO, 2012)

SPI value	Category
>= 2.0	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry/Moderate drought
-1.5 to -1.99	Severely dry/Severe drought
<= -2	Extremely dry/Extreme drought

The SPI allows comparison across different climatic regions and multiple time scales, to reflect the impact of a rainfall surplus/deficit on soil moisture conditions and water resources. The relative frequency of wet and dry periods is determined as (Mohseni Savari *et al*., 2009):

$$RF = \frac{n}{N} x\ 100\% \qquad (3.2)$$

Where:

RF = Relative frequency

n = number of months within SPI values (Table 3.2)

N = number total months

The SPI at a 1 to 6-month time scale is applied to monitor soil moisture conditions, with the 1-month SPI used to monitor meteorological drought, and the SPI between 1 and 6 months used to monitor agricultural drought. At time scales of 6 to 24 months, the SPI monitors hydrological drought with impacts on the levels of rivers, wetlands, reservoirs and groundwater (WMO, 2012; Zhang *et al*., 2015).

Drought occurs when SPI values are consistently lower than, or equal to, -1.0 (McKee *et al*., 1993; WMO, 2012). Drought can be characterized by duration, intensity, magnitude/severity and spatial coverage (Keyantash & Dracup, 2002; WMO, 2012). Given the complexity in defining and characterizing drought, concepts adapted from the literature are defined. Drought *period* defines the start and end time during which the drought index is consistently below the defining threshold, i.e. SPI less or equal to -1.0 The drought ends when SPI becomes positive (McKee *et al*., 1993; WMO, 2012). Drought *duration* is defined as the sum of the months within the drought period (McKee *et al*., 1993; WMO, 2012). Drought *magnitude*, also referred to as drought severity (Zargar *et al*., 2011), is the sum of all SPI values within the drought period (McKee *et al*., 1993;

WMO, 2012). Drought *intensity*, also referred to as mean intensity (WMO, 2012), is the ratio of drought magnitude to drought duration (Zargar *et al*., 2011). The highest SPI value during a drought period is the *peak intensity*.

The SPI at time scales for 1, 3, 6 and 24 months were calculated for all stations, following the WMO user guideline (WMO, 2012). Characteristics for hydrological drought using the 24-month SPI were determined for all stations.

3.2.2 Historical aerial photograph analysis

Aerial photographs provide an important source of information on catchment and wetland dynamics, with many countries having historical archives dating back to the 1920's (Kent & Mast, 2005; Morgan *et al*., 2010). Using long-term imagery, an assessment of land cover and land use change allows an historical interpretation of environmental change (Ballanti *et al*., 2017). The high spatial resolution of aerial photographs allows the detection of small-scale "within-wetland" change, such as a change in wetland emergent vegetation (Ozesmi & Bauer, 2002; Kleinod *et al*., 2005), indication of erosional and depositional processes (Ballanti *et al*., 2017) and the impact of direct human use/activities such as cultivation or development (Papastergiadou *et al*., 2007). As emergent vegetation is important for the ecological functioning of lakes, and with reports of the increased global loss of aquatic vegetation in lakes (Zhang *et al*., 2017), the area of emergent vegetation in Soetendalsvlei from 1938 to 2014 was mapped from the aerial photographs.

Fine-scale temporal mapping of wetlands at the local scale provides a greater understanding of how wetland attributes and functions have changed over the long-term (Papastergiadou *et al*., 2007). For the purpose of this chapter, within-wetland change of Soetendalsvlei and the land use and land cover surrounding Soetendalsvlei was assessed. The spatial delimitation of the Area Of Interest (AOI) include Soetendalsvlei and the surrounding landscape. To assess the direct impacts of land use change, the spatial AOI was limited to the property/farm level within, and surrounding Soetendalsvlei (Figure 3.2). A spatial review, of parent farms and title deed information from the Surveyor-General's database on the CapeFarmMapper version 2.1.0.3, shows 5 parent farms surrounding Soetendalsvlei with farm size ranging from 142.5 hectares to 2150 hectares. Each parent farm is divided into farm portions. The AOI covers an area of 86.8km^2.

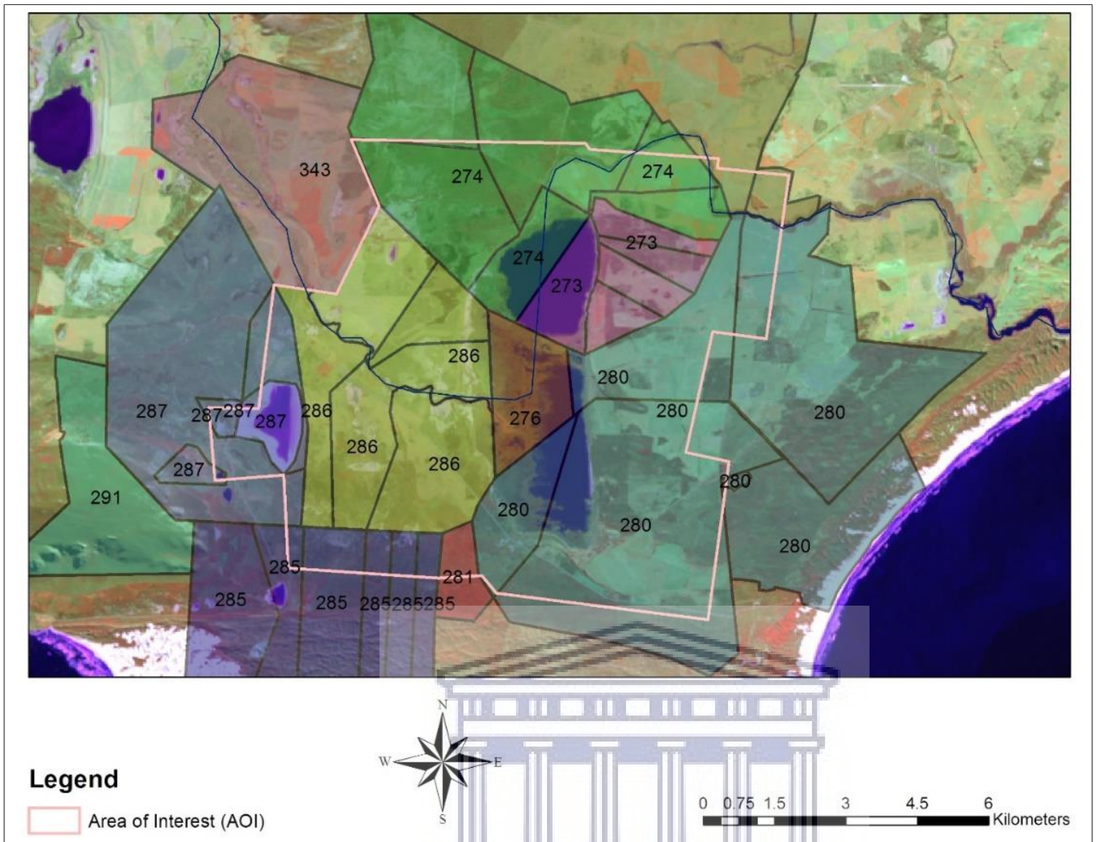


Figure 3.2 **Farm portions or land parcels within the Area of Interest (AOI) (data source: CD:NGI)**

3.2.2.1 Acquisition and pre-processing of historical aerial photographs

Historical vertical aerial photographs were acquired from the South African Department of Rural Development and Land Reform, Chief Directorate: National Geo-Spatial Information (CD:NGI) for the spatial coverage of the Nuwejaars catchment. All aerial photographs captured by the CD:NGI prior to 2008 are available (per request) in high-resolution digital format, and are in a Tagged Image File (TIF) format (Table 3.3).

Table 3.3 **Properties of historical aerial photographs**

Date	Season	Job No	Scale of images
March 1938	Autumn	130	1:25 000
December 1961	Summer	461	1:36 000
March 1973	Autumn	719	1:40 000 – 1:55 000
July 1980*	Winter	820	1: 160 000
December 1989	Summer	931	1: 50 000
November 1993*	Summer	972	1: 150 000
February 2014	Summer	708	0.5m SGD (Surface ground distance)

* *The aerial photogaphs were not included in the historical aerial photograph analysis*

To ensure accurate analysis of the aerial photographs, only photographs with a spatial resolution higher than 1:50000 were selected. The aerial photographs of 1980 and 1993, with a spatial resolution of 1:160 000 and 1:150 000 respectively, were thus not included in the analysis. The aerial photographs of 1938, 1961, 1973, 1989 and 2014 were captured during the summer and early autumn season, and ensures similar phenological states.

A temporal analysis of land cover change detection requires the co-registration and orthorectification of digital historical aerial photographs using a geo-referenced image and the use of control or tie points (Necsoiu *et al*., 2013). The 2014 geo-rectified photograph was used as a reference map as historical aerial photographs were not geo-referenced. To minimize error when linking the historical image to the reference image, common, well-defined and distinct features such as shoreline configurations, road intersections, buildings and isolated trees were used as control points. A minimum of five control points were selected for each photograph. The historical aerial photography was transformed and spatially referenced, using the control points (Tekle & Hedlund, 2000). For each of the acquisition dates, the photographs were mosaicked to form a continuous and spatially referenced representation of the study area.

3.2.2.2 Land cover and land use classification

The visual analysis and manual interpretation of the digital aerial photographs, were guided by the South African National Land-cover classification standard and described by GeoTerraImage (2015). An image interpretation key with a description of characteristics for each category was guided by the principles for photo interpretation by Paine (1981) which describes the texture, colour, tone and hue for different land cover classes (Figure 3.3). Nine land cover and land use classes were identified, namely open water, emergent vegetation, sediment/bare land, agriculture, conservation, shrubland, wetlands, woodlands and infrastructure development. Agriculture as a land cover includes activities where the natural environment was transformed for livestock farming, vineyards, pastures etc. For the classification of this study, conservation areas were identified where the status of the land parcel was changed from agricultural to a protected conservation status.

The interpretation, verification and the improvement of the land cover classification process, was completed with the use of ancillary data, field reconnaissance and the use of an image enhancement technique, namely Modified Normalized Difference Water Index (MNDWI) (see Section 4.2). Ancillary data included the Shuttle Radar Topography Mission (SRTM) digital elevation data, National Freshwater Ecosystems Priority Areas (NFEPA) Map 4, Western Cape Landcover product (2013/2014) and Cape Agulhas Property information. All ancillary data excluding the SRTM data were accessible from the South African National Biodiversity Institute (SANBI).

3.2.2.3 Digitization and change detection

The delineation of the land cover classes within the AOI for each acquisition year was done through on-screen digitization. The temporal and spatial dynamics of the land cover classes from 1938 to 2014 were assessed by comparing the change in the area covered by the different land cover classes (see Figure 3.3 below).

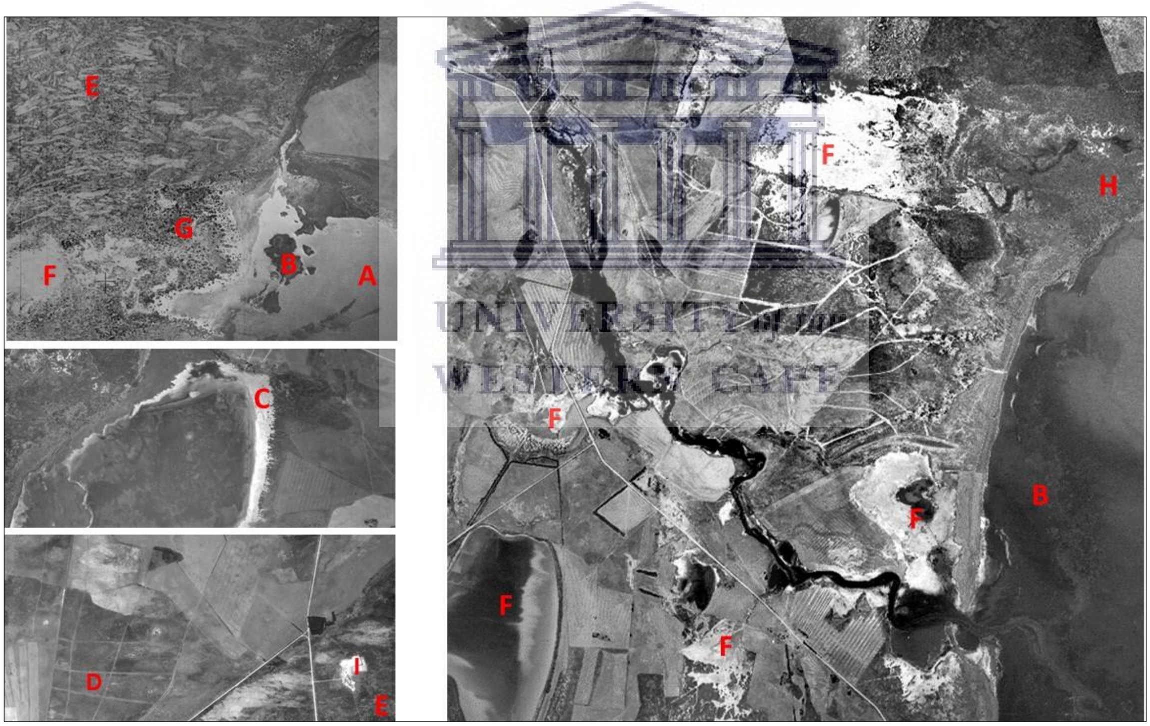


Figure 3.3 Image interpretation key of land use classes interpolated from historical aerial photographs. Open water (A); Emergent vegetation (B); Sediment (C); Agriculture (D); Shrubland (E); Wetlands (F); Low density woodlands (G); High density woodlands (H) and Bare ground (I).

3.2.2.4 Limitations and accuracy

The high resolution of the aerial photographs allowed the identification of specific features such as isolated trees, buildings and roads, while edge zones between natural vegetation and agricultural fields were also distinct. Distinct features facilitated the mosaic process through control points to ensure positional accuracy. A limitation of historic aerial photography is ground truthing. However, the use of historical photographs of a similar time period can be useful in validating data derived from historical aerial photographs. Historical photographs of the Soetendalsvlei were provided by private landowners. The shoreline of Soetendalsvlei was prominent in most images. However, the presence and density of emergent vegetation along the northern, western and southern shoreline together with the varying water level of Soetendalsvlei made the location of the exact shoreline position very challenging.

3.3 Results

3.3.1 Climatic data

3.3.1.1 Spatial and temporal variation of rainfall

The mean annual rainfall varies from 611 mm/annum at Kosierskraal situated within the upper middle catchment of the Nuwejaars, 420 mm/annum at Prinskraal, to 466 mm/annum at Zeekoevlei on the coastal plain (Figure 3.4). There is a significant correlation of rainfall between the three stations (Table 3.4).

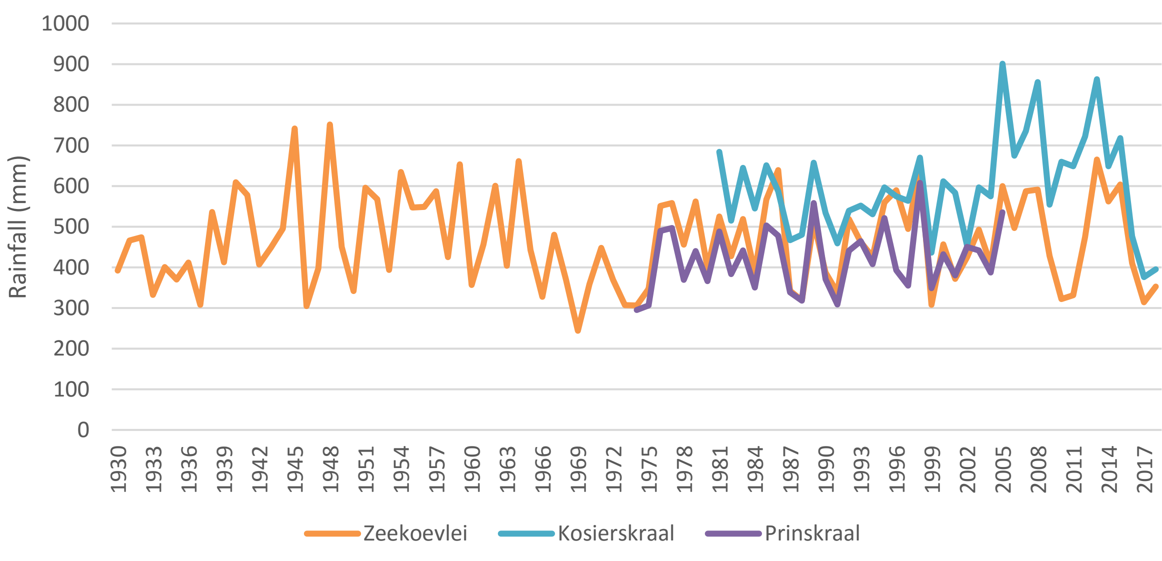


Figure 3.4 Mean annual rainfall for Zeekoevlei, Kosierskraal and Prinskraal

Table 3.4 Pearson correlation (R^2) of monthly rainfall for the rainfall stations

	Zeekoevlei	*Kosierskraal*	*Prinskraal*
Zeekoevlei	1		
Kosierskraal	0.709943	1	
Prinskraal	0.839949	0.709626	1

The minimum and maximum rainfall recorded at Kosierskraal is 436 mm/annum in 1999, and 901 mm/annum in 2005, respectively (Table 3.5). Although winter is the main rainfall season at Kosierskraal, the highest average monthly rainfall is in April, with 70 mm/month. The minimum and maximum rainfall recorded at Zeekoevlei was 244 mm/annum in 1969, and 752 mm/annum in 1948 respectively (Table 3.6). Winter contributes 35% to the mean annual rainfall, with July the main rainfall month at Zeekoevlei. The minimum and maximum rainfall recorded at Prinskraal is 295 mm/annum in 1974, and 608 mm/annum in 1998 respectively (Table 3.7).

Table 3.5 Basic statistics and Mann-Kendall (MK) trend analysis for Kosierskraal (1981–2018)

	Min	**Max**	**Mean**	**%Rain**	**CV**	**MK**	**p-value**	**Sen's slope**
Jan	0	193	36.7	6	111.29	0.20	0.099678	0.37037
Feb	5	76	38.0	6	46.41	0.17	0.163284	0.5
March	9	152	43.1	7	82.35	0.05	0.666906	0.1875
April	15	400	70.4	12	94.83	-0.18	0.141959	-0.625
May	4	119	51.5	8	53.74	0.07	0.563032	0.36
June	10.5	124.5	57.6	9	52.52	0.16	0.177282	1
July	8	187	68.5	11	51.81	0.21	0.08543	0.869565
Aug	14	212.5	64.4	11	68.48	0.17	0.167949	0.84
Sept	6	106	44.7	7	48.79	-0.13	0.285491	-0.375
Oct	6	198	59.29	10	79.30	0.12	0.335093	0.583333
Nov	4.5	210	46.9	8	92.43	0.14	0.259643	0.657895
Dec	0	79.5	29.6	5	70.39	-0.05	0.688803	-0.11111
Summer	42.5	238	104.4	17	41.36	0.12	0.335093	0.7
Autumn	52.5	484.5	165.0	27	46.09	-0.03	0.824009	-0.33333
Winter	92.5	328	190.4	31	30.36	**0.29**	**0.017671**	**2.818182**
Spring	66	344	150.9	25	44.79	0.16	0.202344	1.392857
Annual	436	901	**610.9**	100	18.44	**0.31**	**0.01032**	**4.75**

Note: %Rain is the total contribution to monthly or seasonal totals. Values in bold indicates a significant value with a 95% confidence level

Table 3.6 Basic statistics and Mann-Kendall (MK) trend analysis for Zeekoevlei (1930–2018)

	Min	Max	Mean	%Rain	CV	MK	p-value	Sen's slope
Jan	0	94	20.7	4	112.62	0.10	0.183609	0.06131
Feb	0	292	25.0	5	149.11	0.11	0.123024	0.075
March	1.5	124	30.2	6	87.24	-0.05	0.505168	-0.05115
April	0	219	48.7	10	85.37	0.01	0.937849	0.008906
May	0	162.5	47.1	10	71.14	-0.09	0.216119	-0.13003
June	2.5	147	53.1	11	61.80	0.00	0.951952	0
July	7.5	217	55.4	12	60.34	0.10	0.17238	0.157895
Aug	0	184	53.0	11	57.38	-0.02	0.817788	-0.02792
Sept	0	302	41.7	9	102.12	0.00	0.957596	0
Oct	1.5	343	40.7	9	110.82	0.03	0.657722	0.035714
Nov	0	193	31.3	7	102.30	0.07	0.340322	0.072948
Dec	0	91	18.8	4	103.37	0.02	0.806707	0.007504
Summer	0	296	64.5	14	70.46	0.10	0.173468	0.161765
Autumn	23.5	365.5	126.1	27	50.18	-0.07	0.340383	-0.21025
Winter	65.5	313.5	161.5	35	34.19	0.06	0.414979	0.172745
Spring	33	387	113.7	24	58.77	0.00	0.97738	0
Annual	244	751.5	465.78		24.24	0.08	0.341023	2.6875

Table 3.7 Basic statistics and Mann-Kendall (MK) trend analysis for Prinskraal (1973–2005)

	Min	Max	Mean	%Rain	CV	MK	p-value	Sen's slope
Jan	0.0	86.9	23.9	6	105.51	0.17	0.173084	0.385556
Feb	0.0	114.7	24.0	6	95.11	-0.09	0.465549	-0.2101
March	0.0	133.7	29.5	7	105.57	0.13	0.314631	0.311538
April	3.8	206.4	57.3	14	81.19	0.04	0.733446	0.235084
May	5.4	121.0	39.2	9	58.18	-0.06	0.661499	-0.15038
June	12.0	106.2	43.7	10	56.45	-0.13	0.322564	-0.3875
July	5.0	108.2	45.2	11	59.48	-0.09	0.48561	-0.35817
Aug	7.4	149.1	43.7	10	62.23	-0.09	0.495757	-0.29111
Sept	9.2	77.2	30.9	7	54.98	0.11	0.39008	0.225
Oct	0.3	129.7	37.0	9	80.49	-0.01	0.935377	-0.03485
Nov	3.2	94.2	26.0	6	87.25	0.01	0.974117	0.0075
Dec	0.0	89.9	20.5	5	85.68	-0.04	0.757935	-0.05192
Summer	25.5	163.7	68.4	16	53.51	0.10	0.408215	0.377971
Autumn	38.9	329.2	126.0	30	50.86	0.12	0.34687	1.07834
Winter	75.4	228.2	132.6	32	28.81	-0.21	0.101451	-1.29722
Spring	38.7	177.9	93.8	22	41.72	0.09	0.465549	0.740682
Annual	295.1	607.7	420.9		18.77	0.13	0.306953	1.636053

Note: %Rain is the total contribution to monthly and seasonal totals. Values in bold indicates a significant value with a 95% confidence level

On average Kosierskraal, with a higher elevation in the upper Nuwejaars catchment, experiences higher annual, seasonal and monthly rainfall. The coefficient of variation (CV) of the annual rainfall at Kosierskraal and Prinskraal is 18%, while monthly and seasonal variations are all above 30%. The CV of the annual rainfall at Zeekoevlei is 24%, with monthly and seasonal variations all above 30%. The degree of variability is considered high when the CV is greater than 30% (Asfaw *et al*., 2018).

3.3.1.2 Homogeneity and Mann-Kendall trend test

Results of the homogeneity tests for Kosierskraal suggest that the rainfall data is not homogenous as there was an abrupt change in the rainfall data in 2005 (Table 3.8). The computed *p-value* for Kosierskraal using the Pettitt test, Standard Normal Homogeneity Test (SHNT) and the Buishand's test were 0.005, 0.001 and 0.000 respectively (Table 3.8). The computed *p-value* for the homogeneity tests for Zeekoevlei and Prinskraal suggests that the rainfall is homogenous.

Table 3.8 Homogeneity tests for rainfall series

Station	Pettitt		SHNT		Buishand	
	***p*-value**	**Change point**	***p*-value**	**Change point**	***p*-value**	**Change point**
Kosierskraal	0.005	2005	0.001	2005	0.000	2005
Zeekoevlei	0.443	-	0.605	-	0.237	-
Prinskraal	0.558	-	0.259	-	0.710	-

Abrupt changes in the rainfall series may signal climatic regime shifts, although non-climatic factors such as a change to the properties of the rainfall gauge or changing conditions surrounding the rainfall gauge, may also be responsible (Peterson *et al*., 1998). Although the landowner indicates a change in properties of the rainfall gauge, specific metadata of the Kosierskraal rainfall station is not available. Given the same results for the three homogeneity tests, interpretation of the rainfall series from Kosierskraal is done with caution. The results of the Mann-Kendall trend test for the rainfall for Kosierskraal suggest that there is a trend in the annual and winter rainfall series, with the computed *p*-value of 0.010 and 0.0176, (less than 0.05 at alpha level 0.5) respectively. With a Sen's slope of 4.750 and 2.86, the trend test suggests that the annual and winter rainfall at Kosierskraal, in the upper Nuwejaars catchment, is increasing. The computed *p*-value for Zeekoevlei (p = 0.341) and Prinskraal (p = 0.307) was greater than 0.05 at alpha level

0.5, and showed no trend in the rainfall data series. Trend analysis for the rainfall stations shows no statistically significant trend in the monthly rainfall data (Table 3.5 to Table 3.7).

3.3.1.3 Wet and dry conditions

The Standard Precipitation Index (SPI) for the 1, 3, 6 and 24-month time scales for Kosierskraal, Prinskraal and Zeekoevlei show periods of *very* and *extremely wet* and *dry* conditions (Figure 3.5 - Figure 3.7). *Very wet* conditions are graphically illustrated when the SPI values exceed +1.5, i.e. the upper red line on the chart. *Very dry* conditions are graphically illustrated when the SPI values exceed -1.5, i.e. the lower red line on the chart (Figure 3.5 - Figure 3.7). The SPI shows periods of extreme wet conditions, with SPI values above 2.0 occurring at Zeekoevlei and Kosierskraal in 2005 and between 2013 and 2014. The relative frequency of *very* and *extremely wet* periods were more common than *very* and *extremely dry* periods for all stations at the 1 and 3-month SPI (Table 3.9).

At the 6-month SPI, the relative frequency of *very* and *extremely wet* conditions were more prominent than *very* and *extremely dry* conditions at Zeekoevlei. The SPI results show that the frequency of extreme wet periods are more prominent than dry periods at Kosierskraal in the upper Nuwejaars catchment, while extreme dry periods or hydrological drought (i.e. 24-month SPI) occur more frequently than flood events within the lower Nuwejaars catchment.

The occurrence and timing of wet and dry periods vary within the catchment. The SPI-24 shows one specific period, i.e. 2011 to 2013, where Zeekoevlei experienced *very dry* conditions (Figure 3.6), while Kosierskraal experienced *near normal* to *moderately wet* conditions (Figure 3.5). At Zeekoevlei, *severe* drought conditions from 2011 to 2013 are followed by *extreme* wet conditions between 2013 and 2014, and *severe* drought conditions from 2017 (Figure 3.6).

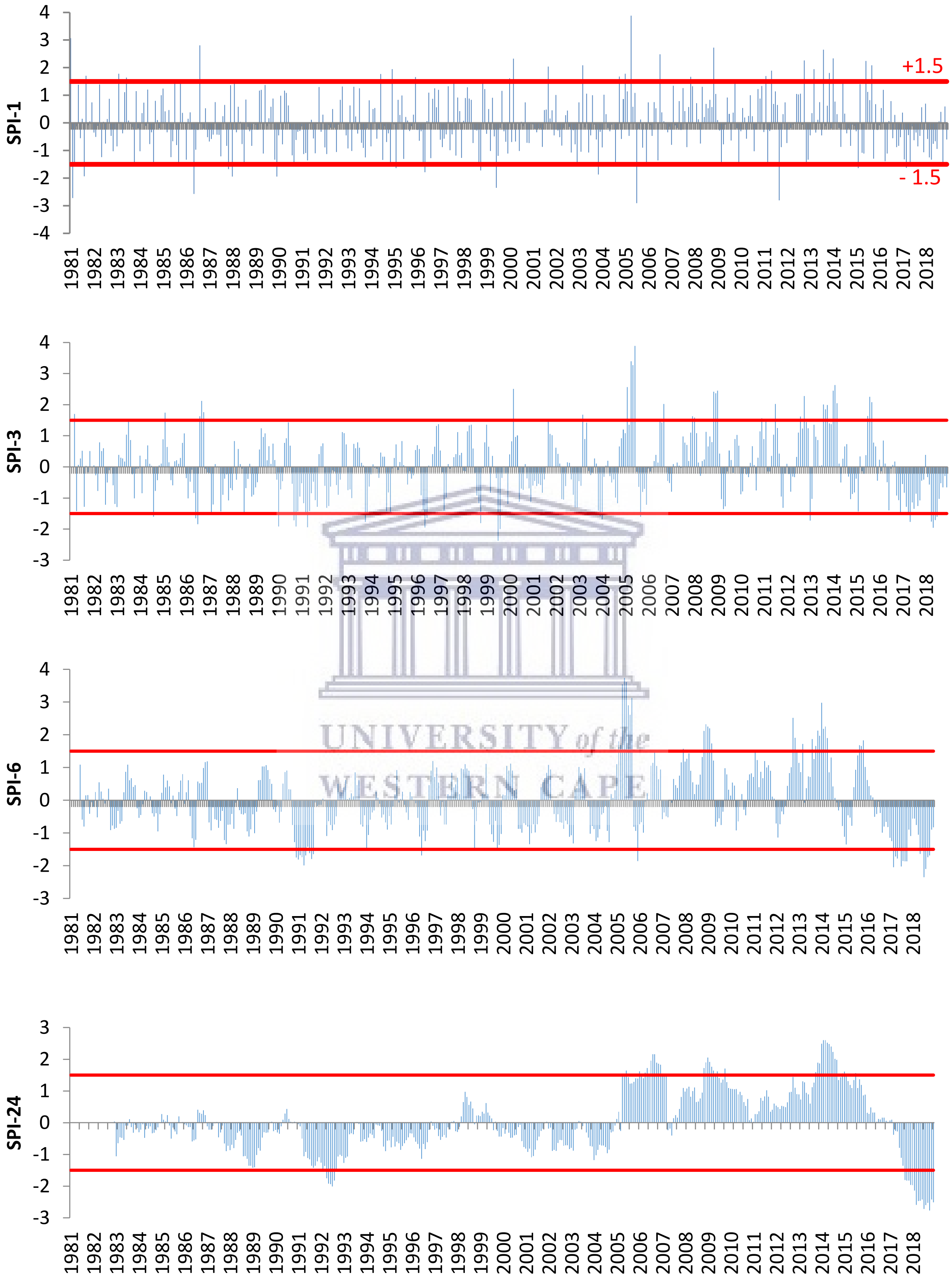


Figure 3.5 SPI values for Kosierskraal (1981 – 2018)

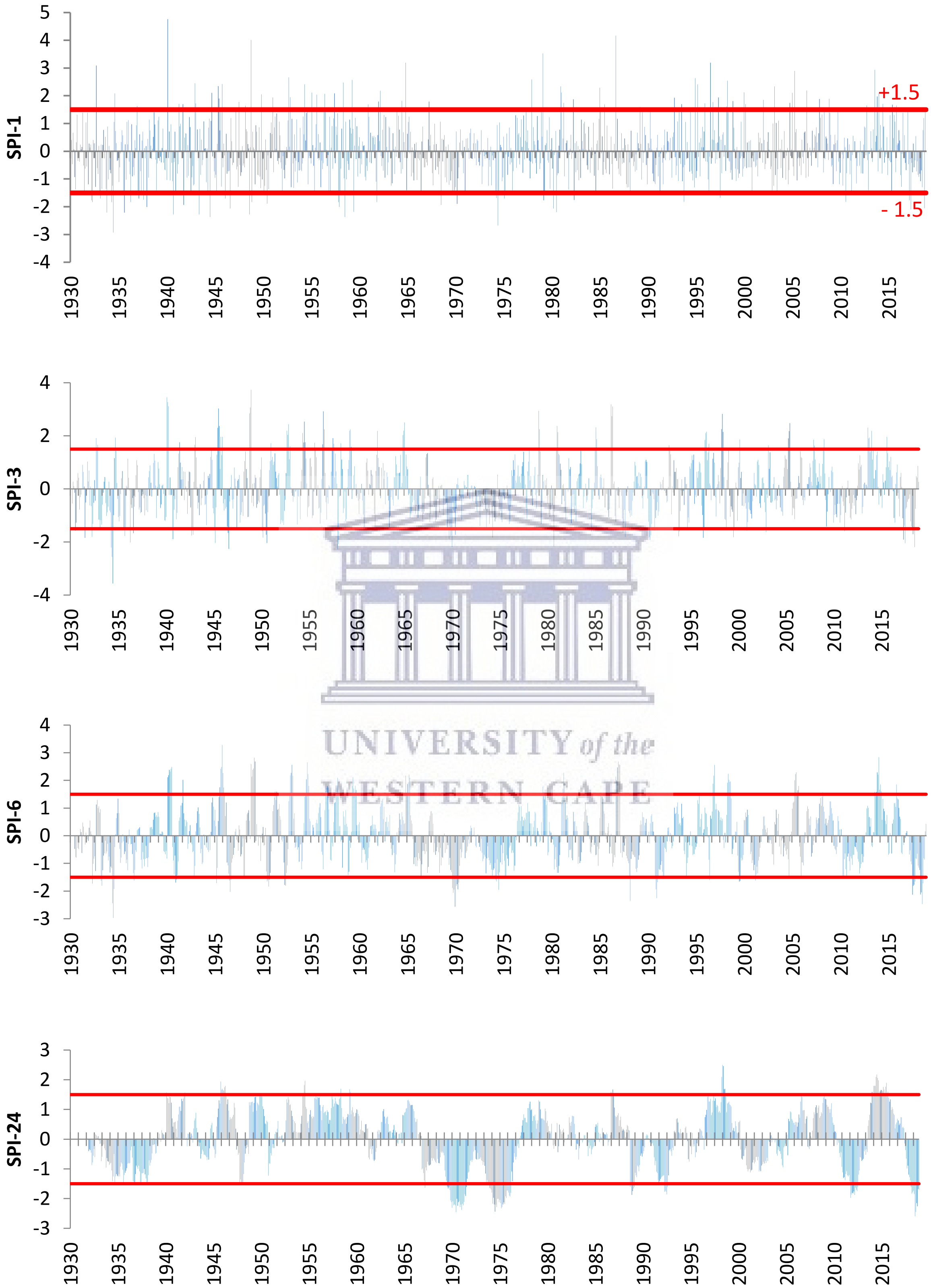


Figure 3.6 SPI values for Zeekoevlei (1930 – 2018)

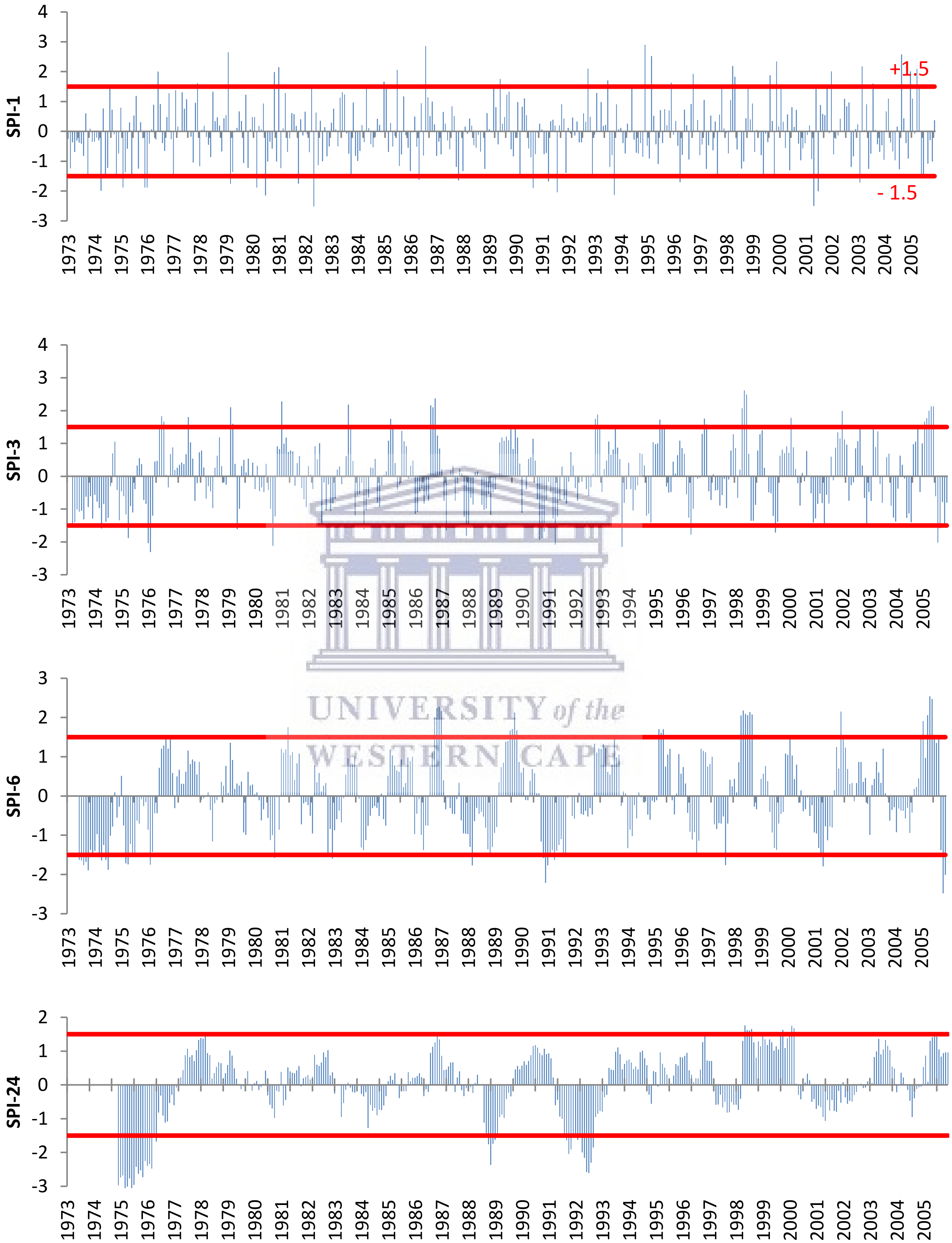


Figure 3.7 SPI values for Prinskraal (1973 – 2005)

Table 3.9 Relative frequency (%) of near normal, *wet* and *dry* periods for the SPI at various time scales in the Nuwejaars catchment

	Extremely wet	Very wet	Moderately wet	Near normal	Moderate drought	Severe drought	Extreme drought
Prinskraal (1973 – 2005)							
SPI-1	4.0	4.5	7.8	66.7	10.4	4.8	1.8
SPI-3	3.3	5.6	9.6	63.2	12.2	4.6	1.5
SPI-6	3.8	4.1	11.0	62.7	10.0	7.7	0.8
SPI-24	0.0	3.5	12.9	70.8	3.2	3.5	6.2
Zeekoevlei (1930 – 2018)							
SPI-1	3.3	4.5	7.2	69.0	10.9	3.4	1.8
SPI-3	4.1	3.4	8.6	67.6	10.3	4.9	1.1
SPI-6	4.1	4.1	8.4	67.8	9.4	4.5	1.7
SPI-24	0.9	6.7	12.0	63.1	8.2	6.1	3.0
Kosierskraal (1981 – 2018)							
SPI-1	3.1	3.9	10.7	65.6	11.2	4.4	1.1
SPI-3	4.2	3.3	9.0	66.1	11.0	5.7	0.7
SPI-6	3.5	3.3	9.1	69.2	8.6	5.1	1.1
SPI-24	3.0	6.7	9.7	67.7	7.6	2.1	3.2

3.3.1.4 Drought characteristics

Characteristics of the 24-month SPI in the Nuwejaars catchment illustrate *severely dry* and *extremely dry* conditions where SPI values are less than -1.5 (Table 3.10). The *extremely dry* periods of the 1970s is reflected for Zeekoevlei and Prinskraal. The duration of the severe 1970 hydrological drought at Zeekoevlei is 119 months from March 1967 to February 1977 with a peak intensity of -2.46, a magnitude of -159.8 and a mean intensity of -1.34. With rainfall data only available at Prinskraal from 1973, the drought period is from December 1974 to March 1977, with a duration of 27 months, a peak intensity of -3.18, magnitude of -52.13 and mean intensity of -1.93. Although *extremely dry* periods between September 1991 and April 1993 were observed for all stations, the characteristics of drought varied (Table 3.10). The severe drought conditions experienced throughout the Western Cape, South Africa from 2016 to 2018 is reflected with SPI values less than -2.0 for both Kosierskraal and Zeekoevlei (Figure 3.5, Figure 3.6 and Table 3.10). The onset of extreme hydrological drought (24-month SPI less than or equal to -1.5) is reflected at Kosierskraal in September 2017 and in February 2018 at Zeekoevlei. Between 1925 and 2018 (i.e. 93 years) there have been 3 extreme drought events at Zeekoevlei, within the lower Nuwejaars catchment.

Table 3.10 Drought characteristics for the 24-month SPI

	Period		Duration	Peak Intensity	Magnitude	Mean
	Start date	End date	(months)	(SPI value)	(Sum)	Intensity
Zeekoevlei	1919-08-01	1921-06-01	22	-1.65	-23.1	-1.05
	1925-07-01	1932-09-01	86	-2.75	-90.46	-1.05
	1969-10-01	**1977-02-01**	**88**	**-2.32**	**-119.07**	**-1.35**
	1988-09-01	1990-05-01	20	-1.88	-20.19	-1.01
	1992-04-01	**1993-04-01**	**12**	**-1.86**	**-12.31**	**-1.03**
	2011-10-01	2013-08-01	22	-1.97	-25.39	-1.15
	2017-11-01	**2018-12-01**	**14**	**-2.45**	**-21.65**	**-1.97**
Prinskraal	**1974-12-01**	**1977-03-01**	**27**	**-3.18**	**-52.13**	**-1.93**
	1988-10-01	1989-10-01	12	-2.37	-12.95	-1.08
	1991-09-01	**1993-04-01**	**19**	**-2.61**	**-29.14**	**-1.53**
Kosierskraal	**1992-01-02**	**1993-01-08**	**18**	**-2.01**	**-21.51**	**-1.19**
	2017-09-01	**2018-12-01**	**16**	**-2.77**	**-37.03**	**-2.3**

**Values in bold show overlapping periods of hydrological drought*

The impacts of historic flood and drought conditions on the water resource of Soetendalsvlei were recorded in the Van Breda Journal from 1840 to 1944 (Bickerton, 1984), with records of the desiccation of Soetendalsvlei from 1929 to 1934. A journal entry on 13 May 1929 reads: "*The deepest part of the vlei which has been drying up consistently for 2 years is now 19 inches* (48,6 cm)" (Bickerton, 1984, p11). The desiccation of Soetendalsvlei in the 1930s is associated with a hydrological drought, with a peak intensity of -2.75 and a drought duration of 86 months for the 24-month SPI at Zeekoevlei (Table 3.10). Bickerton (1984) also notes the drying-up of Soetendalsvlei in 1970. The desiccation of Soetendalsvlei in the 1970s is associated with peak intensity values of the 24-month SPI ranging from -2.32 and -3.18 for Zeekoevlei and Prinskraal respectively. Severe drought conditions from 2017 to 2018 caused the desiccation of Soetendalslvlei. Drought conditions from 2017 to 2018 are associated with peak intensity values of the 24-month SPI ranging from -2.45 and -2.77 for Zeekoevlei and Kosierskraal respectively. The three occurrences of the desiccation of Soetendalsvlei are associated with 24-month SPI values less than -2.32 at Zeekoevlei.

3.3.2 Historical analysis of land cover change of Soetendalsvlei (1938 – 2014)

The evidence of cultivated fields and infrastructure, such as roads, is prominent in the study area by 1938, already signifying the importance of agriculture in shaping the cultural landscape (Figure 3.8). The spatial and temporal land cover of Soetendalsvlei and the surrounding landscape changed significantly from 1938 to 2014 (Tables 3.11).

Table 3.11 Extent (in km^2) and proportion of land cover change in, and surrounding, Soetendalsvlei from 1938 to 2014 (The (-) and (+) signs indicate a respective increase and decrease in percentage)

	Area (km^2)					Change in percentage	
Lake Area	**1938**	**1961**	**1973**	**1989**	**2014**	**1938 - 1989**	**1989 - 2014**
Open water	13.2	7.98	3.24	10.23	8.26	-29	-24
Emergent Vegetation	2.7	7.6	9.82	5.66	7.63	+53	+26
Sediment	0.06	0.42	2.94	0.11	0.11	+46	0
Surrounding Landscape							
Agriculture	15.8	25.9	32.3	33.8	21.8	+114	+36
Shrubland	40.4	29.7	23.2	22.8	24.1	-43	+6
Wetland	13.0	12.8	12.8	10.6	12.6	-18	+19
Low density woodlands	0.7	0.5	0.6	0.4	0.9	-43	+125
High density woodlands	0.2	0.8	1.1	2.1	1.2	+950	-43
Bare soil	0.2	0.1	0.2	0.1	0.0	-50	-100
Infrastructure	0.5	0.6	0.6	0.6	0.4	+20	-33

3.3.2.1 Historic land cover of Soetendalsvlei

The spatial extent of the land cover of Soetendalsvlei has changed significantly between 1938 and 2014 (Figures 3.8 and Table 3.11). The ratio of open water to emergent vegetation is dependent on the water level of the lake and occurrence of vegetation (Sánchez-Carillo *et al.*, 2004). The open water area of Soetendalsvlei was variable between 1948 and 2014, with a significant decline in 1973 due to drought conditions. Emergent vegetation increased by 138% from 1938 to 2014, while exposed sediment increased by 83%. A distinctive feature in Soetendalsvlei is the delta created when the Nuwejaars River flows into the lake.

In 1938, emergent vegetation covered 2.7 km^2 of Soetendalsvlei, approximately 17% of the surface area. The emergent vegetation was distributed along the western shore, along the Nuwejaars River at the inflow into Soetendalsvlei, along a narrow band extending from the mid-to-eastern shore and at the outflow to the Heuningnes River (Figure 3.8).

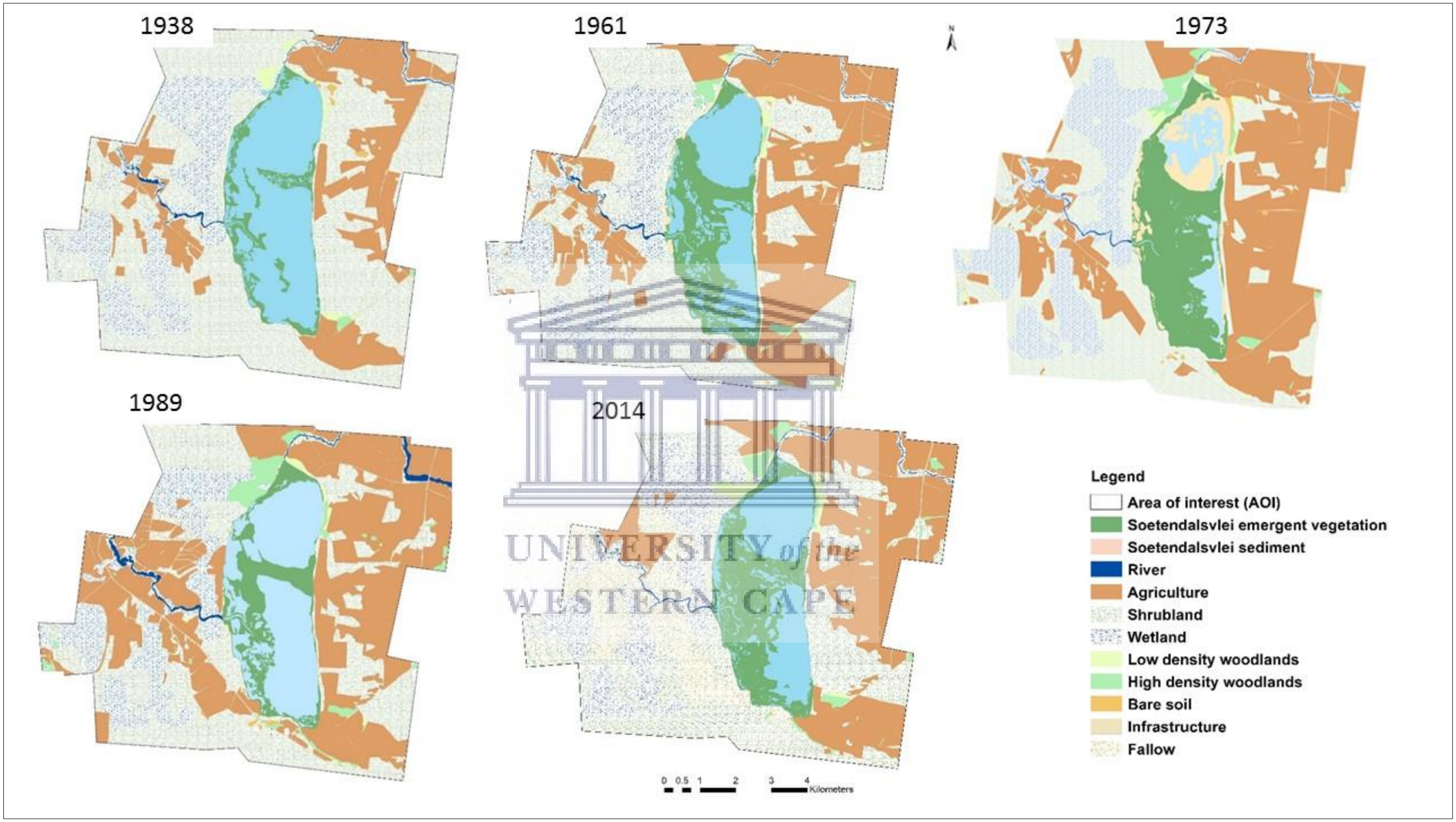


Figure 3.8 **Land cover/land use for 1938, 1961, 1973, 1989 and 2014**

The northern-eastern shoreline of Soetendalsvlei, during 1938, is sandy and un-vegetated (Figure 3.9A&D). With a lower water level in 1961, compared to 1938, more emergent vegetation is observed in 1961, with interspersed and isolated pools of water along the western shoreline. The mid-to-eastern shore vegetation is more prominent, visibly separating the lake into two open water bodies.

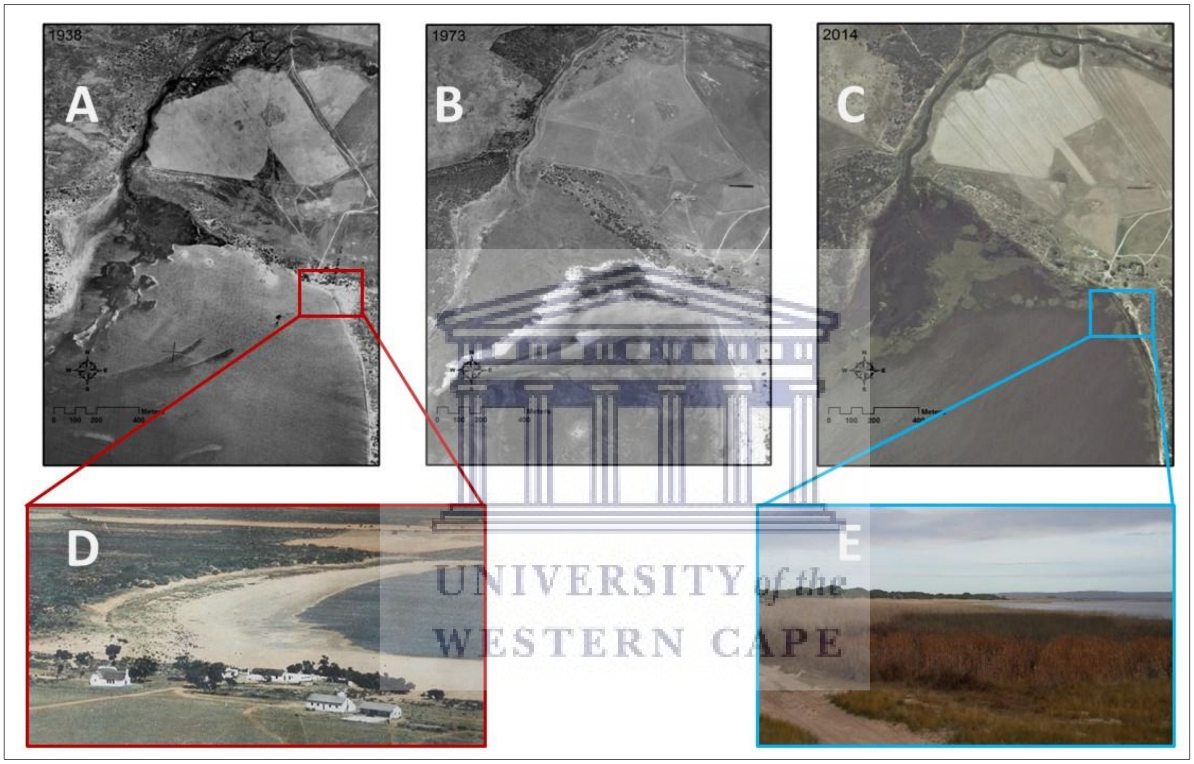


Figure 3.9 Historical aerial photographs of the (A) northern shoreline of Soetendalsvlei for 1938, (B) 1973 and (C) 2014; Photographs illustrating vegetation cover on the northeastern shore of Soetendalsvlei (D) is almost absent between 1939 and 1945 and (E) prominent in 2017

The most prominent change in the land cover in Soetendalsvlei is evident from the 1970s drought; with the sandy, exposed and receding lake shoreline and the open water decreased to 2.32 km^2 (Figure 3.8). Informal discussions with a farmworker at Vissersdrift indicated that the water level of the northern pool of Soetendalsvlei, during the drought of the 1970s, was so low "*one could walk straight across*" the lake. The anecdotal response correlates well with the exposed lake bed visible from the aerial photograph of 1973 (Figure 3.9B). The aerial photographs of 1989 and 2014 reflect high lake water levels, with Soetendalsvlei South covering a larger area of open water than the northern depression for both years. Emergent vegetation increased by almost 2 km^2 from 1989 to 2014.

A comparison of a photograph taken in 2017 and a historical photograph taken during World War II (i.e. between 1939 and 1945), courtesy of the landowner of Vissersdrift, supports the proliferation of reeds and sedges in, and along the northern shoreline of Soetendalsvlei from 1938 to 2014 (Figure 3.9D&E).

3.3.2.2 Land use and land cover surrounding Soetendalsvlei

The historical significance of Soetendalsvlei within the national farming community is partly attributed to the birth of the commercial merino sheep industry in South Africa by Michiel van Breda and John Frederick Reitz, who produced the first merino crossbreed and started wool farming at the south end of Soetendalsvlei in 1817 (Wilson, 1990). Between 1938 and 1973, almost 40% of the natural shrubland area was transformed into cultivated land and for livestock grazing (Figure 3.9 and Table 3.11). The change in land cover (from natural vegetation to cultivated land) was prominent to the east of Soetendalsvlei, along the Nuwejaars River and along the gravel road to the south of Soetendalsvlei. The spatial extent of high density woodlands increased by almost 2 km^2 from 1939 to 1989, and was prominent on the western shore of Soetendalsvlei and at the outflow to the Heuningnes River. Small nucleated and linear patterns of high-density woodlands are also located close to farmhouses and along infrastructure.

Roads across the Nuwejaars and Heuningnes River were visible in 1938. There are 2 road crossings along the Heuningnes River. The first road crossing, at the outflow at Soetendalsvlei, is a farm road also referred to as a drift (with one pipe culvert), is still in use. The second road, a bridge, currently no longer used, was the main road from Bredasdorp to Struisbaai (R319). In 1943, a new bridge was constructed on the R319 across the Heuningnes River (Bickerton, 1984). There is one farm road crossing on the Nuwejaars River.

Between 1938 and 1961 the sinuous pattern of the Heuningnes River between the outflow of Soetendalsvlei and the first road crossing, changed to a straight channel, with remnants of the 'old channel' partially filled with water (Figure 3.8 and Figure 3.9). The presence of vegetation along, and in, the Heuningnes River, increased significantly from 1938 to 1961.

Land cover change surrounding Soetendalsvlei is evident from the 1989 aerial photograph (Figure 3.9). Wetlands to the west of Soetendalsvlei were converted to agricultural lands with interconnected drainage ditches channelled into the Soetendalsvlei via one ditch (Figure 3.10). Cultivation and the growth of woodlands were prominent along the western shoreline of Soetendalsvlei (Figure 3.9). Shoreline development is visible by 2014, with an inlet and concrete jetty constructed along the eastern shoreline of Soetendalsvlei. According to informal discussions with both private landowners, the water quality of the lake allowed direct abstraction of water from Soetendalsvlei for domestic and agricultural uses. Boating, fishing and kite surfing were common forms of recreation on the lake. The two private landowners have rental accommodation facilities along Soetendalsvlei.

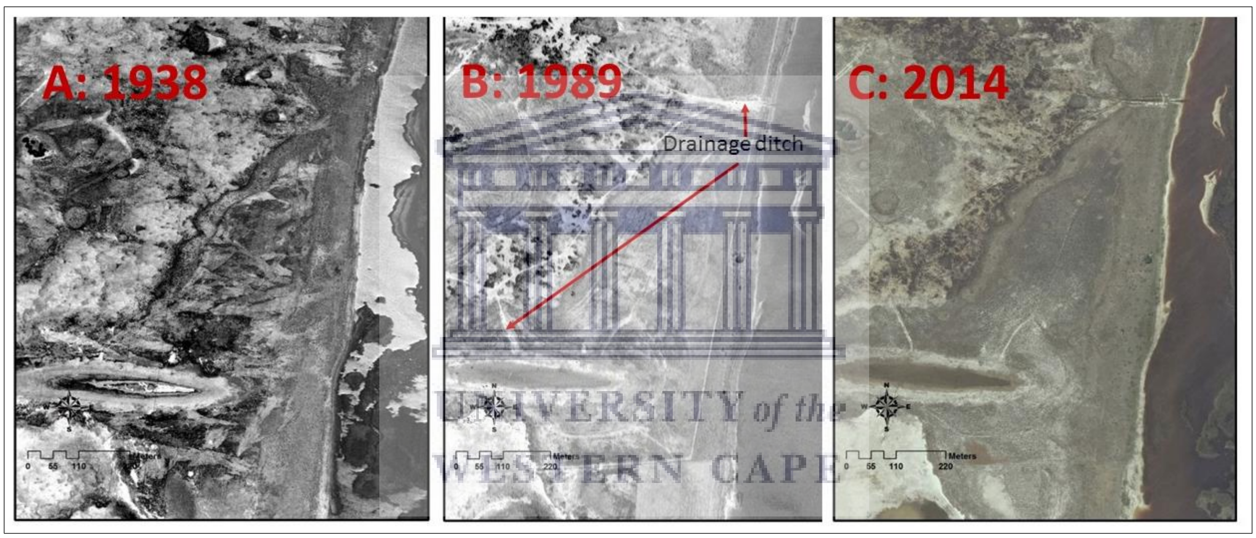


Figure 3.10 Historical aerial photographs of western shoreline of Soetendalsvlei for (A) 1938: natural vegetation, no agriculture, (B) 1989: cultivated land and ditches and; (C) 2014: rehabilitation of ditches with the agricultural footprint still evident.

By 1938, the area of the Soetendalsvlei, divided into 9 farm/erf portions, was under private land ownership (Figure 3.2). According to Barham (1968), direct abstraction of water on the western shore of Soetendalsvlei was limited due to the dense growth of reeds. Soetendalsvlei farm/erf number 276 was declared ‘Crown land’ in the 1940s, with the status as State Forest under the Forestry Act, 1888 (Cape Colonial Act 28 of 1888). According to a representative of the Nuwejaars Wetlands Special Management Area (NWSMA), farm 276, which is located within the centre of Soetendalsvlei (Figure 3.2), was identified/used for the landing of sea planes during World War II. The spatial area of farm 276, which originally formed part of the Zoetendals Vallei property, covers an area of 4.08 km^2 and forms part of the De Mond Nature Reserve Complex, under the provincial authority of Cape Nature. Soetendalsvlei Nature Reserve (farm/erf 276) was proclaimed a protected area in 1977, with World Heritage Status in 2015 (van Wilgen *et al*., 2016a), and represents 26% of the total area of the lake under formal protection/conservation.

The proclamation and the development of the Agulhas National Park (ANP) in terms of the National Parks Act (Act 57 of 1976), began in 1998/1999 (Kraaij *et al*., 2009) and had a direct influence on the land use and land cover dynamics in the study area. Farm portions of erf 280 and 286, to the west of Soetendalsvlei were proclaimed part of the ANP, and under national management (Figure 3.2). The change in landuse from agricultural to conservation status between 1989 and 2014 is evident with the fallow fields to the west and southwest of Soetendalsvlei (Figure 3.9). Fallow fields along the Nuwejaars River close to the inflow to Soetendalsvlei is also evident by 2014 due to the change in conservation status. Within the ANP, SANParks rehabilitated wetlands, with the rehabilitation of the drainage ditch into Soetendalsvlei being completed in 2004 (Appel. A, personal communication, 1 February 2017). The clearing of invasive alien vegetation in the ANP was evident by 2014. The area of Soetendalsvlei under the national management of SANParks represents 3.8 km^2 of the lake under formal national protection, with World Heritage Status in 2015. According to the conservation manager at the De Mond Nature Reserve (Ndlovu. T, personal communication, 13 December 2016), Cape Nature was in the process of transferring ownership of Soetendalsvlei farm/erf number 276 to SANParks. The remaining 4 farm portions (erf 273,274 and 280) of Soetendalsvlei are privately owned by 2 landowners, and forms part of the Nuwejaars Wetlands Special Management Area (NWSMA), with (informal) protection at a local level. By 2014, the coastal lake of Soetendalsvlei was afforded 100% protection, at national, provincial and local level.

3.4 Discussion

There are a complex range of factors, at different spatial, temporal and institutional scales, which have an impact on the extent of land cover and land use change in a landscape (Lambin *et al*., 2001; Musakwa & Wang, 2018) and on the consequent functioning of lake and wetland ecosystems (Schallenberg *et al*., 2013). Rainfall variability and land use and land cover change immediately surrounding the coastal lake of Soetendalsvlei were assessed to understand how the properties of the lake had changed from 1938 to 2014.

3.4.1 Rainfall variability

Rainfall variability, specifically extreme events, is an important influence on catchment hydrology with significant impacts on surface and groundwater resources (Abiy *et al*., 2019) and aquatic ecosystem service provision such as water regulation, water quality amelioration and groundwater recharge (Talbot *et al*., 2018). Rainfall variability influences the timing and spatial extent of surface flooding (Halabisky *et al*., 2016; Buma *et al*., 2018) with consequent influences on wetland soils and plants (Casanova & Brock, 2000). An understanding of the temporal and spatial variability of rainfall, particularly where *in-situ* hydrological data is non-existent, can thus provide insight into how lakes and wetlands change and/or respond over time.

The spatial variation of rainfall in the Nuwejaars catchment is reflected with higher annual rainfall at Kosierskraal in the upper catchment, decreasing to lower annual rainfall at Zeekoevlei and Prinskraal to the east of the catchment. These results agree with the general decrease of rainfall along a west-east spatial gradient in South Africa (Bickerton, 1984), and is attributed to topographic effects, altitude, atmospheric processes and rainfall producing mechanisms (Midgely *et al*., 2005). The spatial variability has important implications for water resource management in the Nuwejaars catchment, as the upper catchment is an important recharge zone for groundwater resources that, in turn, sustain aquatic ecosystems within the lower Nuwejaars catchment (Toens *et al*., 1998). The temporal variation of rainfall in the Nuwejaars catchment is characterized by monthly, seasonal and inter-annual variability. Rainfall in the Nuwejaars catchment during autumn and winter, are primarily due to cold fronts and cut-off-low weather systems (Pharoah *et al*., 2016). Rainfall during autumn and winter account for almost 60% of the annual rainfall totals at all 3 rainfall stations in the Nuwejaars catchment. Below average rainfall during the rainy season, primarily due to the poleward migration of the moisture corridors can cause drought conditions with significant declines in water resources within the greater Western Cape (Sousa *et al*., 2018).

Considering only the homogenous rainfall data, there is no evidence of a significant change in the mean annual, seasonal or monthly rainfall for Zeekoevlei and Prinskraal. Previous trend assessments of annual and seasonal rainfall in the Western Cape, South Africa, using the Mann-Kendall test, also found no significant trends in the mean annual precipitation for the period 1960 – 2010/2017 (MacKellar *et al*., 2014; Lakhraj-Govender & Grab, 2019). Notable in both of these studies is the lack of rainfall stations in the Nuwejaars/Heuningnes catchment, except for the Cape Agulhas station at the south-end of the catchment. When changing the period of observation from 1987 to 2017, for the same observed rainfall stations/data, Lakhraj-Govender & Grab (2019) and assessments by Botai *et al* (2017) found decreasing trends in annual rainfall for most of the select stations in the Western Cape, including Cape Agulhas. Assessing trends will thus vary depending on the geographic location and the period of observation. What is vital is understanding the spatio-temporal rainfall trends, and the consequent impact on water resources, aquatic ecosystems and livelihoods. Thus while the SPI is a useful drought monitoring tool, its application as an impact-based tool on surface water resources can have useful application.

The Standard Precipitation Index (SPI) at different temporal scales has highlighted the occurrence, frequency, intensity, magnitude and duration of extreme wet (floods) and dry (drought) events within the Nuwejaars catchment, and is a useful monitoring mechanism for surface water resources. Extreme wet events in the Western Cape, and particularly in the Nuwejaars catchment from 2003 to 2014, were due to cut-off-low pressure systems (Pharoah *et al*., 2016) and are associated with SPI values greater than 1.9 in the Nuwejaars catchment. Floods in January 2014 to September 2015 (de Waal *et al*., 2017); April 2005 (Cleaver & Brown, 2005) and July 1978 (Cleaver & Brown, 2005) were particularly noteworthy in causing significant damage to property and livelihoods. The sediment accumulation rate associated with the April 2005 flood in the Nuwejaars catchment was determined at 0.83 mm/year in 2006 (+/-0.03), as compared to the sediment accumulation rate of 0.237 mm/year in 2004 (Gordon *et al*., 2012).

The utility of the SPI has been significant in indentifying the frequency of agricultural, meteorological and hydrological drought within the Nuwejaars catchment. The recent onset of drought conditions from 2016 within the greater Western Cape caused significant declines in water resources, with huge financial losses to the agricultural and tourism sectors (Sousa *et al*., 2018). The utility of the SPI in monitoring surface water resources has also been documented for Lake Sibayi (Nsubuga *et al*., 2019); Lake Chad (Ndehedehe *et al*., 2016) and Poyang Lake (Zhang *et al*., 2015). While acknowledging the complexity of the relative impacts of rainfall variability, catchment conditions and anthropogenic influences on surface water resources, Zhang *et al*., (2015) found that drought characteristics, such as drought duration, magnitude and intensity provided context to understanding the impacts on water inflow into the lake, and the lake level fluctuation of Poyang Lake. Results from this present study supports Zhang *et al*., (2015), particularly when understanding the impact of extreme events on Soetendalsvlei. Extreme hydrological drought, where the peak intensity is less than -2.3, within the Nuwejaars catchment, results in the desiccation of Soetendalsvlei. Further exploration of the impacts of rainfall variability, particularly extreme events, on surface water resources would be beneficial at a finer temporal and spatial scale (and will be explored in Chapter 4).

The pattern of wet and dry rainfall periods is not similar within the Nuwejaars catchment, and this spatial variation may be attributed to diverse factors influencing rainfall variability within this most southerly catchment in South Africa (Midgely *et al*., 2005). There was an identifiable increase in consecutive extreme events from 2010 to 2018, with hydrological drought from 2011 to 2013; floods in 2014 to 2015, and the recent hydrological drought from 2016 to 2018. Although the long-term monthly rainfall data in the Nuwejaars catchment does not support the predicted general decline in annual rainfall in the Western Cape (Dallas and Rivers-Moore, 2014; MacKellar *et al*., 2014), the impact of the consecutive extreme climatic events on the livelihoods of communities in the Nuwejaars catchment, may contribute to the perception of climate change. Given the SPI results, understanding the perceptions of climatic variability/change and the consequent adaptation strategies is particularly important for water resource management.

3.4.2 A changing landscape

Within the timeframe utilized for this study (1938 to 2014, i.e. 76 years) the trajectory of environmental change related to land use and land cover within the lower Nuwejaars catchment can be identified by two 'paradigms' that are intricately connected to human decisions and activities, with direct and indirect impacts on the coastal lake of Soetendalsvlei.

3.4.2.1 Agricultural intensification

The first paradigm, "agricultural intensification", between 1938 and 1989 was associated with agricultural-related activities causing the increased transformation of natural vegetation and wetlands into/for cultivated fields and livestock grazing; as well as the proliferation of invasive alien vegetation. Similar trends of agricultural expansion, during the period 1938 to 1989, occurred throughout South Africa (Halpern & Meadows, 2013; Weyer *et al*., 2015; Petersen *et al*., 2017) and in other countries such as China (Song *et al*., 2012), the United States of America (Mitsch & Gosselink, 2007) and Slovakia (Kanianska *et al*., 2014) with negative consequences on wetland functions (Cohen-Shacham *et al*., 2011).

The agricultural policies of the South African government prior to the 1980s, was to lean towards self-sufficiency of the country in its ability to feed the growing population (Hoffman, 2014). The intensification of agriculture between 1938 and 1989, within an area dominated by white commercial farmers, such as the Nuwejaars catchment, (Conradie, 2010) was guided by agricultural-related policies and programmes that promoted food security, and was supported through financial aid which included tax-incentives and subsidies (Hoffman, 2014). While the ‘swampy areas’ or ‘water logged areas’ of wetlands were not well-defined in relevant legislation, the Agricultural Resources Act (Act 43 of 1983) promoted the development of drainage works to protect irrigated soils (Kirsten *et al*., 1994). The conversion and cultivation of wetlands, and the disregard for buffer zones around wetlands indicates a lack of protection policies for wetlands (Breedt & Dippenaar, 2013) and the overriding economic benefit of food production as opposed to wetland conservation (Song *et al*., 2012). The impact of policies and governance systems can be significant in determining how land is utilized and managed (Kanianska *et al*., 2014; Yin *et al*., 2018) with significant impacts on runoff characteristics (Sajikumar & Remya, 2015) and ecosystem functioning (Weyer *et al*., 2015).

The negative impact of agricultural-related activities on wetlands has been documented worldwide (Mitsch & Gosselink, 2007). Technological advancement is identified as a significant driver of wetland and ecosystem change (van Asselen *et al*., 2013) and this is evident with increased drainage of wetlands in the lower Nuwejaars catchment between 1973 and 1989. The development of agricultural drainage ditches decreases waterlogging by increasing the transfer of surface and/or shallow groundwater to a downstream outlet (Dollinger *et al*., 2015). Natural depressions such as Soetendalslvei, conveniently act as the storage ‘outlets’ from drainage ditches and from return flows, thereby altering the amount and timing of flow conditions between the depression and the drained surrounding landscape (McCauley *et al*., 2015). In addition, these drainage ditches increase the potential transport of sediment and nutrients from the cultivated fields to the ‘outlets’ (Russell, 2003; Moorman *et al*., 2017). Gordon *et al*., (2012) assessed sedimentation accumulation rates for Soetendalsvlei through radiocarbon dating of sediment cores, and found an increasing rate of sedimentation, the equivalent of 0.106 mm/year from 1916 (+/- 64) to 0.237 mm/year in 2004 (+/- 0.46) mainly due to a change in land use activities. Sediment accumulation rates ranging from 0.35 and 0.42 cm/year in Lake Sibayi, South Africa, higher than the rates for Soetendalsvlei, is associated with increased human development and the clearing of swamp forest along the western shore of the lake (Humphries & Benitez-Nelson, 2013). In an assessment of sediment accumulation rates for 278 European lakes since 1850, Rose *et al*., (2011) concluded that lowland lakes, as compared to high altitude lakes had a higher rate of sedimentation mainly due to the impacts of upstream landuse change, agricultural practices and eutrophication.

The altered hydrology, increased sedimentation and nutrient enrichment due to the intensification of agricultural activities in the catchment is the most likely cause of the proliferation of emergent vegetation, such as *Phragmites Australis,* within Soetendalsvlei and along the floodplain wetlands (Liira *et al*., 2010; Canavan *et al*., 2018). Although natural succession processes can cause growth of emergent vegetation in water bodies, the long-term assessment of aquatic macrophytes, using aerial photographs, for Lake Issaqueena, USA (Pilgrim *et al*., 2015), Lake Cheimaditida in Northern Greece (Papastergiadou *et al*., 2008), Lake Stymfalia, Greece (Papastergiadou *et al*., 2007) and the Wilderness Lakes, South Africa (Russell, 2003) have been linked to land use intensification within lake catchments. The expansion of emergent vegetation between 1938 and 2014 is especially prominent within the south pool of the Soetendalsvlei, at the inflow of the Nuwejaars River into the lake and at the outflow into the Heuningnes River. This is significant for two reasons. Firstly, according to Ollis *et al*., (2013), 2 m is the maximum depth where rooted emergent vegetation is found. Without repeat bathymetric maps and/or *in situ* water levels, inference can be made about the shallow(ing) depth (less than 2 m) and changing morphology and conditions of the Soetendalsvlei, by considering the increased spatial extent of emergent vegetation from 1938 to 2014 (Liira *et al*., 2010). Secondly, although the expansion and single species domination of *Phragmites Australis* in the Wilderness Lakes is considered a threat to the biodiversity of fauna and flora (Russell & Kraaij, 2008), the expansion of reeds in the Soetendalsvlei, and along the floodplain wetlands, enhances ecosystem services. According to the manager at De Mond CapeNature, the reeds provide water quality amelioration and increased habitat diversity (Ndlovu. T, personal communication, 13 December 2016). A comparison of wetland status of selected wetlands in the Western Cape, South Africa from 1991 to 2014, regards the water quality in Soetendalsvlei as "fairly similar or possibly improved" (Malan *et al*., 2015). While increased macrophytes in aquatic ecosystems enhances water clarity, improves water quality and provide habitat and food for birds (Kotze *et al*., 2009; Zhang *et al*., 2017), continuous monitoring of lake dynamics are required to detect any change of this macrophyte-dominated aquatic ecosystem.

While land use and land cover change within a catchment can significantly affect the magnitude, timing and quality of water to the downstream catchment, where coastal lakes are intermittently influenced by tidal exchange, conditions within the estuarine zone can impact upstream coastal lakes. Due to the relatively flat coastal plain, when the mouth of the Heuningnes River is blocked by drifting sand, flooding of the cultivated low-gradient landscape would occur (Bickerton, 1984). To protect cultivated lands, the drifting sand was stabilized by 1942 to prevent mouth closure, and the artificial breaching of the estuarine mouth took place to prevent flooding (Bickerton, 1984). The estuarine manipulation 15 km downstream of Soetendalsvlei, prevented the "back-flooding of estuarine water into the lake", and have thus influenced the present conditions of the lake (after 1972), and the connectivity of the lake and the downstream estuary (Gordon, 2012, p192).

3.4.2.2 Conservation awareness

The 1970s was seen as a new global era in terms of conservation. In 1975 South Africa became a signatory to the Convention on Wetlands of International Importance (RAMSAR convention). The implementation of key environmental policies such as National Parks Act (Act 57 of 1976), the Conservation of Agricultural Resources Act (Act 43 of 1983), the Environment Conservation Act (Act 73 of 1989), the Water Act (Act 36 of 1998) and the National Environmental Management Act (Act 107 of 1998) afforded legal protection to the natural environment including wetlands. In 1995, South Africa ratified the Convention on Biological Diversity to ensure the conservation of biological diversity. While various legislation have been developed for wetland protection, there are various reasons why the implementation of these policies are challenging (Breedt & Dippenaar, 2013). Given the nature of wetlands, i.e. the transition of terrestrial and aquatic systems, these ecosystems are governed by various legislation, and thus policy for wetland protection is highly fragmented (Goosen & Blackmore, 2019). In addition, the capacity of government for wetland monitoring and enforcement of policy is limited (van Wilgen *et al*., 2016a).

Increasing concern on the loss and fragmentation of ecosystems, such as the Cape Floristic Kingdom that includes the Nuwejaars catchment received much attention at international, national and local level (Cole *et al*., 2000; van Wilgen *et al*., 2016a). Several authors (Cole *et al*., 2000; Jones *et al*., 2000; Cleaver & Brown, 2005; Malan *et al*., 2015) summarize the biodiverse importance of the fauna and flora, and the diverse wetlands in the Nuwejaars catchment, with van Wilgen *et al*., (2016a) providing a comprehensive overview of scientific research and conservation measures in the Cape Floristic Region between 1945 and 2015. The review by van Wilgen *et al*., (2016a) provides insight to the influence of political and institutional change, management strategies and projects (particularly the Cape Action for People and the Environment (C.A.P.E) project and the Agulhas Biodiversity Initiative (ABI)) which had direct and indirect impacts on management strategies for the Nuwejaars catchment.

The second paradigm that is post-1989, reflects a trajectory of "conservation awareness and action/reaction" within the Nuwejaars catchment. This paradigm broadly reflects the recognition (through action, behavior and commitment) of the importance of biological diversity and the natural environment through the formal and informal protection of both aquatic and terrestrial ecosystems. Prominent within the Nuwejaars catchment is the change of land ownership from private to government/state, cementing the change in the status of land from agricultural use to statutory conservation status (Weyer *et al*., 2015). Challenges in expanding state-owned protected areas are the financial cost of land acquisition and the unwillingness of farmers to sell their property (Knight *et al*., 2011). The other main mechanism for the expansion of protected areas, and the most cost effective for government, has been through biodiversity conservation (stewardship) programmes where landowners retain ownership of their land, but formerly agree to protect and manage biodiverse areas (van Wilgen *et al*., 2016a; Skowno *et al*., 2019). With a significant proportion of wetlands on farmland (i.e. erven), farmers are “primary de facto managers” of these resources (Smith & Sullivan, 2014, p72), and thus farmers play a significant role in promoting biodiversity. The collaborative action of farmers and communities in the lower Nuwejaars catchment, together with the support of key stakeholders, were instrumental in forming the Nuwejaars Wetlands Special Management Area (NWSMA). Although the establishment of the NWSMA may initially have been a strategic decision/response by farmers in ensuring the long-term property rights during the process of land appropriation for conservation, the primary goal of the NWSMA is to promote sustainable development, with the conservation of wetland ecosystems a key priority. The NWSMA has transcended the individual property/erven boundary to ensure the collective conservation of the Nuwejaars wetland ecosystems. The commitment from private landowners affiliated to the Nuwejaars Wetlands Special Management Area (NWSMA) to the sustainable use of natural resources and the protection of the environment, are evident by 2014, with the agricultural landscape being transformed through the cessation of agricultural activity, regrowth/recovery of natural ecosystems, rehabilitation of drainage ditches and the clearing of dense stands of invasive alien vegetation. The rehabilitation of floodplain wetlands along a stretch of the Nuwejaars River, which includes the clearing of invasive alien vegetation, is linked to the increased extent and quality of habitat provision, particularly for bird species (NWSMA, 2019). To give effect to the conservation of biodiversity, the NWSMA promotes “connecting with partners to promote our conservation work” (NWSMA, 2019, p9), and has established a number of partnerships with various organizations (Figure 3.11). For example the partnership with Birdlife SA, the Overberg Crane Group and Overberg Renosterveld Conservation aim to promote the collation of relevant data to enhance the understanding of avian habitat preference, and so ensure appropriate conservation strategies within the agricultural landscape (NWSMA, 2019).

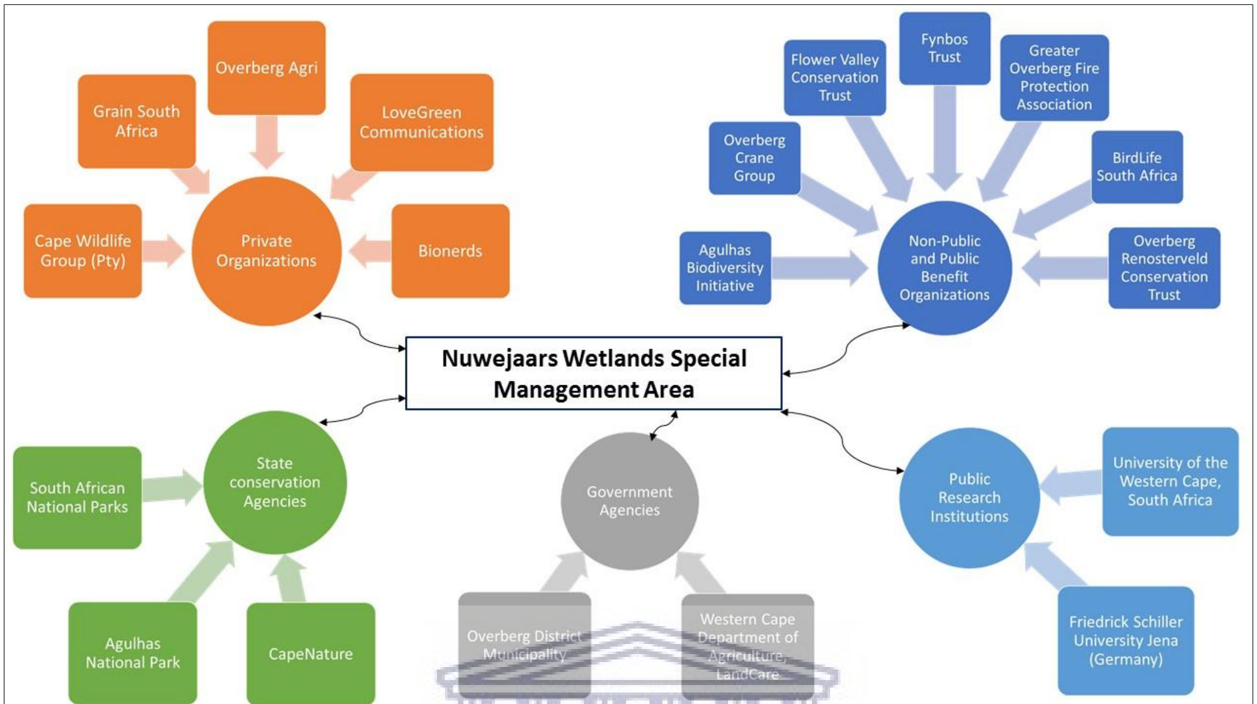


Figure 3.11 Partners affiliated to the Nuwejaars Wetlands Special Management Area (adapted from NWSMA, 2019)

The establishment of public-private-community partnerships with the NWSMA (Figure 3.11), with support from donors (such as the German Government, Global Environment Facility (GEF), World Wide Fund for Nature (WWF)), are regarded as an integral component of a co-management process which allows for knowledge generation, social learning and adaptive management (Cleaver & Brown, 2005; Berkes, 2009; NWSMA, 2019; Skowno *et al*., 2019). Together the NWSMA, SANParks and CapeNature ensure the protection of approximately 68% of wetlands in the Nuwejaars catchment (G50B and G50C). With wetland conservation provided at national, provincial and local level, the protected landscape identifies and promotes the importance of the 'waterscapes' and the connectivity of rivers, wetlands and the estuary in the Nuwejaars catchment. The formal conservation areas, managed by CapeNature (provincial authority) and SANParks (national authority) should comply with provincial and national legislation, international conventions and treaties that ensures the protection of biodiversity (Kraaij *et al*., 2009; Goosen & Blackmore, 2019). At the same time, and key to the successful management of conservation areas, the conservation authorities should also develop and strengthen stakeholder engagement and participatory management with relevant stakeholders, particularly communities surrounding the conservation area, and upstream within the catchment (Kraaij *et al*., 2009; Biggs *et al*., 2017;

Sterling *et al*., 2017). Thus, society and the influence of human decisions at different institutional levels (and at different times in the South African history) have direct and indirect impacts on the local landscape in terms of land use and land cover, and the consequent functioning of wetland ecosystems.

3.5 Conclusion

Rainfall variability in the Nuwejaars catchment and land use and land cover within and surrounding Soetendalsvlei were assessed with the aim of identifying environmental change and understanding the consequences of change in relation to the functioning of the coastal lake. The long-term rainfall data shows no evidence of trends in the lower Nuwejaars catchment, although increasing rainfall in the upper catchment was detected. The Standard Precipitation Index (SPI) was useful in identifying the variable seasonal and inter-annual rainfall in the Nuwejaars catchment, and the occurrence of *very wet* and *very dry* periods. Extreme meteorological and agricultural drought has occurred three times within the last 93 years (i.e. 1925 to 2018), with a significant impact on water resources. The intensity and duration of the 24-month SPI is a good indicator of the impacts of hydrological drought on Soetendalsvlei. Hydrological droughts have historically caused desiccation of Soetendalsvlei.

With the complex interactions of geomorphology, climate, hydrology, vegetation and fauna, the properties and functions of wetlands are inherently dynamic over time. However, the influence of human activities and decisions can change the conditions and characteristics of water flow, indirectly affecting the integrity and functioning of wetlands. The transformation of wetlands and shrublands into cultivated areas, the fragmentation of wetlands through the development of agricultural drainage ditches and transport infrastructure and the growth of invasive alien vegetation are identified as key anthropogenic effects in the lower Nuwejaars catchment since 1938. The underlying drivers of change during this period are mainly attributed to food security, economic growth and institutional factors such as economic and political policies. After 1989, there is evidence through the rehabilitation of wetlands, the occurrence of fallow fields and the reduction of cultivated fields, that the conservation, and possibly, the sustainable use of natural resources were important issues in the study area. The role of international and national legislation, the recognition of the value of natural ecosystems and its protection, as well as collaboration between key stakeholders were key driving forces in the conservation efforts within the study area. Although local conservation efforts may have been existent in the study area by 1938, the proclamation of the De Mond Nature Reserve Complex (which includes Soetendalsvlei) and the Agulhas National Park (ANP), through the respective national and provincial governments, gave effect to the statutory protection of wetlands in the study area. By 1999, Soetendalsvlei was provided with formal protection at national and provincial level. The decision by the local farming community surrounding the state protected areas, to provide informal protection status to the wetlands, together with multiple stakeholders in developing and supporting this NWSMA, effectively ensures commitment to the protection of the Soetendalsvlei, and surrounding wetlands, in the lower Nuwejaars catchment.

CHAPTER 4

LONG-TERM VARIATION OF INUNDATION: CASE STUDY OF SOETENDALSVLEI

4.1 Introduction

Freshwater resources such as lakes and wetlands are important for human well-being, while also supporting diverse biological communities. For many countries, specifically arid regions, the supply of water for domestic and agricultural use is crucial, and thus an understanding of inundation is vital for water resource management (Swenson & Wahr, 2009; Wu & Liu, 2015b). With many aquatic ecosystems adversely affected by changes in catchment hydrology and climate variability, the improved monitoring of freshwater resources is important (Niedda *et al*., 2014). However, hydrological monitoring networks are declining, lacking or absent in many catchments across the globe due to the remote nature of many of the lake systems (Gal *et al*., 2016) as well as inadequate funding (Pitman, 2011). The availability of remote sensing images, coupled with algorithms, mathematical models and Geographic Information Systems (GIS) provides an opportunity for monitoring lakes, while contributing significantly to understanding lake processes, particularly in areas where *in situ* measurements are not available (Ozesmi & Bauer, 2002; Swenson & Wahr, 2009; Song *et al*., 2014; Dörnhöfer & Oppelt, 2016). The advantage of remote sensing is that owing to its high spatial and spectral resolution, large-scale studies of catchment processes affecting lake dynamics can be monitored, at relatively short revisit times (Li *et al*., 2013; Ovakoglou *et al*., 2016). Satellite imagery has been applied in mapping the extent of surface water, water level changes, as well as water and vegetation properties of lakes (Ozesmi & Bauer, 2002; Song *et al*., 2014; Politi *et al*., 2016).

The lake area covered by water is commonly used as a proxy for depth and volume of water stored (Tebbs *et al*., 2013; Song *et al*., 2014). The water level and volume of water stored depend on a number of factors, including, but not limited to, the morphological characteristics of the lake and a balance of inflows and outflows. The patterns of inundation can be characterized by the frequency and duration of flooded areas. The patterns of inundation have important implications for scientific research, but are also important variables for classification of inland aquatic systems such as lakes and wetlands. Remotely sensed data on inundation patterns have been used for lake monitoring (Deus & Gloaguen, 2013; Gal *et al*., 2016; Wu & Liu, 2015a), lake surface change detection (Grundling *et al*., 2013; Nsubuga *et al*., 2015; Wu & Liu, 2015b), estimation of volume of water stored (Duan & Bastiaanssen, 2013; Lu *et al*., 2013), monitoring of birds (Boshoff & Piper, 1992; Tebbs *et al*., 2013; Pickens & King, 2014), habitat quality assessment (Bortels *et al*., 2011), as well as vegetation patterns and analyses (Dronova *et al*., 2012; Deng *et al*., 2014; Hu *et al*., 2015). The conclusion from these studies is that remote sensing provides a feasible approach to advance the understanding of complex and variable lakes and wetlands, especially in areas that are inaccessible or poorly gauged. Central to this understanding is the accurate detection, mapping and delineation of surface water, with a variety of remote sensing techniques developed and refined for the extraction of water.

The most common techniques for the detection, mapping and delineation of surface water include image classification, and thresholding of spectral bands, with each method having advantages and limitations (Sun *et al*., 2012). An important consideration in the selection of the technique(s) is the spatial extent and nature of the study area (Mahdavi *et al*., 2017). Lakes are complex systems consisting of open water of varied size, depth and water quality, as well as transition zones between the open water, flooded emergent vegetation and saturated soils, all of which influence the spectral characteristics of surface water (Zhao *et al*., 2011). The technique used should thus differentiate between water and non-water features, while accurately mapping the complex and varied dynamics of the lake. In the remote sensing of lake inundation, the technique should thus also account for the availability of training or reference data to ensure accuracy (Jawak *et al*., 2015; Schaffer-Smith *et al*., 2017).

Image classification include supervised and unsupervised methods, with many researchers combining these methods into a hybrid classification (Zhang *et al*., 2018). Supervised classification allows the user to classify representative image pixels into specific or relevant classes using training data (Ozesmi & Bauer, 2002). Examples of common supervised classification methods applied to derive lake inundation are maximum likelihood (Doña *et al*., 2016; Schaffer-Smith *et al*., 2017), decision trees (Han *et al*., 2018) and neural network classification. The unsupervised classification methods make use of algorithms that group pixels based on maximizing the difference in spectral properties between classes. An Iterative Self-Organizing Data Analysis Technique Algorithm (ISODATA) is a commonly used unsupervised method, and was applied to assess inundation for Poyang Lake, China (Chen *et al*., 2014), the Tibetan inland lakes (Li *et al*., 2017) and Lake Chad, Africa (Ndehedehe *et al*., 2016). Supervised and unsupervised image classification methods have been widely applied in assessing lake inundation with varied accuracy depending on the nature, structure and texture of the surface features (Guo *et al*., 2017) as well as the spatial and spectral resolution of the satellite imagery.

The accurate mapping of multiple features within a given pixel, particularly where there is not sufficient ground reference data can lead to misclassification errors, and bias for areal estimates of lake inundation (Chen *et al*., 2014). The application of image classification methods is thus limited with the mapping of large inundated areas, and where surface flooding is highly variable (Li *et al*., 2013).

Thresholding using various spectral and water indices has been widely applied in estimating lake inundation. Spectral water indices are algorithms developed to discriminate water from other surfaces using one or more spectral bands. Single-band threshold methods have commonly been based on near infrared or mid infrared spectral bands given the low reflectivity of water which effectively discriminates water from non-water features (Thomas *et al*., 2015; Doña *et al*., 2016; Schaffer-Smith *et al*., 2017). Multi-band threshold methods, such as water indices, perform better at detecting surface water than single-band methods, by combining different reflective spectral bands to enhance the mapping of the varied water characteristics of lakes and wetlands (Xu, 2006; Thomas *et al*., 2015). McFeeters (1996) combined the visible (green) and near infrared band to develop the Normalized Difference Water Index (NDWI). The Modified Normalized Difference Water Index (MNDWI) is a multi-band spectral index that uses the visible (green) band and the short-wave infrared band to discriminate between water and other land features (Xu, 2006). According to Sun *et al*., (2012) the MNDWI performed better than the NDWI because clear water had greater positive values than the visible (green) band and the short-wave infrared band NDWI. In a comparative study of MNDWI and NDWI, Sun *et al*., (2012) concluded that the performance of the water indices were influenced by the characteristics of the land and water features. Using thresholds of zero, the NDWI performed better in extracting turbid water, while the MNDWI had an improved accuracy in extracting mixed pixels of clear water and vegetation (Sun *et al*., 2012). Buma *et al*., (2018) concluded that the MNDWI with a threshold of 0.2 to 0.5 could accurately delineate shallow turbid water from non-water features, and performed better than the NDWI in mapping the inundation for Lake Chad. Feyisa *et al*., (2014, p24) introduced the Automated Water Extraction Index (AWEI), a multi band index using the green, near-, middle- and shortwave infrared to improve on available water indices, by "automatically suppressing classification noise from shadow and other nonwater dark surfaces". However, Buma *et al*., (2018) and Schaffer-Smith *et al*., (2017) noted that both NDWI and MNDWI outperformed the AWEI.

There is some uncertainty in determining the threshold for discriminating between water and non-water features using water indices. Although a default value of zero has been applied in many applications in delineating water (Xu, 2006; Sun *et al*., 2012), the threshold value in areas with shallow water and flooded vegetation may vary (Di Vittorio & Georgakakos, 2018). The threshold values may also differ depending on the location and the time of image acquisition (Feyisa *et al*., 2014). Several studies have used threshold values greater than zero in identifying water features (Tebbs *et al*., 2013; Feyisa *et al*., 2014; Gautam *et al*., 2015; Buma *et al*., 2018). Tebbs *et al*., (2013) selected a threshold of 0.5 and found that a small change in the MNDWI threshold could cause a small change in the estimates for lake surface inundation. Although the determination of thresholds are subjective (Ji *et al*., 2009; Buma *et al*., 2018), the accuracy of mapping inundation can be improved by integrating knowledge of the study area, while using fieldwork and supplementary high resolution imagery for validation is recommended (Ji *et al*., 2009; Thomas *et al*., 2015).

With limited or no historic data on either lake water levels, or consequently the inundated areas of depressions such as Soetendalsvlei, the use of remote sensing offers a viable option for understanding the dynamics of this lake. The main aim of this chapter is thus to establish the spatial and temporal variations of inundation during the 1989 to 2019 period with the aid of remote sensing.

The key objectives of this chapter are to:

1. Determine the spatial extent, duration and frequency of inundation from 1989 to 2019.
2. To assess inundation trends in the study area.
3. Assess the relationship between inundation with *in situ* water levels.
4. Establish the extent to which antecedent precipitation explains changes in inundation.

4.2 Methods

The extent, duration and variability of inundation were determined by a systematic process in which remotely sensed images were acquired and processed, as outlined in Figure 4.1.

4.2.1 Image selection

The Landsat archive provides free, archival images with a medium spatial resolution of 30 m and a temporal resolution of 16 days, and thus offer the opportunity to understand the long-term inundation of surface water bodies such as Soetendalsvlei. The study used images from the Landsat archive which cover the Nuwejaars Catchment. This included the Landsat 8 Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS), Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and the Landsat 5 Thematic Mapper (TM). Level 1T Landsat scenes were selected as these scenes have been processed to Standard Terrain Correction, which provides radiometric and geometric accuracy (http://landsat.usgs.gov//landsat_level_1_standard_data_products.php).

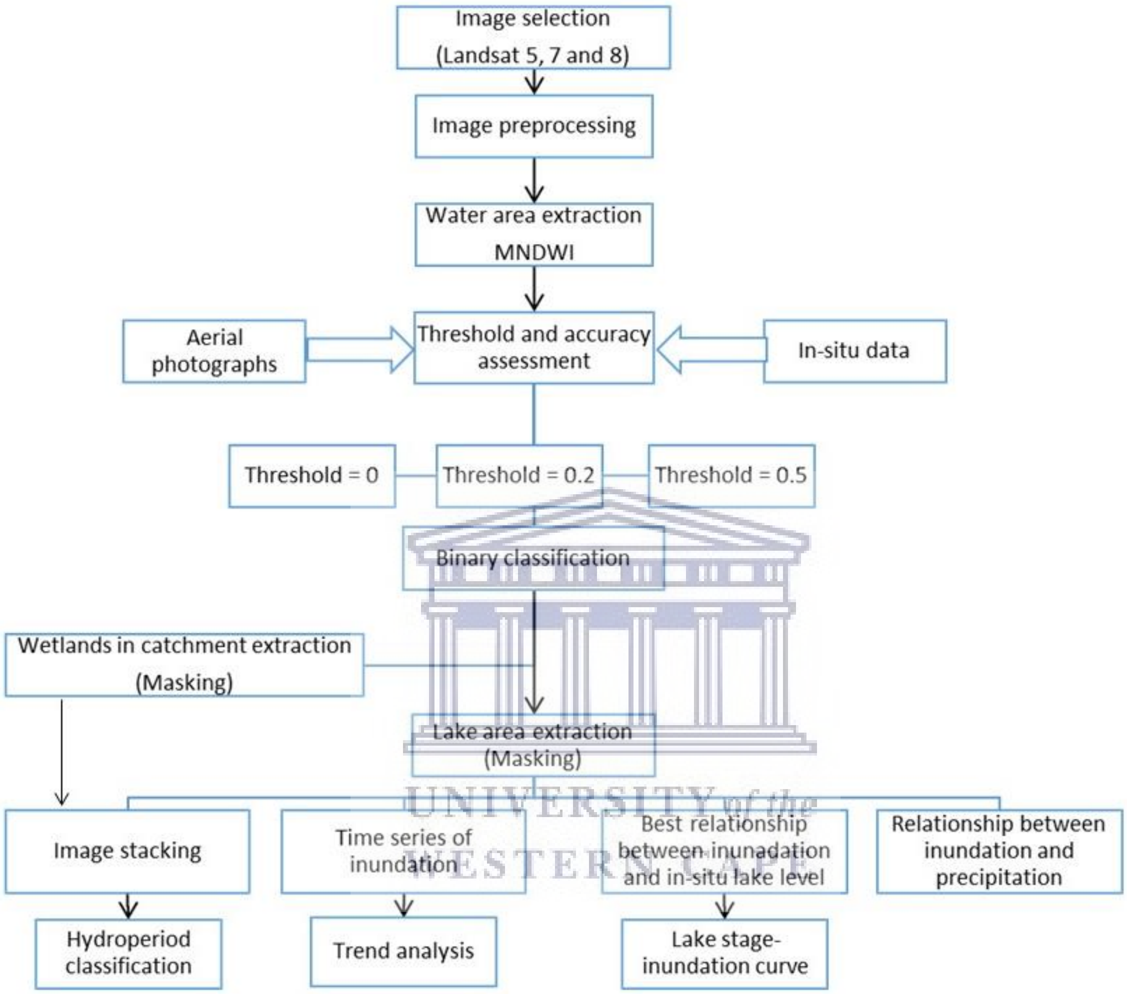


Figure 4.1 Flowchart showing the process in determining the extent, duration and variability of inundation

The images were acquired from the United States Geological Survey (USGS) Global Visualization Viewer (http://glovis.usgs.gov) and were in row 84 of path 174. Due to a scan line corrector failure after 31 May 2003, the Landsat 7 ETM+ has diagonal striations which represent missing data. In images from these satellites, approximately 75% of data is still acquired from each scene (http://landsat.gsfc.nasa.gov/landsat-7). Soetendalsvlei is located within each of the scenes where there is no missing data, and thus the available Landsat 7 images offers continuity to ensure Landsat observations from 1989 to present.

A visual inspection of all available Landsat 5, 7 and 8 images for the study area was manually conducted and images with no or minimal cloud cover in the Nuwejaars catchment were selected. In total, 125 images, for the period April 1989 to May 2019 (i.e. 30 years), were selected for analysis. All available images were projected to Hartebeesthoek 1994 Global Coordinate System (LO19 coordinate system) and World Geodetic System 1984 Ellipsoid as Landsat standard data products have the Universal Transverse Mercator (UTM) map projection.

4.2.2 Image preprocessing

As multiple images from different time periods were used, the radiometric normalization and atmospheric correction of the images are suggested to eliminate the effect of haze and the variable solar angles (Li *et al*., 2013). Landsat images acquired from the USGS provide quantized and calibrated scaled Digital Numbers (DN) (https://landsat.usgs.gov/using-usgs-landsat-8-product). The conversion of DN to Top Of Atmosphere (TOA) radiance and reflectance were completed using the relevant conversion equations for the different Landsat images (Li *et al*., 2013). Rescaling coefficients used in the conversion were provided in the metadata file for each image. A composite image, which shows the contrast between land, water and vegetation, was created for each Landsat image. This provided supplementary visual information on the extent of inundation while enabling a distinction between 'open water' and mixed pixels of water and vegetation.

4.2.3 Water extraction for the catchment and lake

Previous studies have shown that Modified Normalized Difference Water Index (MNDWI) is suitable for extracting mixed pixels for this study, while also eliminating built-up land noise (Sun *et al*., 2012). The MNDWI was applied to all images to delineate the water bodies for each Landsat scene. This index can be stated as (Xu, 2006):

$$MNDWI = \frac{Green - SWIR1}{Green + SWIR1} \quad (4.1)$$

where:

$Green$ = TOA reflectance of the green band

$SWIR1$ = TOA reflectance of the short-wave infrared (SWIR1) band

The MNDWI produces a greyscale image where surface water bodies appear as bright features with positive values and are separated from the soil and built-up features (which appear as dark features) and with values less than zero. Surface water bodies have positive values because they absorb more SWIR than soil and built-up features (Feyisa *et al*., 2014). The MNDWI (Equation 4.1) results in values ranging from -1 to +1 (Figure 4.2).

Histograms were generated for the MNDWI values within the Soetendalsvlei to assess the optimal threshold value of water. The histogram shows the distribution of pixels, where values range from -1 to +1. Although the value of 0 is suggested to discriminate between water and non-water (Xu, 2006), the evaluation of the optimal threshold using reference data is advised (Thomas *et al*., 2015; Buma *et al*., 2018). Error matrices were constructed to assess the accuracy of the threshold value of water by using a threshold of 0, 0.2 and 0.5. The threshold with the highest overall accuracy was selected as the threshold value for water. This threshold was applied for the extraction of all water within the Nuwejaars catchment.

All values above the threshold value for water were classified as water; with each image having different classes of water due the variability of the spectral reflectance (Thomas *et al*., 2015). The variability is due to the depth of water, the presence and mixing of water and emergent vegetation and the vegetation phenology (Olthof, 2017). A final MNDWI inundation map for each acquired image (or date) was created by combining all classes of water, where all water features were classified or assigned the pixel value of 1. Non-water features were classified with a pixel value of 0. The binary classification allows the distinction between water (pixel value of 1) and non-water features (pixel value of 0). All water features were extracted to represent the wetlands in the Nuwejaars catchment (Figure 4.1). All water features from each MNDWI image was extracted for all wetlands in the Nuwejaars catchment by using the wetland spatial information sourced from SANBI (2018) as a mask. To only extract the lake inundation of Soetendalsvlei a mask was created of the lake and consisted of a polygon outlining the outer edge of the shoreline. All processed MNDWI images were masked to only reflect Soetendalsvlei. Knowledge of the area as well as field work were incorporated in the validation of these images. The accuracy and validation are discussed in section 4.2.4. The pixel count representing the inundated lake area was extracted from the attribute table. The spatial extent of inundation for Soetendalsvlei was calculated for each image.

4.2.4 *In situ* measurements, accuracy and validation

The accuracy of the water extraction using the MNDWI was assessed for Soetendalsvlei by using *in situ* ground points and aerial photographs. The survey of *in situ* ground points was completed using a Trimble differential GPS on 24 September 2014, a day prior to the Landsat overpass of 25 September 2014. The Landsat overpass on 25 September 2014 has patches of cloud cover, and thus only the cloud free section of the Landsat image was used for accuracy assessment. The survey of *in situ* points was conducted by officials from the Department of Agriculture, Bredasdorp by walking alongside, but as close as reasonably possible, to the water's edge of Soetendalsvlei.

An error matrix was constructed to assess the accuracy of the MNDWI using an aerial photograph as a reference image. The geo-rectified aerial photograph of Soetendalsvlei dated 11 February 2014 was acquired from the Chief Directorate: National Geo-Spatial Information (CD:NGI) and used as the reference image. The ground sample distance of aerial photographs acquired is 0.5 m. The MNDWI was estimated for the Landsat 8 image of 1 March 2014, the closest remotely sensed image (in terms of date) to the reference image. The MNDWI was calculated for a threshold of 0, 0.2 and 0.5. A total of 100 random points were generated within a sub-set image of the outer edge of the Soetendalsvlei shoreline. The error matrix was constructed for a threshold of 0, 0.2 and 0.5. Errors of omission and commission were determined for each threshold. The optimal threshold for water extraction was applied to all wetlands in the Nuwejaars catchment.

4.2.5 Inundation frequency

An analysis of historical inundation frequency for lakes and wetlands provides insight to the characterization of surface water dynamics (Montgomery *et al*., 2018; Wang *et al*., 2019) and offers information to better manage wetlands (Olthof, 2017). "Inundation frequency is a useful way of spatially summarizing time series of flooded extents and can be used as a proxy of long term patterns of inundation duration" (Ward *et al*., 2014, p47). The inundation frequency was determined by stacking all final MNDWI images and calculating the percentage of all available valid observations where a pixel is classified as water, i.e. where the pixel value is 1 (Olthof, 2017). The inundation frequency was determined at 2 spatial scales: the catchment scale and the lake area of Soetendalsvlei (Figure 4.1). The duration of inundation using a collation of archival remote sensing images have been produced for the St-John River, Canada (Olthof, 2017), Okavango delta (Gumbricht *et al*., 2004) and Poyang Lake (Wu & Liu *et al*., 2015a) by estimating the percentage of time a particular area was inundated over the period of study.

Mathematical methods (Boolean logical operator and Cell Statistics) were used to determine the inundation frequency for the wetlands in the Nuwejaars catchment, and Soetendalsvlei from the MNDWI inundation maps for the period April 1989 to May 2019. Further categorization of inundation frequency provides a description of the classification of the hydroperiod of wetlands (SANBI, 2009; Wang *et al*., 2019). Based on the inundation frequency of all available MNDWI images, the hydroperiod of Soetendalsvlei was further classified into permanent, seasonal and intermittent inundation (Table 4.1). The inundation frequency was also determined for each season.

Table 4.1 Hydroperiods (adapted from SANBI (2009) and Ward *et al*., 2014)

Inundation period	**Description**	**Mathematical operator**	**Inundation frequency** (% of all available valid observations where a pixel is classified as water)
Permanently inundated	Flooded throughout the observation period	Boolean logical operator (If input values are true i.e. inundated, the output is 1 i.e. permanently flooded)	100% of the observation period
Seasonally inundated	Surface water present for extended periods during the observation period	Cell Statistics to determine flooding frequency at 50%; 75% and 100%	25 – 99%
Intermittently inundated	Surface water present for irregular periods during the observation period	Cell Statistics used to determine flooding frequency at 25%	< 25%
Never/rarely inundated	Surface water present for less than a few days at a time	Not calculated or defined	Not calculated or defined

The areas of Soetendalsvlei that are permanently inundated or ‘flooded throughout the observation period’ have an inundation frequency of 100%. Where areas or pixels were inundated between 26 – 99% of the time, i.e. from April 1989 to May 2019, the hydroperiod was classified as seasonally inundated. Intermittently inundated areas were classified if the pixel was inundated between 1 and 25% of the observation period. With a temporal resolution of 16 days for Landsat images, in addition to the unavailability of a regular set of images due to high cloud cover, the inundation period for ‘never/rarely inundated’ (Table 4.1) was not assessed. Error in the determination of the hydroperiod was minimized by having an identical projection for each of the MNDWI images.

4.2.6 Assessing the temporal variability of inundation

A time series of the spatial extent of inundation for Soetendalsvlei was collated from all the images processed. The aim of the time series was to create a baseline of the historical inundation regime of Soetendalsvlei and to examine annual, seasonal and monthly variations. Seasonal variation of inundation was assessed for winter (April, May, June), spring (September, October, November), summer (December, January, February) and autumn (March, April, May).

Monthly rainfall data (from 1910) courtesy of Mr. Albertyn (landowner of the farm Zeekoevlei) represents long-term monthly data of the closest rainfall gauge to Soetendalsvlei. A comparison of the inundation series was made with available rainfall data from Zeekoevlei.

4.2.7 Assessment of change points and trends of inundation

Zimba *et al*., (2018) applied the Mann-Kendall test to an inundation series derived from satellite data of the Bartose Floodplain in the Zambezi River Basin. The study found a significant rising trend in inundation which was attributed to rainfall variability. In this study, the Pettitt test, Standard Normal Homogeneity Test (SHNT) and the Buishand tests were applied to the Soetendalsvlei inundation series to detect if there was a change in the data series (Javari, 2016). The Mann-Kendall test was applied to the MNDWI annual inundation series to assess if the surface area of the lake had changed over time.

4.2.8 Comparison of *in situ* water levels and lake inundation

The best relationship between the lake inundation, estimated using the MNDWI, and the daily average *in situ* lake levels of Soetendalsvlei was derived. The *in situ* lake levels are available from March 2015 when the automatic water level recorder was installed in Soetendalsvlei (Figure 2.6). Due to drought conditions in the study area, the automatic water level recorder was removed in September 2017. The time period for the comparison was from March 2015 to September 2017. There were no cloud free images from January 2017 to March 2017.

4.2.9 Relationship of inundation with precipitation

An assessment of the water balance of lakes is challenging given the absence or limited availability of *in situ* hydrological and meteorological data. Although advances in remotely sensed imagery have provided access to relevant data used in water balance studies of lakes (Dörnhöfer

& Oppelt, 2016; Politi *et al*., 2016) the validation and calibration with limited *in-situ* data is challenging. In a comparative study of remotely-sensed precipitation and *in-situ* observations in the Heuningnes catchment, Western Cape South Africa, Maswanganye (2018) concluded that remotely-sensed products generally underestimated actual rainfall. With no *in situ* hydrological data in the catchment, local *in-situ* rainfall data was used to establish the extent to which precipitation, particularly antecedent, explains changes in inundation.

The Antecedent Precipitation Index (API), primarily developed to estimate peak flows using precipitation data (Beschta, 1990), is a measure of the saturated conditions of a catchment (Tramblay *et al*., 2012). Antecedent precipitation has been shown to enhance flood probability in catchments with gentle topography and large storage capacity (Froidevaux *et al*., 2015). The API is defined as (Beschta, 1990):

$$API_d = kAPI_{d-1} + P_d \qquad (4.2)$$

Where:

API_d = Antecedent Precipitation (mm) for day *d*

k = Dimensionless decay factor less than 1

P_d = Rainfall for day *d*

The *k* parameter was selected by maximizing the correlation between API and inundation. Long-term daily rainfall data is available from Prinskraal weather station (1973 to present). However as the instrumentation was changed at the site in 2006, the API was calculated using daily precipitation from Prinskraal from 2006 to 2019.

The Standard Precipitation Index (SPI) for Zeekoevlei show periods of *very* and *extremely wet* and *dry* conditions (Section 3.3.1.3), with hydrological drought found to be a good indicator of desiccation of Soetendalsvlei. The methodology for determining the SPI (Section 3.2.1.2) was followed to determine the SPI at 1, 3, 6, 12, 18 and 24-month time scale. The relationship of the SPI at the various time scales for Zeekoevlei was compared to inundation.

4.3 Results

4.3.1 Identification and validation of inundated lake areas

Soetendalsvlei has open water, and areas of water with emergent vegetation. Figure 4.2A is a composite image (bands 5-6-4) which displays the contrast between open water and water with emergent vegetation for Soetendalsvlei. The subdivision of the 'open water' of Soetendalsvlei is illustrated by the presence of emergent vegetation. The MNDWI for the Nuwejaars catchment illustrates the presence of water bodies as bright features with positive values, while all other areas appear as dark features with MNDWI values less than zero (Figure 4.2B). Figure 4.2C illustrates the MNDWI mask of Soetendalsvlei which extracts water from the image. The different shades of grey reflect the open standing water and the mixed pixels of water and emergent vegetation. Figure 4.2D and 4.2E displays the MNDWI image produced when all positive values, both open water and mixed pixels containing water and emergent vegetation, were classified as water for the catchment and Soetendalsvlei respectively.

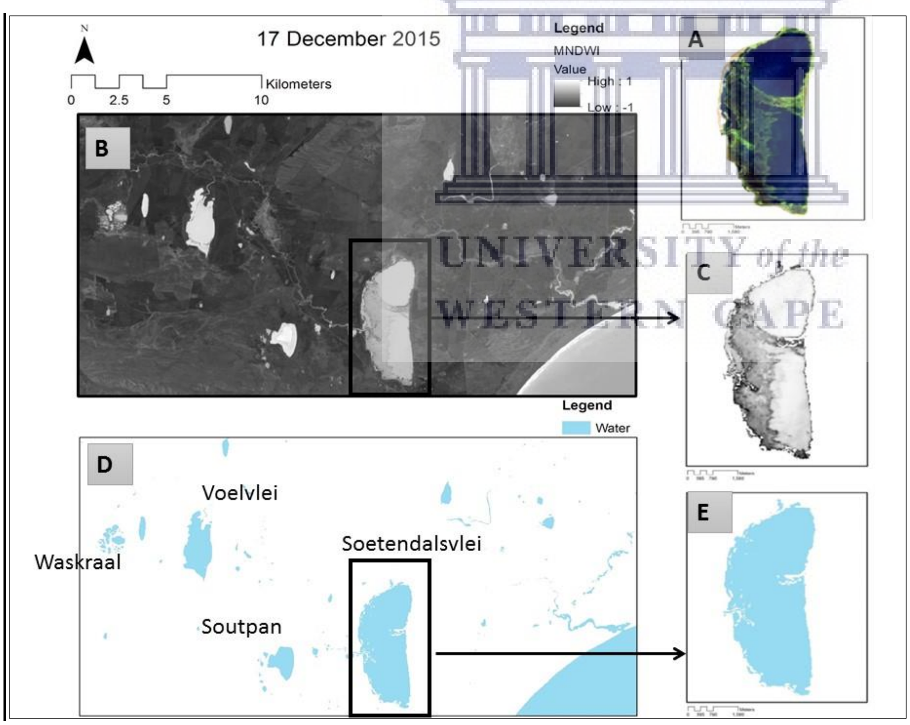


Figure 4.2 Landsat composite of Soetendalsvlei (A) MNDWI for the lower Nuwejaars catchment (B) and Soetendalsvlei (C) with surface water bodies as bright features (more than zero) for 17 December 2015. The variability of the spectral reflectance is illustrated with shades of grey for open water and flooded emergent vegetation. Inundation for the lower catchment, which includes Voëlvlei, Waskraal and Soutpan depressions (D) and Soetendalsvlei (E) are illustrated.

Figure 4.3A illustrates water (in black) in the northern section of Soetendalsvlei where the MNDWI for September 2014 is greater than zero. The ground points are illustrated as yellow dots, and delineates the water of Soetendalsvlei from the surrounding non-water landscape. The inundation maps derived from the different thresholds were evaluated using a high-resolution aerial photograph (Figure 4.3 B-D). The threshold value of 0 had the highest overall accuracy, as the threshold of 0.2 and 0.5 had numerous errors of omission. The threshold value of 0 (Table 4.2a) was the most accurate in extracting water features, while the threshold of 0.5 was the least accurate (Table 4.2c) in extracting water from the Landsat image. The optimal threshold in differentiating land from water was set to 0 for all images.

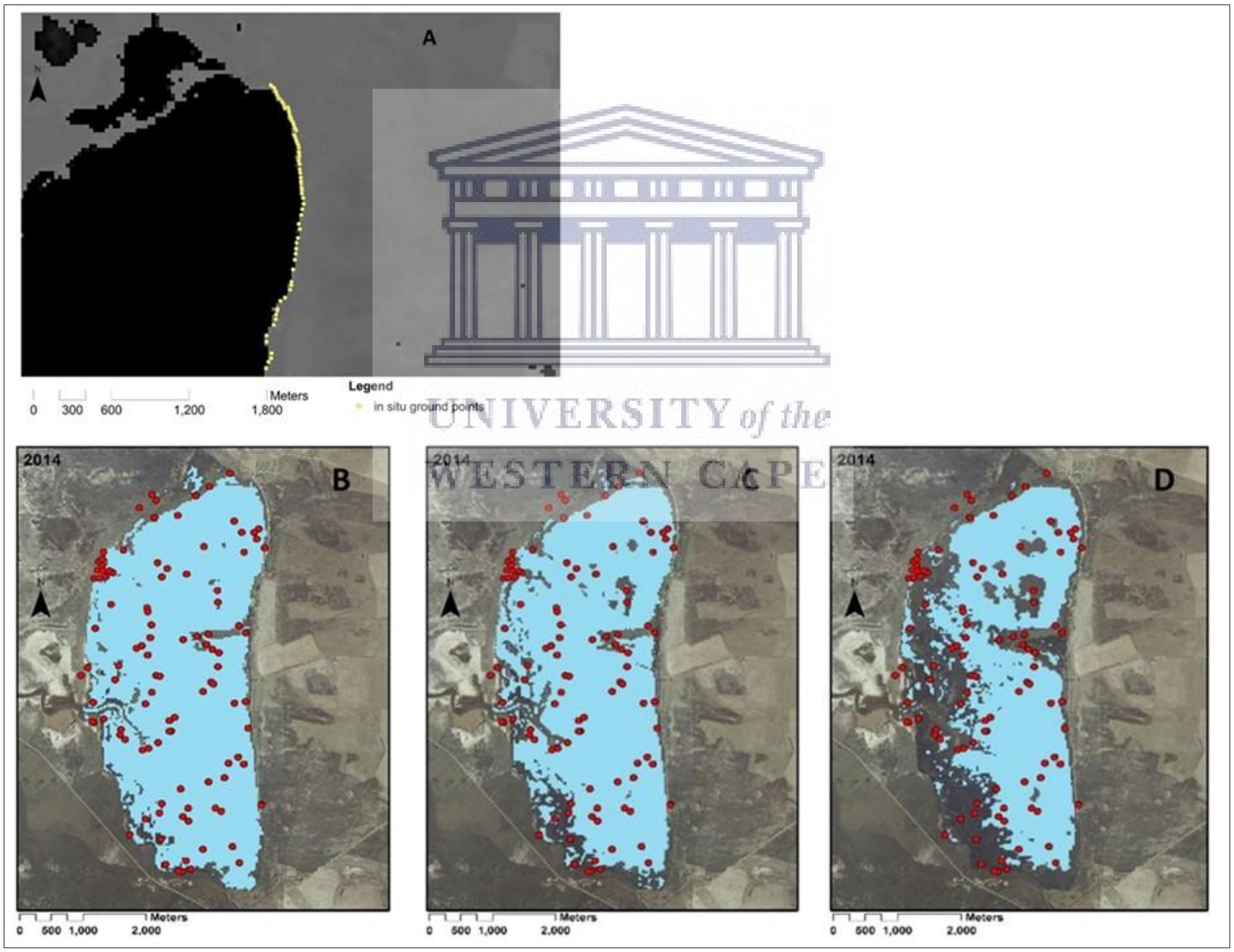


Figure 4.3 Accuracy assessment of the *in situ* ground points delineating the water features (in black) from the non-water landscape (A) for September 2014. Random point locations for accuracy assessment using a geo-rectified aerial photograph as a reference image and the MNDWI (in blue) estimated with a threshold of 0 (B) 0.2 (C) and 0.5 (D).

Table 4.2 Error matrix for a threshold value of (a) 0 (b) 0.2 and (c) 0.5

(a) Threshold of 0		**Reference image: Aerial photograph**		
		Water	Non-water	
Mapped class	Water	77	8	∑ = 85
	Non-water	1	14	∑ = 15
		∑ = 78	∑ = 22	**Overall accuracy:93%**

(b) Threshold of 0.2		**Reference image: Aerial photograph**		
		Water	Non-water	
Mapped class	Water	63	20	∑ = 83
	Non-water	0	17	∑ = 17
		∑ = 63	∑ = 37	**Overall accuracy:80%**

(c) Threshold of 0.5		**Reference image: Aerial photograph**		
		Water	Non-water	
Mapped class	Water	43	40	∑ = 83
	Non-water	0	17	∑ = 17
		∑ = 43	∑ = 57	**Overall accuracy:60%**

Figure 4.4 illustrates the (A) geo-rectified aerial photograph of March 2014 and the same aerial photograph with (B) the water identified using the MNDWI from the Landsat 8 image of 1 March 2014. Using the threshold of zero, the MNDWI could distinguish between water and non-water features with an overall accuracy of 93% (Table 4.2a). All open water areas were correctly identified. In the areas where emergent vegetation is inundated with water, the MNDWI correctly classified water (Point 1, Figure 4.4B) although there were errors of omission, where water was not detected (Point 2, Figure 4.4B). In the littoral zone of Soetendalsvlei, where the water levels are relatively shallow, the MNDWI could detect water (Point 3, Figure 4.4B), but there were errors of omission, where water was not detected (Point 4, Figure 4.4B). Non-water features were correctly classified using the MNDWI (Points 5,6,8,9 and 10, Figure 4.4B). Sediment accumulations in Soetendalsvlei were detected as non-water features (Points 6 and 8, Figure 4.4B), however sediment accumulations smaller than 150 m^2 and surrounded by water, were incorrectly classified as water (Point 7, Figure 4.4B). Due to the irregular shape of the shoreline of Soetendalsvlei, and the small sub-pixel size polygons, errors of commission such as Point 10 (Figure 4.4B) were identified where non-water features were incorrectly classified as water. With an overall accuracy of 93% the threshold value of zero was able to discriminate between water and non-water features, and estimate the extent of inundation for Soetendalsvlei using the

MNDWI. Due to errors of omission, where water was not detected the producer's accuracy was 91%. Errors of commission was 99%, where pixels were misclassified as water.

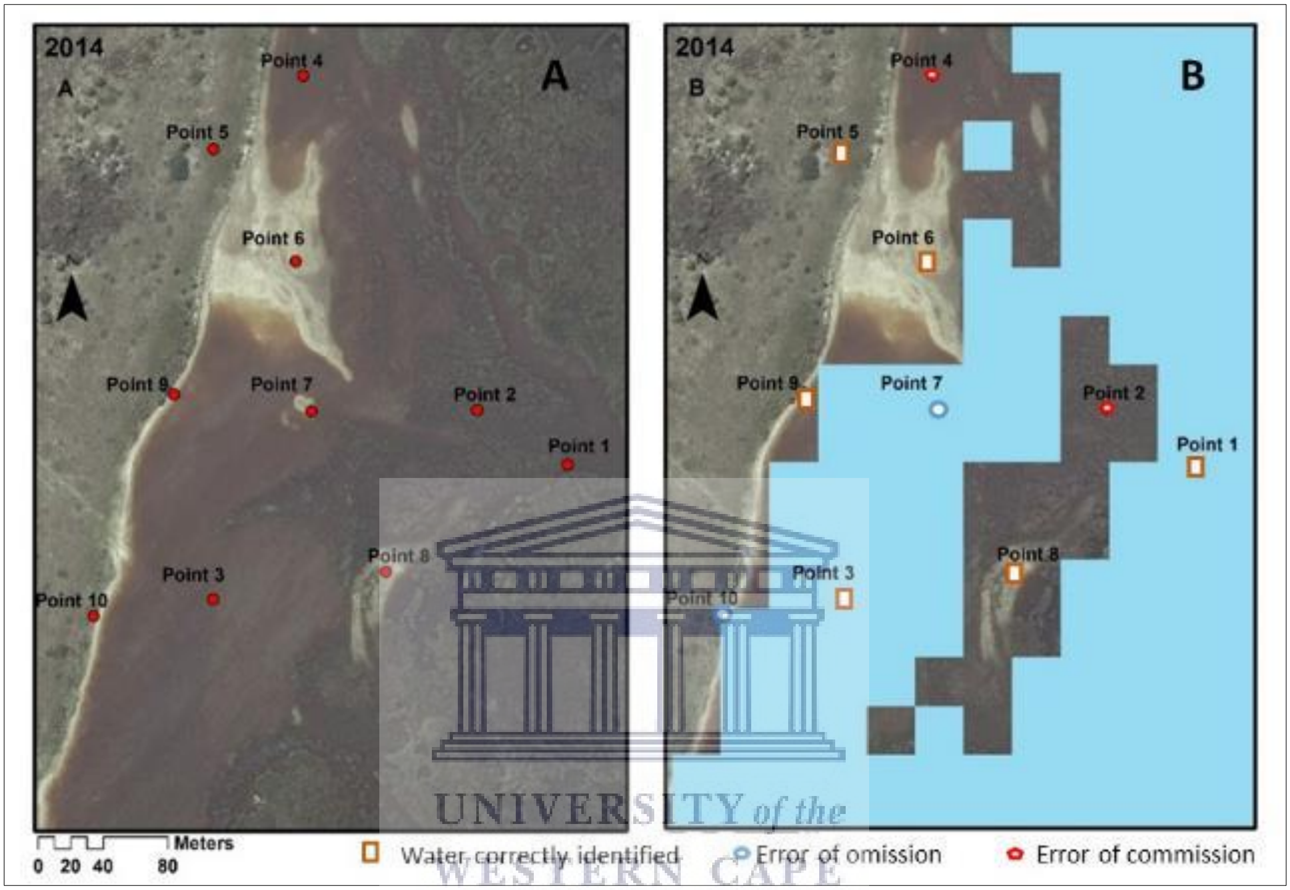


Figure 4.4 Accuracy assessment of the (A) geo-rectified aerial photograph of 11 February 2014 with (B) an overlay of the water features in blue as assessed with the MNDWI for 1 March 2014 (Landsat 8).

4.3.2 Frequency of inundation

The inundation frequency for the wetlands in the Nuwejaars catchment (Figure 4.5) and Soetendalsvlei (Figure 4.6) shows the percentage of all available observations between April 1989 and May 2019, where a pixel was classified as water. The depression wetlands and floodplain wetlands in the upper catchment and along the Nuwejaars River show a high frequency of inundation. Depressions such as Soetendalsvlei, Voëlvlei, Vogelvlei, Waskraal, Langpan, Soutpan and Rhenosterkop have capacity for the storage of water, and thus show a higher inundation frequency than floodplain wetlands (Figure 4.5).

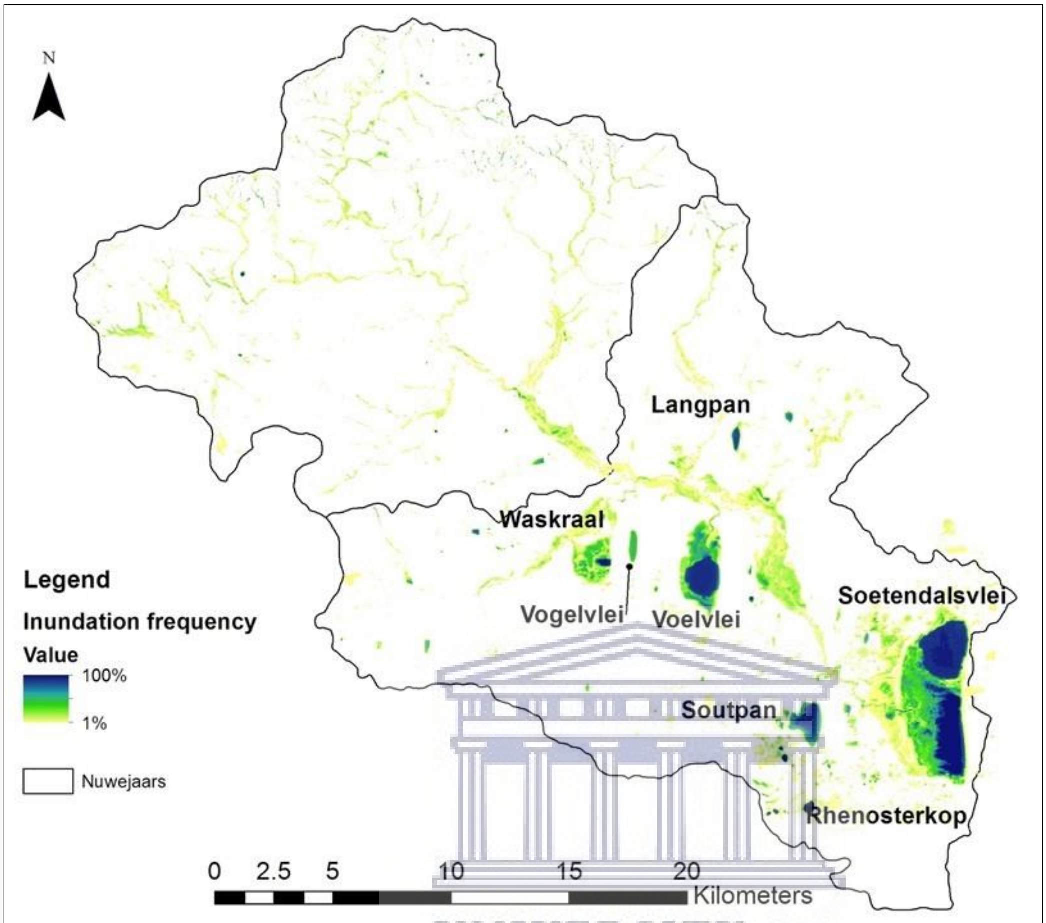


Figure 4.5 Inundation in the Nuwejaars catchment (1989 – 2019)

The correlation of inundation for the depressions in the catchment varies significantly (Table 4.3). The correlation of inundation for Soetendalsvlei with Voëlvlei is the highest with R^2 = 0.80.

Table 4.3 Correlation of inundation for depressions in the lower Nuwejaars catchment

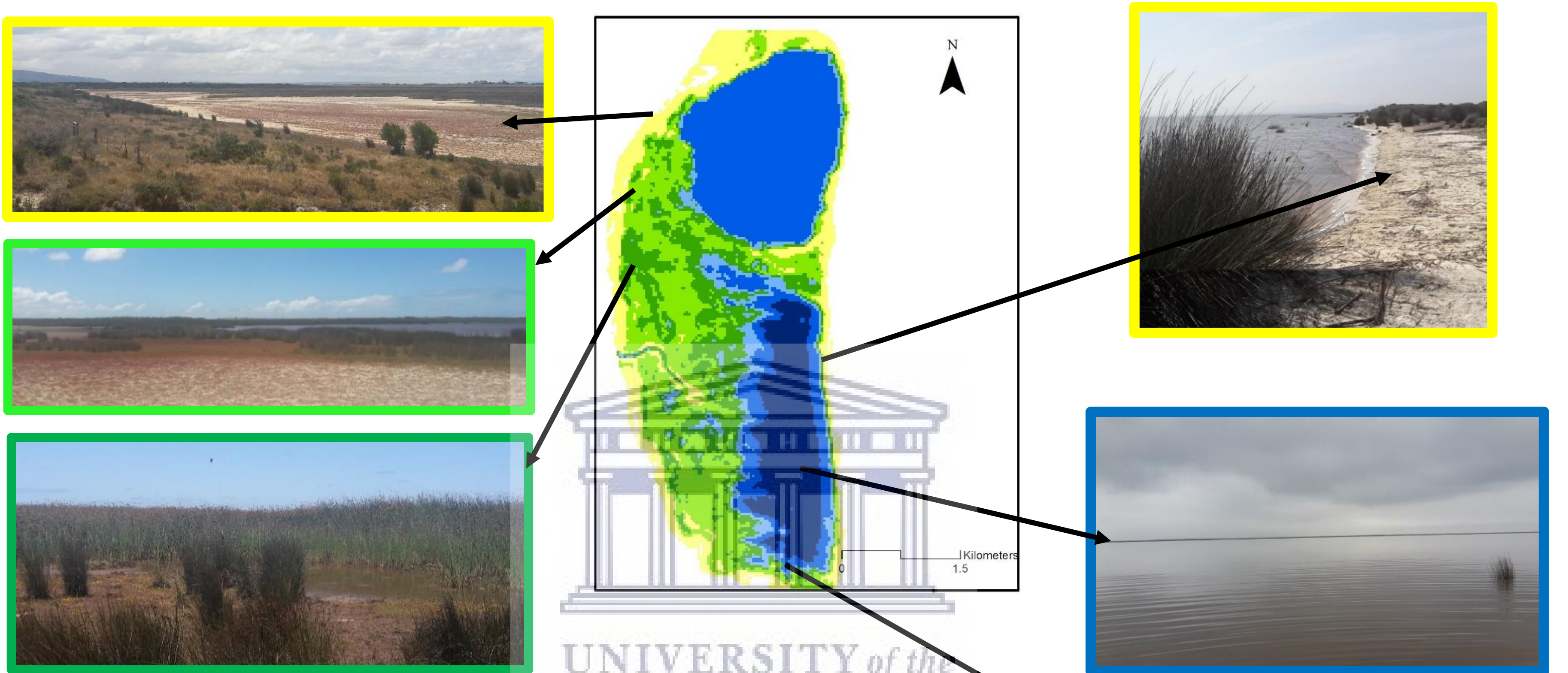
	Soetendalsvlei	*Voëlvlei*	*Langpan*	*Soutpan*	*Vogelvlei*	*Renosterkop*	*Waskraal*
Soetendalsvlei	1.00						
Voëlvlei	0.80	1.00					
Langpan	0.66	0.58	1.00				
Soutpan	0.70	0.77	0.61	1.00			
Vogelvlei	0.61	0.74	0.48	0.72	1.00		
Renosterkop	0.72	0.69	0.69	0.79	0.56	1.00	
Waskraal	0.62	0.85	0.46	0.71	0.76	0.55	1.00

The inundation frequency of Soetendalsvlei was further explored by characterizing the inundation period (hydroperiod). Almost the entire northern pool and the fringes of the permanently inundated portion of the southern pool were inundated between 91 to 99% of the time. Drought conditions in the Western Cape, South Africa from 2016 caused desiccation to the northern part of Soetendalsvlei. Thus, only the southern part of Soetendalsvlei is permanently inundated (100% inundation frequency) with surface water covering an area of 2.03 km^2.

The lake area of Soetendalsvlei, which experiences seasonal inundation with the frequency of flooding ranging from 26 to 90 % of the observation period, covers approximately 7.72 km^2. This area extends from the open water of the lake to the lakeshore. The frequency of flooding in Soetendalsvlei, as shown in Figure 4.6, generally decreases from the permanently inundated areas to the littoral areas of the lake. The western littoral zone of Soetendalsvlei that experiences seasonal inundation is covered by emergent vegetation. The frequency of inundation along the mouth of the Nuwejaars river into Soetendalsvlei varies from 51 to 99%. It is important to note that the occurrence of high density emergent vegetation along this section of the channel result in the misclassification of water pixels.

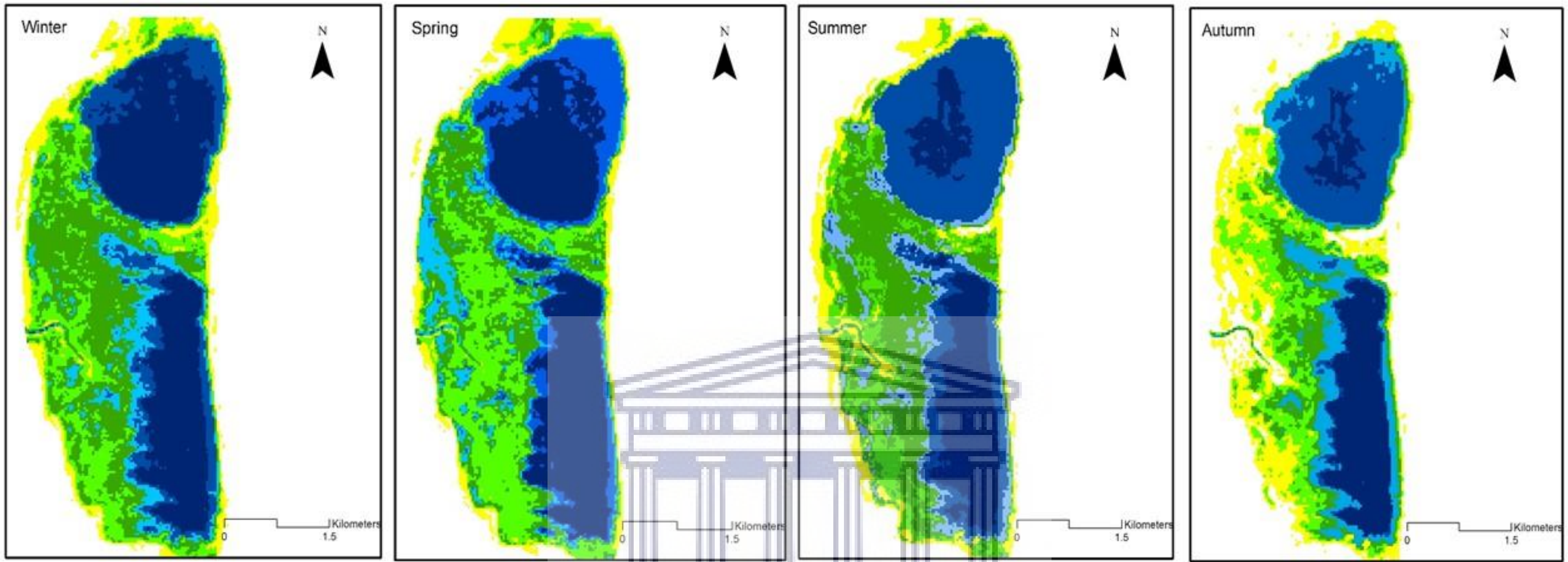
The detection/occurrence of small pools of water along the western shoreline of Soetendalsvlei has a relatively high inundation frequency of between 76% and 90%. Possible reasons for this could be ponding of rainfall due to the micro-scale variation in the topography of the depression, the occurrence of a clay substrate; through-flow from groundwater into and from the adjacent salt marshes; depressions created by the interplay between the sediment and vegetation and the separation of pools due the occurrence of high-density vegetation. Areas of the lake where inundation occurred intermittently (i.e. 1 – 25% of the observation period) were mainly along the shoreline and shallow littoral zones. Intermittent inundation was associated with flooding. In total, 11 of the 125 images were classified as intermittent inundation, with 9 of these images for the months of July, August and September. The two remaining images dated 7 November 1989 and 20 January 2014 were associated with flooding due to frontal systems and cut-off low pressure systems (Pharoah *et al*., 2016).

The hydroperiod influences the diverse habitat characteristics of Soetendalsvlei (Figure 4.6). The water level, duration and frequency of flooding modifies and determines the physiochemical environment specifically the sediment and water chemistry, which influences the presence and occurrence of vegetation and fauna (Mitsch & Gosselink, 2007). The characteristics of the habitats illustrated by Figure 4.6 differ in the frequency of flooding.



Inundation Frequency		Hydroperiod	Area km^2	Habitat/ecosystem Characteristic
(yellow)	1 – 25%	Intermittent	2.52	Shallow littoral habitat. Salt marsh and sandy substrate
(light green)	26 – 50%	Seasonal	3.82	Seasonally inundated; muddy substrate. Salt marsh and sandy substrate. Emergent vegetation dominated by reeds, juncus
(green)	51 – 75%		2.77	
(light blue)	76 - 90%		1.13	
(blue)	91 – 99%		4.84	Depression inundated except during extreme drought conditions
(dark blue)	100%	Permanent	2.03	Maximum water depth less than 3m. No/limited macrophytes

Figure 4.6 Map showing the duration of inundation for Soetendalsvlei, and photographs of habitats in areas of different inundation frequencies (colour of picture border refers to specific inundation frequency)



Inundation		Hydroperiod	Winter (km²)	Spring (km²)	Summer (km²)	Autumn (km²)
	1 – 25%	Intermittent	1.67	1.20	1.73	2.48
	26– 50%	Seasonal	2.46	3.45	2.97	2.14
	51 – 75%		4.08	3.50	3.02	1.70
	76 - 90%		1.37	1.28	1.10	1.85
	90 – 99%		1.98	1.77	4.25	2.67
	100%	Permanent	5.12	5.29	2.95	2.99

Figure 4.7 Seasonal extent of inundation for Soetendalsvlei

Soetendalsvlei shows significant seasonal variation of inundation (Figure 4.7) with spring showing the greatest extent of inundation between 51 and 100%. The occurrence of pools or patches of seasonal flooding are present during all the seasons, but more prevalent in spring. Autumn experiences relatively dry conditions as it has the greatest spatial area where dry land and intermittent (less than 25%) inundation occurs.

4.3.3 Temporal variation of lake inundation

The time series of MNDWI estimates of inundation of Soetendalsvlei, for the period April 1989 to May 2019, shows significant annual and seasonal variations (Figure 4.8). The average and median area of inundation for the period 1989 to 2019 is 11.18 km^2 and 11.39 km^2, respectively. The maximum area of inundation for the period referred to in Figure 4.5 was estimated at 16.24 km^2 for 14 August 1993 with the lowest inundation estimated at 2.17 km^2 for 18 May 2019. The annual variation of inundation from the mean illustrate generally low water inundation (1999 – 2004; 2011 – 2012) followed by high water inundation (2005 – 2009; 2013 – 2015) (Figure 4.9). The average inundation for 2018 was 53% below the average area of inundation. The low average inundation in 2018 was in response to below average rainfall experienced in the study area and the Western Cape, South Africa from 2016 (Figure 4.9).

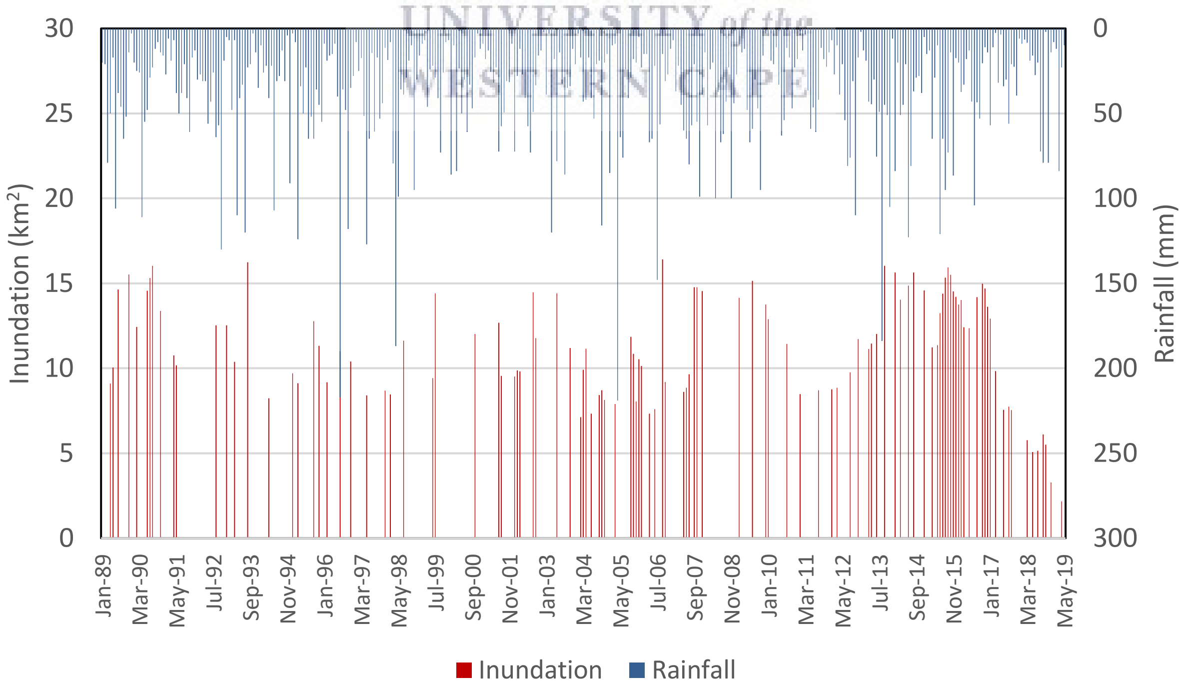


Figure 4.8 Time series of monthly rainfall at Zeekoevlei and lake inundation for Soetendalsvlei (April 1989 – May 2019)

The precipitation data for Zeekoevlei from 1989 to 2018 show variation above and below the mean annual precipitation of 454 mm/annum (Figure 4.9). Based on secondary sources (Cleaver & Brown, 2005) and informal discussions with farmers, significant flood events not depicted in Figure 5.5 occurred between 1989 and 2017, where lake inundation exceeded 15.1 km^2. These flood events were associated with high rainfall in the Nuwejaars catchment mainly due to intense cold fronts and cut-off low weather systems. The only flood event for which no cloud-free Landsat images, and thus no estimate of the NMDWI was available, was April 2005. A total of 219 mm/month of rainfall was recorded at Zeekoevlei, with consequent floods reported for the Overberg region in April 2005.

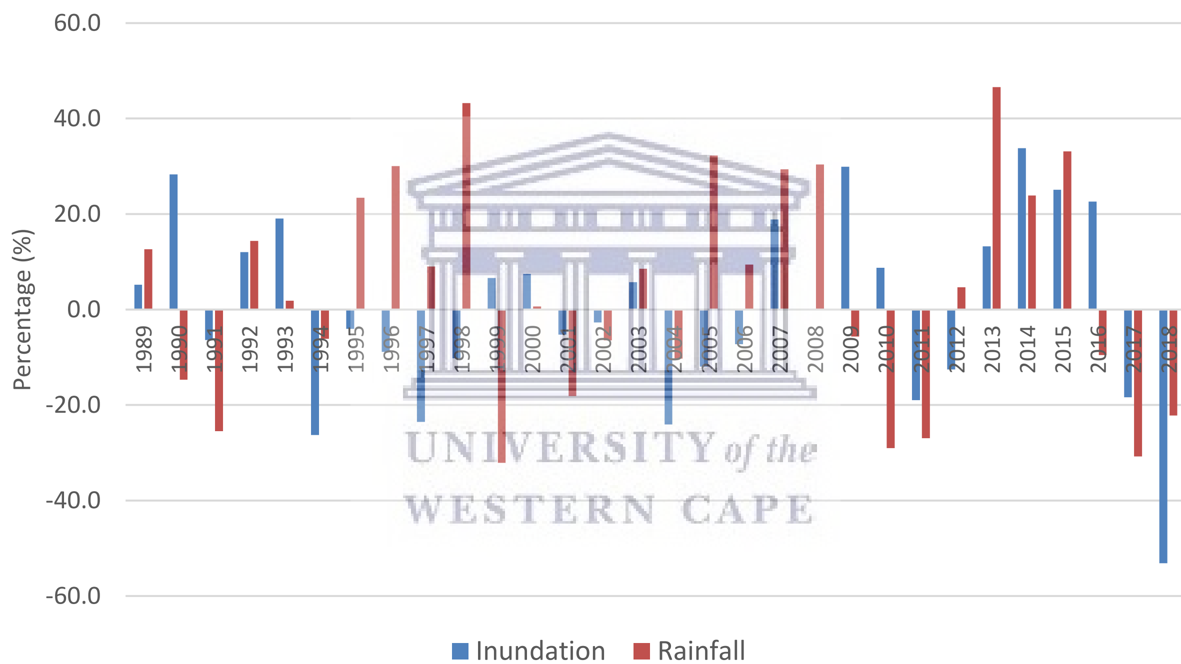


Figure 4.9 Variation in percentage of annual inundation and rainfall (Zeekoevlei) from the mean (1989 – 2018)

The highest rainfall from 1989 to 2018 was recorded for 2013, with a total of 665 mm/annum (i.e. 47% deviation above the mean). For 2014 and 2015, above-average rainfall was also experienced with 24% and 33% deviation above the mean annual precipitation. Following this relatively wet period, the precipitation decreased to 411mm/annum, 314mm/annum and 353 mm/annum for 2016, 2017 and 2018 respectively. In all years, except for the year 1991 and 2000, if below average annual rainfall occurs in one year, below average inundation is experienced in the following year.

The dynamic nature of the Soetendalsvlei is reflected in the transition of inundation from 24 October 2016 to 18 May 2019 (Figure 4.10). In October 2016, Soetendalsvlei had an area of 14.98 km^2, 92% of the maximum surface area. By March 2018, inundation was only detected in the two deeper depressions/pools of Soetendalsvlei, with no visible hydrological connection between the 2 depressions. The most significant change occurred with the complete drying up of the northern pool of Soetendalsvlei (i.e. Soetendalsvlei North) in May 2019. During this 31-month period from October 2016 to May 2019, the area of inundation decreased from 14.98 km^2 to 2.17 km^2, a reduction of approximately 85%. The shrinking of Soetendalsvlei was associated with extreme drought conditions affecting water resources across the Western Cape in South Africa from 2016 to 2019. The inflow of the Nuwejaars River on the western shoreline of Soetendalsvlei is inundated throughout the transition of inundation.

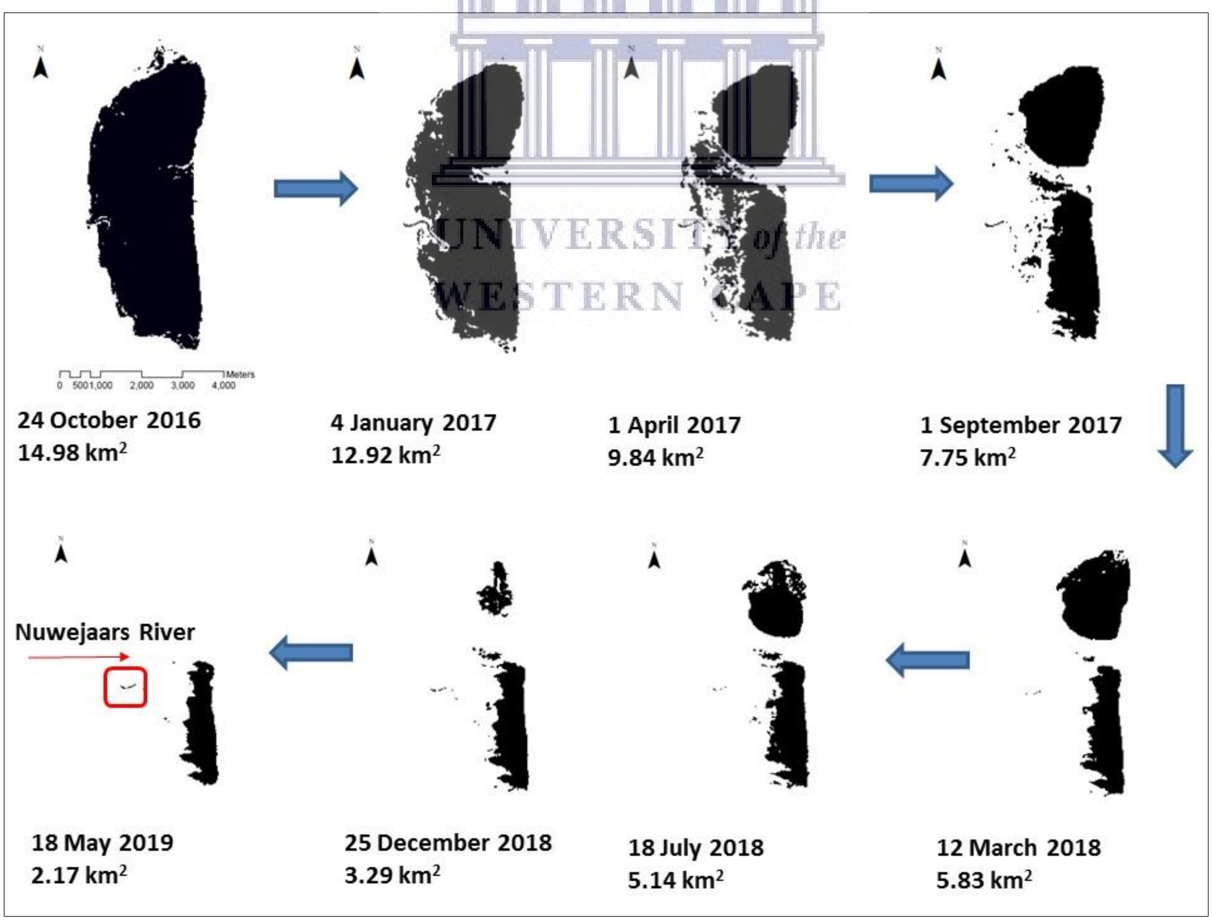


Figure 4.10 Transition of inundation from 24 October 2016 to 18 May 2019

There was significant variation of inundation amongst the four seasons, while variability of inundation within each season is also noteworthy (Figure 4.11). The highest average inundation of 12.16 km^2 is experienced in spring followed by 12.0 km^2 in winter. The interquartile range in spring reflects surface inundation of between 10.3 and 14.78 km^2, while the interquartile range in winter varies between 9.68 and 14.57 km^2. The months of December and January have significantly high median values of inundation, 13.07 km^2 and 12.88 km^2 respectively (Figure 4.12), and thus the summer season has a median value of 12.71 km^2. Autumn has the lowest median value of inundation while the measures of variability, which is also minimal compared to other seasons, indicate that most surface flooding cover an extent of between 8.33 and 11.19 km^2.

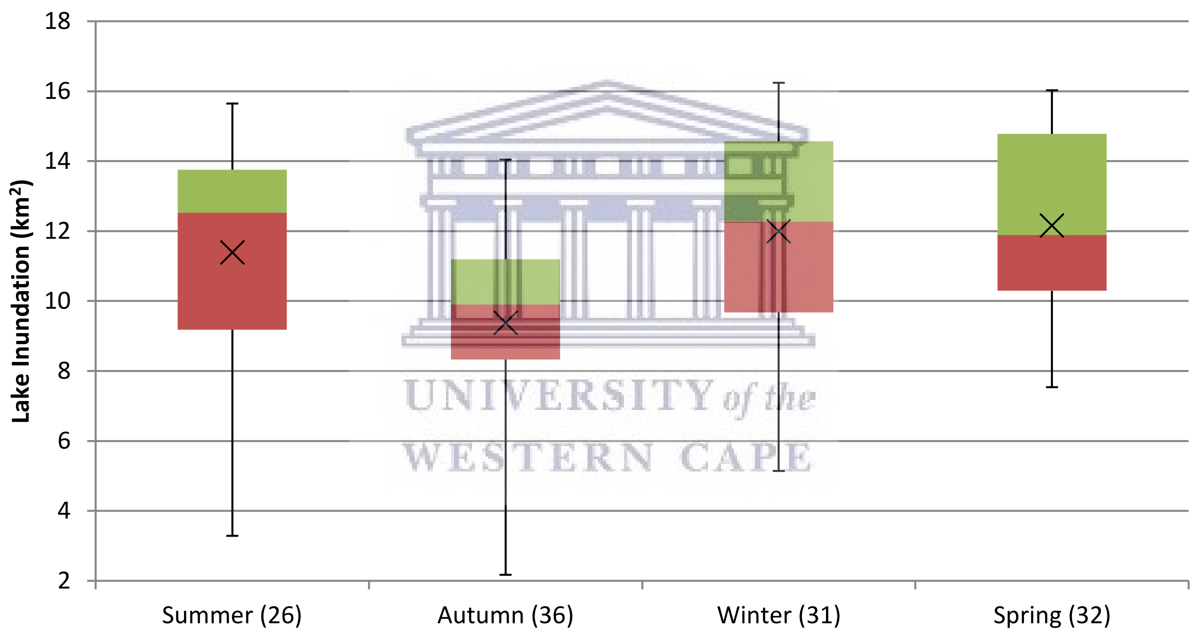


Figure 4.11 Seasonal variation of inundation for Soetendalsvlei based on Landsat time series (1989 – 2019). On the x-axis, the numbers in brackets represent the number of Landsat images which were processed. The cross or figure ‘x’ denotes the average inundation.

The monthly graph of lake inundation (Figure 4.12) shows a maximum surface flooding for March of 14.04 km^2 which was estimated from the Landsat image dated 1 March 2014. The inundation was in response to heavy rainfall from 6 – 10 January 2014 and relatively high antecedent moisture in the Nuwejaars catchment due to widespread flooding in August and November 2013, with respective rainfall of 184 mm/month and 105 mm/month recorded at Zeekoevlei. The high rainfall was due to a cut-off low weather system over the Western Cape, South Africa (Pharoah *et al*., 2016) with widespread flooding reported for the Agulhas region. A total of 84 mm was recorded at Zeekoevlei for the month of January 2014. Average peak inundation and the highest median inundation occurs in the month of August (Figure 4.12). From the rainfall records of Zeekoevlei (1909 – 2018), July is identified as the month with the highest average monthly rainfall (Figure 4.12).

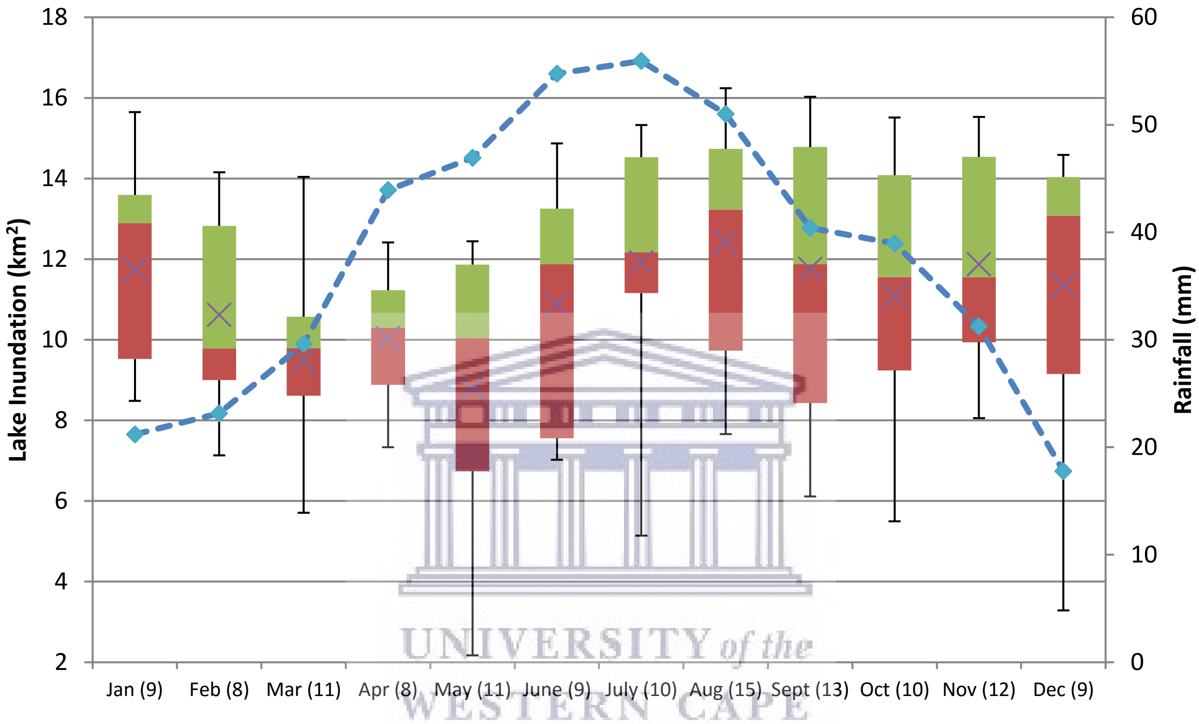


Figure 4.12 Monthly average area of lake inundation for Soetendalsvlei based on Landsat time series (1989 – 2019) and average rainfall (mm/month), indicated as a blue dotted line, for Zeekoevlei. On the x-axis, the numbers in brackets represent the number of Landsat images which were processed for each month. The cross or figure 'x' denotes the average inundation.

4.3.4 Trends in inundation

The annual inundation data series generated from 1989 to 2018 was analyzed for any significant change point in the series using homogeneity tests. The computed *p-value* for the Pettitt test, Standard Normal Homogeneity Test (SHNT) and the Buishand's test were 0.7, 0.43 and 0.28 respectively (Table 4.4). The interpretation from these homogeneity tests suggest that the data are homogenous. To assess the trend in the data series, the Kendall's statistic and the computed *p-value* were 0.09 and 0.52, respectively. The computed *p-value* was greater than 0.05 at alpha level 0.5, and showed no trend in the inundation data series.

Table 4.4 Homogeneity test for annual inundation series data for Soetendalsvlei (1989 – 2018)

	P-value	Alpha (α)	Confidence level	Test decision
Pettitt	0,704	0.05	99%	p-value > α, H_0 accepted
SNHT	0,434	0.05	99%	p-value > α, H_0 accepted
Buishand	0,283	0.05	99%	p-value > α, H_0 accepted

Test interpretation: H_0: Data are homogeneous

4.3.5 Relationship between *in situ* lake level and MNDWI

A significant relationship exists between the *in situ* lake level at Soetendalsvlei and the lake inundation estimated with the MNDWI for the period 12 March 2015 to 1 September 2017 (Figure 4.13). Inundation increases/decreases with an increase/decrease in the lake level. The maximum *in situ* level of 2.39 m was recorded on 10 September 2015, while the largest area inundated was estimated to be 15.95 km^2 on 4 September 2015. The lowest lake level of 1.18 m was recorded on 1 September 2017 before the instrumentation was removed from the field. From 24 October 2016 to 1 September 2017, the inundation decreased significantly from 14.98 km^2 to 7.75 km^2.

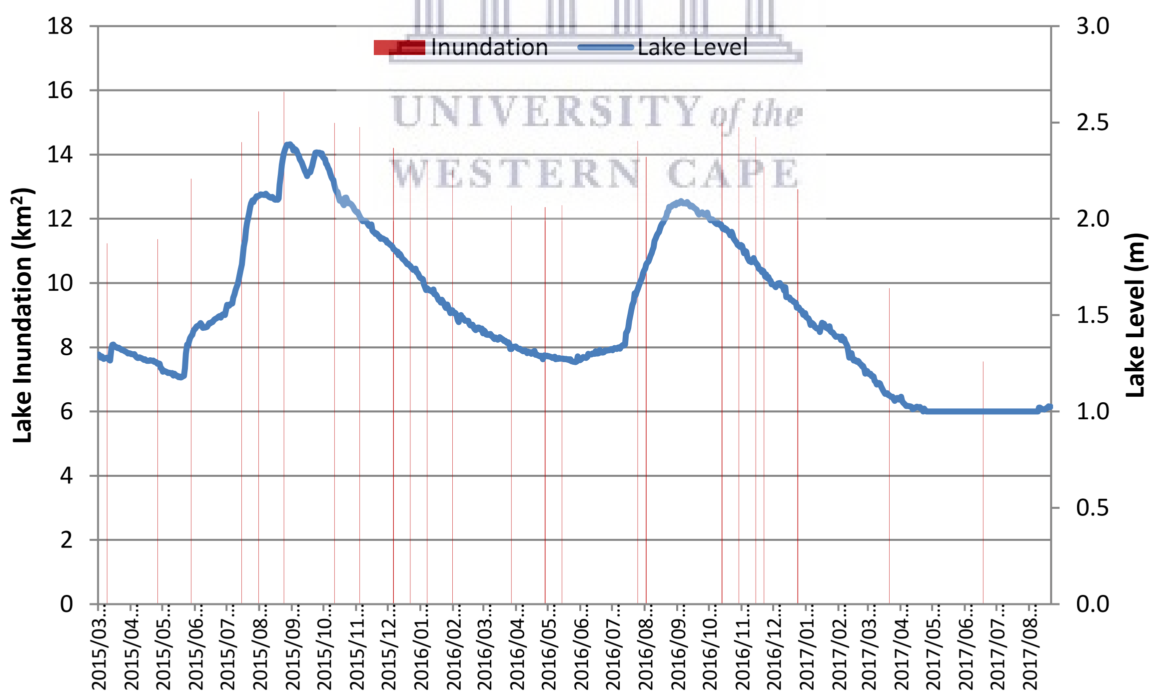


Figure 4.13 Lake levels and MNDWI for Soetendalsvlei (12 March 2015 to 1 September 2017)

The logarithmic graph illustrates the best relationship between the *in situ* lake level of Soetendalsvlei and the inundated area estimated from MNDWI for the period of 12 March 2015 to 1 September 2017 (Figure 4.14). The relationship between the inundated area (A) and water level (h) of the lake reflects the morphometry of the lake basin, which according to Hayashi and van der Kamp (2007) is unique for every basin. This A-h relationship inferred from Figure 4.14 supports a general parabolic shape.

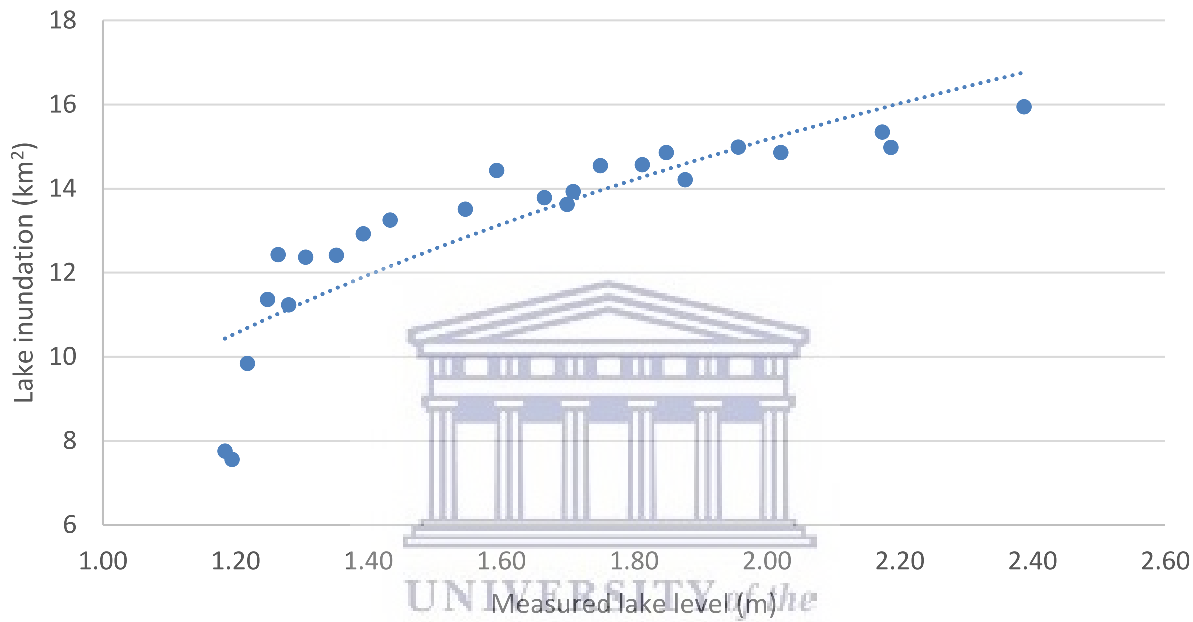


Figure 4.14 Comparison of the measured *in situ* lake level (m) and the surface area (km^2) derived from the MNDWI index using Landsat 8 OLI/TIRS and Landsat 7 ETM+

The relationship derived between the inundated area estimated using MNDWI (A) and measured lake levels (h) were significantly correlated for the period 12 March 2015 to 1 September 2017, with a with R^2 = 0.75:

$$A = 9.0237\ln(h) + 8.9069, \quad (4.3)$$

Utilizing the aforementioned relationship it is possible to estimate, with a reasonable level of accuracy, the inundation for Soetendalsvlei for periods where there is a paucity of remote sensing images and where *in situ* lake levels are available.

The converse relationship between the *in situ* lake level (h) and inundation (A) can be expressed as a third order polynomial, with $R^2 = 0.94$:

$$h = 0.0032A^3 - 0.0811A^2 + 0.6864A - 0.7271 \quad (4.4)$$

4.3.6 Correlation of inundation with precipitation

The best relationship between the Antecedent Precipitation Index (API) using daily rainfall data and inundation was obtained for *k* = 0.99 with $R^2 = 0.42$ (Figure 4.15). Although the *k* parameter varied between 0.85 and 0.95 for rural catchments across Australia (Hill *et al*., 2014), the *k* parameter between 0.85 and 0.98 generated low correlation in this study (Table 4.5).

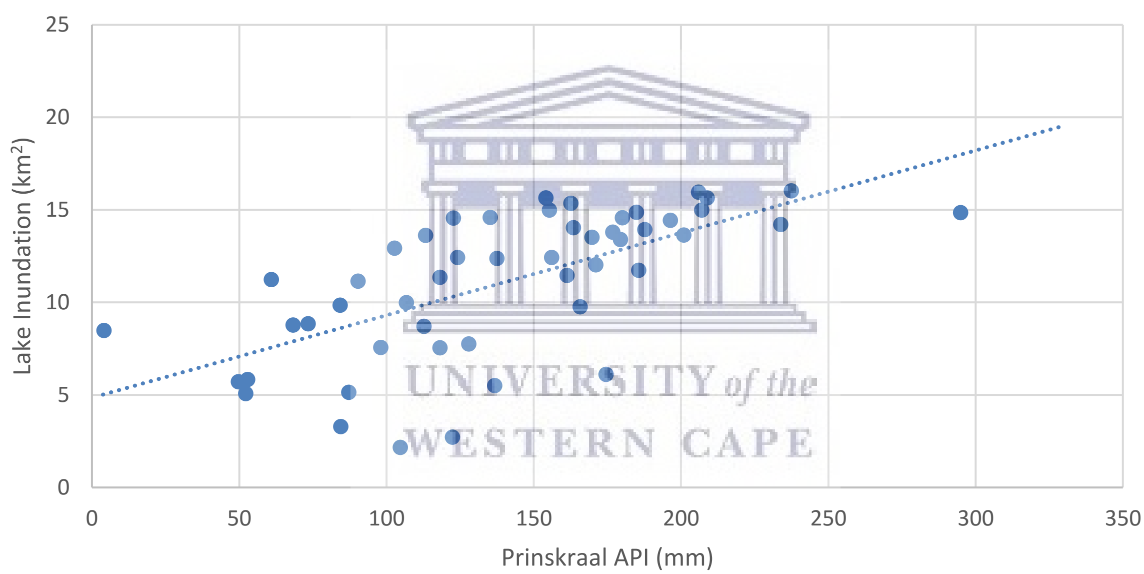


Figure 4.15 Relationship between antecedent precipitation using the API (k = 0.99) and inundation

Table 4.5 The relationship (R^2) between API and inundation for different *k* parameters

k parameter	R^2
0.85	0.06
0.9	0.09
0.95	0.13
0.98	0.26
0.99	0.42

There is a significant positive correlation between inundation and the SPI calculated over different periods (Figure 4.16). The coefficient of determination (R^2) varies from a low of 0.08 (SPI-1 month) with the SPI-18 months the highest positive correlation (R^2 = 0.60). The results suggest that the SPI can serve as a tool in understanding how rainfall variability may influence the inundation for Soetendalsvlei.

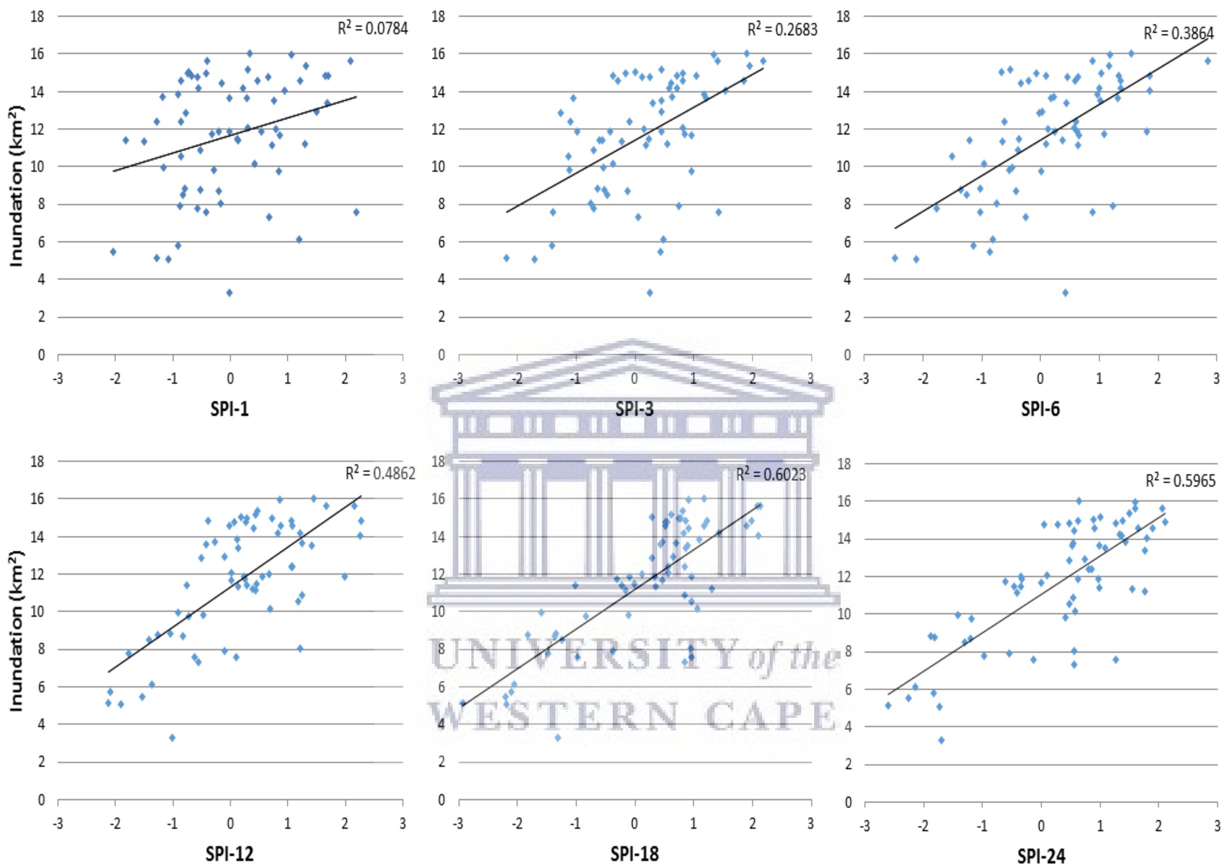


Figure 4.16 Correlation between inundation and SPI (with a significance level alpha=0,05)

The relationship between lake inundation (km²) as derived from the MNDWI (A) and the SPI-18 months (Figure 4.15), with a R^2 = 0.60 is:

$$A = 2.1159(SPI\text{-}18) + 11.206 \quad (4.5)$$

The correlation of 0.60 shows that the inundation is not only influenced by rainfall. Factors that may influence wetland inundation include climatic factors, catchment and landuse properties, as well as anthropogenic influences.

4.4 Discussion

4.4.1 Classification, accuracy and limitations

The use of high-resolution imagery is valuable in selecting optimal thresholds (Schaffer-Smith *et al*., 2017) and assessing the accuracy of water extraction techniques (Thomas *et al*., 2015). Aerial photographs were used to assess the performance using thresholds of 0, 0.2 and 0.5 for the MNDWI. The threshold of 0 had the highest overall accuracy of 93%, due to the improved ability to map the underlying water of flooded emergent vegetation. With a producer's accuracy of 91%, the errors of omission were identified along the shallow littoral zone and the shoreline boundary. Along the littoral zone, shallow water along the shoreline was not detected, specifically when emergent vegetation was present. Spectral mixing between shallow water and mud (Halabisky *et al*., 2016) as well as water and emergent vegetation (Thomas *et al*., 2015) causes misclassifications, and remains a challenge in mapping inundation. The MNDWI, using a threshold of zero, was highly accurate in extracting open water in Soetendalsvlei. With an overall accuracy of 93%, this study is comparable to the 96% accuracy achieved by Buma *et al*., (2018) in mapping inundation for Lake Chad.

The Landsat archive offers a valuable collection of medium-resolution remotely sensed images of the Nuwejaars Catchment, and Soetendalsvlei in particular which, when the MNDWI is derived, allows the temporal and spatial monitoring of inundation. Halabisky *et al*., (2016) reconstructed the surface-water hydrographs for different wetlands using spectral mixture analysis and Landsat images for the period 1984 to 2011, while Buma *et al*., (2018) and Tebbs *et al*., (2013) used archival imagery to establish seasonal and annual variations of lakes. Grundling *et al*., (2013) used Landsat imagery for a wet and dry year to identify permanent and temporary inland wetlands on the Maputaland Coastal Plain in KwaZulu Natal, South Africa, and also identified wetland loss due to anthropogenic influences.

Although the use of remote sensing is immensely valuable, it remains limited, given that frequent cloud cover may result in partially or totally obscured areas of interest (Zimba *et al*., 2018). For Soetendalsvlei in particular, the remote monitoring did not provide a regular 16-day estimate of lake inundation due to cloud cover over the lake. However, from the available images, inter-annual, multi-seasonal and monthly information on inundation were derived from the Landsat imagery from 1989 to 2019.

4.4.2 Frequency of inundation and the hydroperiod

The floodplain and depression wetlands provide a significant area of flooding particularly within the relatively flat, lower Nuwejaars catchment. The spatiotemporal changes of flooding and drying within the Nuwejaars catchment illustrates the importance of hydrological connectivity of the river network and the wetlands. Soetendalsvlei, the largest depression wetland provides storage for water draining the Nuwejaars catchment, before outflow to the Heuningnes River. The spatiotemporal changes of flooding and drying within a wetland is an important determinant of wetland function (Mitsch & Gosselink, 2007). Wu & Liu (2015a) found that the spatial distribution of inundation in Poyang Lake was controlled by the variability of river inflow and lake bathymetry, with deeper depressions in the lake showing less variation of inundation. Although no bathymetric map for Soetendalsvlei exists, studies report that the lake is divided into deeper pools with average depths of 2 m (Hall, 1995). These deeper pools have a higher frequency of inundation, suggesting that bathymetry is an important determinant of the hydroperiod for Soetendalsvlei. The relatively deeper pools of Soetendalsvlei were permanently inundated between April 1989 and September 2017. However, with the drought conditions persisting from 2016 into early 2019, the northern pool of Soetendalsvlei dried out, indicating the importance of climatic conditions in influencing the hydroperiod. Buma *et al.*, (2018) also concluded the importance of bathymetry and climate for Lake Chad. The study found that due to the ponding of water in the deeper pool of Lake Chad during dry conditions, water loss mainly occurred due to evapotranspiration and seepage. The seasonally inundated areas of Soetendalsvlei were mainly confined to areas surrounding the deeper pools, while intermittent inundation was prominent along the shoreline and the shallow littoral zone. The functionality of the hydroperiod is in understanding the dynamic patterns of flooding and the frequency of flooding within a wetland system, and its influence on wetland function. The hydroperiod of relatively shallow lakes and wetlands are dynamic over time and space, and can be 'captured' by the analysis of multitemporal, freely available remotely sensed images (Grundling *et al*., 2013; Buma *et al*., 2018).

The percentage of time a particular area was inundated from 1989 to 2019 identifies 'gradients of wetness' and can thus serve as a proxy for flood frequency. Crisman *et al*., (2005, p381) identifies 'gradients of water depth' as an important determinant of wetland function, and considers the hydrological connectivity (Wohl, 2017) and horizontal transition from the permanently inundated open water to the inundated vegetated shoreline of a lake as representing different functional units, each associated with providing specific ecosystem services. The 'gradients of wetness' identified by the frequency of inundation provides a descriptive account of the hydrology of the wetland, and is a relevant characteristic influencing the physiochemical environment and biota of the wetland.

4.4.3 The temporal variation of inundation

The inter-annual variation of inundation for lakes and wetlands derived from remotely sensed data has been documented as a measure for assessing change in the hydrology linked to climate change and, or anthropogenic activities (Gal *et al*., 2016; Jin *et al*., 2017). Evidence of significant declines in inundation has been documented for Lake Chad (Lemoalle *et al*., 2012) and lakes in China (Ma *et al*., 2010a), while increases in inundation has been mapped for global human-made wetlands (Pekel *et al*., 2016) and endorheic lakes in parts of the Sahel (Gal *et al*., 2016). Although inundation from 1989 to 2018 shows marked inter-annual variability, homogeneity and trend tests for this period suggests no change or trend in inundation for Soetendalsvlei.

The inter-annual and seasonal pattern of inundation for Soetendalsvlei is closely linked to rainfall variations and the periodic influence of extreme climatic events, such as floods and droughts. Soetendalsvlei is characterized by maximum inundation in the month of August and the spring season, mainly due to the winter rains of the Mediterranean climate. However, localized and high rainfall in late spring and summer on the Agulhas Plain due to cut-off low pressure systems, coupled with high antecedent moisture from the winter months, can cause increased inundation during the summer months. The shrinking of Soetendalsvlei and the drying out of the northern pool in May 2019 was in response to three consecutive years of below average precipitation. The drying out of Soetendalsvlei was also recorded in the 1970s after a prolonged drought (Bickerton, 1984). Rainfall variability is thus an important factor influencing inundation (Nsubuga *et al*., 2015; Deng & Chen, 2017; Li *et al*., 2017; Zimba *et al*., 2018; Wang *et al*., 2019).

Drought indices can provide an understanding of the response of wetland inundation to rainfall variability (McCauley *et al*., 2015). In an ungauged catchment where only rainfall data is available, the relationship of remotely sensed inundation data to the Standard Precipitation Index (SPI) provides an understanding of how the water surface area for Soetendalsvlei may be influenced by rainfall. While the utility of the SPI as a drought monitoring and prediction tool has been widely accepted, the SPI can feasibly be extended to predicting the impact on surface water resources.

The correlation between the SPI and inundation for Soetendalsvlei is significant (R^2 = 0.60), but when compared to a similar study for Lake Sibayi, South Africa (Nsubuga *et al*., 2019) where the correlation (R^2) was 0.88, the conclusion is that inundation for Soetendalsvlei is not solely a function of rainfall variability. The consideration of rainfall/drought indices which incorporates evapotranspiration, such as the Standardized Precipitation Evapotranspiration Index (SPEI), should be explored.

4.4.4 Integration of *in situ* and remotely sensed data

The comparison of the *in situ* lake level of Soetendalsvlei and lake inundation derived from the MNDWI index using Landsat showed a significant positive correlation (R^2 = 0.75), and demonstrates the potential of the remote monitoring of this shallow lake. A good relationship between *in situ* water level and inundated areas estimated from remotely sensed images was also shown for freshwater lakes in China (Hu *et al*., 2015; Wu & Liu., 2015a), Lake Champlain in the United States (Bjerklie *et al*., 2014), large reservoirs in the United States (Gao *et al*., 2012) and the Mahakam lakes in Indonesia (Hidayat *et al*., 2017). Zimba *et al*., (2018) found a very strong relationship between inundation of the Barotse Floodplain and water level (R^2 = 0.93) and concluded that inundation extents are mirrored in trends of water level. With the significant correlation between *in situ* lake level and inundation for Soetendalsvlei from 2015 to 2017, the results of this study suggests that inundation can be used as a proxy for lake level.

There are a limited number of lake gauging stations, specifically in developing countries, while manual observations at ungauged lakes are not consistently done (Pan *et al*., 2013). Where *in situ* and remotely sensed information is available, the integration of these data sets for research and monitoring offers an increased understanding of lake dynamics (Dörnhöfer & Oppelt, 2016; Politi *et al*., 2016). A replication of this study, where the collective inundation assessed from remotely sensed data and the water level is measured over a period of at least 2 years, has the potential of generating valuable information and scientific knowledge of similar lake systems, specifically where there is a dearth of hydrological information.

4.5 Conclusion

In areas where no *in situ* hydrological information is available, remote sensing provides a means of monitoring the spatial extent, duration and frequency of wetland inundation. The inundation maps derived from this research demonstrates the potential of monitoring a shallow lake partially covered with emergent vegetation within a semi-arid environment using the MNDWI with a threshold of zero. The maps provide an understanding of the temporal and spatial variation of flooding, and thus add value to research related to water-dependent ecosystems.

Despite the irregular database of remotely sensed data, the characterization of the hydroperiod for wetlands in the Nuwejaars catchment and Soetendalsvlei were established. The dynamic pattern and frequency of flooding is an important determinant of wetland function, and is influenced by climatic conditions and water depth. The hydroperiod for Soetendalsvlei is characterized by permanent and semi-permanent pools of water, with 'gradients of wetness' extending from the pools of water to the littoral zones. The 'gradients of wetness' infers lateral hydrological connectivity within the wetland and characterizes functional units which supports diverse habitats.

The time series of inundation generated from the Landsat archive provide a reasonably accurate, although irregular historic account of surface flooding for Soetendalsvlei. Inundation for Soetendalsvlei over the 30-year period from 1989 to 2019 shows no significant trend in the available time series but displays significant annual, seasonal and monthly variation. The variation of inundation for Soetendalsvlei is closely linked to rainfall variability. The Nuwejaars catchment is subject to intense floods and droughts, with consequent influences on inundation. The Western Cape, South Africa, experienced significant drought from 2016 with the lake area receding by almost 85% from October 2016 to May 2019. The Standard Precipitation Index (SPI) is a useful monitoring tool in understanding the influence of rainfall variability on inundation for Soetendalslvei.

The integration of the 3-year dataset of *in situ* lake levels and/with the remotely sensed inundation, has, for Soetendalsvlei, made the following possible (1) the estimation of the lake level using inundation as the proxy, and (2) the reconstruction of the lake hydrograph for Soetendalsvlei from 1989. With no recorded hydrological data available for Soetendalsvlei prior to March 2015, the time series of inundation offers baseline hydrological information.

CHAPTER 5

MORPHOMETRIC PROPERTIES OF SOETENDALSVLEI

5.1 Introduction

The morphometry of lakes plays a key role in ecosystem functioning (Papastergiadou *et al*., 2007; Evtimova & Donohue, 2016). The geometric shape, depth and size of the lake influence the flow and accumulation of water and matter that influence material cycling, and affect ecosystem productivity (Stefanidis & Papastergiadou, 2012; Li *et al*., 2019). These morphometric properties are critical factors controlling light intensity, water transparency, heat balance, nutrient loading, trophic state and occurrence of vegetation (Håkanson 2005; Scheffer & van Nes, 2007; Nõges, 2009). The shape and orientation of the lake relative to the influence of wind characteristics also has an influence on lake processes such as water circulation, wind-generated wave development and sediment suspension, which influences the occurrence of aquatic vegetation and water quality (Fagherazzi & Wiberg, 2009; Janssen *et al*., 2014). Lake morphometry influences water storage capacity and is key to understanding changes in the water levels and the extent of flooding (Hayashi & van der Kamp, 2007). Every lake has a unique depth-area-volume relationship or hypsometric curve (Hayashi & van der Kamp, 2007). The hypsometric curve provides information on how the surface area or volumetric storage responds to a change in water level (Hayashi & van der Kamp, 2000; Haghighi *et al*., 2016).

The variation of lake water levels is a dominant control on the productivity and diversity of lake ecosystems, with shallow lakes being very productive, diverse and sensitive ecosystems (Wantzen *et al*., 2008). When the water level changes above or below a particular threshold, the functioning of lakes may be affected (Wantzen *et al*., 2008). Using lake vegetation as a proxy in assessing the ecosystem health of a shallow lake on the Yangtze basin, China, Liu *et al*., (2017) established a model linking the lake water level with the spatial coverage of aquatic vegetation. The model was created using bathymetric data to establish the hypsometric curve in relation to the areal extent of vegetation (Liu *et al*., 2017). Shang & Shang (2018) determined the minimum water level for habitat requirements by determining the inflection points of hypsometric curves, and identifying a lake level where a change in volume may cause a change in the surface/habitat area. In assessing the water level requirements for the optimum functioning of lakes an understanding of lake morphometry is essential.

An understanding of the water storage capacity of lakes is important to consider in hydrologic processes (Spence, 2000) particularly where lakes and wetlands are part of the drainage network. Surface outflow from a lake is dependent on the storage properties of the lake, the presence and type of vegetation in the lake, and the cross section, slope and roughness of the outflow channel (Jeng & Yevdjevich, 1966; Kebede *et al*., 2006; Hayashi and van der Kamp, 2007). Surface overflow from a lake will only occur when the lake storage capacity has been exceeded (Kusumastuti *et al*., 2007). Surface outflow from a lake is greater with increased water storage (Hayashi and van der Kamp, 2007). In attempting to find a relation between precipitation and water level in Lake Tana, Ethiopia, Kebede *et al*., (2006) found a significant positive relation between the lake level and the surface flow from the lake. Kumambala & Ervine (2010) also found a significant positive correlation between the lake level and the lake outflows of Lake Malawi. As lakes within a drainage network may influence the timing and magnitude of surface outflow to the downstream catchment, the characterization of these depressions is important (Winter, 2001; Wu & Lane, 2017).

Lake morphometry has been recognized as a key factor in understanding lake response to climate variability (Adams & Sada, 2014; Haghighi *et al*., 2016), anthropogenic influences and lake eutrophication (Janssen *et al*., 2014). In assessing how lake morphometry influences water level fluctuations due to changes in flow conditions, Haghighi *et al*., (2016) developed the Lake Geometry Index (LGI) using hypsometric curves of 152 lakes and reservoirs located in Finland and Iran. Shallow lakes in a flat terrain were classified with a low LGI (i.e. less than 0.75) as these lake systems had a quick response time to flows, while deep lakes with steep sides had a high LGI (i.e. LGI greater than 8.5). The theoretical foundation of LGI is based on the geometry of the lake, with a low LGI reflecting a high area to volume ratio. In arid and semi-arid areas, evapotranspiration loss from a lake is influenced by the water surface area, with a high area to volume ratio resulting in a high loss of water (Haghighi *et al*., 2016). Shallow lakes, more specifically terminal lakes, in arid areas are thus prone to desiccation (Adams & Sada, 2014; Haghighi *et al*., 2016). Buma *et al*., (2018) found that the morphology of Lake Chad, a terminal lake in Africa, influenced hydrological surface isolation/connectivity such that with limited water inflow and enhanced evaporation, the northern pool of Lake Chad was prone to desiccation. Janssen *et al*., (2014) highlighted the importance of connectivity within a lake, and the influence of lake morphometry in influencing the horizontal exchange of water and matter, and the subsequent ecosystem functioning of lakes. Knowledge of lake morphometry is thus important in enhancing our understanding of ecosystem functioning, and in guiding the sustainable use of lakes and wetlands (Yao *et al*., 2018). With most morphometric studies focusing on regulated lakes and reservoirs, there is a pronounced lack of data on the relatively smaller lakes (Sobek *et al*., 2011; Gonçalves *et al*., 2016). Where freshwater outflow from coastal lakes are important in maintaining the ecological integrity of estuarine environments, a greater understanding of the surface connectivity is required. Consequently, there is a need for further morphometric studies, to enhance our understanding of how lakes and wetlands function within a landscape and the properties that influence ecosystem functions. The main aim of this chapter is to investigate the morphometry of Soetendalsvlei in the Nuwejaars catchment. An understanding of the physical structure of a lake will provide insight into the factors affecting the inundation, and the functioning of this lake.

The key objectives of this chapter are:

1. To evaluate the morphometric characteristics of Soetendalsvlei, and how these affect inundation patterns and water storage dynamics.
2. To understand how morphometric characteristics influence ecosystem functions.

5.2 Methods

A bathymetric map provides information of the depth configuration and topography below water level, from which morphometric characteristics such as shoreline perimeter, maximum depth, average depth, surface area and lake volume can be determined. The bathymetric map also facilitates the derivation of the hypsometric curves. The use of coupled fathometers, global positioning systems and Geographic Information Systems (GIS) have enhanced the production and accuracy of bathymetric maps (Dost & Mannaerts, 2008; Ovakoglou *et al*., 2016). The use of geometric models (Hayashi & van der Kamp, 2000; Messager *et al*., 2016) as well as remote sensing data and altimeters (Ovakoglou *et al*., 2016; Politi *et al*., 2016) are alternative and less time-consuming methods to approximate lake morphometry and determine the volumetric capacity of wetlands. However, Trigg *et al*., (2014) has shown that bathymetric uncertainty using geometric models can lead to erroneous estimations of water balance components. In a regional scale study of the Northeastern United States, Hollister *et al*., (2011) used topographic data surrounding a lake to estimate the maximum lake depth of over 27 000 individual lakes. The main premise of the study by Hollister *et al*., (2011) was that geomorphological processes that shaped the lake were similar to the processes that shaped the surrounding lake basin. Although the results from the study were useful in regional modeling studies, with an average estimated error of 5 to 6 m, the methodology does not add value in understanding shallow lakes along a relatively flat coastal plain. There is thus a need for 'actual bathymetric measurements of lakes' (Messager *et al*., 2016). The methodology best suited in assessing the bathymetry of Soetendalsvlei was the use of the coupled fathometers, global positioning systems and Geographic Information Systems (Dost & Mannaerts, 2008), and is described below.

5.2.1 Bathymetric survey

A bathymetric survey of the open water of Soetendalsvlei was completed in September and October 2014. Soetendalsvlei is a wetland freshwater ecosystem priority area (FEPA), which intersects with the Heuningnes estuary, a Ramsar site (Nel *et al*., 2011). The damage or removal of aquatic vegetation, and the disturbance of sensitive ecosystems were important ethical considerations during the data collection process. A description of the equipment, data collection and analysis of data is presented below.

5.2.1.1 Equipment

Access to Soetendalsvlei was arranged with the relevant landowners, Cape Nature and SANParks. As CapeNature manages a section of Soetendalsvlei, special permission was required for the use a motorized boat with 15Hp Yamaha engine in the lake. The methodology as outlined by Dost & Mannaerts (2008) using the GARMIN Fishfinder 250C fathometer and a handheld GPS 72 was used for the bathymetric survey. The fathometer was secured to the bottom of the boat. Before the start of the survey, the depth of the fathometer below the water level was measured. To ensure the positional accuracy of the Garmin GPS 72 unit, ground control points using a Trimble differential GPS unit were established by officials from the Department of Agriculture (LandCare Overberg, Bredasdorp) and were used to calibrate the Garmin GPS 72 unit. Ground control points with accurate absolute coordinates and elevation points were established in close proximity to Soetendalsvlei (Figure 5.1).

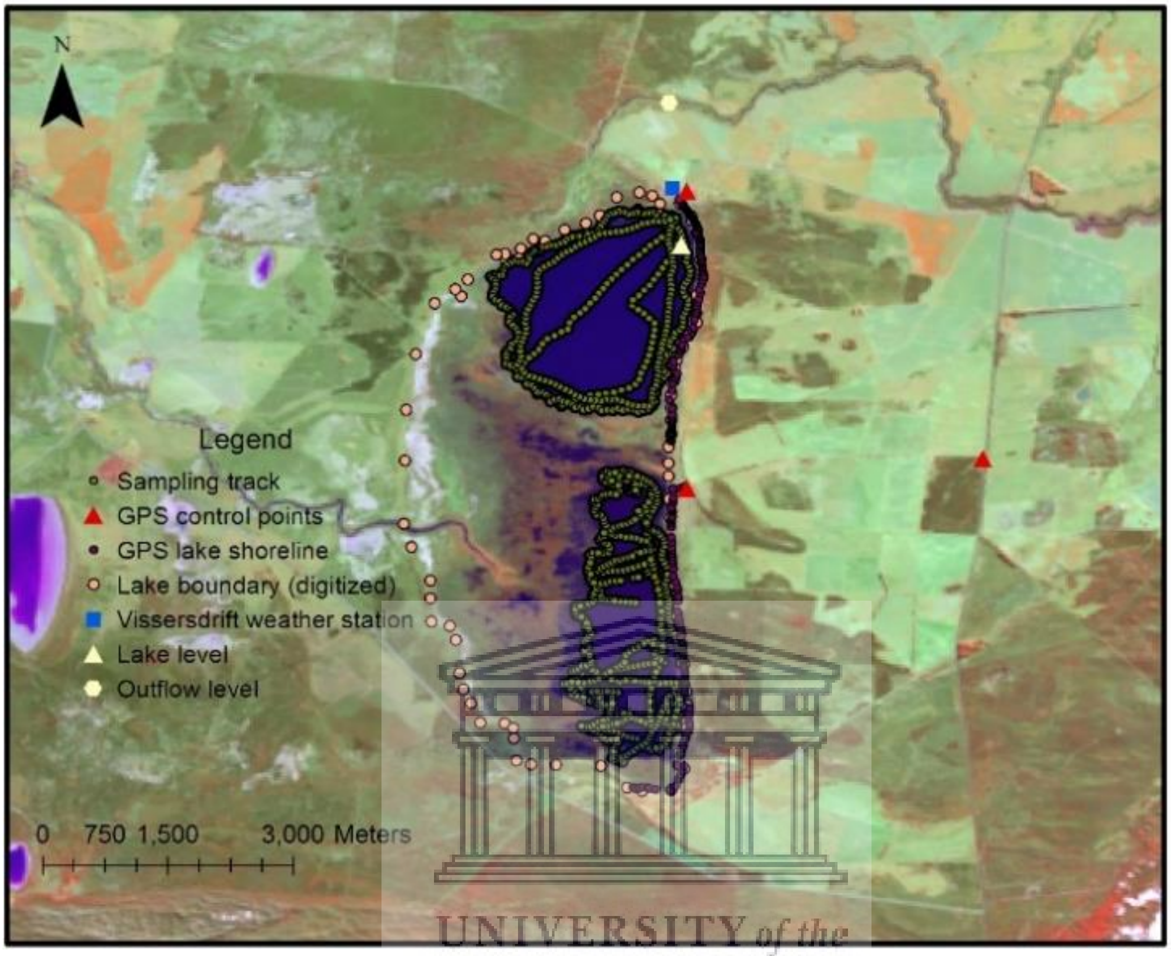


Figure 5.1 Sampling tracks within the northern and southern open water pools of Soetendalsvlei and the lake/wetland boundary derived from the land survey and digitized from Landsat 8

5.2.1.2 Survey

The GPS 72 was set to simultaneously record the depth and geographical coordinates every 20 seconds during the bathymetric survey. The survey speed was less than 15 km/hour. The survey consisted of a combination of shoreline/circular cruises and east-west transects of the open water (Figure 5.1). Soetendalsvlei has a growth of dense emergent reeds which separate the lake into two pools. A shoreline cruise for each of the pools was done by maintaining a depth of approximately 1 m on the eastern shore of the pools. On the northern, western and southern edge of each of the pools the shoreline was inaccessible due to the growth of emergent vegetation (Figure 5.2). Dense, tall stands of *Phragmites* along the western edge of the southern pool and along the northern edge of the northern pool were inaccessible by boat (Figure 5.2A). In the northern pool, emergent vegetation such as *Schoenoplectus* was dominant (Figure 5.2B).

Although access by boat between the *Schoenoplectus* was possible, aquatic weeds were damaged by the propeller, which caused the displacement of the fathometer. Incorrect depth readings in excess of 3 m were recorded when the fathometer was displaced by aquatic reeds. The circular cruise on the western edge of Soetendalsvlei was thus confined to the open water, with depths in excess of 1 m. The accuracy of the depth (fathometer) reading was checked on four separate occasions, within each pool, with a graduated pole.

The bathymetric survey was confined to the open water of Soetendalsvlei.

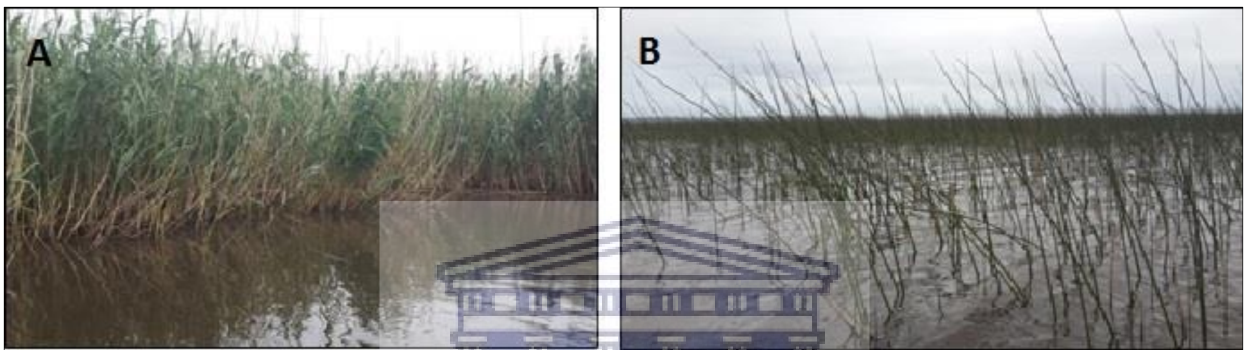


Figure 5.2 Emergent vegetation in Soetendalsvlei dominated by *Schoenoplectus* on the western edge and centre of open water (A) and *Phragmites* along the southwestern and northern edge of Soetendalsvlei (B) (photograph taken in September 2014)

5.2.1.3 Terrestrial survey

To obtain the boundary for the entire lake area, boundary points were digitized from a composite Landsat 8 image captured on 24 August 2014 (Figure 5.1). The closest Landsat image to the date of the bathymetry was 25 September 2014, but due to high cloud cover, the image could not be used. On 24 September 2014, the boundary of the eastern shoreline of Soetendalsvlei was surveyed by the Department of Agriculture using a Trimble differential GPS. The officials of the Department of Agriculture, Bredasdorp conducted the survey by walking alongside the water edge of Soetendalsvlei (Figure 5.1).

5.2.2 Analysis of bathymetric data

The individual depth data sets for the northern and southern pools of Soetendalsvlei were merged to create one data set. The depth of the fathometer located at the base of the boat during the survey, was 10 cm below the lake water level. To offset the depth readings of the fathometer below the water level, a total of 10 cm was added to the value of all depth entries. The lake boundary data set and the merged depth data set for Soetendalsvlei were combined to create a feature layer for further analysis.

The interpolation of depth point data generates values that reflect depth (in metres) with the lake shoreline as reference depth (Yesuf *et al*., 2013). The accuracy of the three interpolation techniques, namely, the inverse distance weighting (IDW), nearest neighbour and kriging techniques (Dost & Mannaerts, 2008; Fotheringham & Rogerson, 2009) were assessed. Before the interpolation techniques were applied to the depth data, 20 random data points were removed from this dataset. These 20 data points were used to determine the error variance (R^2) or accuracy of the interpolation techniques. The interpolation technique with the highest accuracy was selected to generate the bathymetric map. Cross-profiles of the lake were interpolated from the bathymetric map.

The interpolated data were classified into depth classes from which the area and volume were calculated. The relationship between lake depth, area and volume were determined. The lake geometry index (LGI) developed by Haghighi *et al* (2016) assesses how the lake geometry or shape affects the response time to a change in the water balance. The LGI was determined for Soetendalsvlei by converting the volume axis of the hypsometric curve to a logarithmic scale, with "the absolute value of the slope of this line defined as the LGI" (Haghighi *et al*, 2016, p600).

5.2.3 Morphometric characteristics

The morphometric properties for Soetendalsvlei were summarized and calculated from the bathymetric data. The morphometric properties are based on formulae that have been well researched for lakes (Löffler, 2004). The elevation of the shoreline was determined from the terrestrial survey conducted by the Department of Agriculture. The shoreline length and the area of the lake (A) in km^2, was determined from the delineation of the wetland boundary using the Landsat 8 image captured on 24 August 2014. The following morphometric properties represented by Equations (5.1) to (5.4) were calculated from above-mentioned data collected in October 2014.

1. The shoreline development index (D_L)
   The shoreline development index compares the shoreline length (L) to a circular lake with the same area, and is an index that allows the comparison of different lake systems (Wetzel, 2001; Telteu & Zaharia, 2012).

$$D_L = \frac{L}{2\sqrt{\pi A}} \quad (5.1)$$

2. Relative depth (D_{rel})

   The relative depth is the maximum depth (D_{max}) expressed as a percentage of the mean diameter of the lake (Wetzel, 2001) where most lakes are less than 2%.

$$D_{rel} = \frac{50 \times D_{max} \times \sqrt{\pi}}{\mathrm{A}} \quad (5.2)$$

3. Average depth (D_{ave})

   The average depth is the ratio of the volume (V) to the surface area (A) of the water

$$D_{ave} = \frac{V}{A} \quad (5.3)$$

4. Fetch, wave height, wave length and wave period

   The impact of wind on shallow lakes is important in the generation of waves, which can cause the resuspension of substrate sediment and influence water transparency (Wetzel, 2001; Fagherazzi & Wiberg, 2009). Wind-generated waves in shallow lakes can cause stem breakage of emergent vegetation and hinder bud formation, ultimately influencing the occurrence of emergent macrophytes (Coops *et al*., 1991). The impact of wind is dependent on wind speed, but most importantly fetch which is defined as the distance that the wind blowing in the same wind direction passes over a water surface. Based on the dominant wind direction, the effective fetch length is measured from the shoreline in the direction of the wind (Rohweder *et al*., 2008). The development of wind-generated waves are dependent on fetch, wind speed and water depth (Fagherazzi & Wiberg, 2009).

   Wind direction (in degrees) and wind speed (in m/s) are recorded at 15-minute intervals at the Vissersdrift weather station (Figure 5.1). A wind rose diagram showing wind direction and average daily wind speeds was designed from available data. Wind direction in degrees were converted to cardinal wind direction (Rohweder *et al*., 2008). Wind direction frequencies (as percentages) were determined for the cardinal direction. The wind direction with the highest frequencies of recorded events was determined as the dominant wind direction.

   With the available bathymetric and daily wind data for Soetendalsvlei, the wave height, length and period were mapped for the dominant wind direction based on a wind fetch and wave model developed by the U.S Geological Survey (USGS) (Rohweder *et al*., 2008). Algorithms for the wave properties are explained in Rohweder *et al*., (2008). Daily *in situ* lake levels collected at 15-minute intervals provide the only available data to validate wave height. Details of the lake level instrumentation is stated in the section below.

5.2.4 Characteristics of lake storage and surface outflow

5.2.4.1 Lake stage-outflow rating curve

Surface outflow from a natural or unregulated lake is influenced by the amount of water stored in the lake, the level/stage at which outflow occurs, and the properties of the channel where outflow occurs (Jeng & Yevdjevich, 1966; Shaw *et al*., 2011). The lake stage-outflow rating curve, the relation between surface outflows (Q_o) and the lake stage at which outflow occurs (H) is normally expressed as a nonlinear relation (Kebede *et al*., 2006; Kumambala & Ervine, 2010):

$$Q_o = a(H)^b \tag{5.4}$$

Continuous water levels within the northern and southern pools of Soetendalsvlei were measured with the use of automatic water level recorders (OTT Orpheus Mini water level logger) (Figure 5.1). In the northern pool the water level logger was installed on 9 May 2015 and placed at the bottom of a concrete structure which extends from the eastern shore of the lake. On 3 March 2015 the water level logger was placed within a lake inlet in the southern pool. Both water level recorders were placed along the eastern shoreline of Soetendalsvlei where the growth of vegetation did not limit access or create interference. The loggers in the northern and southern pools in Soetendalsvlei record the water levels at 30-minute intervals. The daily water levels were calculated from the average water level readings taken each day. The pressure transducers were removed from the Soetendalsvlei due to the lake drying during drought conditions from mid-2017.

With no access to the channel at the outflow from Soetendalsvlei due to the growth of reeds, the surface outflow of Soetendalsvlei via the Heuningnes River was located 1 km downstream of lake outflow (Figure 5.1). At this site, a Solinst water level data logger was installed on 17 October 2014. The logger records the water levels at 30-minute intervals. The pressure transducer was removed from the outflow site between November 2015 and June 2016 due to vandalism concerns.

With sufficient stage measurements, the relationship between downstream and upstream stage can be determined using simple regression methods (Shaw *et al*., 2011). The lake stage-outflow stage rating curve between the daily stage in the northern pool and daily outflow stage (downstream) was assessed from May 2015 to September 2017 through regression methods.

Based on the best relationship between the lake stage and outflow level, missing outflow data were interpolated from the relationship.

In an unregulated lake, surface outflow from a lake will occur once the lake reaches a critical storage (Spence, 2000; Li *et al*., 2019). A change in surface or lateral flow conditions between the lake and outflow stage measurements can be identified by a change in the slope of the rating curve (Shaw *et al*., 2011). The critical storage of Soetendalsvlei (i.e. storage at which surface outflow occurs) was assessed by analyzing the slope of the lake stage-outflow rating curve.

5.2.4.2 Lake storage and surface outflow – a retrospective analysis

With no historical lake storage or discharge data for lake surface outflow, the assessment of historical trends in surface inundation using remote sensing allows a retrospective analysis of surface water dynamics (Tebbs *et al*., 2013; Halabisky *et al*., 2016, Buma *et al*., 2018). Assuming that the bathymetry of Soetendalsvlei remained unchanged from 1989 to 2019, the surface inundation using the MNDWI (Section 4.3.3; Figure 4.5) was converted to volumetric storage using the hypsographic curves. The critical storage for surface outflow from Soetendalsvlei, determined from the lake stage-outflow rating curve, is used to assess the frequency of lake overflow to the downstream Heuningnes River.

5.3 Results

5.3.1 Bathymetry and morphometric properties of Soetendalsvlei

The sampling track for Soetendalsvlei consisted of 1038 water depth measurements, with depths varying between 0.7 and 2.2 m. A "lost satellite reception" for the GPS 72 unit was encountered several times during the survey and thus no geographic coordinates were logged for certain depth readings. Due to variable winds and wind-generated waves, the orientation of transects were not regular in terms of (east-west) direction. Wind-generated waves were observed during the bathymetric survey and resulted in the bathymetric survey being postponed on some days. The accuracy of depth measurements, verified with *in situ* measurements using a graduated pole, were within 10 cm of the readings displayed on the GARMIN Fishfinder 250 reading device.

Both the inverse distance weighting and the nearest neighbour interpolation techniques had an overall accuracy of 90%, while the kriging technique had an accuracy of 70% (Figure 5.3). The nearest neighbour technique was selected for the generation of the bathymetric map. The interpolated depth values ranged from 0 to 2.2 m.

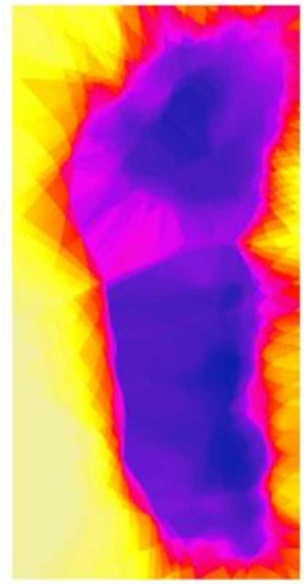
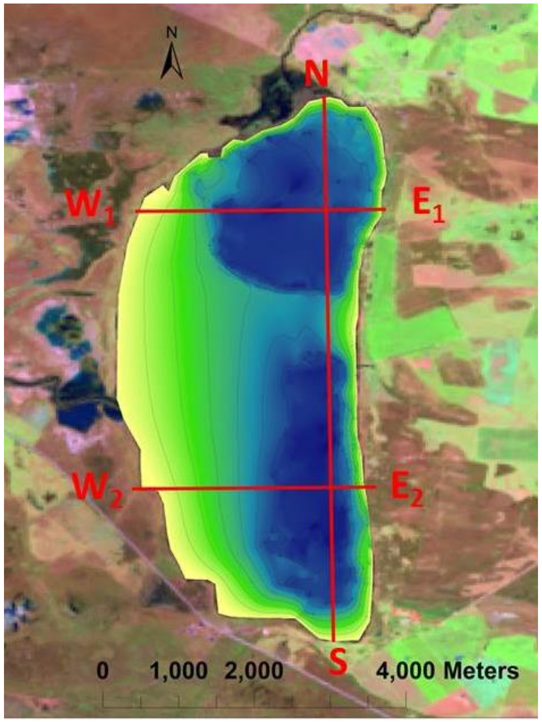
Model	**Inverse Distance Weighting (IDW)**	**Nearest Neighbour**	**Kriging**
Stretched Raster Data 			
			
R^2	90%	90%	70%

Figure 5.3 Depth interpolation for Soetendalsvlei using different techniques and corresponding accuracies

Accuracy related to the bathymetric survey were due to the lack of *in situ* depth points in areas that were inaccessible due to dense emergent vegetation, specifically along the western shore of Soetendalsvlei (Figure 5.2). The proportion of the lake covered by emergent vegetation, where no depth data was measured, is approximately 57% of the lake area.



Depth Class	Depth Range (m)	Total Area (m²)	Total Area (ha)	Total Volume (m³)
	0 - 0.29	1940248.10	194.02	273212.31
	0.29 - 0.61	1817817.89	181.78	854710.65
	0.61 - 0.94	1801932.42	180.19	1452122.28
	0.94 - 1.28	1851492.55	185.15	2113393.27
	1.28 - 1.59	2159789.08	215.98	3169065.27
	1.59 - 1.85	2174722.69	217.47	3806016.93
	1.85 - 2.19	3800688.12	380.07	7540687.46
All		15546690.85	1554.67	19209208.16

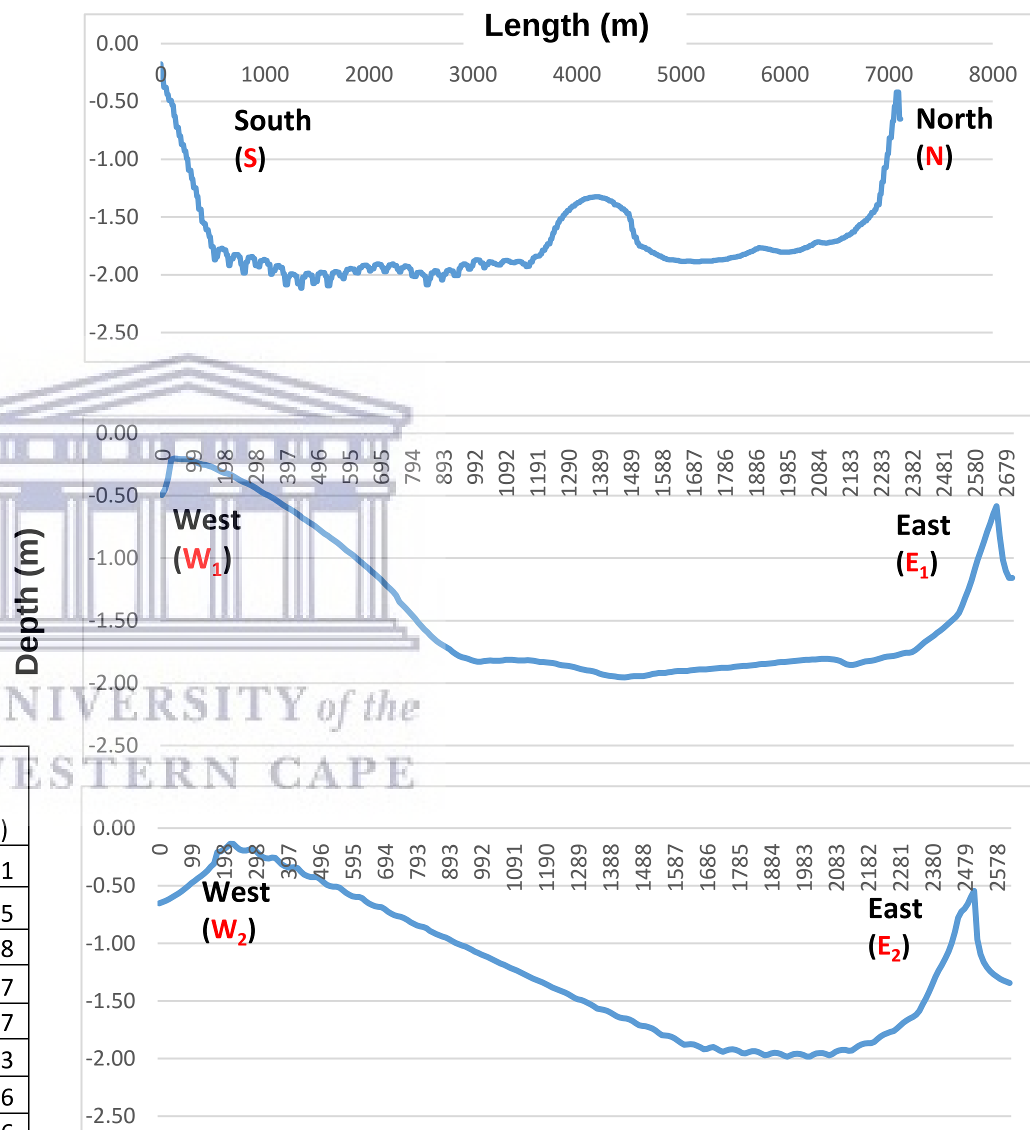


Figure 5.4 Bathymetric map and cross-profiles of Soetendalsvlei

Errors related to the position of the shoreline is minimal as a combination of a terrestrial survey with a differential GPS and the use of satellite imagery was used (Figure 5.1). The positional data collected during the terrestrial survey overlaps with the shoreline positions digitized using the satellite imagery.

Based on the bathymetric results, the inundated area of Soetendalsvlei (in October 2014) was estimated to be 15.55 km^2 (Figure 5.4). Soetendalsvlei is an asymmetric depression, with a shape that varies between parabolic and concave. The depth increases from the shoreline towards the central portion of the wetland (Figure 5.4). The bathymetry shows the occurrence of two sub-depressions, one on the northern part and another on the southern part of Soetendalsvlei, herein referred to Soetendalsvlei North and Soetendalsvlei South respectively. Cross profiles across the width of Soetendalsvlei shows that the wetland is concave but asymmetrical, with a gently sloping profile from the west shoreline to the area of maximum depth (Figure 5.4). The Nuwejaars River flows into Soetendalsvlei South, with the river branching into 2 distinct channels within the depression, forming a delta (Figure 5.1). Emergent vegetation is found between Soetendalsvlei North and Soetendalsvlei South. The outflow channel from Soetendalsvlei North via the Heuningnes River indicates that the depression is exorheic.

Morphometric characteristics derived from the bathymetry of Soetendalsvlei are provided in Table 5.1. The shoreline development index of 1.30 indicates a non-circular geometric shape. Soetendalsvlei has an elongated geometric shape in the north-south direction with a maximum length of 7 km and maximum width of 2.59 km. The elevation of the shoreline in October 2014 was 2.17 metres above mean sea level (mamsl).

Table 5.1 Morphometric characteristics of Soetendalsvlei based on the bathymetric survey

Characteristic	
Elevation (shoreline)	2.17 mamsl
Surface area	15.55 km^2 or 1554.67 ha
Maximum depth	2.19 m
Average depth	1.23 m
Relative depth	0.01
Shoreline length	18.06 km
Shoreline development	1.30
Maximum length	7.07 km
Maximum width	2.59 km
Effective fetch	3.94 km
Ratio of Lake Area to Volume	0.8
Lake Geometry Index (LGI)	0.5

The shoreline length of Soetendalsvlei varies with inundation, but at the time of the bathymetric survey in October 2014, the shoreline length was 18.06 km and the surface area was 15.55 km^2. With the Nuwejaars catchment estimated at 631 km^2 the ratio of the catchment area to the lake area is 42.

Based on the bathymetric results, the average depth of the lake area of Soetendalsvlei (in October 2014) was estimated at 1.23 m. The average depths for Soetendalsvlei North and South were 1.67 and 1.78 m respectively. The maximum depth of 2.19 m was measured in Soetendalsvlei South (Figure 5.4). Considering the shoreline is 2.17 metres above mean sea level (mamsl), the maximum depth of the lake (i.e. 2.19 m) is aligned to sea level. The north-south (N-S) cross-profile of Soetendalsvlei shows an elevated lakebed and vegetated substrate dividing the two depressions. Although the N-S cross-profile in Figure 5.4 represents one section of the lake, it does suggest a critical depth of 1.33 m that hydrologically isolates the surface water of the two depressions. In October 2014 during the bathymetric survey, no emergent macrophytes were found where the water depth was greater than 1.9 metres. This open and relatively deeper water was mainly confined to the Soetendalsvlei North and Soetendalsvlei South depressions, where water depths exceeded 2 m. Limnetic systems, which have a maximum depth greater than 2 m (Ollis *et al*., 2013) represent approximately 25% of the surface area of Soetendalsvlei. The western shore of Soetendalsvlei where the depth is less than 1 m (Figure 5.4) consists of littoral/fringe wetlands. Littoral wetlands include salt marshes, reed/sedge beds with a muddy substrate, open small depressions of water with no emergent vegetation and depressions of water with emergent vegetation. The eastern shore of Soetendalsvlei is relatively steeper than the western shore and consists of sandy substrate, and emergent vegetation such as reeds and sedges.

The dominant wind direction is southeasterly with average wind speeds of approximately 2.5 metres/second (m/s) and maximum wind speeds of 11 m/s (Figure 5.5). The highest average wind speeds occur in the late afternoon between 15:00 and 17:00, with average wind speeds of 5 m/s. Westerly winds have on average the highest wind speeds.

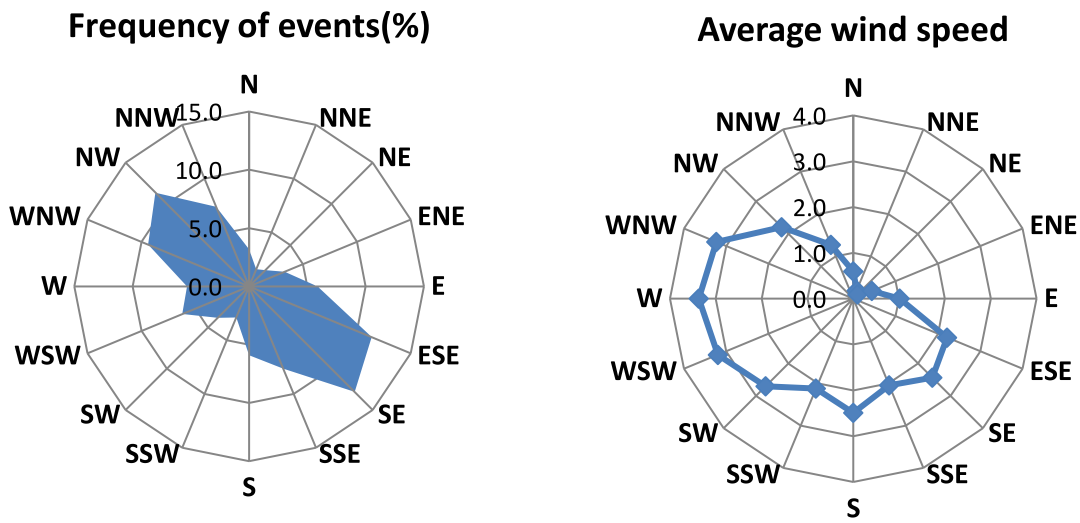


Figure 5.5 Wind direction frequencies and average wind speed at Vissersdrift

Based on the dominant southeasterly wind, the fetch of Soetendalsvlei is influenced by lake shape, with maximum fetch on the western shore of the lake (Figure 5.6). Assuming maximum lake inundation and limited emergent macrophytes, the fetch has a maximum distance of 4500 metres. However, if the fetch is limited to open water, the fetch has a distance of approximately 2000 m. For comparison, the fetch was also calculated for the northwesterly winds, as these winds have on average higher wind speeds. The northwesterly winds, associated with cold fronts are prominent along the south coast of southern Africa (Schumann, 1992). Due to the shape of Soetendalsvlei relative to the northwesterly winds, the maximum fetch is 3114 m.

In the open water of Soetendalsvlei, and based on an average wind speed of 2.5 m/s, wave height is limited to 0.1 m, and wave length has a maximum value of 1.5 m for southeasterly winds. Although the fetch of the north northwesterly winds are much shorter than the southeasterly winds, due to the higher average winds speeds of 3.3 m/s, the wave height is also limited to 0.1 m, while the wave length varies between 1.3 m and 2.4 m. The limiting wave period of 1.3 seconds for both wind directions is based on the average water depth of 1.23 m. Although maximum wave heights were estimated for the shorelines of Soetendalslvei, the impact of emergent vegetation will have a dissipating effect on wave growth (Rohweder *et al*., 2008).

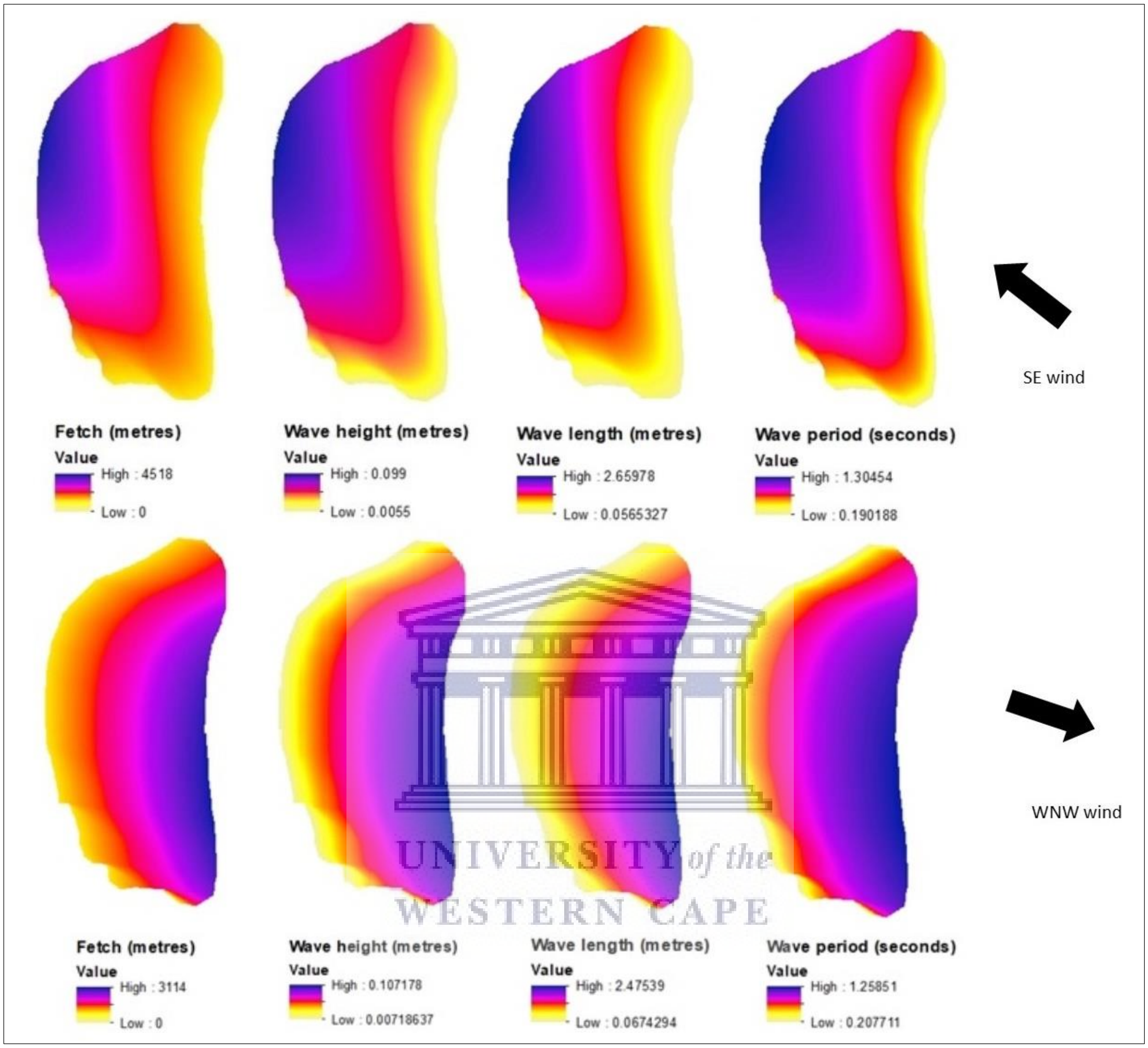


Figure 5.6 Wind and wave properties of Soetendalsvlei of southeasterly (SE) and west-northwest (WNW) winds

The observed wind direction (degrees) and wind speed (m/s) at Vissersdrift, and lake level (m) data in Soetendalsvlei North at 30-minute intervals are illustrated from 11 to 13 May 2015 (Figure 5.7). Although the observed data interval is illustrated at 30 minutes, it provides an indication of the influence of wind on the diurnal lake levels. The range of the water level is estimated at 0.1 m, and is most significant on 13 May 2015, when northwesterly winds with maximum wind speeds of 5.8 m/s are prominent. Southeasterly winds dominate in the morning and afternoon on 11 May 2015, with maximum wind speeds in the afternoon. The lake levels are fairly smooth from 11 to

12 May 2015. The levels are recorded at 15 minute intervals, and reflect relatively constant average values indicative of conditions where wind does not generate significant waves.

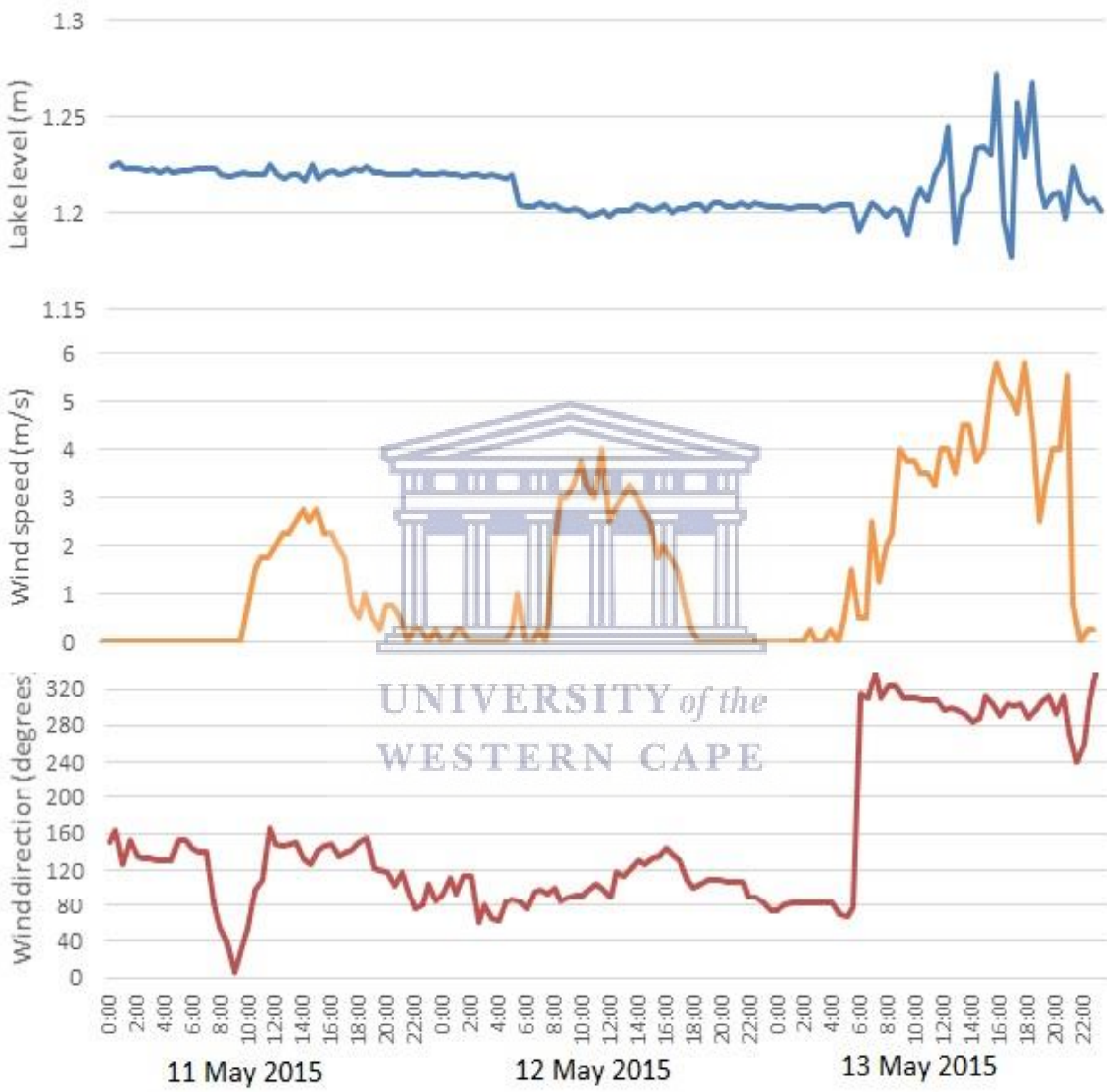


Figure 5.7 Observed wind direction (degrees) and wind speed (m/s) at Vissersdrift, and lake level (m) data in Soetendalsvlei North at 30-minute intervals from 11 to 13 May 2015

5.3.2 Soetendalsvlei water level-area-volume relationship

The hypsometric curves of Soetendalsvlei (Figure 5.8) were derived from the bathymetric survey. The relationship between the water level (H in metres) and surface area (A in m^2) of Soetendalsvlei is represented by the equation ($r^2 = 0.99$):

$$H = -5x10^{-15}A^2 + 2x10^{-7}A - 0.2585 \quad (5.5)$$

$$A = 1.73\ x10^6H^2 + 2.59\ x10^6H + 1.29\ x10^6 \quad (5.6)$$

The relationship between the water level (H in metres) and volume (V in m^3) is represented by the equation ($r^2 = 0.99$):

$$H = 7.27x10^{-4}V^{0.4825} \quad (5.7)$$

$$V = 3199281H^{2.06} \quad (5.8)$$

At the time of the bathymetric survey, with a water depth of 2.19 m, the lake had a storage capacity of 19 Mm^3. Based on the hypsographic curve (Figure 5.8) and the variation of volume with depth (Figure 5.4), approximately 50% of the water storage occurs when the lake level is 1.5 m.

The relationship between the surface area (A in m^2) and volume (V in m^3) is represented by the equation ($r^2 = 0.99$):

$$A = 4341 \times V^{0.4858} \quad (5.9)$$

$$V = 4x10^{-4}A^{2.0567} \quad (5.10)$$

Equations (5.5) to (5.10) and Figure 5.8 represent the unique hypsometric relationships for Soetendalsvlei.

The lake geometry index (LGI) for Soetendalsvlei is 0.5, and is considered low (i.e. less than 0.75). The low LGI reflects the shallow nature of the lake, with a high lake area to lake volume ratio.

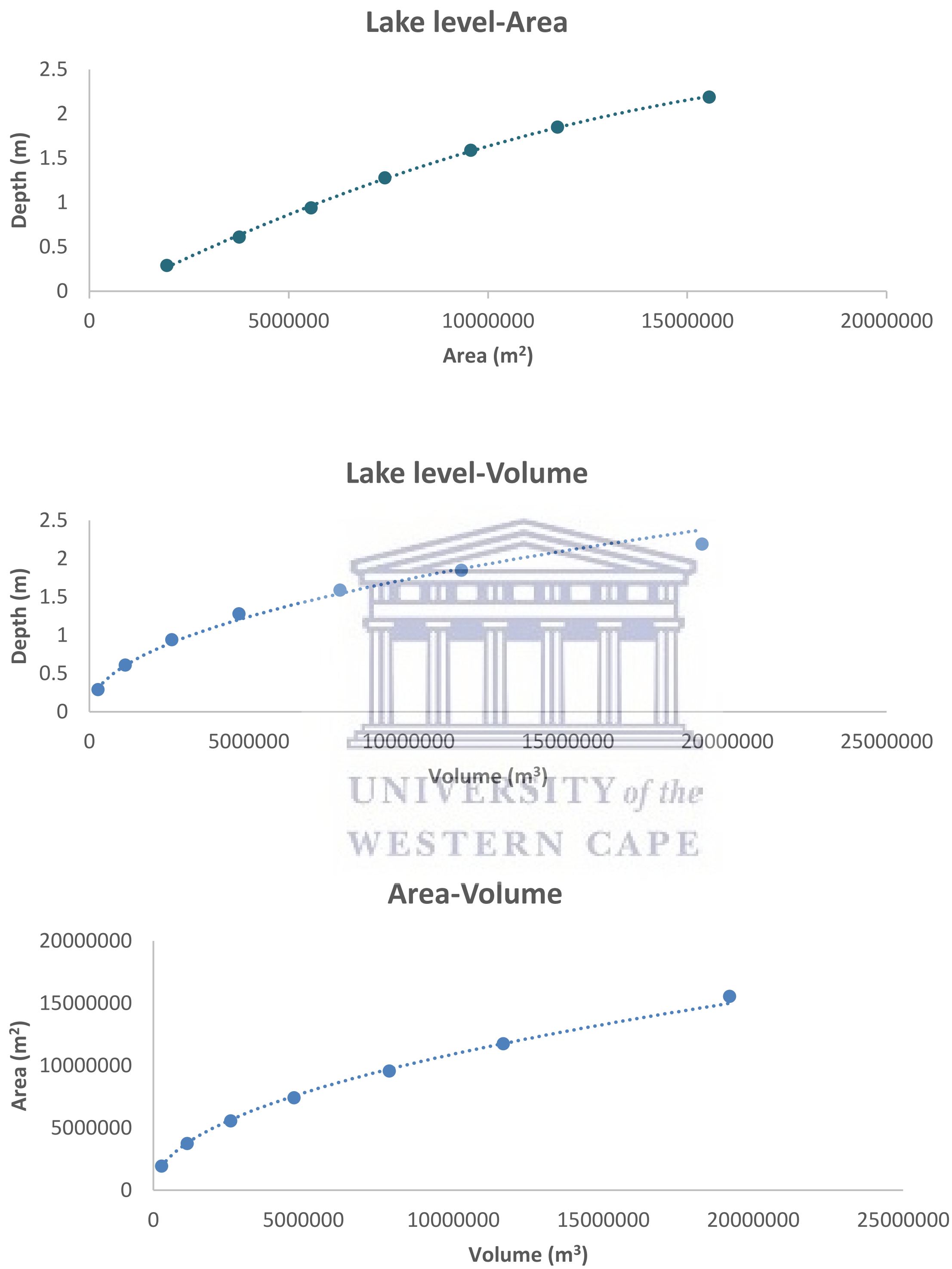


Figure 5.8 Hypsometric curves for Soetendalsvlei

5.3.3 Characteristics of lake storage and surface outflow

5.3.3.1 Lake stage-outflow rating curve

The temporal variations of daily lake levels and stage (water depths) in the Heuningnes River (outflow) from May 2015 to September 2017 show a similar flow pattern, with peak lake stage occurring on the same day, or a day before peak outflow level (Figure 5.9A). The second-order polynomial graph (Figure 5.9B) illustrates the best relationship between the lake stage (H) and outflow stage (Q_o) with $R^2 = 0.98$:

$$Q_o = 0.9448H^2 - 2.1232H + 1.4995 \quad (5.11)$$

Missing values for lake outflow levels were interpolated using Equation (5.11).

The outflow stage remains relatively constant at 0.34 m when the lake stage varies between 1.00 and 1.66 m (Figure 5.9B, graph A). According to the owner of the Vissersdrift farm, when there is no surface outflow from the Soetendalsvlei, surface flow in the Heuningnes River occurs further downstream from the lake outlet. This information was confirmed by visually assessing satellite imagery. Observation from Google satellite imagery on 9 March 2016, when the lake stage is 1.43 m, shows no surface water (i.e. outflow) from Soetendalsvlei to the Heuningnes River (Figure 5.9). The monitoring of the interaction between the unconfined primary aquifer and river levels at the Vissersdrift flow monitoring by Visser (2001) from March 1998 to November 2000, illustrated that the Heuningnes River was a gaining river (except during the months of June to August 2000 when rainfall was below average).

The non-linear relationship between the lake and outflow stage shows a significant change in slope when the lake level is above 1.66 m (Figure 5.9B). The outflow level in the Heuningnes River starts increasing when the lake stage increases above 1.66 m (Figure 5.9B, graph B). Observation from Google satellite imagery on 7 December 2016, when the lake stage is 1.70 m, shows an intermittent flow between Soetendalsvlei and the Heuningnes River (Figure 5.9B). Based on the change in the lake stage-outflow rating curve (Figure 5.9B), and the visual observation of surface water connectivity between the lake outlet and outflow channel (Figure 5.10), surface outflow from the lake was estimated at a lake stage of 1.70 m. Based on the relationship between the water level (H in metres) and volume (V in m^3) using Equation (5.8), the surface outflow from Soetendalsvlei occurs when the volume/storage exceeds 9 545 027.08 m^3.

The lake stage-outflow rating curve also shows a change in slope when the lake level exceeds 1.9 m (Figure 5.9B, graph C). When the lake level is 1.9 m, the volumetric capacity is 12 Mm^3

(Equation 5.8). When the depth range of Soetendalsvlei increases from 1.70 m to 1.9 m, the volumetric capacity of the lake increases by 7.54 Mm^3 (Figure 5.4) which may alter flow conditions between the lake and outflow channel.

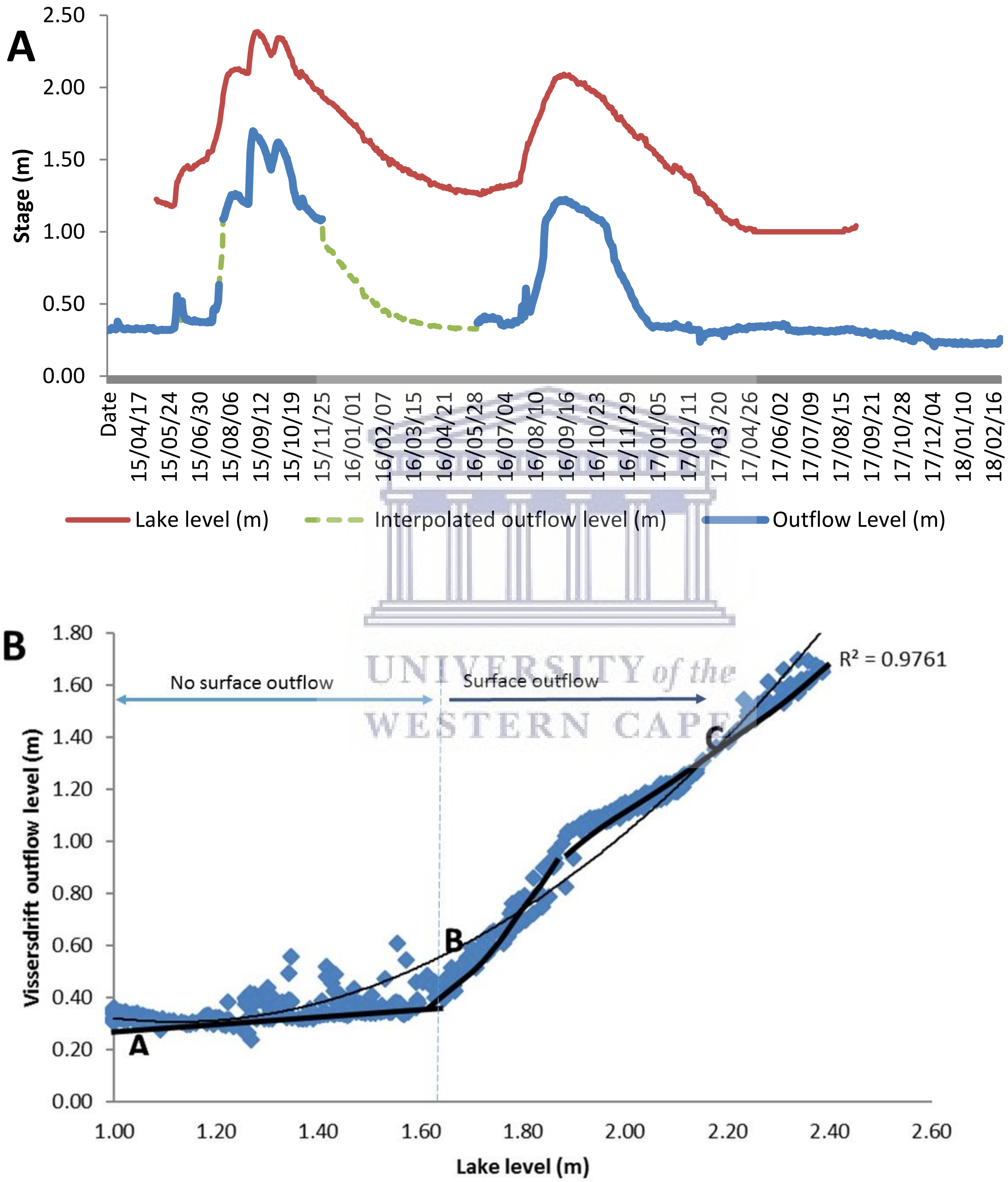


Figure 5.9 Measured daily lake (m) and surface outflow stage (m) from May 2015 to September 2017 (A), and the relationship between daily lake and surface outflow stage (B)

The lake stage-outflow rating curve (Figure 5.9B) displays distinct changes in slope. Sörengård & Di Baldassarre (2017) highlighted that where the characteristics of discharge varies, the use of multi-segmented discharge rating curves instead of single discharge rating curves should be explored.

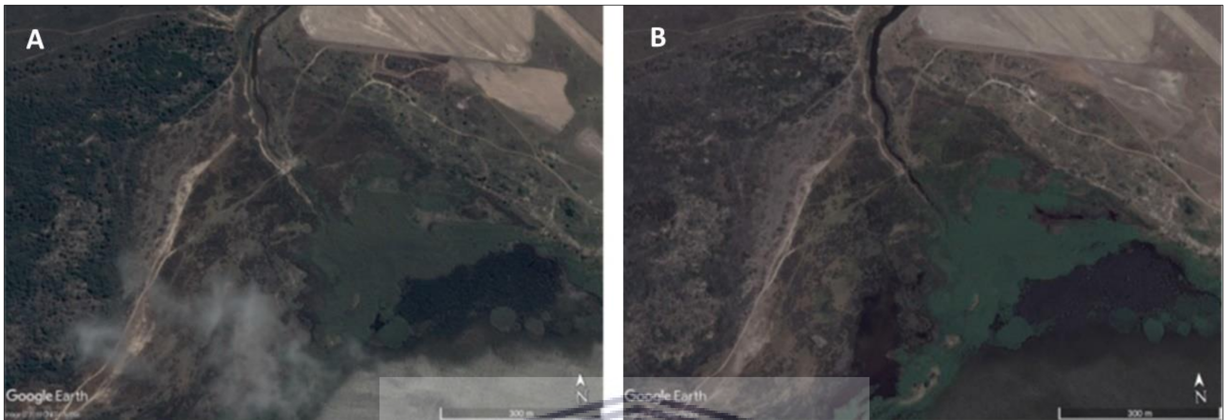


Figure 5.10 Observation from satellite imagery on 9 March 2016 shows no outflow from Soetendalsvlei (A), observation from satellite imagery on 7 December 2016 shows an intermittent flow between Soetendalsvlei and the Heuningnes River (B)

5.3.3.2 Lake storage and surface outflow

A retrospective analysis using remotely sensed lake inundation (Figure 4.8) and the storage-area relationship (Equation 5.10) was used to assess the volumetric capacity of Soetendalsvlei from 1989 to 2017 (Figure 5.11). The retrospective analysis was limited to 2017 (and not until 2019) due to drought conditions in the Western Cape South Africa from 2016. The retrospective analysis does not take into account any possible changes in the bathymetry of the lake which may have occurred between 1989 and 2017. As Soetendalsvlei is an exorheic depression with outflow via the Heuningnes River, the cessation of outflow from Soetendalsvlei represents the surface disconnect between the lake and the Heuningnes River and estuary. Based on the lake stage-outflow rating curve, the estimated threshold storage of Soetendalsvlei for outflows to occur is 9.5 Mm^3. Based on the estimation of inundation for available remote sensing images, the number of instances where outflow occurred from Soetendalsvlei between 1989 and 2017 is 33, i.e. 26% of time.

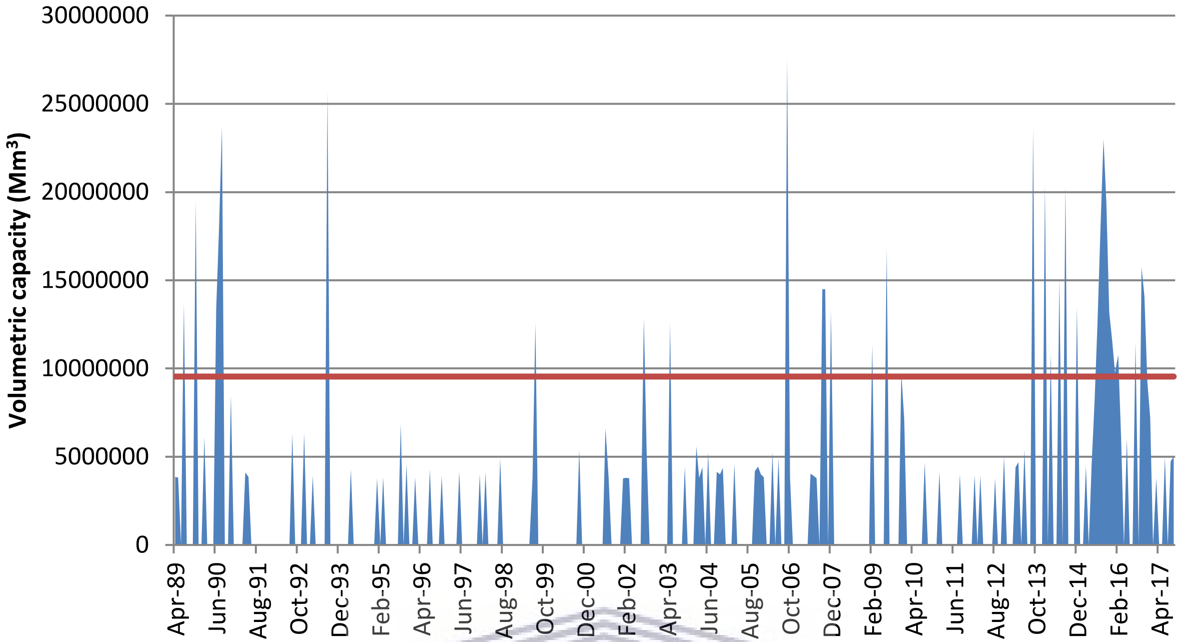


Figure 5.11 Estimation of volumetric capacity of Soetendalsvlei from 1989 to 2017. The red line indicates the threshold water storage of 9.5 Mm^3 in Soetendalsvlei for outflows to occur

5.4 Discussion

Morphometric properties are important in describing depression wetlands (Janssen *et al*., 2014; Onorato *et al*., 2017) and in classifying depression wetlands according to particular characteristics such as hydrological connectivity (Spence, 2000), flow regulation (Quin & Destouni, 2018), water mixing and water quality (Löffler, 2004; Martin *et al*., 2011; Stefanidis & Papastergiadou, 2012). An understanding of morphometric properties within a broader landscape perspective provides context to how wetlands function (Janssen *et al*., 2014; Gownaris *et al*., 2018). With limited access to detailed morphometric data, the bathymetric and terrestrial survey of Soetendalsvlei provides information that supports an understanding of the ecosystem functioning of depression wetlands.

Located on the flat coastal Plain of the Agulhas, 15 km upstream of the estuary, and with no current/limited tidal influence (Noble & Hemens, 1978; Gordon *et al*., 2012; van der Ende, 2015), Soetendalsvlei can be considered an inland depression wetland system. The bathymetry of Soetendalsvlei shows that the depression is parabolic/concave in form, but not symmetrical. Based on the shape of the Soetendalsvlei, and its position within the landscape and drainage network, this wetland, within the framework of the Classification System for Wetlands and other Aquatic Ecosystems in South Africa (Ollis *et al*., 2013), is an exorheic depression with channelled outflow. Soetendalsvlei, depending on the water level, is further sub-divided into two distinct depressions and shallower fringe wetlands. The general shape of depressions (i.e.pans) and lunette dunes on the Agulhas Plain is attributed to geomorphic and climatic processes that have shaped the landscape since the late Pleistocene and Holocene (Carr *et al*., 2006; Gordon *et al*., 2012). Lunette dunes on the eastern shore of Soetendalsvlei have heights reaching 15 m above sea level, and serve as a contemporary geomorphic control to the lake basin. Sediment cores sampled from the lake bed of Soetendalsvlei South by Gordon *et al* (2012) provide evidence of early to mid Holocene deposits consisting of calcified sand and shell fragments to the more recent (dated 1916(+/- 64) AD) organic muddy deposits. According to Hattingh (1996) and Carr *et al* (2006), the oscillation between periods of aridity and humidity; tectonic uplift and sea level changes due to marine regression and transgressions along the South African coastline; were complex factors that also influenced fluvial processes and shaped the present landscape. According to Carr *et al*., (2006) with the beginning of the post-glacial marine transgression episode, these complex factors may have caused increased sedimentation in Soetendalsvlei due to a reduction in river competency. The contemporary asymmetric shape of Soetendalsvlei South, with shallow depths on the western shoreline, presence of the river delta and greater occurrence of emergent vegetation thus reflect the influence over time, of the upstream catchment processes on the shape of Soetendalsvlei.

With the shape and geometry of many lakes described by simplistic shape factors (Hayashi and van der Kamp, 2007), the bathymetric map of Soetendalsvlei illustrates the spatial heterogeneity of the lake basin. The variation of the lake water level or 'gradients of water depth' influences the structure and functioning of shallow littoral wetlands (Crisman *et al*., 2005; Evtimova & Donohue, 2016). Approximately 75% of the surface area of Soetendalsvlei has a depth less than 2 m, and this littoral zone is where rooted emergent vegetation may be found. The emergent vegetation is mainly located along the western shore of Soetendalsvlei. With the vegetation in Soetendalsvlei classified as Cape Inland Salt Pans vegetation (Mucina & Rutherford, 2006), a diversity of vegetation is found within the littoral wetlands. Although the structure of vegetation within the littoral wetland is influenced by multiple and integrated environmental factors (Evtimova & Donohue, 2016; Sieben *et al*., 2018), the variation of water depth was characterized by salt marshes along the shallow western shoreline where inundation is intermittent. *Juncus* and mixed sedge was dominant until a water depth of 0.6 m, with the occurrence of *Schoenoplectus scirpoideus* and *Phragmites australis* in the deeper littoral zones to a maximum depth of 1.9 m.

The variation of water storage is a function of morphology, climate, landscape position and connectivity to surface and subsurface water flow (Coops *et al*., 1991; Haghighi *et al*., 2016). The varied morphology of Soetendalsvlei provides for a maximum water storage capacity of approximately 20 million cubic metres, with water storage varying significantly from 2015, and desiccation of Soetendalsvlei North occurring due to drought conditions in 2018. With surface outflow from Soetendalsvlei to the Heuningnes River, the depression is classified as exorheic (i.e. an open lake). However, below a critical storage threshold of 9.5 Mm^3, surface channel outflow does not occur, with the nature of the depression/lake changing to a closed lake (i.e. assuming that groundwater exchange is zero). Within a closed lake, the dominant loss of water is via evapotranspiration (Ollis *et al*., 2013). Surface and groundwater interaction was not considered in this study, although the resistivity results illustrate the occurrence of shallow saturated material (Figure 2.7). Further monitoring of the surface and groundwater levels are required to better understand the interaction on water storage of depressions.

An understanding of the variation of storage with lake level, through the development of the hypsometric curves, and the significant implications in terms of the lake stage-outflow rating curve, provides an understanding of landscape surface hydrologic connectivity (Liu *et al*., 2019) and ecosystem services derived from hydrologic attributes (Brauman *et al*., 2007). Without long-term *in situ* hydrological data, this study combined remotely sensed data, hypsometric curves and lake stage-outflow rating curves to better understand the incidence and timing of freshwater channel outflow from a coastal freshwater lake. Freshwater outflow from coastal lakes are important in the ecological functioning of downstream habitats (Wetzel, 2001; Winter, 2001) and ecological flow requirements for estuarine environments (Adams, 2014; Whitfield *et al*., 2017). The hydrological connectivity between coastal lakes and estuarine environments has practical implications for water quality and the movement of fish communities between the freshwater and estuarine waters (Whitfield *et al*., 2017). In the case of Soetendalsvlei, the freshwater channel outflow is important to the ecological flow requirements of the Heuningnes estuary. Soetendalsvlei supports *Lithognathus lithognathus* (sparid) and *Mugil cephalus* (mugilid) fish species which require some connectivity to the estuarine environment (Whitfiled *et al*., 2017). A comparison of fish surveys conducted in May 1968 and March 2005 found that both of these species have declined (Cleaver & Brown, 2005). While sampling and environmental conditions will influence the fish survey results, Whitfiled *et al*., (2017) cautions that the loss of connectivity between the freshwater lake of Soetendalsvlei and the Heuningnes estuary will result in these fish species disappearing from the lake within one or two decades.

The morphology of lakes influences inundation (Hayashi & van der Kamp, 2007; Wu & Liu, 2015a; Buma *et al*., 2018; Yao *et al*., 2018). Many lakes display a heterogeneous morphology that, depending on the lake water level, influences the spatial distribution of water and the surface hydrological connectivity within the lake (Janssen *et al*., 2014; Liu *et al*., 2019). Janssen *et al*., (2014) refers to 'internal connectivity' between different sections in a lake, where a high degree of internal connectivity means no obstruction to water flow such that the lake is well-mixed. Soetendalsvlei displays a varied lake morphology, such that the open water is mainly within the two relatively shallow depressions of Soetendalsvlei North and South. With surface water inflow into Soetendalsvlei South, and surface outflow from Soetendalsvlei North, the morphology, growth of emergent vegetation, as well as the lake water level influences the internal connectivity within the lake, particularly the north-south flow of water through Soetendalsvlei. Similar surface water connectivity exists between the northern and southern pools of Lake Chad, which are divided by a shallow sill. Flow from the southern to the northern pool of Lake Chad will only occur once the water level is above a critical lake level (Lemoalle *et al*., 2012). The lateral hydrological connection of the deeper limnetic permanently inundated depressions to the shallower littoral/fringe wetlands of Poyang Lake (China) is also influenced by depth variation and water level, with an understanding of this 'internal connectivity' relevant to the water quality and ecosystem functioning of seasonal littoral wetlands (Li *et al*., 2019).

The characteristics of wind and wind-generated waves are important influences on ecological processes within lakes (Seibt *et al*., 2013). Wind-generated waves influence the occurrence and spatial coverage of aquatic vegetation by creating hydraulic pulling forces which may cause shoot breakage or uproot macrophytes (Schutten *et al*., 2004; Janssen *et al*., 2014). The efficacy of the fetch and wave model (Rohweder *et al*., 2008) in determining the fetch and wave characteristics for small lakes (Seibt *et al*., 2013) was demonstrated for Soetendalsvlei. With a north-south lake orientation, and dominant southeasterly wind, wind-generated waves are prominent on the open water of Soetendalsvlei. While water depth may influence the occurrence of emergent vegetation, the expansion of emergent vegetation to the deeper limnetic depressions is influenced by fetch and the shear stress of wind-generated waves (Azza *et al*., 2007). Lake shape, geometry and size, landscape characteristics and lake orientation relative to wind characteristics are important variables in understanding the occurrence and influence of wind-generated waves for Soetendalsvlei. Coastal zones along the coastline of South Africa have been classified as "strong wind climatic zones" (Kruger *et al*., 2010, p37). Wind direction and wind variability along the south and east coast of South Africa are influenced by sea temperature, atmospheric pressure conditions, topography and weather parameters (Schumann, 1992). With many lakes found along the coastal margin of South Africa (Hart, 1995), the influence of wind and the resultant wind-generated waves need further consideration in understanding the impacts on lake processes.

5.5 Conclusion

Based on the morphometric properties, Soetendalsvlei is a shallow exorheic limnetic depression/lake with channelled inflow. The heterogeneous morphology supports open water and littoral wetlands which are found below water levels of 1.9 m. The lake water level and subsequent water storage varied significantly on an annual and seasonal scale from 2015 to 2017. The impact of wind is significant in generating waves on the lake with subsequent impacts on hourly lake water levels. The shallow depth, occurrence of emergent vegetation, shape of the depression and wind characteristics are important influences on lake processes. The development of the hypsometric curve for Soetendalsvlei supports the understanding of how the water level in this lake influences the extent of surface flooding as well as the variation of storage of the depression, and thus the research adds value in the management of this wetland. With the varying water level, geometric shape of the lake basin, and complex interaction between lake substrate and vegetation characteristics, Soetendalsvlei can be characterized as a dynamic depression wetland system, with the occurrence of different habitat assemblages. The lake stage-outflow rating curve represents the surface connectivity of a depression wetland or lake within the river continuum, and highlights the importance of storage variation and by implication any factors influencing storage, in supporting lake overflow for downstream water use. The lake stage-outflow rating curve, hypsometric curve and available remotely sensed inundation allowed a retrospective analysis of the hydrological surface connectivity of Soetendalsvlei to the Heuningnes River, and highlights the important role of freshwater coastal wetlands for estuarine ecosystems.

The morphometric properties developed for Soetendalsvlei contributes to the general understanding of the functioning of limnetic depressions/shallow lakes, and provides insight to the ecosystem services provided by this shallow lake. With a diversity of coastal lakes along the South African coastline, knowledge of morphometric characteristics can enhance our understanding of these wetland systems and the ecosystem services they provide.

CHAPTER 6

THE WATER BALANCE DYNAMICS OF SOETENDALSVLEI IN THE NUWEJAARS CATCHMENT

6.1 Introduction

The hydrological regime of a lake is characterized by the variation of storage and the corresponding fluctuation of the lake water level over time (Wantzen *et al*., 2008). Lakes may exhibit hourly, diurnal, seasonal, annual and inter-annual lake level variation. Lake level and water storage variation is mainly influenced by the characteristics of the climate (Szesztay, 1974; Wantzen *et al*., 2008), morphology and biophysical properties of the lake, position of the lake within the catchment, properties of the contributing catchment which influences the timing and magnitude of runoff and subsurface flow; and the direct abstraction of water for human use (Spence, 2000). The relative significance of each of these factors will influence the degree to which the water balance components influences storage, and how the lake responds to change (Bracht-Flyr *et al*., 2013). The hydro-climatological factors that influence the functioning of lakes have been incorporated into the design of lake classification models. Szesztay (1974) classified lakes using water balance criteria, and distinguished between 'flow-controlled' and 'climate-controlled' lakes, with significant difference between open and closed lakes. Bracht-Flyr *et al*., (2013) developed a steady-state lake model using lake to basin area, climatic and runoff data as well as landcover characteristics to understand lake response to change and identifying thresholds for change. By identifying lakes that are sensitive to change, specifically due to climatic factors, provides invaluable insight for lake management (Bracht-Flyr *et al*., 2013).

Lakes, especially closed lakes, are sensitive to changes in rainfall (Mbanguka *et al*., 2016) and land use activities (Bracht-Flyr *et al*., 2013) resulting in variable lake water levels (Gownaris *et al*, 2018). Schwerdtfeger *et al*., (2014) found that precipitation especially during the rainy season in Brazil recharges the groundwater reserves which then sustains inflow to the lakes during the dry season. In a comparison of four lakes within temperate and tropical environments, Wantzen *et al*., (2008) illustrates the seasonal and inter-annual variation of lake water levels in response to rainfall and flooding cycles, and highlights the importance of drier and wetter periods for increased productivity of lakes. The levels of Lake Victoria in East Africa which displays diurnal, seasonal and inter-annual variability, shows a general lake level decline, with cyclic trends of the water level coinciding with rainfall and occurrence of drought (Awange *et al*., 2007; Vanderkelen *et al*., 2018).

Lake Victoria, the largest lake in Africa with a surface area of approximately 68 000 km^2, and covering two-thirds of the contributing catchment, provides an ideal example of where lake storage of a hydrologically connected lake, is mainly driven by direct rainfall onto the lake (76%) and not surface inflows (Vanderkelen, *et al*., 2018). Direct rainfall onto the lake may also be the dominant inflow for many isolated lakes. Parsons & Vermeulen (2017) established that Groenvlei, an isolated lake in the Southern Cape, South Africa, is a rainfall-driven lake with direct rainfall accounting for 71.6% of the total inflows. The water level fluctuations of seepage lakes, where groundwater flow is the dominant inflow to lake storage, is primarily influenced by the groundwater flux and evapotranspiration from the lake surface (Schwerdtfeger *et al*., 2014). Although seepage lakes were thought to be less vulnerable to climate change, increased groundwater abstraction and drought conditions may result in reduced groundwater recharge to lakes (Tweed *et al*., 2009; Lee *et al*., 2014), which highlights the importance of the connectivity of lakes to surface and subsurface flows (Boyle, 1994; Li *et al*., 2019).

Gownaris *et al*., (2018) assessed the hydrological regime of 13 African lakes and found that lake level fluctuations were fundamental controls on ecosystem functioning in terms of trophic levels, biomass and production, with subsequent impacts on livelihoods. Change to the hydrological regime of lakes influences the structure and functioning of the littoral zones (Evtimova & Donohue, 2016), with negative influences on the abundance and diversity of waterbirds and ecosystem functions in general (Zhang *et al*., 2017). Central to any management approach of lakes and wetlands requires an understanding of the hydrological processes that govern the function and health of these aquatic ecosystem (Sivapalan, 2005; Maherry *et al*., 2016). Through the analysis of observations, an understanding of underlying process controls, and continued evaluation and learning, the variable and complex hydrological processes may exhibit patterns that allow simplification and representation of these processes (Sivapalan, 2005). This simplicity or complexity of processes may reflect the diverse approaches to hydrological modelling, the scales of modelling, available models, expertise of the researcher and availability of field data (Sivapalan, 2005). In a review of conceptual hydrological flow models used for water resource assessment in South Africa, Maherry *et al*., (2016, pviii) recommends "further studies which investigate and conceptualise the key dominant hydrological processes of wetlands".

Once a model for the system is conceptualized, scenario analysis allows insight to how the system will change, if specific model factors or parameters change (Borgonovo *et al*., 2017). Mbanguka *et al*., (2016) applied a one-factor sensitivity analysis to a water balance model of Lake Babati in Tanzania to assess the influence of climate variability. Mbanguka *et al*., (2016) concluded that a reduction of 17% of the annual average rainfall would result in a 5.3 m drop in the lake level causing desiccation, while a 10% increase in rainfall would cause lake overflow. Ohlendorf *et al*., (2013) used scenario analysis for a 60-year interval to assess the main driving forces causing lake level change in a lake in Argentina. The storage capacity of the lake, changing catchment conditions, precipitation, wind speed and temperature were the main factors governing lake-level change. Ohlendorf *et al*., (2013) used the scenario analysis to simulate Last Glacial Maximum and mid Holocene conditions and provided insight to meteorological parameters that could cause a 33 m decrease and a 22 m increase in the lake level.

The utility of scenario analysis is in assessing the lake response time to changes of lake inflows (Haghighi *et al*., 2016). In the lake-level simulation of natural and man-made lakes with varied morphology, Haghighi *et al*., (2016, p606) determined the magnitude of flow and the response time required for lakes to reach dynamic equilibrium after a change in flow. Haghighi *et al*., (2016) found that open and shallow lakes could reach dynamic equilibrium within 2 to 20 years after flow modifications. With many key functions of lakes related to the hydrological regime of lakes, an understanding of factors affecting the dynamic equilibrium of lakes is similarly important in understanding the ecological resilience of lakes (Özkundakci & Lehman, 2019) and the minimum flow requirements for efficient ecosystem functioning (Shang & Shang, 2018).

With the increasing demand for water resources, coupled with the effects of climate variability, a conceptual understanding of the processes that influences the hydrological regime/pattern and the associated functions of lakes and wetlands are essential in ensuring the sustained provision of ecosystem services. Soetendalsvlei represents a shallow freshwater coastal lake that provides essential ecological functions, but lacks any hydrological monitoring or data to understand how the system functions. The water balance components of inflows (from direct precipitation, catchment runoff and groundwater) and the outflows (evaporation, surface and groundwater outflow) which regulate the variation of lake water storage is unknown. The main aim of this chapter is to estimate the water balance components of a shallow freshwater coastal lake through the development of hydrological and meteorological monitoring sites, and to understand how these components influences the variation in water storage. Knowledge of the variation of storage provides insight to related ecosystem services.

Key objectives of this chapter are to:

1. Determine the relative contribution of the water balance components on lake water storage

2. Provide an understanding of the hydrological processes and conditions that influence the water balance dynamics of Soetendalsvlei.
3. Assess how the hydrological response of the lake storage influences ecosystem services.

6.2 Methods

6.2.1 Estimation of the water balance components

The water balance of open lakes is influenced by inflow of water through direct precipitation onto the lake, surface runoff from rivers and groundwater inflow. Outflow from the lake is through evaporation from the lake, surface runoff and groundwater outflow. The water balance is also influenced by direct abstraction. The total surface area of the Soetendalsvlei is considered to include the open water and inundated littoral wetlands.

The daily balance between inflows and outflows governs the change in the volume of water storage (Hayashi & van der Kamp, 2007; Mitsch & Gosselink, 2007), and is expressed as:

$$\Delta V = P_i + Q_i + G_i - ET_o - Q_o - G_o - Ab_o \qquad (6.1)$$

Where

ΔV = change of lake water storage

P_i = precipitation over the lake

Q_i = surface flow into the lake

G_i = groundwater discharge into the lake

E_o = daily evaporation rate

Q_o = surface flow from the lake

G_o = groundwater flow from the lake

Ab_o = direct abstraction from the lake

6.2.1.1 *Precipitation in the catchment and onto the lake*

An automatic weather station (HOBO U30 Station) was installed at Vissersdrift less than 60 m from the northern bank of the Soetendalsvlei on 21 December 2014 (Figure 6.1). Data for precipitation is recorded at 15 minute intervals. The daily volume of precipitation onto the lake (P_i) was estimated from the depth of daily precipitation (in mm day^{-1}) falling onto the lake surface area on that day (A_t). The surface area was derived from the hypsometric curve for Soetendalsvlei.

Data from the automatic weather station at Spanjaardskloof within the upper catchment of the Nuwejaars catchment was collected to compare the two sites, and to provide insight to the inflow from the upstream catchment.

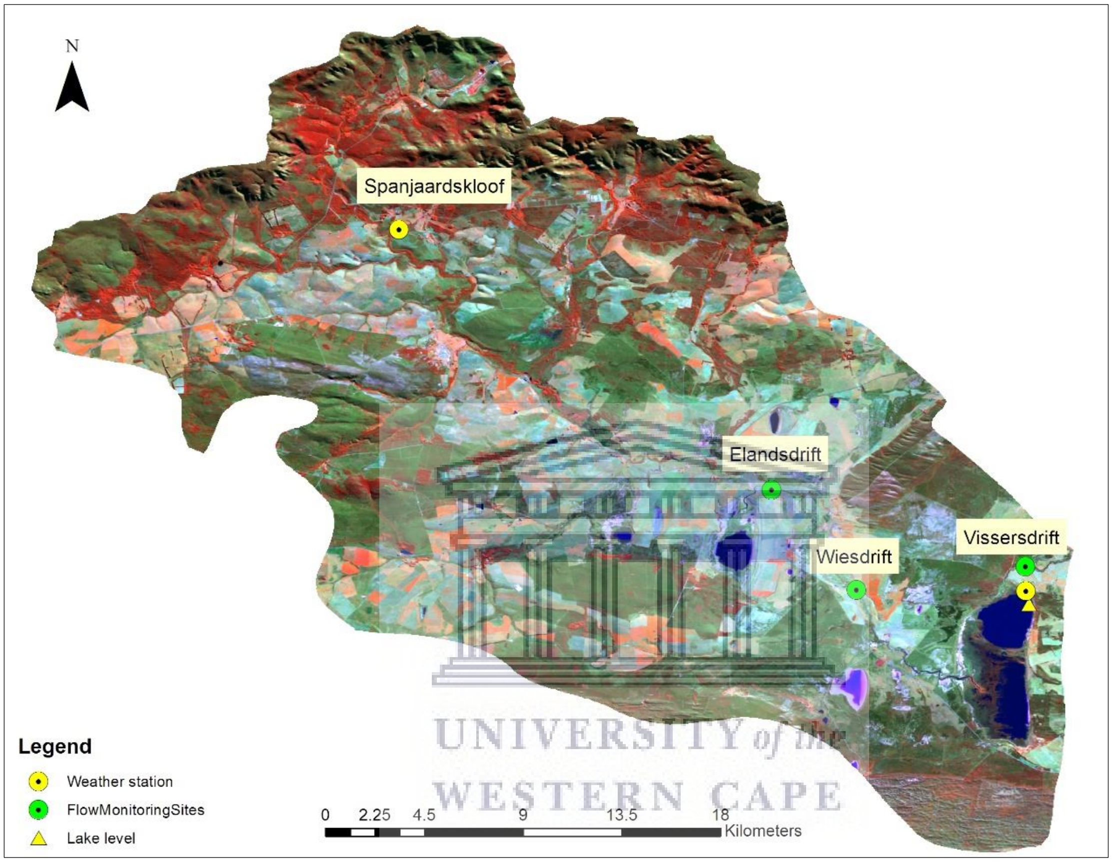


Figure 6.1 Monitoring sites for the assessment of the water balance components of Soetendalsvlei

6.2.1.2 Evaporation from the lake

Evaporation may be a major outflow component of the water balance of a lake and wetland, particularly in semi-arid environments. The accurate on-site direct measurement using instrumentation and/or estimation of lake and wetland evaporation by means of modeling techniques has thus been the focus of many studies (Dye *et al*., 2008; Shaw *et al*., 2011; Mohamed *et al*., 2012; McMahon *et al*., 2013). One of the most widely used combination methods to indirectly estimate open water and wetland evaporation is the Penman-Monteith method. In comparing measurements of evaporation using eddy covariance at Lake Taihu in China, where mean lake depth is 1.9 m, Wang *et al*., (2014) found that the combination methods such as Penman-Monteith performed the best when compared to temperature based methods. The dominant control on lake evaporation is the available radiation energy, and thus evaporation models where the observed net radiation serves as input, provide the best estimates for monthly and annual evaporation rates (Mohamed *et al*., 2012; Wang *et al*., 2014).

In shallow lake systems consisting of open water partially covered with heterogeneous emergent vegetation, lake evaporation (consisting of open water evaporation and evapotranspiration from flooded vegetation) is strongly influenced by the characteristics of the vegetation and climatic conditions (Mohamed *et al*., 2012; McMahon *et al*., 2013). In assessing open water evaporation and transpiration from inundated emergent vegetation in a floodplain wetland in Spain, Sánchez-Carillo *et al*., (2004) found that open water evaporation rates averaged 8.0 mm/day while inundated reeds (*Phragmites australis*) and cut-sedge (*Claudium mariscus*) averaged 7.7 and 15.6 mm/day respectively. By upscaling pan measurements to lake evaporation, Parsons & Vermeulen (2017) estimated that open water and evapotranspiration (ET) rates from the *Phragmites* reed collar surrounding Groenvlei Lake (along the south coast in South Africa) were similar, except during winter and summer. In summer, ET was 10% more than open water evaporation, and in winter, ET from the inundated reeds was minimal due to plant senescence. The reed collar along the Groenvlei shoreline is dense, and thus water detection within this reed collar using satellite imagery and the Modified Normalized Differential Water Index (MNDWI) was not always possible (Thys, 2019).

In assessing evaporation from Soetendalsvlei, the area of the lake was considered to include the open water and inundated emergent vegetation in the littoral wetland. The dominant emergent vegetation in the lake are *Phragmites* and *Schoenoplectus* which extend to a maximum height of 2 m and 1 m respectively above the lake water level (observation done in September 2014). Given that the water supply in the lake is unlimited, water was accurately detected within the inundated emergent vegetation via remotely sensed data (Chapter 5), and given the available meteorological data, it was assumed that evaporation from the open water and inundated emergent vegetation was similar. With an average depth of 1.23 m, and the influence of wind-generated waves in the lake, the water in the lake is considered to be well-mixed with no thermal stratification.

Daily meteorological data from the Vissersdrift weather station include temperature, solar radiation, relative humidity, wind speed, wind direction, dew point, wetness and pressure recorded at 15-minute intervals. Daily data was used in the estimation of reference evaporation (E_o) depth (mm) for Soetendalsvlei. The formula for the Penman-Monteith method is as follows:

$$E_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u^2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (6.2)$$

Where:

E_o is reference evaporation (mm day^{-1}), Δ slope of the vapour pressure curve; R_n is net radiation at the crop surface (MJm^{-2}day^{-1}); G is soil heat flux density (MJm^{-2}day^{-1}); T is mean daily air temperature at 2 m height (C); u_2 is wind speed at 2 m height (ms^{-1}); e_s is saturation vapour pressure (kPa); e_a is actual vapour pressure (kPa); $e_s - e_a$ is saturation vapour pressure deficit; γ is the sychrometric constant (kPa^{o}C^{-1}). The albedo reflection coefficient value (α) for surface water of 0.07, was used in the calculation of R_n (Hagemann, 2002).

The daily volume of evaporation (E_o) from Soetendalsvlei was estimated from the daily evaporation depth multiplied by the inundated lake surface area on that day (A_t).

6.2.1.3 Inflows to the lake

The Nuwejaars River is the only source of channelled flow into Soetendalsvlei. Continuous water level measurements to determine the surface inflow of the Nuwejaars River were made using the HOBO Water Level Data Logger (Model 3001). Water level measuring stations were established at Wiesdrift on 24 October 2014 and at Elandsdrift on 17 October 2014, along the Nuwejaars River (Figure 6.1). Both these stations are located on bridges, with Wiesdrift the last man-made structure in the Nuwejaars River before inflow to Soetendalsvlei. The Wiesdrift road crossing has 10 culverts with a width of 1.2 m. The Wiesdrift water level measuring station would have been the best choice for estimating the inflow to Soetendalsvlei, however, during fieldwork the accumulation of sediment and the growth of vegetation between the culverts were observed at this site. The Elandsdrift water level measuring station was thus used to determine the inflow of water into Soetendalsvlei. Elandsdrift bridge has 2 rectangular culverts with a height of 1.56 m (Figure 6.2).

Velocity measurements using an OTT MF pro electromagnetic current meter was recorded at specific depths within the bridge culverts at Elandsdrift (Mehl, 2019). Discharge measurements at Elandsdrift were determined by the velocity-area method (Shaw *et al*., 2011). Due to low flow conditions in the Nuwejaars River the pressure transducer at Elandsdrift was removed from

January to May 2015, as well as in December 2016. The rating equation for the relationship between the discharge (Q) and stage (H) at Elandsdrift (Figure 6.2) is be expressed as:

$$Q = 1.256H^{2.961} \qquad \text{if } H < 1.2 \text{ m}$$

$$Q = 0.108\exp(2.504H) \qquad \text{if } H > 1.2 \text{ m} \qquad (6.3)$$

With the availability of continuous water level measurements at Elandsdrift, the daily surface inflow into Soetendalsvlei was derived from the rating curve.

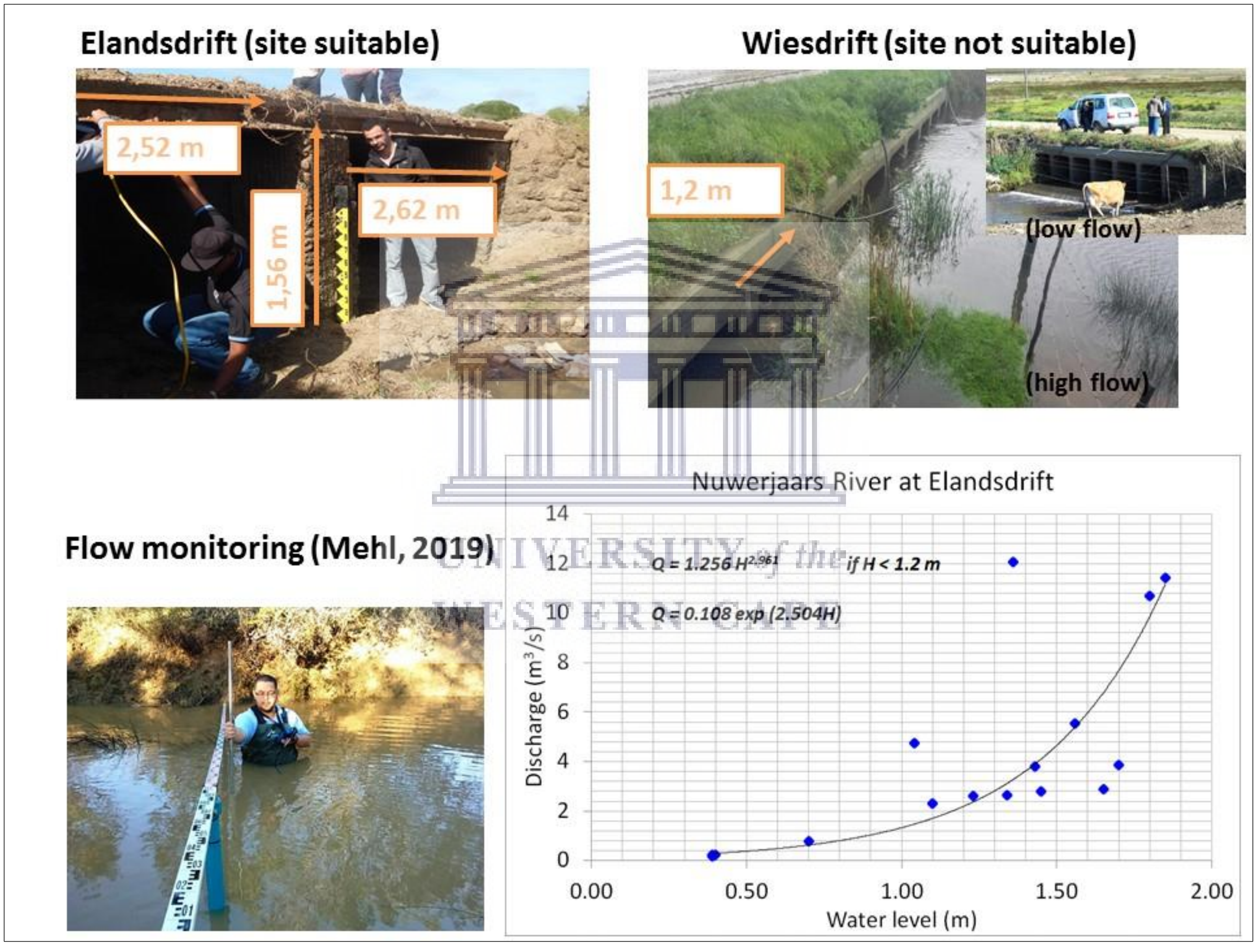


Figure 6.2 Flow monitoring sites along the Nuwejaars River to monitor inflow to the lake

The complex nature of the ungauged lower Nuwejaars catchment from Elandsdrift to the inflow of Soetendalsvlei, includes the Soutpan sub-catchment, and represents a challenge in estimating accurate inflows to the lake. The Soutpan subcatchment includes a non-perennial river, floodplain wetlands, flats and pans (Figure 6.3). Soutpan is the largest pan, with an area of 1.86 km^2. A gravel road crossing between Struisbaai and Elim marks the inflow from the Soutpan catchment into the Nuwejaars River. Flooding on this road occurs during extreme rainfall events. The inundation frequency for 2015 (relatively wet year) and 2017 (a relatively dry year) of the ungauged catchment was assessed using the methodology in Section 4.2.7. In 2015, the pans including Soutpan are inundated (Figure 6.3). Outflow from the pans will only occur once a threshold for overflow occurs. With no *in situ* data available for the pans, the inundation frequency provides an assessment of overflow from the pans; and from the Soutpan sub-catchment. Intermittent inundation at the inflow of the Soutpan catchment at the Nuwejaars catchment is observed. In 2017, the impact of the drought is observed with surface water only detected in depressions (Figure 6.3). Depressions and flats to the west of Soetendalsvlei show no surface connectivity to the lake. Daily surface flow from the ungauged sub-catchment was not considered in the water budget of Soetendalsvlei.

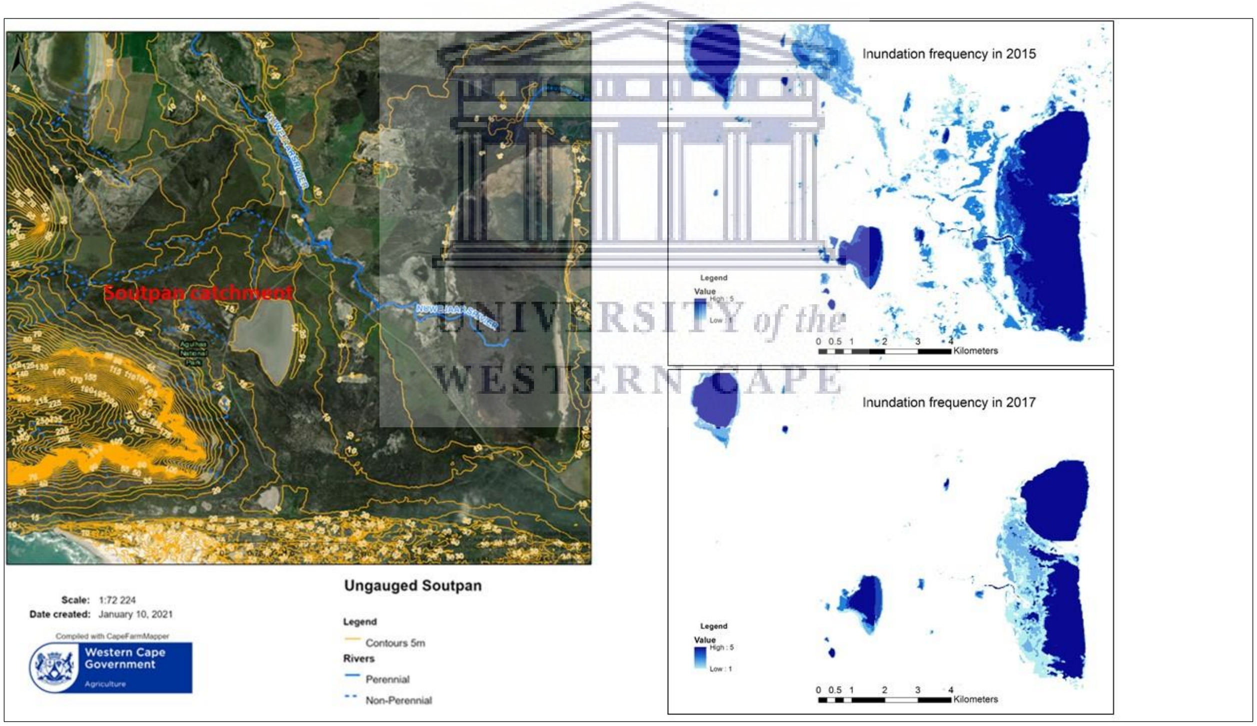


Figure 6.3 The ungauged Soutpan sub-catchment (with 5 m contours and rivers) (source: CapeFarmMapper) and the inundation frequency for 2015 and 2017

6.2.1.4 Surface outflow from the lake

The surface outflow gauge is located approximately 1 km downstream from the lake outflow (Figure 6.1). Continuous river level/stage data is available, except during low flow periods when the equipment was removed. A lake level-outflow level rating curve relationship was developed for the outflow (Q_o) from Soetendalsvlei (Section 5.2.4) with outflow only occurring once the volumetric capacity of the lake (V_t) exceeded the minimum storage (V_{min}) of 9.5 Mm^3 (Equation 6.4).

$$Q_o = a(V_t - V_{min})^b \quad (6.4)$$

The development of the rating equation for discharge (*Q*) and stage (*H*) at the Vissersdrift outflow site was challenging for a number of reasons. The location of the pressure transducer for measuring the river water level is located about 4 m upstream from where discharge measurements at the road culvert is measured. Site-specific factors that may influence the accuracy of the discharge-stage rating curve are the growth of emergent vegetation at the site, and backwater effects of the road. Only eight flow measurements were recorded at the outflow-gauging site between August 2015 and August 2016 using an OTT MF pro electromagnetic current meter. During high precipitation events in 2015, the monitoring site was flooded and due to safety concerns, no measurements were taken. The development of a rating curve based on a limited number of flow measurements and a lack of measurements for diverse flows contributes significantly to uncertainty in estimating discharge values (Shaw *et al*., 2011). Surface outflows (Q_o) represent an unknown in the water balance equation.

6.2.1.5 Abstraction

Informal discussions with the two private landowners surrounding Soetendalsvlei indicate that water use from the lake, depends on the water quality and agricultural water demand. Water pumped from the lake is for general household use and agricultural activities. Water for general household use was considered negligible. Water use from the lake for agricultural use is based on demand as farmers also have access to groundwater resources. According to informal discussions with a private landowner, direct abstraction from Soetendalsvlei for agricultural use does not exceed 1 Mm^3 per annum, with no abstraction from 2016 due to receding water levels and poor water quality. Abstraction was considered negligible for the period of observation, and not included in the water balance model.

6.2.1.6 Lake water level

Continuous water levels within the northern pool of Soetendalsvlei were measured with the use of automatic water level recorders (OTT Orpheus Mini water level logger). The water level logger was installed on 9 May 2015, and secured at the bottom of a concrete jetty. Water level readings are recorded at 30-minute intervals. A gauge plate was also installed by the Department of Water and Sanitation (Figure 6.1). Due to the ongoing drought, the automatic water level recorders were removed from the lake in September 2017.

6.2.2 Water balance model

6.2.2.1 Daily water balance model

A conceptual model allows representation of reality, and an understanding of factors that influences a system. A daily water balance model of Soetendalsvlei, formulated as a spreadsheet, was used to simulate the change in lake storage based on the water balance components described in Section 6.2.1. The known observed inflows to the lake are precipitation over the lake (P) and surface flow from the gauged catchment (Q_{in}). The known observed outflow is evaporation from the lake (E), while surface outflow is unknown (Q_{out}). Abstraction from the lake is considered negligible. With no continuous groundwater data around the lake, the net groundwater exchange was assumed as zero. The water storage balance between inflows and outflows represented by Equation (6.1) was therefore rewritten as Equation (6.6) to represent the daily water storage of Soetendalsvlei:

$$V_t = V_{t-1} + Q_{in,t} + P.A_t - Q_{out,t} - E.A_t \quad (6.6)$$

Where

V_t = volume of lake storage (m^3) on day t,

V_{t-1} = volume of lake storage (m^3) for the previous day t – 1,

$Q_{in,t}$ = surface runoff (m^3) from the Nuwejaars River on day t,

$O_{out,t}$ = outflows (m^3) from the lake through the Heuningnes River on day t,

A_t = surface area (m^2) of the lake on day t,

E = daily evaporation rate (m/day) on day t,

P = daily precipitation over the lake (m/day) on day t,

The surface area of the lake (A_t) was determined on a daily basis by converting the lake storage of the previous day (V_{t-1}) to surface area, using the hypsographic curve derived from the bathymetric survey:

$$A_t = 4341\, V_{t-1}^{0.486} \quad (6.7)$$

With surface outflow the unknown in the water balance model, Equation 6.6 was rearranged to solve for $O_{out,t}$:

$$Q_{out,t} = V_{t-1} - V_t + Q_{in,t} + P.A_t - EA_t \quad (6.8)$$

The lake stage-outflow rating curve (Section 5.3.3) suggests that outflow only occurs when the lake storage reaches a critical threshold V_{min}, such that:

$$Q_{out} = \propto (V_t - V_{min})^{\beta} \quad if\ V_t > V_{min}$$

$$Q_{out} = 0 \quad if\ V_t < V_{min} \quad (6.9)$$

The calibration of the outflow parameters (α and β) and evaluation of the model are discussed in Section 6.2.2.2.

Drought conditions was prevalent in the Western Cape, South Africa from 2016, with a decrease in surface water in the Nuwejaars catchment. Water level loggers were removed from select sites in the study area, including Soetendalsvlei, from September 2017. The daily volume of lake storage was simulated using Equation 6.6 from December 2014 to December 2017. The daily volume of lake storage (V_t) was converted to the simulated daily lake level (H_{sim}) in metres by using the volume-water level rating curve derived from the bathymetric survey:

$$H_{sim} = 7.27 \times 10^{-4}\, V_t^{0.4825} \quad (6.10)$$

6.2.2.2 Model calibration and evaluation

The performance of the daily water balance model and optimization of the model parameters were evaluated using the ratio of the root mean square error (RMSE). The model was optimised by minimizing the difference between the measured and simulated lake levels. Data visualization also provide a qualitative approach to calibration (Ayenew & Gebreegziabher, 2006).

The model parameters that were subject to optimization were the initial lake water storage and the outflow values of α and β (Equation 6.9). With the water level recorders for the lake only installed in March 2015, the lake level for January 2015 was unknown, and the initial volume of lake storage could not be determined from the hypsographic curve. The initial volume of lake storage for the water balance model was estimated at 11 051 926 m^3. The minimum critical lake storage or volumetric capacity for outflow (V_{min}) to occur was determined at 9.5 Mm^3 (Section 5.2.4).

Outflow parameters

The values of α and β (Equation 6.9) depend on the shape of the outlet, channel roughness, water surface slope of the outflow river reach and the type of flow (Jeng & Yevdjevich, 1966). In natural lakes, the value of β normally varies between 0 and 3, with a value of 0 indicating constant outflow, and a value of 1 indicating a linear relationship (Kebede *et al*., 2006; Kumambala & Ervine, 2010). A value of β greater than 1 means that with a small change in lake level or volumetric capacity, the outflow will change significantly (Kebede *et al*., 2006). Assuming a single power-rating curve to express the outflow as a function of lake storage, the parameters *α* and β were estimated for the water balance model by minimizing the difference between the measured and simulated lake levels (Table 6.1).

Table 6.1 Model parameters for estimated outflow

Model parameter			**Explanation**
Lake volumetric capacity (V_{min}) = 9.5 Mm^3			V_{min} is the minimum volumetric capacity for outflow to occur. V_{min} applicable to both Models 1 and 2
Model 1 (single outflow-lake storage rating curve)			
	α	**β**	Based on Equation 6.9
Single	2×10^{-7}	1.8299642	
Model 2 (2-segmented outflow-lake storage rating curve)			
Point of segmentation (Vseg) = 12 Mm^3			Point of segmentation (Vseg) indicates a change of flow dynamics between the lake-outflow stage
	α	**β**	Based on Equation 6.11
Segment 1	2×10^{-7}	1.830	
Segment 2	1×10^{-7}	1.840	

When the critical lake storage is exceeded, the lake stage-outflow rating curve shows a change in the flow dynamics between the lake and outflow stage when the lake depth and corresponding lake storage is 1.9 m and 12 Mm^3 respectively (Figure 5.9). Where there is a clear change in the rating curve, the use of segmented rating curves for river-floodplain systems has been shown to improve the accuracy of low flow conditions (Sörengård & Di Baldassarre, 2017). In the construction of segmented rating curves, Goltsis Nilsson (2014, in Sörengård & Di Baldassarre, 2017) proposed assessing the number of segments and determining the rating curve for each segment. Assuming a 2-segmented power-rating curve to express the outflow (Q_{out}) as a function of lake storage (V_t) when the lake storage is above the minimum critical lake storage (V_{min}), and based on the log-log lake stage-outflow stage for Soetendalsvlei, the point of segmentation (V_{seg})

was visually determined as 12 Mm^3 (Equation 6.11). The parameters α_i and β_i were estimated for the two segments (i = 1 and 2) of the water balance model (Model 2) by minimizing the difference between the measured and simulated lake levels (Table 6.1).

$$Q_{out} = \begin{cases} \alpha_2(V_t - V_{min})^{\beta 2} & if\ V_t > V_{seg} \\ \alpha_1(V_t - V_{min})^{\beta 1} & if\ V_{min} < V_t < V_{seg} \\ 0 & if\ V_t < V_{min} \end{cases} \quad (6.11)$$

Buffering impact of floodplain wetlands

Floodplain wetlands may have a significant effect on the timing and flow of surface runoff (Dessie *et al*., 2015). Floodplain wetlands extend along the Nuwejaars River and its tributaries, provide regulating ecosystem services such as flow regulation and flood attenuation (Mehl, 2019). Mehl (2019) estimated the water storage of the Nuwejaars floodplain wetlands at 6.55 Mm^3 and found that the wetland reduced the timing of flow by 27 hours. Maintaining all lake model parameters mentioned above, the lake level was simulated with a daily time lag of surface inflows (to account for the ungauged floodplain wetlands). The lake level was simulated with a time lag of 1, 2 and 3 days. Model performance of the time lag was visually assessed, and through the RMSE.

6.2.2.3 Residence time

The hydraulic residence time is the average time that water remains in a lake, and is dependent on factors which influences the inflows to, and outflows of water from a lake (Mitsch & Gosselink, 2007; Messager *et al*., 2016). The residence time is influenced by extreme climatic events such as floods and drought, with consequent impacts on the ecosystem services provided by lake ecosystems (Zwart *et al*., 2017). The residence time is significant for nutrient and sediment processes, water quality, species diversity and lake productivity (Messager *et al*., 2016). Based on the average volume of water storage in Mm^3 (V_{ave}) and total outflow rate (Mm^3)/day (S_{out}), the hydraulic residence time in days (R_t) was determined for 2015 to 2017:

$$R_t = \frac{V_{ave}}{S_{out}} \quad (6.12)$$

The total outflow rate was established by totaling evaporation and surface outflow for each year and dividing by 365 days.

6.2.2.4 Scenario analysis

A practical application of a model is "what-if" scenarios to understand the response of a system to possible change (Shaw *et al*., 2011). Scenario analysis is guided by the complexity of a hydrological model and the objective of the analysis (Devak & Dhanya, 2017). In a simple water balance model with limited parameters, changing one model parameter at a time within the scenario is efficient and simulates realistic results (Sharda *et al*., 2009; Devak & Dhanya, 2017). With the development of the simple water balance model, the objective of this scenario analysis is to assess how the lake will respond to a change in surface inflows and a change in lake storage capacity.

a) Scenario description 1: Change of surface inflows

The first scenario provides an understanding of how a change in surface inflows influences lake storage, and the subsequent outflows to the Heuningnes estuary. With possible water resource development in the upper catchment, and where land use change, such as the clearing of invasive alien vegetation, the change of surface inflow scenario is feasible. The analysis involved an iterative change to the surface runoff ($Q_{in,t}$) in the water balance model (Equation 6.6). The surface runoff (m^3) for the 2015 to 2017 was changed (i.e. an increase and decrease) by increments of 10% to 90%. The value of all other input parameters to the water balance model for 2015 to 2017 remained the same.

b) Scenario description 2: Change in lake storage capacity

With desiccation prominent in many global lakes, the scenario of a change in the lake storage capacity (or initial storage volume) will reflect antecedent moisture/storage, and the magnitude of flows required to restore equilibrium (Haghighi *et al*., 2016). The initial storage of the water balance model was estimated at 11 051 926 m^3. Scenarios for lake storage was based on knowledge of the variation of storage by depth (Figure 5.4). The lake storage values used for the scenarios is illustrated in Table 6.2. A what-if scenario where the initial storage volume was 0 m^3 was also simulated.

Table 6.2 Initial lake storage values for scenario analysis

Scenario	Lake depth (m)	Volume (m^3)
V = 0	0	0
V = 0.2	0.29	273212
V = 1.1	0.61	1127923
V = 2.58	0.94	2580045
V = 4.69	1.28	4693439
V = 7.86	1.59	7862504
V = 19.2	2.2	19209208

6.3 Results

6.3.1 Measurements of water balance components and meteorological properties

Water balance components influencing the water budget of Soetendalsvlei for the period 2015 to 2017 are illustrated in Figure 6.4. The correlation between daily rainfall at Spanjaardskloof and Vissersdrift is relatively good, with R^2 = 0.80. Rainfall in the upper catchment is generally higher. Rainfall at both stations was highest during July and September for 2015 and 2016, while reaching a maximum in November 2017. Rainfall is variable, with a general decrease from 2015 to 2017. The distribution of daily rainfall measured at the Vissersdrift weather station shows that the number of rainy days were fairly similar for 2015, 2016 and 2017, with higher magnitude rainfall events occurring in 2015 (Table 6.3). In 2015 and 2016, Spanjaardskloof had more rainy days than Vissersdrift. In 2015, daily rainfall events greater than 30 mm/day were more frequent at Vissersdrift than Spanjaardskloof. Based on the mean annual rainfall of 454 mm/annum recorded at Zeekoevlei (1910 – 2018) located 5 km to the northeast of Vissersdrift, the annual rainfall for 2015 to 2017 is highly variable.

Daily evaporation depth from the lake shows a clear seasonal variation, with average daily evaporation ranging from 6.0 mm/day during summer and 1.8 mm/day in winter (Figure 6.4). The seasonal variation is in response to Mediterranean climatic conditions with reduced temperatures and solar radiation during winter. Daily average winter evaporation at Vissersdrift from 2015 to 2017 is 1.6 mm/day, 1.5 mm/day and 2.0 mm/day respectively. Although the average daily temperature in winter (2015 – 2017) is 12.5 ^oC, the range of maximum and minimum daily temperatures during the winter of 2017 (i.e. 19.0 and 5.4 ^oC) was more variable than 2015 (i.e. 17.7 and 7.7 ^oC). The daily average solar radiation during the winter of 2017 was 11.0 MJ/day compared to 9.2 MJ/day during the winter of 2015.

The surface inflow measured at Elandsdrift represents the surface runoff from the contributing Nuwejaars catchment. Due to low flow conditions from December 2014 to May 2015 and from December 2016 to June 2017, the water level recorder was removed from the Elandsdrift station and thus no inflow data are available for these periods (Figure 6.2). Flows exceeding 8.0 m^3/s were associated with rainfall events greater than 30 mm/day. Daily flows at Elandsdrift increased to a maximum of 12.1 m^3/s in September 2015, and receded to 0.1 m^3/s in December 2015. In 2016, the highest flow of 8.3 m^3/s was recorded in July 2016 in response to a rainfall event greater than 30 mm/day on 26 July 2016. The highest flow in 2017 was 0.55 m^3/s, recorded in September 2017. The highest 2017 rainfall event in the catchment occurred on 14 November 2017 with a total rainfall of 30 mm/day. On that day, the flow at Elandsdrift showed no response to the rainfall event, with the water level increasing 0.01 m only 2 days after the rainfall event.

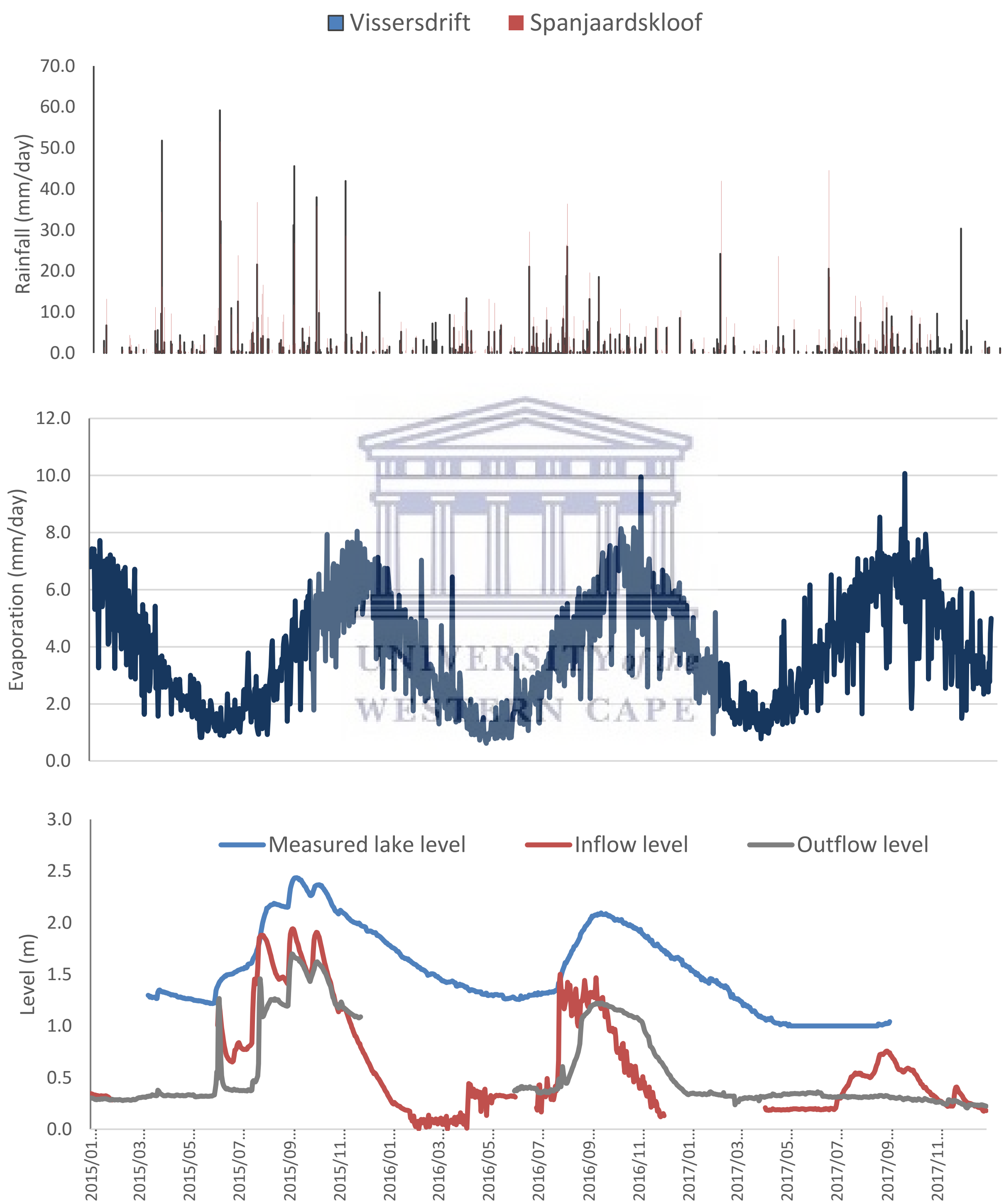


Figure 6.4 Water balance components and parameters relevant to the water balance of Soetendalsvlei

Table 6.3 **Distribution of daily rainfall at Vissersdrift and Spanjaardskloof (2015 – 2017)**

	2015			**2016**			**2017**		
Vissersdrift									
Daily rainfall (mm)	Number of rainy days	Cumulative rainfall (mm)	% of annual rainfall	Number of rainy days	Cumulative rainfall (mm)	% of annual rainfall	Number of rainy days	Cumulative rainfall (mm)	% of annual rainfall
>50	2	111	20	0	0	0	0	0	0
40 - 49,9	2	87.6	16	0	0	0	0	0	0
30 - 39,9	3	101.4	18	1	36.4	9	1	30.4	11
20 - 29,9	1	21.6	4	2	56	13	3	44.8	16
10 - 19,9	3	38.4	7	5	68	16	1	11	4
5 - 9,9	10	69.6	12	23	149	35	12	89.4	31
0,1 - 4,9	82	128.8	23	84	111.2	26	84	113.2	39
	103	**558.4**	100	115	**420.6**	100	101	**288.8**	100
Spanjaardskloof									
Daily rainfall (mm)	Number of rainy days	Cumulative rainfall (mm)	% of annual rainfall	Number of rainy days	Cumulative rainfall (mm)	% of annual rainfall	Number of rainy days	Cumulative rainfall (mm)	% of annual rainfall
>50	1	51.6	8	0	0	0	0	0	0
40 - 49,9	0	0	0	0	0	0	2	86.6	23
30 - 39,9	3	107	17	1	36.4	7	0	0	0
20 - 29,9	4	105.8	17	2	56	11	1	23.6	6
10 - 19,9	10	133	21	10	130.4	26	10	93.3	25
5 - 9,9	15	108.8	17	24	165.5	32	10	67.8	18
0,1 - 4,9	86	122.4	19	96	140.6	23	68	104	28
	119	**628.6**	100	121	**528.9**	100	91	**375**	100

The measured lake level and outflow level at Vissersdrift show a similar response in 2015 and 2016, with increased water levels associated with catchment rainfall. The maximum water level recorded for each year in Soetendalsvlei was 2.44 m in September 2015, 1.82 m in September 2016 and 1.52 m in January 2017.

The response of the water levels to cumulative rainfall from July to October from 2015 to 2017 is significantly different (Figure 6.5). The lake level and outflow level show a similar response to inflow at Elandsdrift, although the timing of the response differs. The measured lake level and outflow level for 2015 show a similar hydrological response to the inflow measured at Elandsdrift in response to the cumulative catchment rainfall (Figure 6.5). However, in July, September and October 2015, the lake outflow peaked before the water level at Elandsdrift. This may be in response to precipitation on the lake, as well as surface inflows from the inundated ungauged catchment. In 2017, only the inflow level increased significantly in response to catchment rainfall, while the measured lake level and outflow level remained relatively the same.

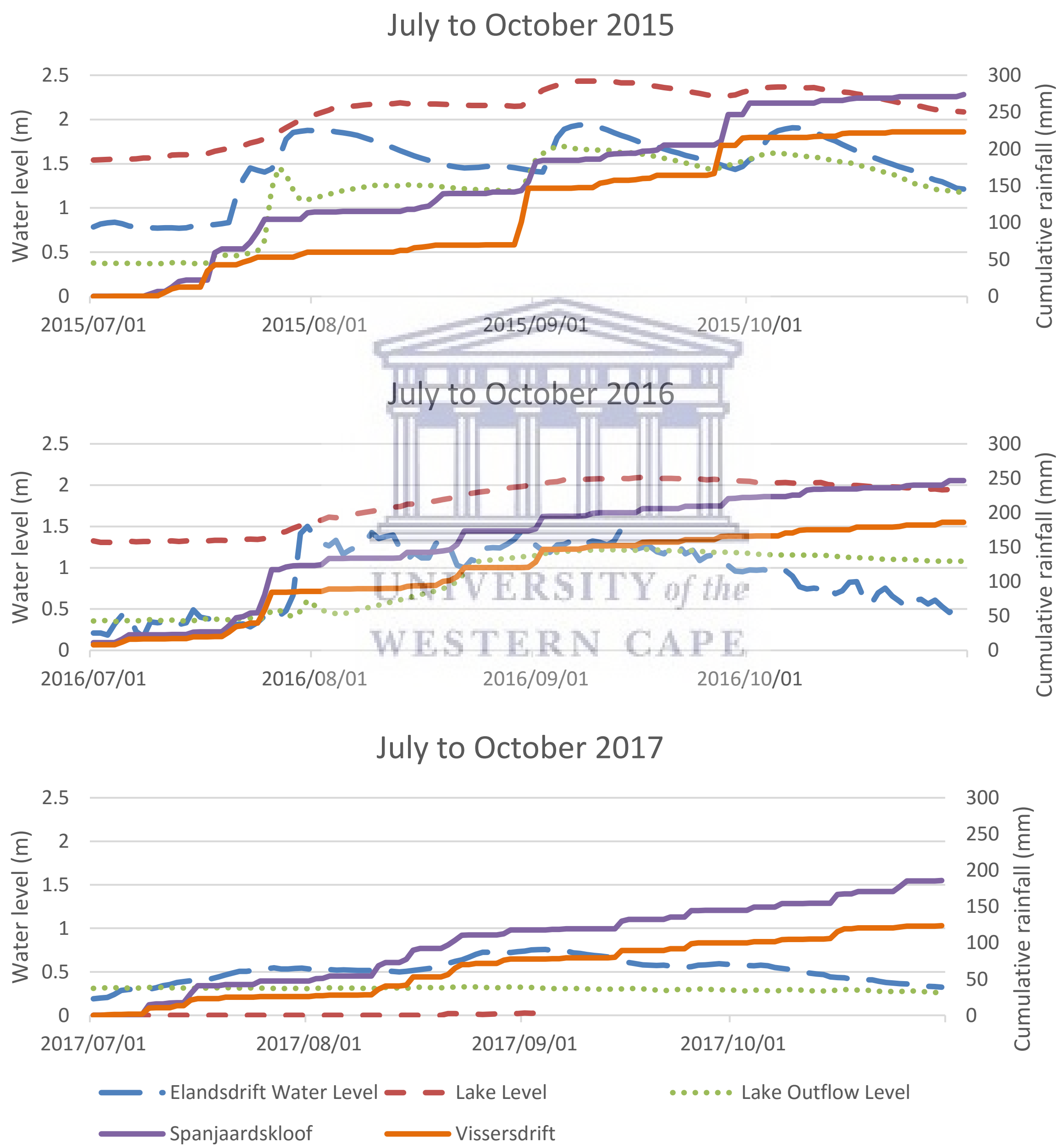


Figure 6.5 Cumulative rainfall (at Spanjaardskloof and Visserdrift) and water levels for July to October 2015 – 2017

6.3.2 Water level simulation

The simulated lake levels show a good match with the measured lake water level (Table 6.4 and Figure 6.6). The water balance model with the 2-segmented rating curve (Model 2) generally performed better, with the coefficient of determination varying about 0.99 and the root mean square error (RMSE) at 0.05 m. The water balance model with the 3-day lag time performed the poorest for both the single-rating and 2-segmented rating curve models. The simulated lake level with the 2-segmented rating curve and 1-day lag time performed the best. All further results and references to the simulated lake level is based on the model using the 2-segmented rating curve and 1-day lag time (M2, 1-day lag). The good match suggests that the model is a realistic representation of the rainfall and evaporation on/from the lake, surface inflows and surface outflows. The net groundwater flux was considered to be zero in the water balance model. The underestimation of the simulated lake level in September 2015 may be due to an overestimate of surface outflow from Soetendalsvlei, or due to inaccuracy of inflow estimates.

Table 6.4 Determination of coefficient and root mean square error (RMSE)

	Water balance model simulation	Coefficient of determination (R^2)	RMSE
Model 1 (M1) (single-power outflow-storage rating curve)	**No time lag**	0.9805	0.06
	1-day lag	0.9813	0.06
	2-day lag	0.9814	0.06
	3-day lag	0.9809	0.06
Model 2 (M2) (segmented power outflow-storage rating curve)	**No time lag**	0.9888	0.05
	1-day lag	0.9893	0.05
	2-day lag	0.9885	0.05
	3-day lag	0.9873	0.06

The measured and simulated lake levels for Soetendalsvlei show that the lake is responsive to direct rainfall onto the lake, but specifically to the surface runoff generated from the Nuwejaars catchment. A significant lake level increase of 1.2 m from 1 June to 31 August 2015 was in response to high rainfall within the catchment. Rainfall measured at Vissersdrift from 1 June to 31 August 2015 totals 274 mm, while surface runoff from the Nuwejaars River was estimated at 28.0 Mm^3 for the same period. Due to two rainfall events exceeding 30 mm/day in September and October 2015, lake water levels measured 2.44 m on 10 September 2015 (2.44 m) and 2.37 m on 7 October 2015. The progressive decline in the lake level from October 2015 to June 2016 is due to reduced inflows, significant surface outflows and evaporation loss from the lake. During the summer months, evaporation contributes significantly to water outflow from the lake. The total evaporation for the summer and autumn months (i.e. December to May) for 2015 to 2017, were 8.2, 8.4 and 6.6 Mm^3. The low evaporation in 2017 is due to the shrinking of Soetendalsvlei and reduced availability of surface water.

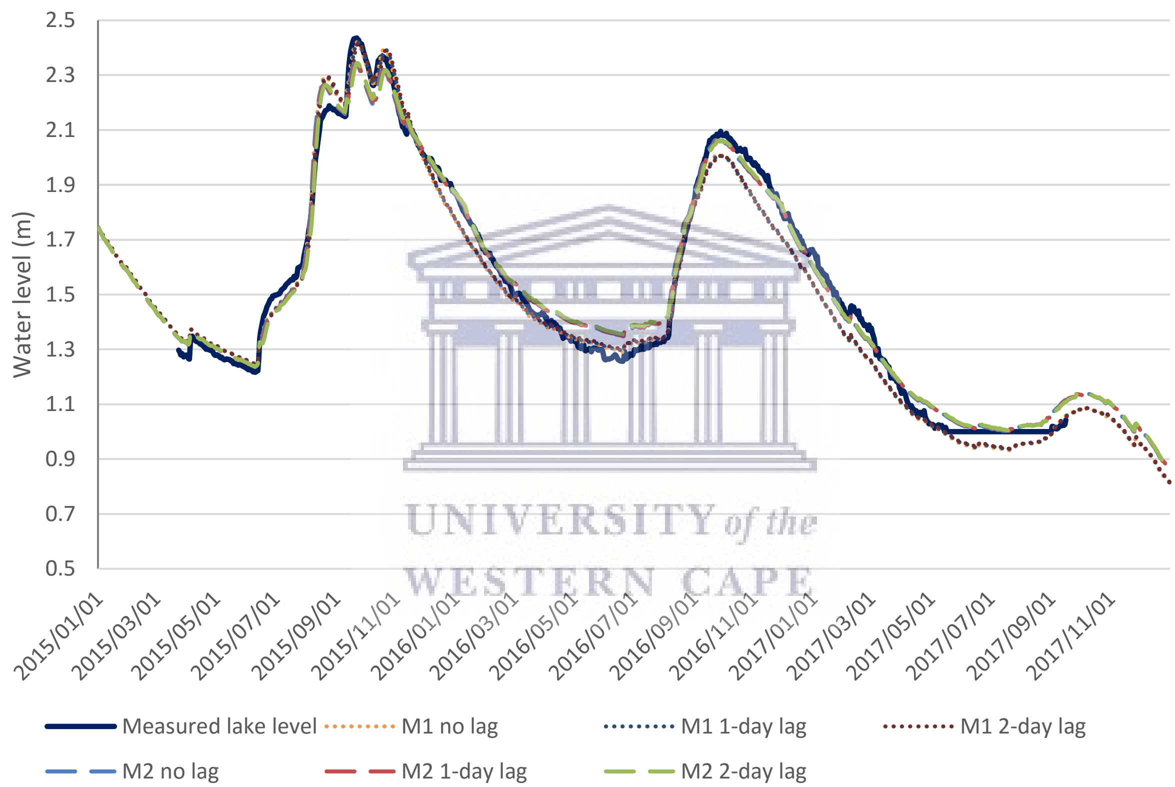


Figure 6.6 Measured and simulated lake levels for Soetendalsvlei (2015 – 2017)

Surface outflows only occurs when the lake reaches a critical water storage volume of 9.5 Mm^3. Surface outflow was estimated from the water balance model, with a maximum surface outflow of 9.8 m^3/s in September 2015 (Figure 6.7). The observed outflow level and simulated outflow show a similar response pattern. The number of days with simulated outflows from the lake were 172, 160 and 0 from 2015 to 2017 respectively.

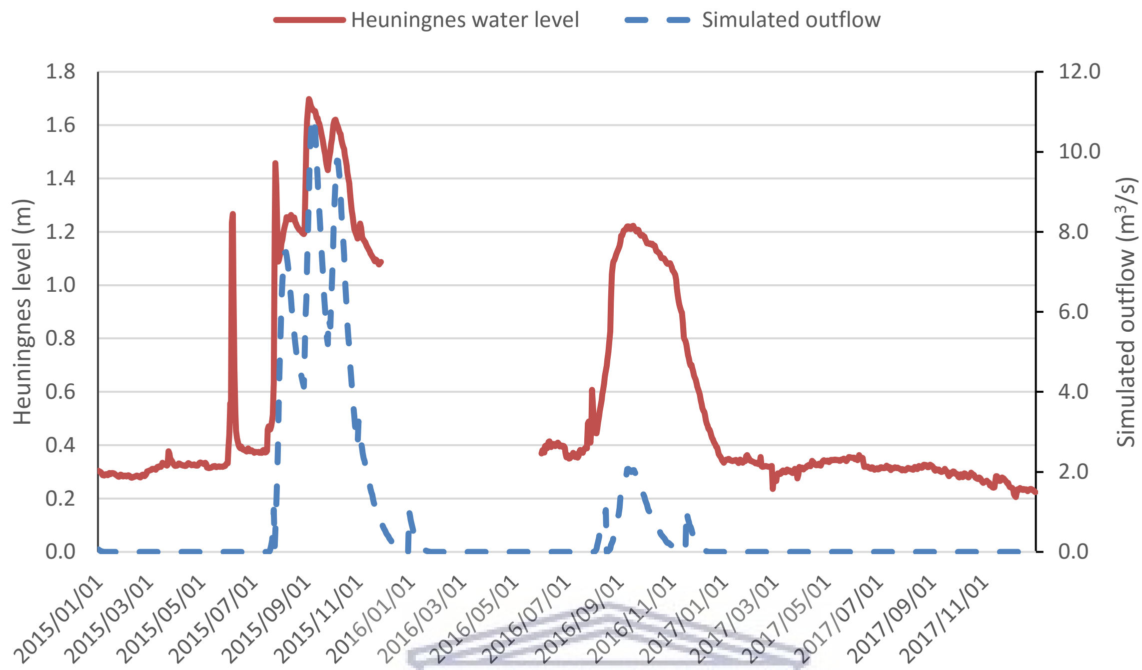


Figure 6.7 Measured lake levels (m) and simulated outflows (m^3/s) for the Heuningnes River

6.3.3 Water balance components

The annual water balance components of Soetendalsvlei show considerable variation from 2015 to 2017 (Table 6.5). The net increase in storage in 2015 is indicative of the high mean annual rainfall, with high runoff to the lake. In 2016 and 2017, the annual total outflow is more dominant than inflows, with a general decrease of lake rainfall and surface inflows (Table 6.5). Surface flows from the Nuwejaars River contributes the greatest proportion of inflows to Soetendalsvlei. In 2015, flows from the Nuwejaars River contributed 70.5 Mm^3/annum, i.e. 92% of inflows to storage in Soetendalsvlei. Drought conditions can be inferred from the low inflows in 2017. Rainfall onto the lake surface contributes 8% and 22% to inflows in 2015 and 2016 respectively. In 2017, when surface flow is significantly lower, rainfall onto the lake contributes 45% of the total inflows.

Surface outflow is a significant component of the water balance of Soetendalsvlei when storage reaches the critical threshold for overflow of 9.5 Mm^3. Due to high storage in 2015, outflows peaked at 59.7 Mm^3/annum. There was no surface outflow in 2017. With Soetendalsvlei changing from an open to a closed lake system in 2017, the dominant outflow is evaporation. The decline in the annual evaporation from 2015 to 2017 is due to the shrinking lake surface and the availability of surface water. The relative contribution of lake evaporation is greater than the direct rainfall onto the lake from 2015 to 2017.

The hydraulic residence time in Soetendalsvlei from 2015 to 2017, (Table 6.5) varied from 55, 151 and 147 days respectively. The hydraulic residence time does not take into account any factors, such as wind, that may affect the mixing regime in the water body (Mitsch & Gosselink, 2007). With reduced or no outflows from the lake, the residence time increases.

Table 6.5 Annual water balance components in Mm^3 of Soetendalsvlei for 2015 - 2017

Water balance components	2015	2016	2017
Lake aerial rainfall	6.3	4.3	2.1
Surface inflow	70.5	15.8	2.5
Total Inflows	***76.8***	***20.1***	***4.6***
Lake aerial evaporation	15.6	14.8	10.8
Surface outflow	59.7	8.6	0.0
Total Outflows	***75.3***	***23.4***	***10.8***
Average storage	11.3	9.7	4.4
Change in storage	**1.6**	**-3.3**	**-6.2**
Residence time (days)	**55**	**151**	**147**

Monthly and intra-seasonal variation of the water balance components of Soetendalsvlei is significant from 2015 to 2017 (Figure 6.8 and Figure 6.9). Surface inflows are dominant during winter and spring, and decreasing from 2015 to 2017. Surface outflows have a similar pattern to surface inflows (with a peak in September). Rainfall onto the lake is highest during winter for 2015 to 2017. However, rainfall during March, September and November is considerably higher in 2015 than in 2016 and 2017. Monthly and seasonal evaporation are similar for 2015 and 2016. The lower evaporation in 2017, specifically from August to December is due to lower storage and available water surface area.

Surface inflow and outflows show the greatest monthly variation of the water balance components. Precipitation onto the lake provides greater inflow than surface flow during March. Precipitation onto the lake surface is significant from June to September. With a progressive decline in storage from September 2016, the minimum lake storage for surface outflows to occur is reached by November 2016. Outflows from the lake from August to October (winter and spring) is mainly by surface flow to the Heuningnes River. Monthly evaporation from the lake shows a seasonal variation with maximum loss during the summer months. Average monthly loss from evaporation exceeds inflows from December to May (summer and autumn).

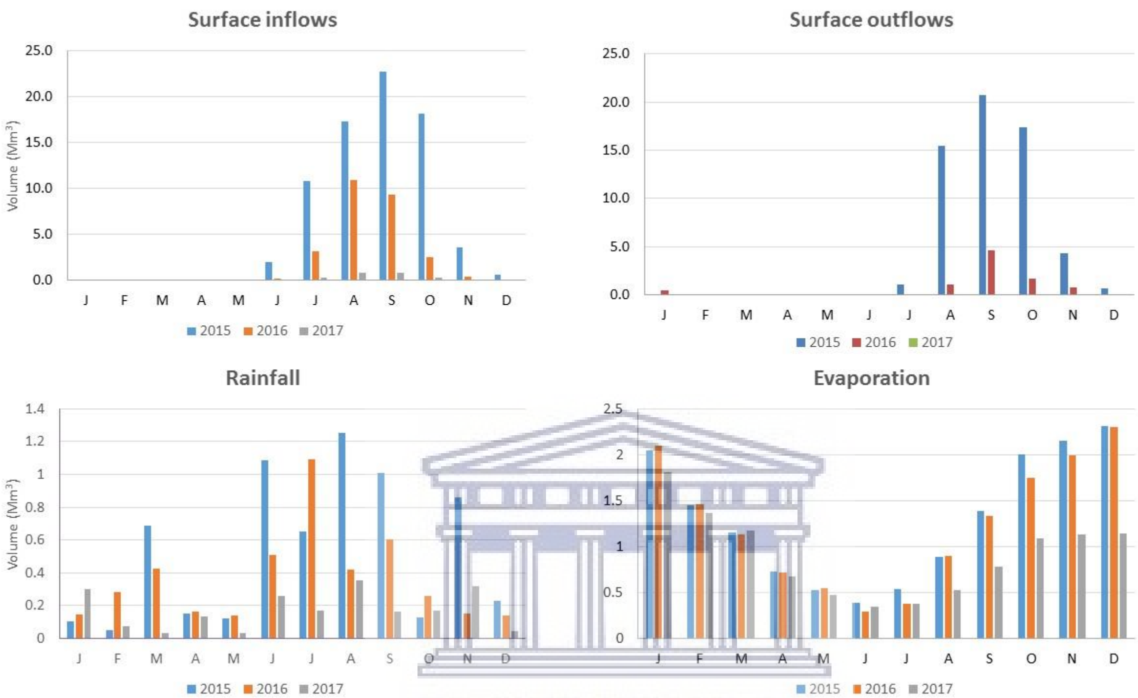


Figure 6.8 Monthly water balance components of Soetendalsvlei (2015 – 2017). Rainfall and evaporation refer to rainfall on and evaporation from the lake surface.

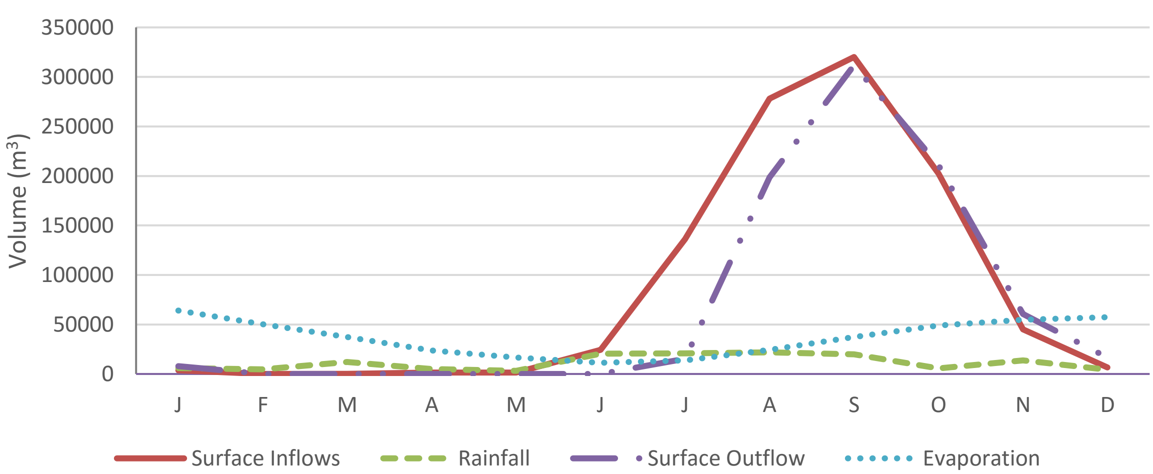


Figure 6.9 Average monthly water budget of Soetendalsvlei (2015 – 2017). Rainfall and evaporation refer to rainfall on and evaporation from the lake surface.

6.3.4 Scenario analysis

6.3.4.1 Scenario 1: Change of surface inflows

The scenario analysis shows how a change in surface inflows affects lake water levels from 2015 to 2017 (Figure 6.10). As only a change in the volume of surface inflows was simulated, the scenarios show a similar pattern of response, while the magnitude of change varies. The simulated scenarios where increased surface inflow was above 10% show a similar response, and did not exceed a lake level of 2.5 m. This illustrates the maximum storage capacity of the lake basin, and the theoretical balance between the inflows and the outflows.

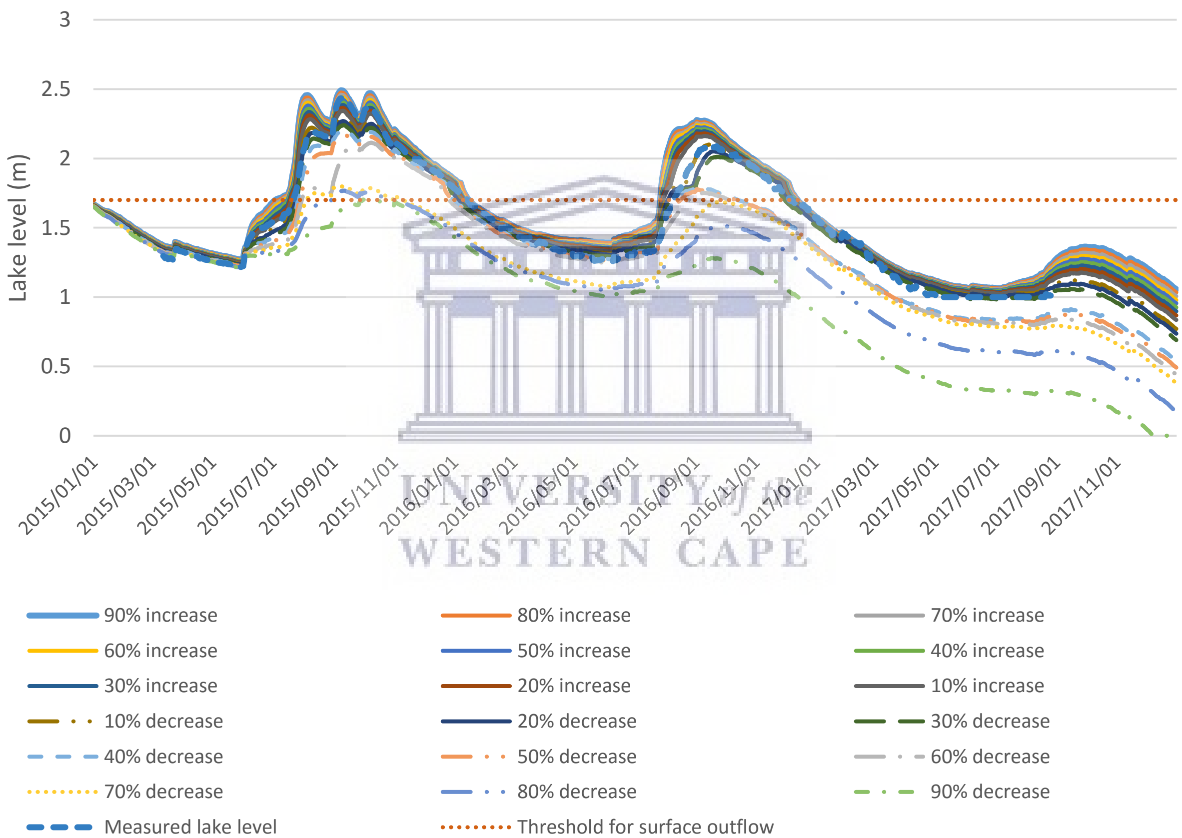


Figure 6.10 Measured and simulated lake level scenarios based on a percentage change of surface inflows from 2015 to 2017. The lake level threshold for surface flows was estimated at 1.7 m.

Based on the lake water balance model for Soetendalsvlei, lake storage and outflow are sensitive to change in surface inflow. The progressive decrease of daily surface inflows causes a significant reduction in surface outflow from the lake and average annual lake storage. When total surface inflow was reduced by 90% there was no outflow from the lake. Assumptions of the one-factor scenario analysis are that all other parameters of the water balance model remain unchanged (Borgonovo *et al*., 2017). Given that a change in surface inflows may be due to changing rainfall conditions, a degree of error is incorporated into the scenario analysis as the rainfall onto the lake remains unchanged. However, the relative contribution of rainfall onto the lake compared to surface inflows was less than 22% during wet and average rainfall conditions.

6.3.4.2 Scenario 2: Change in storage capacity

Simulated scenarios where the initial lake storage capacity is changed and all other parameters remain the same shows the varied behavior of the lake until the threshold for surface outflow of 9.5 Mm^3 is reached (Figure 6.11).

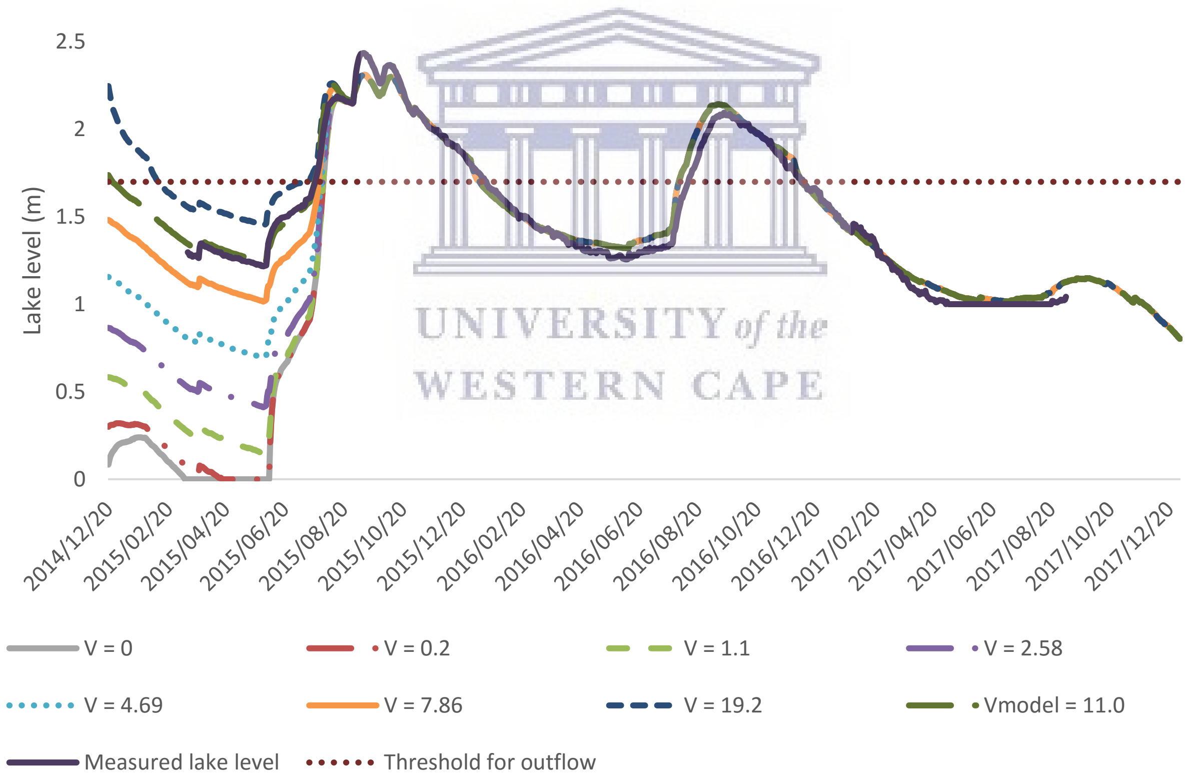


Figure 6.11 Measured and simulated lake level scenarios based on a change of initial storage (V=Mm^3). The lake level threshold for surface outflows was estimated at 1.7 m.

As expected, with a high antecedent storage (V=19.2) the time taken (i.e. 11 days) for the lake to reach the threshold for surface outflow is shorter than the measured lake level/storage. Once the lake reaches the threshold capacity for surface outflow by end July 2015, the simulated hydrological behavior for all scenarios are identical. From January to end July 2015 the estimated surface inflows was approximately 12 Mm^3. Given that the storage capacity of Soetendalsvlei is approximately 20 Mm^3, and that the surface inflow for 2015 was estimated at 70.5 Mm^3/annum the inference is that a relatively wet period/year has the ability to "fill" the lake.

6.4 Discussion

6.4.1 The conceptual model of an open lake

"The art of modelling" is in creating an "appropriate model structure with good model performance", which advances our understanding of hydrological behavior and strives to improve the "current state of knowledge" (Savenije, 2009, p160). With the available hydrological and meteorological data for the Nuwejaars catchment, a conceptual water balance model was developed for the shallow lake of Soetendalsvlei from 2015 to 2017. Water balance models based on the "equation of continuity" in which a change in storage is balanced by inflows and outflows is extensively used to understand the water balance dynamics of wetlands and lakes (Ollis *et al*., 2013; Maherry *et al*., 2016). The estimation of inflows and outflows for Soetendalsvlei were based on meteorological, water level and flow data, with groundwater flux and surface outflows from the lake the unknown model components. Surface outflows was simulated as the residual or unknown component of the model. Limitations of the water balance model are the assumptions that the net groundwater flux is zero, and the exclusion of the ungauged catchment in accurately estimating inflows.

Sources of error are inherent in the uncertainty of measurement, estimation or interpretation of water balance components, as well as the assumptions and limitations of model parameters (Winter, 1981; Niedda *et al*., 2014). Possible explanations for the overestimation of storage may be due to flow regulation by floodplain wetlands (Dessie *et al*., 2015), the effect of storage deficit caused by upstream depression and floodplain wetlands (Spence, 2000), groundwater recharge or uncertainty in the model components. The improved performance of the water balance model for Soetendalsvlei with a 1-day lag time of surface inflows from Elandsdrift highlights the importance of the floodplain wetlands in regulating flow (Mehl, 2019). The relatively flat topography and occurrence of floodplain and depression wetlands in the lower Nuwejaars catchment, specifically between Elandsdrift and Soetendalsvlei, represents a dynamic and ungauged landscape that requires further investigation.

The underestimation of storage in 2016 and 2017 may be due to the omission of subsurface flow in the water balance model or uncertainty in the model components. In an assessment of the reserve determination for Verlorenvlei, an estuarine lake along the west coast of South Africa, Watson *et al*., (2019) found that constant baseflow and the quick response of baseflow to rainfall events were a major source of inflows to the lake.

An extensive monitoring network to understand the interaction of the subsurface flows, floodplain and depression wetlands and rivers in response to climatic conditions will enhance the current understanding of the hydrological behavior of wetlands and improve water resource management (Maherry *et al*., 2016). Accurate assessments of lake evaporation, partitioning of evaporation and transpiration, and a better understanding of the seasonal water use of different hydrophytes will also enhance our understanding of outflows from the lake. Based on estimations of surface inflows, precipitation on the lake, evaporation from the lake and simulated outflows, the model performance was relatively good (R^2 = 0.99).

6.4.2 The water balance of Soetendalsvlei

The hydrological regime of Soetendalsvlei has a pronounced seasonal and inter-annual variation of storage, primarily influenced by climatic factors, lake morphology and properties of the contributing catchment. Climatic factors, specifically rainfall and evaporation, directly/indirectly influences lake water balance components and the resultant storage (Szesztay, 1974; Parsons & Vermeulen, 2017). Rainfall variability influences the amount of direct rainfall onto the lake, while the magnitude and timing of runoff and subsurface flows is influenced by the contributing catchment area, land use activities and characteristics of the catchment (Mitsch & Gosselink, 2007, p107; Barron *et al*., 2011). During the observation period from 2015 to 2017, surface inflows from July to October from the Nuwejaars catchment was the dominant inflow to Soetendalsvlei. During drought conditions, and when water storage is below the threshold for outflow, evaporation is dominant, otherwise surface flow is the main outflow from Soetendalsvlei. Lake evaporation reflect a seasonal variation that is influenced by the Mediterranean climate. Lake evaporation exceeds direct rainfall onto the lake, except during the winter months (July to September). Climatic and/or anthropogenic factors which thus impact surface inflows or runoff, will affect the water balance of the lake. Water storage in Poyang Lake, China (Zhang *et al*., 2015), Lake Sibayi, South Africa (Smithers *et al*., 2017), Lake Chad (Lemoalle *et al*., 2012) and lakes in South-East Australia (Tweed *et al*., 2009) have declined due to decreasing annual rainfall, increased evapotranspiration and an increased demand for upstream water resources.

Though surface outflow is modulated by topographic controls in unregulated lakes, Kebede *et al*., (2006) found a significant positive relationship between rainfall variation, lake water level and surface outflow from Lake Tana (Ethiopia). Similarly, depending on storage capacity and antecedent storage; the catchment rainfall influences inflow to the lake, the lake-water level and outflow from Soetendalsvlei. At the start of the wet season, inflows accumulate and increases the lake storage. The 2-segmented outflow-lake storage rating curve derived as the unknown in the water balance model for Soetendalsvlei provides insight to the response of the lake at different levels of storage. The response/behaviour of the surface outflow to storage is influenced by the lake morphology, and the nature of inflow to the lake. Once the threshold for lake overflow is reached, the surface outflow is influenced by the surface inflows. Anecdotal evidence from the surrounding landowners, indicate that the extreme flood events in April 2005 resulted in significant flooding on the cultivated landscape resulting from the overspill of the lake. The threshold of shallow lakes to shift from open to closed lakes is thus dependent on climatic conditions (Szesztay, 1974; Mbanguka *et al*., 2016). With the capacity for water storage, and the presence of emergent vegetation, the depression of Soetendalsvlei thus has an influence on flow attenuation.

While there is consensus that climate variability will influence freshwater ecosystems (Dallas & Rivers-Moore, 2014), there is less certainty on how it will affect these freshwater ecosystems. The influence of rainfall variability on the water storage of Soetendalsvlei was markedly evident with the lake at maximum storage due to above mean annual rainfall in 2015, and shrinking to almost 90% of the water storage capacity due to drought conditions in 2017. The lake response and sensitivity to rainfall variability from 2015 to 2017 thus provide insight to ecosystem functions associated with the water-level fluctuation.

6.4.3 Lake response to change

Based on the decline of storage from 2015 to 2017, rainfall variability is a natural driver of the water balance of Soetendalsvlei, with consequent impacts on the hydrological functioning of the lake. The capacity to store water, the temporal and spatial variations of storage, and residence time of the water are hydrological attributes that influences the ecosystem services provided by lakes (Brauman *et al*., 2007). Threshold of lake storage to surface outflow, infers temporal connectivity and the spatial flow of hydrological ecosystem services to the downstream catchment (Spence, 2000; Bracken *et al*., 2013; Li *et al*., 2019). In a surface-inflow dominated lake, such as Soetendalsvlei, climatic and catchment factors that influences the magnitude, frequency and timing of inflows will thus affect water storage and surface outflows. In ensuring the ecological integrity of lakes and wetlands, any future upstream developments should thus consider the impacts on the downstream flow regime.

The importance of high rainfall periods and/or high rainfall events in 'filling' lakes and reducing residence time are important in maintaining the hydrological and ecological functioning of lakes. Barron *et al*., (2011) refers to "storage recovery stage" as the period where the storage of lakes, wetlands and groundwater are being filled at the beginning of the wet season or wet period when annual rainfall reaches a threshold for runoff to occur. The storage recovery time is influenced by lake morphology, antecedent storage of the lake, as well as the magnitude of inflows to the lake. Soetendalsvlei is sensitive/responsive to high rainfall events, and depending on the antecedent lake storage, once the lake storage reaches the threshold for outflow, the residence time is reduced. Surface and subsurface connectivity of wetlands particularly during high rainfall events/periods and within a relatively flat coastal plain requires greater attention in refining our understanding of the hydrological behavior and response of the lake.

An understanding of water storage and residence time for coastal lakes are important for maintaining ecosystem health. Harding (1992) found that winter rainfalls caused "hydraulic flushing" for the freshwater coastal lake of Princess Vlei in the Western Cape, South Africa. The hydraulic flushing increased the water clarity and reduced phytoplankton in the lake (Harding, 1992). "Relatively low flushing rates" of the Wilderness Lakes, combined with high nutrient fluxes from both catchment-derived sources and *in-situ* bacteriological remineralization were the main drivers for stimulating cyanobacteria, resulting in poor ecosystem health (Taljaard *et al.*, 2018). The importance of high rainfall events for "filling up" and "ecosystem regeneration" was also highlighted for Verlorenvlei along the west coast of South Africa, where the increased frequency of low lake water levels was associated with climate variability and increased demand for water resources (Watson *et al*., 2019). The high rainfall variability for the Nuwejaars catchment for 2015 to 2017 is reflected with high variability of water storage, storage outflows and residence time. The high fish mortality in Soetendalsvlei in 2017 due to reduced storage was due to drought conditions, and illustrates the impacts of rainfall variability on the ecosystem health of the lake.

A water balance model offers an understanding of the response of lakes to inflows and outflows, and allows insights to maintaining or ensuring improved ecosystem functioning (Samhouri *et al*., 2010). The temporal and spatial variations of surface inflows to a lake, represents the complex movement and interaction of water, with land, energy and man within a heterogeneous catchment. The one-factor scenario analysis thus provides a simple but quantitative method for simulating impacts of a change in the magnitude of surface inflows, without considering the complex processes that may influence the magnitude and timing of surface inflows.

6.5 Conclusion

A conceptual model based on the hydrological behavior of the Soetendalsvlei was developed from the estimation of surface inflow, precipitation on the lake, evaporation from the lake, and simulated outflows. Groundwater exchange to and from the lake was assumed as zero. The model was based on a daily time step from 2015 to 2017. A 1-day time delay of surface inflows due to the flow regulation by floodplain wetlands between Elandsdrift and Soetendalsvlei yielded a good comparison of the simulated and measured lake level. The water balance model was optimised by calibrating surface outflow, the unknown component in the model. The estimation of surface outflow using a 2-segmented rating curve improved the performance of the water balance model. Interaction between the groundwater and the lake was not included. Despite uncertainties of the water balance components, the simulated lake level compared well with the measured lake level (R^2 = 0.99).

Surface flows from the Nuwejaars River contributes significant inflows to the overall water budget of Soetendalsvlei. In 2015, when mean annual rainfall was 558 mm/annum, surface inflows from the Nuwejaars River contributed 92% of the total water storage. With increased lake storage in 2015, total surface outflow to the Heuningnes River increased. Drought conditions from 2016 caused a significant decline in lake storage. In 2017, the mean annual rainfall was 289 mm/annum, with total storage reduced to 2.2 Mm^3. With no surface outflows in 2017, Soetendalsvlei changed from an intermittently open lake, to a closed lake. Total annual surface inflows and outflows for 2015 to 2017 were dominant in September after sustained inflows during the winter season. Evaporation from the lake from 2015 to 2017 showed strong seasonal fluctuation, with maximum water loss from December to May (summer and autumn). When Soetendalsvlei changes from an open to a closed lake, evaporation is the dominant outflow. Evaporation from the lake is dependent on surface water availability.

The development of the water balance model for Soetendalsvlei allowed insight into how lake storage and surface outflows would likely change with modifications to surface inflow. Based on a one-factor scenario analysis, storage and outflow logically changed with surface inflow. When total annual surface inflow was reduced by 80% to 5.1 Mm^3, and assuming rainfall onto the lake remain unchanged, there was no outflow from the lake. The water balance model can be used to hypothesize how the lake will respond to change due to possible water resource development, land use activities or variable rainfall within the Nuwejaars catchment. As surface outflow from the lake contributes to the ecosystem functioning of the Heuningnes River and estuary, the water balance model can provide insight to the timing and magnitude of flows from Soetendalsvlei.

CHAPTER 7

WETLAND ECOSYSTEM SERVICES: HABITAT PROVISION FOR BIRDS IN THE NUWEJAARS CATCHMENT

7.1 Introduction

Wetlands are diverse and dynamic ecosystems that provide essential ecosystem services such as habitats for waterbirds. The use and selection of wetland habitats by various waterbird species during their life history may vary for specific needs such as shelter, resting, breeding, nesting, moulting and foraging (Ma *et al*., 2010b). The *in situ* wetland properties affecting habitat quality for waterbirds are primarily related to the hydrological regime, soils and vegetation, while larger scale environmental factors include wetland connectivity, surrounding land use, food availability, climate change and human disturbance (Raeside *et al*., 2007; Ma *et al*., 2010b; Cumming *et al*., 2012). The high mobility of waterbirds means that species will, depending on their needs, respond to changes in environmental conditions and habitat quality (Cumming *et al*., 2012). The seasonal migration of nearly 200 bird species between the Palearctic (Europe and Asia) and sub-Saharan African regions; the migration of about 50 species from Africa to Antarctica and oceanic Islands, and the seasonal migration of more than 580 species within the African continent are examples of broad scale patterns of movement of migratory birds for optimal conditions for breeding and survival (Turpie, 1996). Many southern African resident bird species that breed and make use of the region/habitats throughout the year, will also undertake local or long-distance movements within the region, in response to the quality of the habitat (Harebottle, 2011). The global degradation and loss of wetland habitats have thus been associated with significant decrease in many waterbird species (Ma *et al*., 2010b).

Given the specific habitat requirements of different waterbird species, and their mobility, "managing wetland habitats for waterbirds" requires both a large-scale and regional approach, as well as a local-specific or ecosystem-based approach (Ma *et al*., 2010b, p15). Given the diverse and complex factors influencing the selection of wetland habitats, substantial research shows that the habitat requirements of waterbirds are directly and indirectly influenced by the hydrological regime of wetland ecosystems (Boshoff & Piper, 1992; Raeside *et al*., 2007; Bowker & Downs, 2008; Ma *et al*., 2010b; Harebottle, 2011; Whittington *et al*., 2013; Russell *et al*., 2014; Zhang *et al*., 2016). Specific studies have described the relationship of bird species in relation to *in situ* water level or depth (Harebottle, 2011; Chastant & Gawlik, 2018), flow (Cummings *et al*., 2012;

Zhang *et al*., 2016) and wetland inundation derived from remotely sensed data (Jia *et al*., 2018). The water level fluctuation of lakes and wetlands have been found to benefit specific waterbird species depending on their life history, bird morphology (e.g. leg length, beak shape and size), foraging behaviour and habitat requirements (Ma *et al*., 2010b). For example, decreasing water levels in the pans within the Ndumo Game Reserve, a Ramsar site in KwaZulu-Natal, South Africa, caused an increase in waterbird species, particularly of shoreline birds that favour the invertebrates found in the exposed mudflats (Whittington *et al*., 2013). Cumming *et al*., (2012) also found that the variation of the flow regime of the Okavango River in Namibia, influenced the abundance of food resources, which directly influenced the foraging and species composition of waterbirds. An understanding of how different waterbird species are influenced by the hydrological regime of wetlands can thus allow a more species-targeted approach particularly where the conservation of threatened species is important (Ma *et al*., 2010b). Bowker & Downs (2008) investigated the impact of the water level fluctuation of Lake St Lucia, a world heritage site in KwaZulu-Natal, and found that when water levels "were too high or too low" the great white pelican (*Pelecanus onocrotalus*) was not observed. While the water level was not directly influencing the abundance of pelicans, the water level was influencing the availability of their food. With this knowledge, Bowker & Downs (2008) recommended that the great white pelican is an indicator species for medium to low water level for Lake St Lucia.

An understanding of the hydrological regime of wetlands in relation to the occurrence or non-occurrence, species richness and diversity of waterbird species can thus inform conservation or restoration strategies particularly where anthropogenic influences and impacts of climate change may affect biodiversity. Research has identified the importance of the hydrological regime of lakes in influencing waterbird assemblages in specific coastal lakes and wetlands in South Africa (Boshoff & Piper, 1992; Harebottle, 2011; Russell *et al*., 2014). Given the significance for local/ecosystem-based assessments (Ma *et al*., 2010b), there is thus a need to understand how the hydrological regime of the Nuwejaars wetlands influences waterbird abundance, richness and diversity. In aligning to the main aim of the thesis, the aim of this chapter is to relate the spatial and temporal wetland inundation to the provision of habitat for waterbirds.

Key objectives of this chapter are to:

1. Assess the temporal and spatial variation of species richness of waterbird species in the Nuwejaars catchment
2. Evaluate how wetland inundation influences bird abundance, richness and diversity

7.2 Methods

7.2.1 Citizen science data

SABAP2 data is collected by registered volunteer citizen scientists, who provide a checklist of bird species observed within a pre-defined pentad during a specific visit. A pentad is defined by a geographical rectangular area with a 5' by 5' grid. Each pentad is approximately 61 km^2 in area. Registered volunteers submit a checklist to SABAP2 which includes the species observed, and the date and time of observation within the pentad. Submitted data are checked and reviewed, with all data freely available and accessible from their internet site (http://sabap2.birdmap.africa). The spatial information and species summary of each pentad was exported from the SABAP2 site. The number of checklists and total species for each pentad in the Nuwejaars catchment from 2014 to 2019 were tabulated.

A description of pentads within the Nuwejaars catchment was sourced from the Agulhas Plain Birding report of 2018 (de Klerk, 2018). In addition, the percentage of wetlands and protected areas (data available from the SANBI BGIS website: http://bgis.sanbi.org) within each pentad were determined.

While the SABAP2 provides data allows an understanding of species richness, the data does not provide an understanding of species abundance. Bird counts are available from the Coordinated Waterbird Counts (CWAC), Animal Demography Unit at the University of Cape Town, and provide data on the number of birds of each species for selected sites across the Western Cape. CWAC data are freely available and accessible (http://cwac.birdmap.africa/index.php). Within the Nuwejaars catchment, bird counts were conducted at Soetendalsvlei (site code: 34431958) from 2000 to January 2017 and at Voëlvlei (site code: 34401952) from January 2017 to present. Bird counts are not conducted consistently throughout the year(s), with most counts conducted in winter and/or summer.

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7.2.2 Species functional groups

The use of species functional groups or traits provide information on species composition that allows a better understanding of the interaction of species with the environment (Kandziora *et al*., 2013). Bird species were classified into functional groups based on occurrence status, species groups, habitat preference and feeding guild using Harebottle (2011) as a guide. A description of species groups and feeding guilds are illustrated in Table 7.1. Occurrence status is defined as South African resident species or Palearctic (migrant) species. Southern African resident species are bird species that breed in southern Africa with local or long-distance movements within the region, while Palearctic species breed in Palearctic regions and migrate to the southern hemisphere during austral summer (September to April). Habitat types were classified based on water and vegetation characteristics, with five habitat types identified: open water, tall emergent vegetation (such as *Phragmites australis*), short emergent vegetation, terrestrial and bare shoreline/mudflats.

Table 7.1 Description of functional groups (source: Harebottle, 2011)

Functional group	Variable	Description	Examples
Species group	Cormorants	Family Phalacrocoracidae, 63 – 101 cm in length with long hooked bill, large feet	African Darter; Bank Cormorant, Cape Cormorant, Reed Cormorant
	Cranes	Long-legged with long-neck, family Gruidae	Blue Crane
	Flamingos	Wading birds, long-legged with long neck, distinct pale pink to white plumage	Greater Flamongos, Lesser Flamigos
	Gulls	Family Laridae, webbed-feet with long bills	Grey-headed Gull, Kelp Gull, Hartlaub's Gull
	Kingfishers	Bright coloured birds, range in size from 12 to 45 cm.	Half-collared Kingfisher, Giant Kingfisher, Malachite Kingfisher , Pied Kingfisher
	Pelicans	Large water birds, family Pelecandiae	Great White Pelican
	Rallids	Family Rallidae, includes species of rail, crake	African Rail, Black Crake, Baillon's Crake
	Raptors	Predatory birds	African fish-eagle, Osprey, March Owl, African Marsh-Harrier, Black Harrier
	Shorebirds	Include Families Charadriidae, Scolopacidae	African Oystercatcher; Common Greenshank, Little stint
	Terns	Family Rynchopidae	Caspian Tern
	Waders	Include Families Ardeidae, Scopidae, CCiconiidae, Threskiornithidae, Phoenicopteridae, Recurvirostridae	Blacksmith Lapwing, Glossy Ibis, African Spoonbill, African Sacred Ibis
	Waterfowl	Open-water species including Anatidae, Podicepedidae, and Red-knobbed Coot and Common Moorhen (Rallidae species)	Spur-winged Goose, South African Shelduck, Yellow-billed Duck , Red-knobbed Coot
Feeding guild	Herbivores	Plant matter including seeds, nuts, leaves, roots, fruits	Spur-winged Goose, Egyptian Goose
	Invertebrate feeder	Animals with no vertebrate column (worms, insects, algae)	Three-banded Plover, White-backed duck, Hadeda Ibis, Little Bittern, White-fronted Plover, Water Thick-Knee,
	Piscivore	Mainly fish, but diet also includes vertebrates and invertebrates	African Oystercatcher, Common Greenshank,Chestnut-banded Plover
	Raptor (carnivore)	Birds of prey that feed on vertebrates	African Marsh-Harrier, Black Harrier

7.2.3 Species abundance, richness and diversity

To assess the spatial distribution of birds in the Nuwejaars catchment, the total bird species for pentads within the catchment were summarized from 2014 to 2019 using data from SABAP2. An understanding of species distribution provides insight to biodiversity maintenance, defined as providing habitat and maintaining the natural processes of an ecosystem (Kotze *et al*., 2009).

CWAC data were summarized for each site, with diversity indices calculated for each bird count. The following indices were summarized for each wetland:

1. Species richness is the number of species in an area or habitat. Species richness was determined for resident and Palearctic/migrant species.
2. Overall species abundance is the number of birds of each species in an area. Abundance was also summarized for resident and migrant bird species.
3. Bird species diversity is the abundance of the different bird species in an area and is an indicator that is commonly used to provide information on habitats. A common index to illustrate diversity is the Shannon Diversity Index (*H*') (Lamb *et al.*, 2009).
   The Shannon Index (*H*') considers the number of species (*s*) and the proportion of the sample (p_i) that belongs to the *i*th species:
   $$H' = -\sum_{i=1}^{s} p_i \ln(p_i)$$
   The values generated by the Shannon Index normally varies from 1.5 to 3.5.

7.2.4 Wetland inundation and bird diversity

A change in wetland inundation reflects a change in the flooded surface area of the wetland, and may, depending on the wetland morphology, reflect a change in the lake water level, characteristics of the shoreline and submerged/exposed emergent vegetation. These changes have consequent impacts on foraging and nesting habitats (Raeside *et al*., 2007; Russell *et al*., 2014). With limited hydrological data for the Nuwejaars catchment, wetland inundation was determined for the Nuwejaars catchment from 1989 to 2019 using the MNDWI derived in Section 4.3.2. For the purpose of this chapter, the frequency of wetland inundation (i.e. the hydroperiod) for the catchment was mapped for each year from 2014 to 2019 to allow comparison with the SABAP2 data.

The area and frequency of wetland inundation for Soetendalsvlei was determined in Section 4.2.5 and 4.2.6. The same methodology was used to determine the area and frequency of wetland inundation for Voëlvlei. Based on the wetland inundation frequency for wetlands in the Nuwejaars catchment, Soetendalsvlei and Voëlvlei experience similar changes/timing in the inundation (Table 4.3). The inundated wetlands are composed of open water and flooded emergent vegetation, with inundation strongly influenced by rainfall (indirectly through catchment runoff and direct rainfall onto the lake). The hydroperiod for the two lakes show areas which are permanently inundated, which are mostly the deeper open water. Given the knowledge of wetland inundation, morphology of the lakes (Chapter 5 and Seaton, 2016) and occurrence of emergent vegetation allows a better understanding of how a change in wetland inundation influences habitat quality.

The area of inundation closest to the day of the CWAC counts were selected for analysis. The correlation between wetland inundation and the number of waterbirds for functional groups was done using the available CWAC data for Soetendalsvlei and Voëlvlei. As the dates of the CWAC data at Voëlvlei and Soetendalsvlei do not coincide, no comparison can be made between the datasets.

7.3 Results

7.3.1 Species richness

Ten pentads from the SABAP2 database which cover the majority of the Nuwejaars catchment were assessed for bird species richness (Figure 7.1).

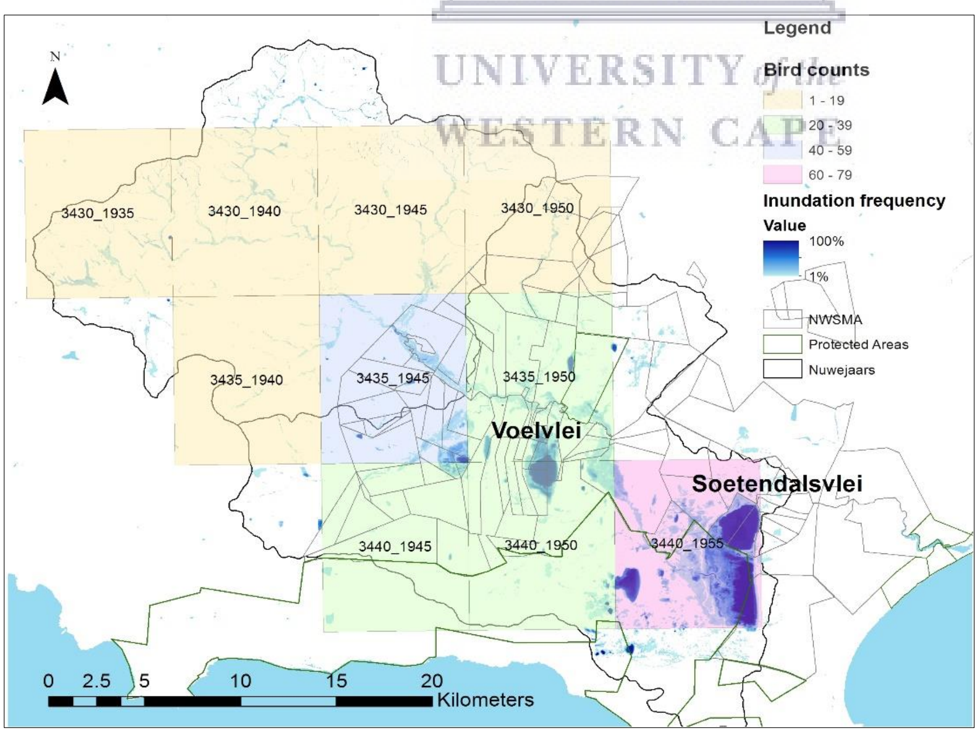


Figure 7.1 Pentads and number of completed bird counts/checklists for pentads in the Nuwejaars catchment

Pentad 3440_1955 consists of Soetendalsvlei, Soutpan, smaller depression wetlands and the floodplain wetlands of the Nuwejaars River. Pentads 3440_1950, 3435_1945 and 3435_1950 cover Voëlvlei, Waskraal and the upper floodplain wetlands of the Nuwejaars River. Details of the pentads are tabulated in Table 7.2. The occurrence of wetlands and spatial extent of the NWSMA and state protected areas are illustrated in Figure 7.1, with information for each pentad summarised in Table 7.2

Table 7.2 Description of pentads in the Nuwejaars catchment

Pentad	General description (source: de Klerk, 2018)	Wetlands (%)	Protected (%)
3440_1955	**Zoetendalsvlei**: Cultivated land, Ferricrete Fynbos, Shale Renosterveld, Sand Fynbos, dams, Soetendalsvlei, Nuwejaars floodplain wetland, Springfield saltpan (wetland types: floodplain wetlands, unchannelled valley-bottom, valleyhead seeps, flats)	74	100
3440_1950	**Voëlvlei**: Cultivated land, Ferricrete Fynbos, Shale Renosterveld, Sand Fynbos, dams, Voëlvlei, seasonal pans, small portion of the Nuwejaars floodplain wetland (wetland types: floodplain wetlands, unchannelled valley-bottom, valleyhead seeps, flats)	34	100
3440_1945	**Rietfontein**: Cultivated land, alien trees, patches of Southwest Ferricrete Fynbos, salt pan, part of Waskraal (wetland types: floodplain wetlands, seeps, flats depressions)	7	95
3435_1950	**Bo-Voëlvlei**: Cultivated land, Ferricrete Fynbos, Shale Renosterveld, Sand Fynbos, alien trees, Nuwejaars river and floodplain wetlands, part of Rondepan and Voëlvlei(wetland types: floodplain wetlands, unchannelled valley-bottom, valleyhead seeps, flats, depressions)	34	100
3435_1945	**Elim**: Cultivated land, Ferricrete Fynbos, Nuwejaars river and floodplain wetlands, Waskraal, dams, natural fynbos, Skaamgesiggie bird sanctuary	27	70
3435_1940	**Viljoenshof**: Alien trees, Ferricrete Fynbos, small dams (wetland types: floodplain wetlands, unchannelled valley-bottom, valleyhead seeps, seeps, flats)	7	0
3430_1950	**Kosierskraal**: Ferricrete Fynbos (dominant), Sandstone fynbos, alien trees, cultivated land, river (wetland types: floodplain wetlands, unchannelled valley-bottom, valleyhead seeps, seeps, flats, depressions)	6	35
3430_1945	**Pietersieliefontein**: Cultivated land, farm dams, alien trees, Ferricrete Fynbos, Elim Nature Reserve, Elim sewerage works, river (wetland types: floodplain wetlands, unchannelled valley-bottom, valleyhead seeps, seeps, flats)	14	1
3430_1940	**Janswartskraalrivier**: Cultivated land, Ferricrete Fynbos (dominant), Sandstone fynbos, large area of alien trees, small dams, Koue river (wetland types: floodplain wetlands, unchannelled valley-bottom, valleyhead seeps, seeps, flats)	12	0
3430_1935	**Kouerivier**: Cultivated land, Southern part falls within Agulhas plain. Small holdings, small dams, and alien trees. Tierkloof Conservancy. (wetland types: floodplain wetlands, unchannelled valley-bottom, valleyhead seeps, seeps, flats)	9	0

The spatial and temporal variation of species richness is illustrated by the number of species recorded per pentad for the Nuwejaars catchment from 2014 to 2019 (Figure 7.2). Pentad 3440_1955 has the highest species richness from 2014 to 2017. Pentad 3435_1945, which includes Waskraal and floodplain wetlands, had the highest recorded species in 2018 and 2019.

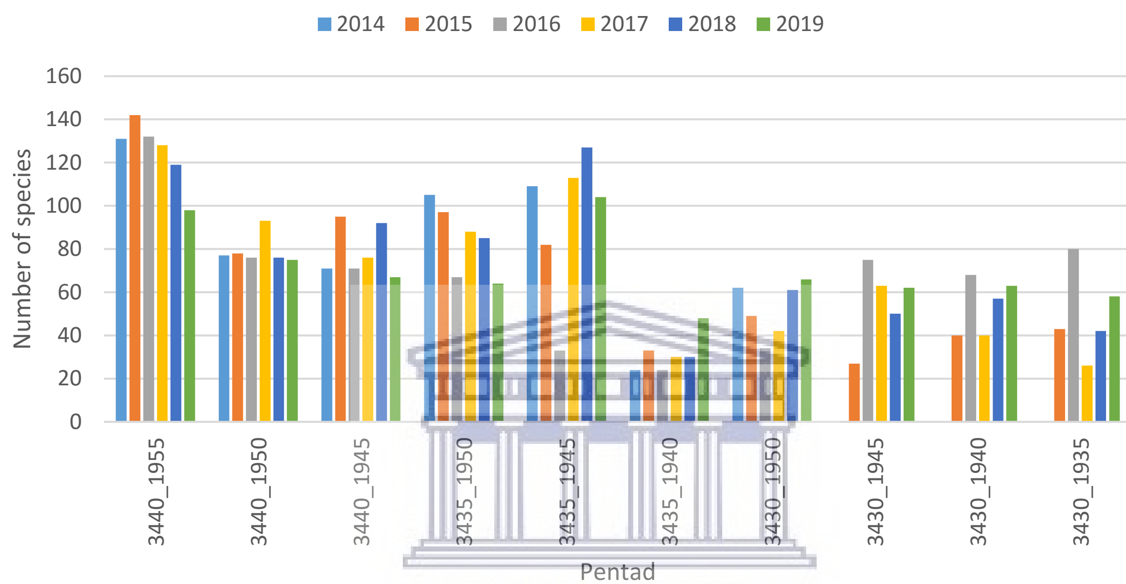


Figure 7.2 **Species richness of all bird species per pentad for the period 2014 to 2019**

After extreme wet conditions in the Nuwejaars catchment in 2014, below average rainfall in 2016 was followed by severe drought conditions from 2017 to 2019 (Section 3.3.1). Drought conditions caused a reduction in wetland inundation (Figure 7.3). According to De Klerk (2019) the impact of drought generally caused a decrease in the number of species recorded in the Nuwejaars catchment from 2017 to 2019, and this is reflected with decreased wetland inundation (Figure 7.3). The five pentads with the lowest species richness are located within the upper Nuwejaars catchment. These five pentads also have the lowest number of completed checklists or bird counts (Figure 7.3).

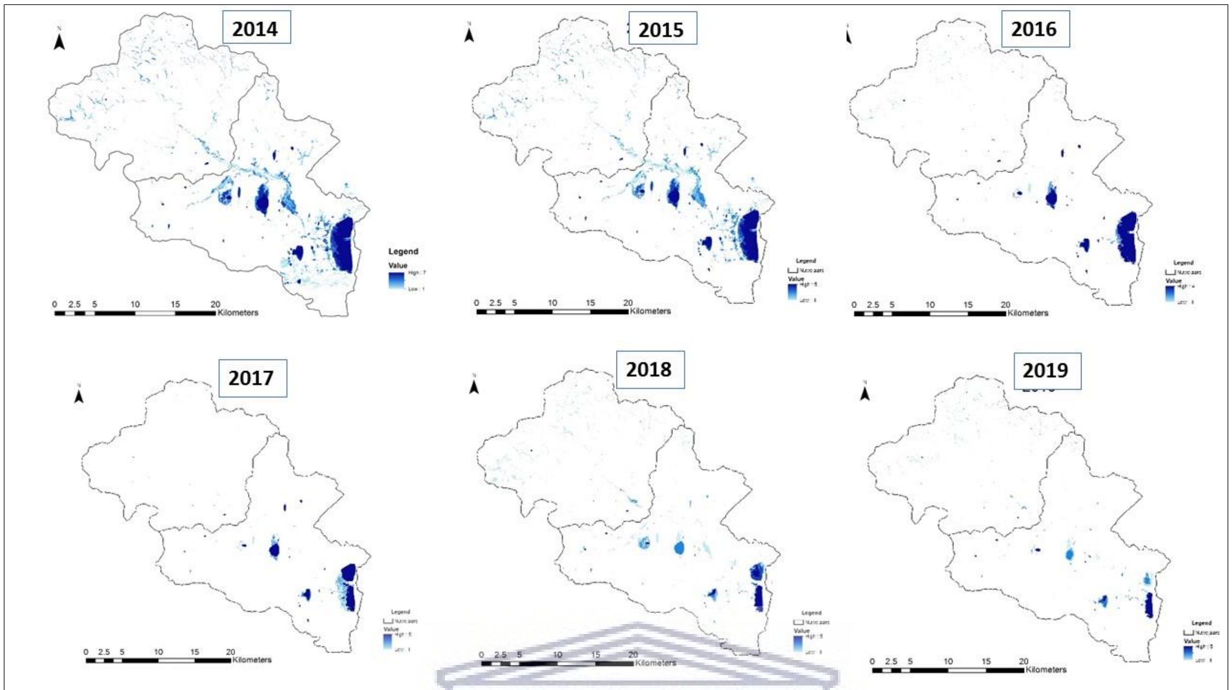


Figure 7.3 Wetland inundation in the Nuwejaars catchment from 2014 to 2019

7.3.2 Species abundance and diversity at Soetendalsvlei

Thirteen CWAC bird counts were conducted at Soetendalsvlei between 2000 and 2017, with no bird counts conducted after 2017. Based on bird counts, Southern African resident birds are more prominent than Palearctic bird species at Soetendalsvlei (Table 7.3 and Figure 7.4). Bird counts have declined significantly from 2000 to 2017.

Table 7.3 Species diversity and wetland inundation at Soetendalsvlei from February 2000 to January 2017

	February 00	August 00	March 07	July 07	February 08	July 08	February 09	February 13	April 14	January 15	January 16	July 16	January 17
Species richness	38	28	28	28	28	35	31	15	11	17	11	16	16
Southern African resident abundance	1296	695	599	344	507	175	447	723	90	217	73	123	102
Palearctic abundance	329	0	52	0	41	18	8	2	0	3	0	1	9
Overall abundance	1625	695	651	344	548	193	455	725	90	220	73	124	111
Shannon Index	2.44	2.51	2.23	2.37	2.66	2.89	2.58	1.37	1.90	2.15	1.55	1.75	2.17
Inundation (km^2)	13.21	12.01	11	11.67	10.51	14	14.16	11.14	14.04	14.59	13.79	14.43	12.92

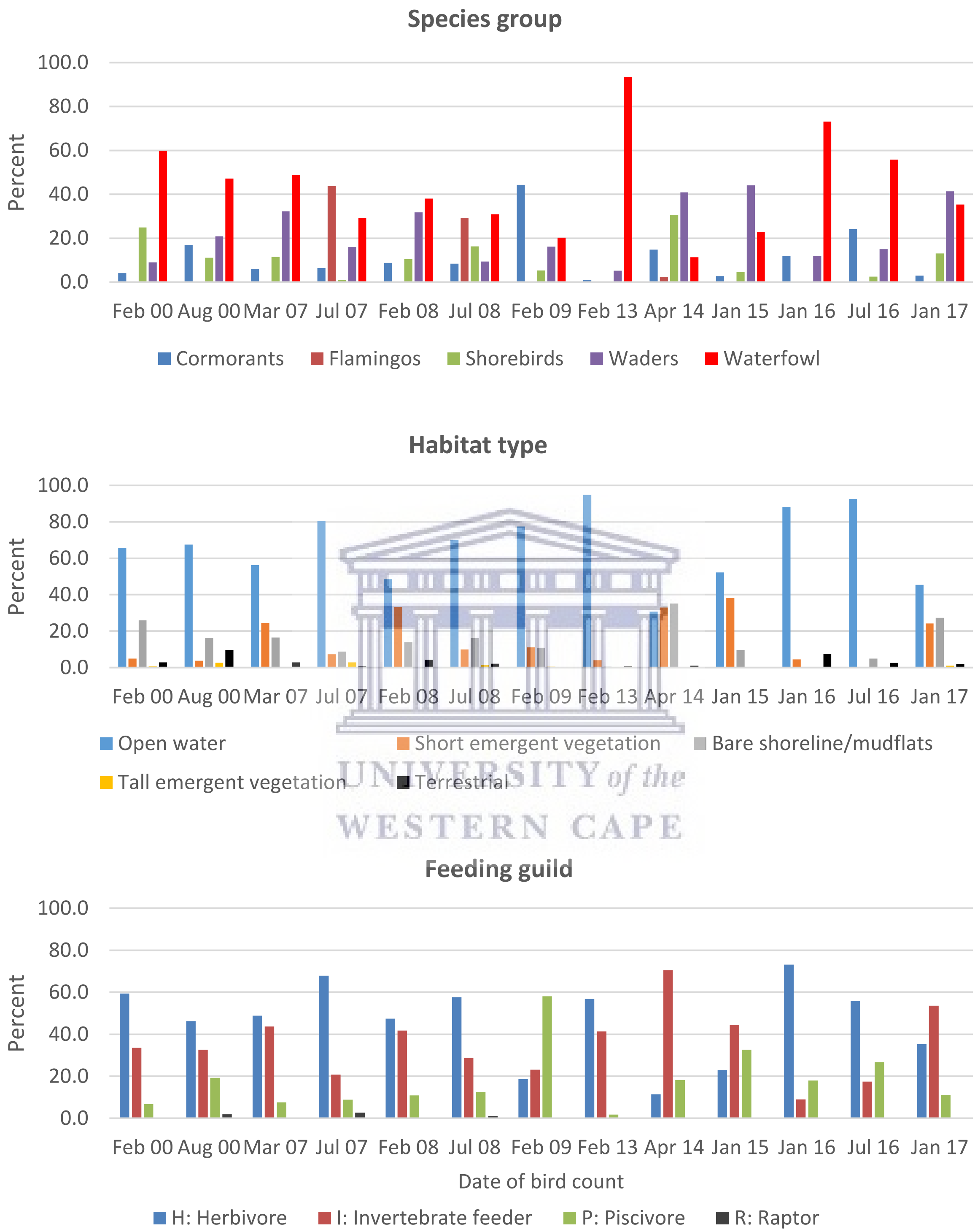


Figure 7.4 Feeding guild, species group and habitat type of birds at Soetendalsvlei from February 2000 to January 2017 (Data source: Coordinated Waterbird Counts (CWAC), Animal Demography Unit, University of Cape Town)

The five most abundant bird species for the available bird counts are cormorants, flamingos, shorebirds, waders and waterfowl (Figure 7.4). Soetendalsvlei supports a diversity of habitat types (Figure 7.4) (deeper open water; shallow flooded area; flooded area with tall reeds; flooded area with short emergent vegetation; sandy shoreline; mudflats and salt marshes) that changes relative to the flooding regime (Figure 4.6 and 4.7). The flooded vegetated areas located along the shoreline and shallower vegetated areas on the west of Soetendalsvlei (where depth varies to a maximum of 1.9 m) would be most prone to change when the water level fluctuates. A change in the water level/inundation will, depending on the lake bathymetry and vegetation properties, influence the accessibility, habitat suitability and availability of food for the different bird species.

Based on bird counts, the open water supports the highest abundance of waterfowl, due largely to periodic high abundances of terrestrial feeding Egyptian Geese, Spur-winged Goose and Yellow-billed Duck. Generally, the number of birds increases with inundation (Figure 7.4). Notes from the CWAC counts confirmed the breeding of Egyptian Geese at Soetendalsvlei in August 2000. The notes also included the "possible breeding" of cape cormorant and three-banded plover. A positive correlation exists between inundation and the number of waders (R^2 = 0.52) (Figure 7.5), with the Hadeda Ibis and Cattle Egret representing the highest abundance. The African Darter and Reed Cormorant represents the highest cormorant abundance, while the Three-banded Plover was consistently the most abundant shorebird. Notes from the CWAC counts indicated the sighting of 15 breeding pairs of reed cormorant on the west shoreline of Soetendalsvlei in February 2009. Notes from the CWAC count state that "the area is also still very wet which has allowed the birds to move to other *less disturbed areas*". These notes support the high inundation of 14.16 km^2 for Soetendalsvlei in February 2009. The CWAC notes also makes reference to the "less disturbed areas" on the west shoreline, which by 2009 was proclaimed as part of the Agulhas National Park.

Soetendalsvlei supports mainly herbivores, invertebrate feeders and piscivores. Raptors (birds of prey) were only observed for 5 of the 13 bird counts. The highest number of raptors were recorded in August 2000, with a count of 13 Water Thick-knee birds. As inundation increases, the number of piscivores increases (R^2 = 0.21). The highest number of piscivores (count of 262) were recorded in February 2009, when the inundation was 14.12 km^2. Based on the lake stage-outflow rating curve and hypsometric curve (Equation 5.6), surface connectivity between Soetendalsvlei and the Heuningnes River occurs when surface inundation exceeds 10.7 km^2. Surface connectivity implies the migration of fish species between the lake and Heuningnes River/estuary, which may result in the increased availability of fish in the lake. Increased connectivity between the lake and the estuary could thus explain the higher number of piscivores at Soetendalsvlei. As inundation decreases, there is an increase in counts for herbivorous (R^2 = -0.36) and invertebrate feeders (R^2 = -0.43), showing a preference for conditions where shallow water, tall reeds, short emergent vegetation and substrate is more prevalent than the flooded conditions (Figure 7.5).

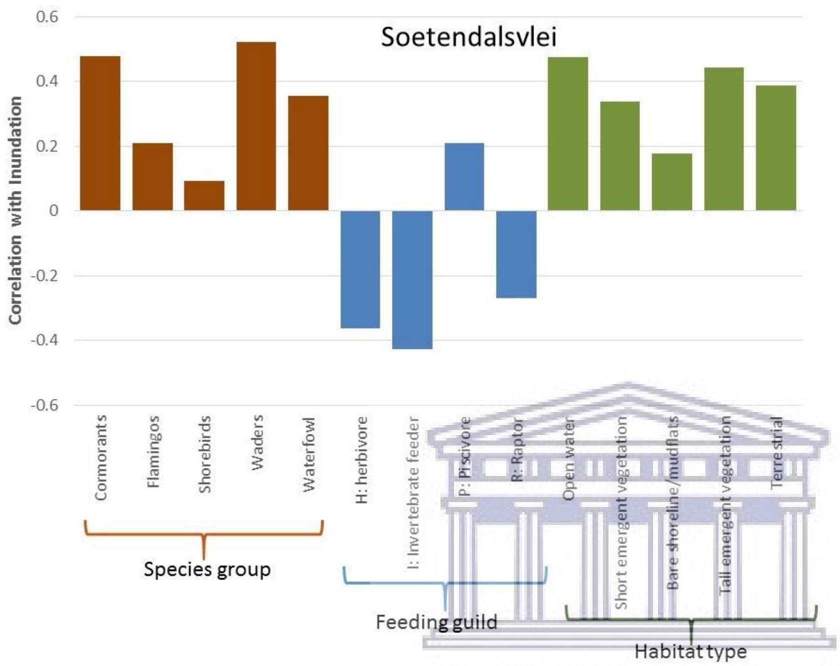


Figure 7.5 Correlation of inundation with bird species group, feeding guild and habitat type for Soetendalsvlei

Vulnerable and near threatened waterbird species were recorded between February 2000 and January 2016. The Lesser Flamingo is near-threatened, with the species only recorded at Soetendalsvlei in July 2007 and July 2008. In July 2007, when inundation was 11.6 km^2, 150 flamingos were observed. The number of vulnerable and near threatened species were absent from July 2016. The Shannon Diversity Index at Soetendalsvlei varied from a minimum of 1.37 to a maximum of 2.89 (Table 7.4). There is no significant relationship between inundation and the Shannon Diversity (species diversity) for Soetendalsvlei (R^2 = - 0.01), while there is a negative weak relationship between overall abundance and inundation (R^2 = - 0.24). Understanding that species diversity is influenced by many interrelated factors (water level, water quality, season, availability of food etc.), the correlation of inundation with species group, feeding guild and habitat type shows a significant relationship for certain waterbirds (Figure 7.5). According to Harebottle

(2011) time-lag responses for bird species are attributed to habitat suitability at different times, and for different purposes; and thus significant correlations are not always present.

7.3.3 Species abundance and diversity at Voëlvlei

Eleven CWAC bird counts were conducted at Voëlvlei between January 2017 and October 2019. A list of all species observed at Voëlvlei is included in Appendix A. Based on the bathymetric survey conducted by Seaton (2016) the average depth of Voëlvlei is 1.8 m (Figure 7.6). With a shoreline length of approximately 12 km, Voëlvlei supports similar habitats as Soetendalsvlei, with deeper open water; shallow flooded area; flooded area with tall reeds; flooded area with short emergent vegetation; sandy shoreline; mudflats and salt marshes that changes relative to the inundation frequency (Figure 7.6). Aerial photographs depicting Voëlvlei during relatively dry conditions on 12 January 2011, and wet conditions on 11 February 2014 (Figure 7.6), provides an illustration of the inundated area of the depression, and the conditions of the wetland and surrounding landscape.

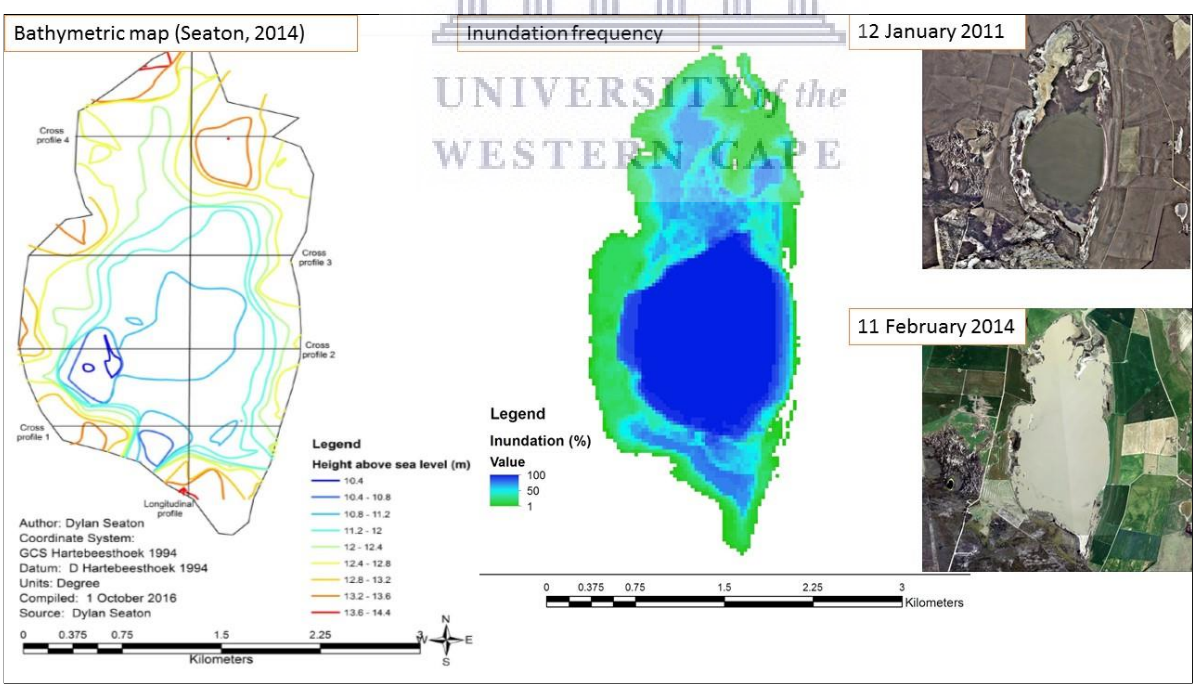


Figure 7.6 Bathymetric map, inundation frequency and aerial photographs illustrating the Voëlvlei depression

A maximum of 34 avian species were recorded at Voëlvlei in March 2017 when inundation was 3.1 km^2 (Table 7.4). The lowest inundation was 0.001 km^2 (or 1000 m^2/0.1 hectare) in July 2018, with only 6 species recorded. Drought conditions in the Nuwejaars catchment had significant impacts on water availability, although water was still detected in natural depressions such as Voëlvlei, Waskraal, Soutpan, Soetendalsvlei and other smaller depressions within the floodplain wetlands. There is a significant positive correlation between wetland inundation and species richness (R^2 = 0.88) as well as wetland inundation and overall abundance (R^2 = 0.70) at Voëlvlei, and thus species richness and overall abundance were significantly affected by drought conditions (Table 7.4). Southern African resident birds are more prominent than Palearctic bird species at Voëlvlei, except for January and April 2019 with Little Stints counts of 3986 and 681 respectively (Table 7.4).

Table 7.4 Species diversity and wetland inundation at Voëlvlei from January 2017 to October 2019

	January 17	March 17	July 17	September 17	March 18	July 18	October 18	January 19	April 19	July 19	October 19
Species richness	23	34	28	28	3	6	24	24	20	13	9
Southern African resident abundance	4399	1921	1315	1165	19	67	1365	3428	583	150	52
Palearctic	2179	1052	86	631	0	0	1256	4100	681	0	0
Overall abundance	6578	2973	1401	1796	19	67	2621	7528	1264	150	52
Shannon Index	1.50	2.41	2.30	2.28	0.81	0.87	1.71	1.57	1.66	1.59	1.86
Inundation (km^2)	3.168	3.046	1.810	2.000	0.003	0.001	*	1.598	0.925	0.051	0.027

(* no inundation estimates available due to cloud cover)

Voëlvlei supports mostly waterfowl and shorebirds, although in September 2017 and July 2019 the Greater Flamingo represented a large proportion of the total count (Figure 7.7). The Greater Flamingo is a near threatened species, and prefers shallow water, muddy and sandy substrate (Harebottle, 2011). From January to September 2017, approximately 1000 Greater Flamingos were counted on 4 separate counts. Great White Pelican and Lesser Flamingo are also near threatened, and were also observed at Voëlvlei. The Shannon Diversity Index at Voëlvlei varied from 0.81 to 2.41 (Table 7.4). There is a positive correlation between inundation and the Shannon Diversity Index for Voëlvlei (R^2 = 0.60).

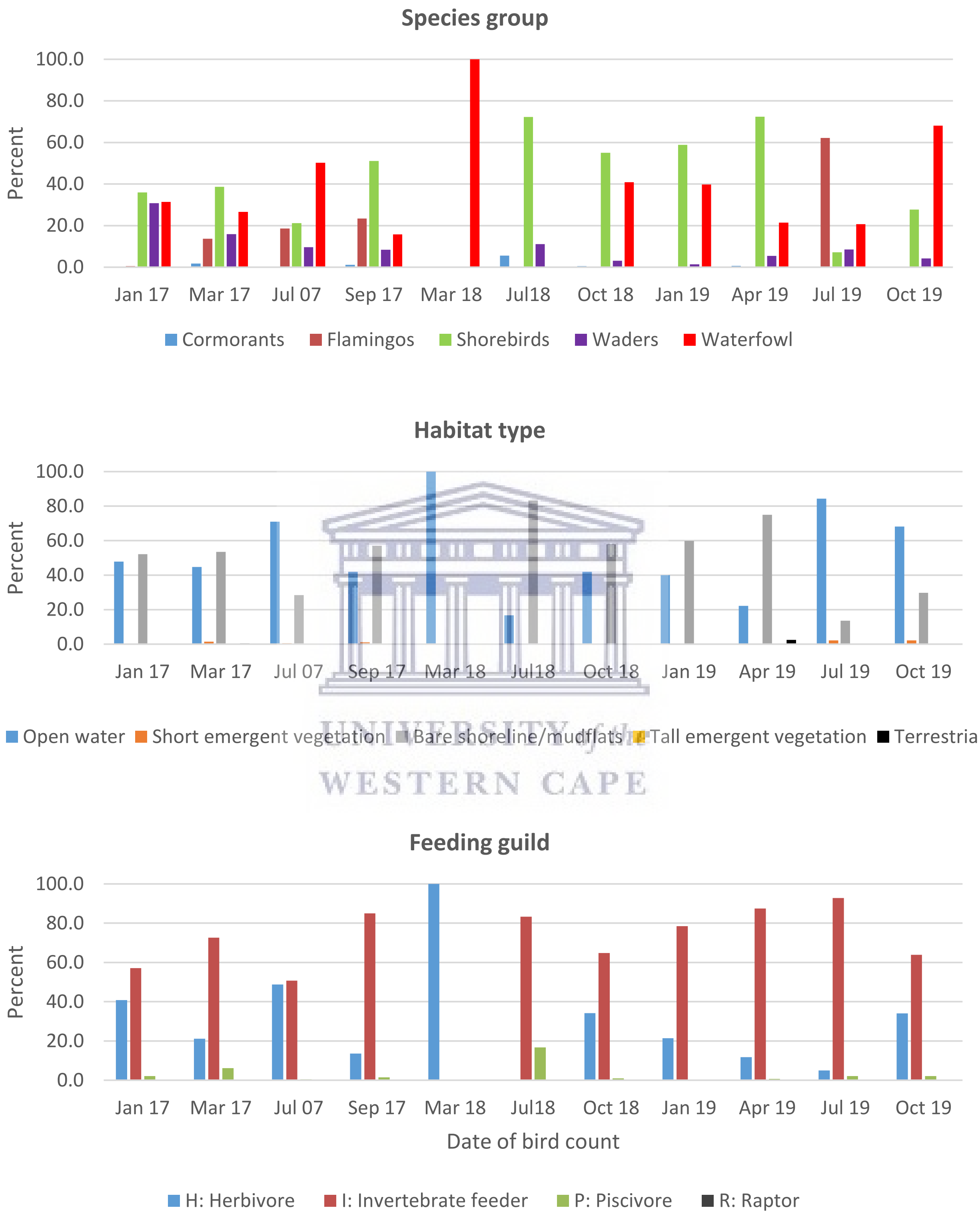


Figure 7.7 Feeding guild, species group and habitat type of birds at Voëlvlei from January 2017 to October 2019 (Data source: Coordinated Waterbird Counts (CWAC), Animal Demography Unit, University of Cape Town)

The correlation of inundation with species group, feeding guild and habitat type for Voëlvlei shows significant positive correlation except for birds that prefer terrestrial habitat types (Figure 7.8). With inundation varying from 0.001 to 3.2 km^2, as inundation increases the area of open water, depth of the water, flooded areas with vegetation, and the shoreline length increases (Figure 7.6). The morphology and inundation thus has an influence on environmental conditions of the depression and the available habitat types. Voëlvlei also has a unique hydrology, in that during high rainfall events, instead of water naturally draining the depression into the Nuwejaars River, flow from the Nuwejaars River drains into the depression. This reverse flow, and flow from the surrounding catchment influences the water quality and phytoplankton community structure of Voëlvlei (Gordon *et al*., 2011), and will thus influence the ecological system, including birds. In assessing phytoplankton community, which is a food source for flamingo, for the depressions of Voëlvlei, Waskraal and Soetendalsvlei, Voëlvlei was the only depression where cyanobacteria dominated (chlorophyll *a* levels were more than 400 μg l^{-1}) except during a high rainfall event in August 2007 (Gordon *et al*., 2011). *Phragmites* and *Schoenoplectus* are dominant in the north and south of Voëlvlei (Gordon *et al*., 2011; Malan *et al*., 2015), and with a change in inundation/water level, the extent of submerged vegetation will also change. A change in the available habitat type and food resources, will influence conditions for foraging, nesting and moulting for the various bird species (Colwell & Taft, 2000).

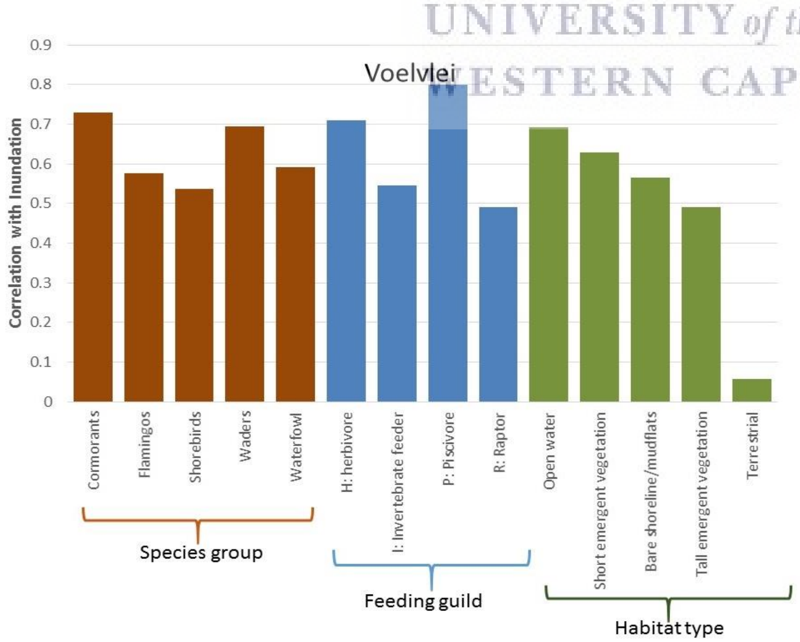


Figure 7.8 Correlation of inundation with bird species group, feeding guild and habitat type for Voëlvlei

7.4 Discussion

7.4.1 Bird abundance, richness and diversity

The abundance, richness and/or diversity of waterbirds have commonly been used as indicators of environmental conditions and ecosystem health (Kandziora *et al*., 2013; Zhang *et al*., 2016). In South Africa the decline of specific waterbird species have been associated with the degradation of wetland ecosystems, mainly due to increased pollution, habitat loss and altered hydrology (Barshep *et al*., 2017; Skowno *et al*., 2019). Ryan (2013) also reported a decrease of specific coastal bird communities (such as migrant waders) in the Western Cape, South Africa, and concluded that although local biotic and abiotic factors influence bird populations, a change in habitat preference and factors outside the region were influencing trends. There may thus be a complex set of interrelated factors at a global and regional scale, influencing the abundance and diversity of waterbirds at a specific location.

On a landscape or catchment scale, the pentads which cover the Nuwejaars wetlands, in the lower catchment, are associated with a higher number of waterbird species. According to Ma *et al*., (2010b) and Harebottle (2011), an individual lake or wetland may not provide for all habitat requirements of waterbird species, and thus the interconnectivity of diverse wetlands within a landscape provides a selection of different habitats for specific needs. Thus while the morphology, vegetation and hydrological regime of the large depressions such as Voëlvlei and Soetendalsvlei illustrates the spatially diverse habitats at an individual wetland, the interconnectivity of the different wetland types, size, hydroperiod and water quality in the lower catchment are important for waterbird diversity (Figure 2.5). However, as previous studies have indicated, the species abundance and diversity is also associated with the degree to which a landscape is protected (Duckworth & Altwegg, 2018) and how the surrounding land use influences the quality of habitats and the availability of food resources (Magnall & Crowe, 2003; De Kock & Lee, 2019). A large percentage of wetlands and the natural environment in the Nuwejaars catchment are protected. These protected areas are being cleared of invasive alien vegetation, which further contributes to increased species richness and abundance of herbivorous birds (Mangachena & Geerts, 2017). Within cultivated landscapes, the seeds and plant matter are a source of food for herbivorous birds (Magnall & Crowe, 2003; De Kock & Lee, 2019), while invertebrate feeders will also be abundant where cultivated fields support insects (Duckworth & Altwegg, 2018). Within cultivated landscapes, farmers also secure access to water with the construction of farm dams/ponds, with the surface area and structural diversity of these ponds/dams creating opportunities for enhancing waterbird diversity (Froneman *et al*., 2001). The mosaic of cultivated fields, fynbos, farm ponds/dams and diverse wetlands thus provide for conducive environmental conditions which increase habitat availability and quality for waterbird species. The awareness of the Nuwejaars catchment as an important bird and biodiversity area is reflected by partnerships amongst various organizations such as SanParks, CapeNature, the Nuwejaars Wetlands Special Management Area (NWSMA), Birdlife South Africa, the Overberg Crane Group and Agulhas Plain Birding Project to monitor avian species in the area (NWSMA, 2019).

The results of the temporal variation of waterbirds based on the occurrence/non-occurrence of species from 2014 to 2019 for this study, was limited as no general trends could be considered with such a limited dataset. The results did however illustrate the decrease of overall abundance from 2018 to 2019 for select pentads, which was associated with drought conditions within the catchment (NWSMA, 2019). Pentads within the lower Nuwejaars catchment where wetland inundation decreased, generally had a decrease in the number of bird species. Only the Elim pentad (3435_1945) which covers the Waskraal depression wetland, floodplain wetlands of the Nuwejaars river, farm dams and the Skaamgesiggie bird sanctuary had an increase of bird species during the drought period. Possible reasons for the higher bird species in the Elim pentad could be related to favourable habitat quality and conditions for the waterbirds, together with the decline of available habitats within the local environment. Given the mobility of birds, nomadic species move unpredictably in response to local habitat conditions (Harebottle, 2011).

The Nuwejaars wetlands are regarded as an important bird area in the Western Cape, and is geographically nestled between the Ramsar wetland sites of De Mond (site 342) and De Hoop (site 34) to the east, and the Bot-Kleinmond estuarine system (Ramsar site 2291) to the west. The Nuwejaars wetlands may thus serve as a 'stop-over' site for mobile waterbirds in the Western Cape (Harebottle, 2011), and highlights the connectivity of wetlands on a local and regional scale. Another factor to consider in the interpretation of the results of this study, is the quality and the assessment of the occurrence/non-occurrence SABAP2 data. For example, when considering the number of completed SABAP2 checklists, there is a higher frequency of visits to the lower Nuwejaars catchment, as opposed to the pentads within the upper catchment, which may influence species detection. Accessibility to areas (pentads) within the catchment is an important limitation and thus more coordinated and collaborative bird counts, conducted during the winter and summer seasons should be explored (de Klerk, 2018; De Kock & Lee, 2019).

7.4.2 Wetland inundation and waterbird abundance and richness

The integration of hydrological data and species diversity data allows greater insight to how flooding regimes may influence bird populations. With a variable climate, and within agricultural landscapes where the use of surface and groundwater resources may alter the hydrological regime of wetlands, a better understanding of how water level fluctuation influences waterbird diversity can inform adaptive and proactive strategies to manage water levels (Ma *et al*., 2010b; Cumming *et al*., 2012; Pickens & King, 2014; Yang *et al*., 2014). With hydrological data such as water levels not available for many lakes and wetlands, this study used wetland inundation as a proxy, together with wetland morphology, to understand how inundation influences habitat provision for waterbirds. By considering the functional traits of waterbirds, this study allowed greater insight to how inundation influences habitat preference and feeding guilds of waterbird species.

Given the morphology of Soetendalsvlei and Voëlvlei, the variation of inundation reflect changes in water depth, length of the shoreline, exposed substrate and the ratio of open water to flooded emergent vegetation. Within each depression, this variation of inundation, together with the interaction of vegetation and other environmental variables, create different functional conditions or units that can be associated with the provision of specific habitats and food resources for waterbirds. Given the connectivity of these depression within the Nuwejaars fluvial network, the spatial and temporal variation of inundation, will be influenced by catchment conditions, with subsequent impacts on wetland habitats. Increased fish within the depression may cause a reduction in the availability of algae and diatoms, a food source for insectivores (such as flamingo). Loss of connectivity with the fluvial network also influences food availability by, concentrating prey and thus providing access to food resources. For Voëlvlei, where the dominant feeding guild are the invertebrate feeders, optimum conditions are mainly, and indirectly influenced by inundation. While water quality, winter die-back of emergent vegetation, climatic factors (especially wind) and landuse factors influences phytoplankton biomass and community, the residence time of water in the lake is a critical factor in the phytoplankton composition shift from a chlorophyte to cyanobacteria-dominated state (Gordon *et al*., 2011). According to Cummings *et al*., (2012), a change in the natural flow regime influences the food resources that are available to waterbirds. For depressions such as pans and lakes, a change in inundation will thus cause the creation or loss of habitat (depending on vegetation dynamics) and influence the food resources along the shallow littoral areas, particularly for shorebirds (Bolduc & Afton, 2008; Harebottle, 2011; Mundava *et al*., 2012; Whittington *et al*., 2013; Russell *et al*., 2014). Inundation thus reflect complex interactions and environmental conditions, such that each species, at the wetland-scale, may respond to habitat conditions in a different way.

Given that the time period of CWAC counts for Soetendalsvlei and Voëlvlei do not coincide, species comparisons between the two depressions cannot be made. A previous avifauna survey was conducted by CapeNature at these depressions on 9 to 11 March 2005 (Cleaver & Brown, 2005), and thus offer some baseline data. At Voëlvlei, 33 species were recorded with a total richness of 1651, with a count of 565 for Little Stint, 227 of Ruff and 213 of Egyptian Geese (Cleaver & Brown, 2005). CWAC counts for Voëlvlei between 2017 and 2019, recorded a maximum of 38 species and a maximum overall abundance of 7528. Palearctic species such as Little stint (with a maximum count of almost 4000 in January 2019), Ruff and flamingo were observed during the 2017 to 2019 counts, illustrating the importance of the Voëlvlei for habitat provision. The inundation measured within the 2017 to 2019 period in the Nuwejaars catchment reflect climatic conditions that were below normal rainfall (Figure 3.5 and Figure 3.6), and thus further analysis should assess waterbird abundance and diversity within a range of climatic and wetland conditions.

The CapeNature counts for Soetendalsvlei recorded 44 species and 716 waterbirds in 2005 (Cleaver & Brown, 2005). Based on the CWAC counts from 2000 to 2017, the overall abundance and species diversity have decreased over time. With only 13 bird counts for Soetendalsvlei, the data is not continuous, and seasonal variations are not reflected. The time of day, period and location of observation when conducting the CWAC counts are also different among the 13 counts, and could influence the data quality. The 13 bird counts span from 2000 to 2017, in which time, significant land use change had taken place within the catchment, and surrounding the Soetendalsvlei. For example, during this 17-year period, a few changes in the catchment include the proclamation of the Agulhas National Park, increased viticulture, farm dam development, restoration of wetlands and clearing of invasive alien trees. While there was no significant trend of wetland inundation for Soetendalsvlei over time (Figure 4.8), the emergent vegetation within the lake increased, while the open water decreased over time (Figure 3.8). These changes may directly or indirectly impact the habitat quality for waterbirds, as supported from notes from the CWAC count in February 2008, where “the thickening reed bed is making it difficult for some of the waders as the shallow areas are being taken over by reeds”. Similar findings when comparing species composition of waterbirds for Swartvlei (part of the Lake Wilderness Lake Complex, South Africa) between 1992 and 2010, found that altered flow conditions to the Swartvlei Lake (Petersen *et al*., 2017) and the proliferation of *Phragmites australis* (Russell, 2003) are possible causes of the change in habitat quality, and the change from a more piscivorous-dominated community to a lake that is dominated by herbivorous waterbird species (Russell *et al*., 2014). Given that the avifauna count at Soetendalsvlei show that waterfowl and waders, that prefer open water habitats, are the dominant waterbird species (i.e. for 9 of the 13 counts, the combined count of waterfowl and waders account for more than 52% of species) conservation measures targeting these species need to monitor the ratio of open water to vegetation dynamics.

The current and more frequent bird counts at Voëlvlei illustrates the diversity of avifauna on the Agulhas Plain. While the temporal avifauna database is limited, the integration with inundation, particularly during the drought period, provided some awareness of the possible impacts of climate variability on diversity. Continued avifauna and hydrological monitoring by the various stakeholders in the Nuwejaars catchment, will enable a better understanding of the dynamic factors influencing habitat provision.

7.5 Conclusion

In this study the integration of citizen science data with data on wetland occurrence, morphology and inundation, provided insight to the importance of the hydrological regime of wetlands on the abundance and diversity of waterbirds. The mosaic of cultivated fields, fynbos, farm ponds/dams and diverse wetlands, together with the protected status of the lower Nuwejaars catchment, provide suitable habitats for birds, with a maximum of 142 species observed in the Soetendalsvlei pentad. In 2019, drought conditions caused a significant decrease in wetland inundation, with bird species also decreasing in pentads within the lower Nuwejaars catchment.

Depression wetlands play an important functional role in providing suitable habitats for waterbirds, with a maximum of 38 and 34 waterbird species at Soetendalsvlei and Voëlvlei, respectively. The open water, varied water depth, emergent vegetation and heterogeneous shoreline provide diverse habitat types. A change in wetland inundation influences the habitat types and availability of food, with a significant correlation between inundation and the different functional traits of waterbirds. Findings from this present study shows that the depression wetlands of Voëlvlei and Soetendalsvlei, both provide a functional role as suitable habitats for waterbird species. The results of the integration of wetland inundation and avifauna data, highlights the complexity of the interaction among the different biotic and abiotic components, but also demonstrates the opportunities to further our understanding of this dynamic ecosystem.

CHAPTER 8

WETLAND ECOSYSTEM SERVICES: CULTURAL VALUE OF WETLANDS IN THE NUWEJAARS CATCHMENT

8.1 Introduction

Wetlands contribute to sustainable livelihoods and human well-being by providing access to provisioning (such as water provision, food, medicinal plants, grazing resources and non-edible materials); regulating (such as water flow regulation, water quality amelioration) and cultural ecosystem services (such as recreation, aesthetics, inspiration and knowledge) (MEA, 2005; de Groot *et al*., 2010; Brander *et al*., 2013). Where wetlands may provide multiple benefits over time, society may assign more value to certain wetland ecosystem services due to environmental, political and socio-economic factors, resulting in intentional and unintentional tradeoffs (Jessop *et al*., 2015). The drainage of wetlands for agricultural development and increased food security is one of the major tradeoffs resulting in wetland degradation (Mitsch & Gosselink, 2007; Swanepoel & Barnard, 2007). Tradeoffs due to wetland degradation is also associated with habitat loss and a decline in biodiversity (Mitsch & Gosselink, 2007), as well as the reduced capacity of wetlands to provide regulating ecosystem services which buffer society from natural hazards such as droughts and floods (Belle *et al*., 2018). With increased population growth and demand for food, and cumulative impacts of climate change, the negative effects on wetland ecosystems are likely to increase (Jackson *et al*., 2016). There has thus been an increased focus on “the conservation and wise use of all wetlands through local, regional and national actions and international cooperation” (MEA, 2005; Finlayson, 2012). Contracting countries to the Ramsar Convention, such as South Africa, have implemented relevant legislation, developed management strategies, plans, tools and frameworks to “promote the protection, rehabilitation and wise use of wetlands” (Kotze *et al*., 2009; Rountree *et al*., 2009) and water resources in general (Nepfumbada & Seetal, 2020). Central to the successful implementation of all these measures is the importance of people/society, and the interaction of society with, and within the environment (Chan *et al*., 2012).

The ecosystem services framework which creates an awareness of the importance of ecosystem services to human well-being, and aids in decision making is commonly adopted in conservation strategies. Current research and management strategies are encouraging a stronger focus on cultural ecosystem services, particularly “what matters, where and why to people” (Fish *et al*., 2016, p214). The definition of cultural ecosystem services adopted in this research is the “contributions to the non-material benefits that arise from human-ecosystem relationships” (Chan *et al*., 2012, p9). This dynamic relationship is not linear or unidirectional, as society not only benefits from ecosystems, but alters and manages ecosystems to maximize certain benefits (Comberti *et al*., 2015; Fish *et al*., 2016). Managing specific ecosystem services may cause feedbacks, tradeoffs and/or synergies that may have cascading, complex effects on the social-ecological system (Cumming *et al*., 2017). Given the complex interaction between society and ecosystems, a place-based approach to understanding the spatial context affecting “societal choices and values” is encouraged (Potschin & Haines-Young, 2011, p580).

One of the main questions of this chapter is thus *“which wetlands do society value for providing specific benefits”?* Similar questions have been investigated in the literature by spatially quantifying or mapping which wetlands stakeholders’ value, and by using qualitative approaches to understand why these ecosystems have value to society. By spatially mapping cultural ecosystem services in an agricultural landscape in Eastern Germany, Plieninger *et al*., (2013) concluded that patterns of values were related to well-being of individual residents. In an agricultural landscape in the Netherlands, van Berkel & Verburg (2014) found that tourists preferred elements of landscape features that were linked to recreation and spiritual aspects of cultural value. These findings were relevant in identifying spatial areas where maintenance and restoration of ecosystems were prioritized (van Berkel & Verburg, 2014). According to Elshafei *et al*., (2014) understanding societal values can provide insight to how society responds to change (for example how society responds to drought or change in access to water), and the feedbacks associated with their response.

Within predominantly agricultural landscape where wetland degradation has generally been prominent (van Asselen *et al*., 2013), the wise use and conservation of wetlands can be promoted where knowledge (both scientific and traditional ecological knowledge) is available, accessible and shared. In assessing wetland degradation in a communal landscape in the Eastern Cape, South Africa, one of the strategies advised by Owethu Pantshwa & Buschke (2019) for the sustainable development of wetlands, is the sharing of ecological information through traditional leadership structures within a rural community. Honig *et al*., (2015, p395) found that sustainable development within commercial farming communities in the Cape Winelands region in South Africa, was promoted by “developing human capital, including knowledge” whether through experiential learning or by interacting with other stakeholders (such as other farmers or extension officers). Within the context of the Nuwejaars catchment, where wetlands are located on private agricultural land and state protected areas, partnerships, collaboration and interactions amongst various stakeholders have been established (and is still on-going), with the aim of promoting sustainable agricultural development and the conservation of biodiversity (Section 3.4.2.2). Within the context of a "Living Laboratory" (Section 1.7.1), diverse stakeholder engagement can promote beneficial learning and the co-production of knowledge (Zingraff-Hamed *et al*., 2019). Environments or ecosystems that are used to acquire knowledge (Mocior & Kruse, 2016), broaden knowledge (Plieninger *et al*., 2013) or that provide information for cognitive development (Hattam *et al*., 2015) provide cultural ecosystem services. Education and scientific value have generally, been collectively assigned as a cultural ecosystem service. Given the various definitions and measures of education and scientific value as cultural ecosystem services (Mocior & Kruse, 2016), the definition by Haines-Young & Potschin (2018, p25) of scientific value as the characteristics of ecosystems that enables the "scientific investigation or the creation of traditional ecological knowledge" is adopted in this research. Scientific value is a cultural ecosystem service that increases awareness of ecosystems and provides support for decision making (Friess *et al*., 2020). Within the context of the Nuwejaars catchment as a "Living Laboratory", another question is thus "*what is the scientific value of wetlands in the Nuwejaars catchment", and how does that translate into strategies for wetland conservation*?

The aim of this chapter is to understand which wetland ecosystems provide benefits to, and add value to society.

Key objectives of this chapter are to:

1. Evaluate the scientific value of wetlands, and provide insight to enabling conditions that promote scientific value
2. Assess the values assigned to wetlands, by exploring which wetlands society regard as providing benefits

8.2 Methods

8.2.1 Scientific value of wetlands in the "Living Laboratory"

Since the formal inception of research by the Institute for Water Studies at the University of the Western Cape (IWS-UWC) in the Living Laboratory in 2014, a number of scientific research/studies were conceptualized which aim to promote the understanding of factors influencing water resources, and wetland ecosystem functioning in particular (Mazvimavi, 2018). Financial support, mainly from the Netherlands Organisation for International Cooperation in

Higher Education (NUFFIC) and the Water Research Commission (WRC) facilitated instrumentation in the catchment and supported capacity building of postgraduate students and hence facilitated the opportunity for scientific value. With support from the Nuwejaars Wetlands Special Management Area (NWSMA) which includes Elim, and the various government stakeholders (Departments of Agriculture and Water and Sanitation), the selection of sites on private property were made *accessible* for scientific investigation.

To assess the scientific value of wetlands in the 'Living Laboratory' between 2014 and 2019, a review of research relating to wetland properties, functions, benefits and/or values within the Nuwejaars catchment was conducted. The University of the Western Cape (UWC) library website provides access to digital databases (including Google Scholar, Science Direct and Web of Science), scholarly journals and electronic theses and dissertations. Using the UWC library website, key words used in the literature search included "Agulhas", "Nuwejaars", "wetland", "benefit", "value" and "ecosystem service". The review of scientific literature was limited to theses (Masters and PhD), journal articles and reports published between 2014 and 2019. A report is considered a written document published by an organization which provides information based on expert and/or local knowledge which adds scientific value. Publications which only mentioned specific wetlands of the Nuwejaars catchment but did not explicitly report on findings of research conducted were excluded. Details of postgraduate students from the University of the Western Cape (UWC) that were affiliated to research in the Living Laboratory were accessed from Mazvimavi (2018) and provided a supplementary guide to postgraduate research in the Nuwejaars catchment. A summary of the specific wetland, ecosystem properties, research methods and the relevant ecosystem functions and services were noted for each reference. In assessing the scientific value of protected areas, Smit *et al*., (2017) recommends a distinction is made between direct and indirect interaction with the environment, by including whether *in situ* data is collected. The spatial scale of the research, i.e. national, regional, catchment, and/or wetland type, was recorded for each publication. The national and regional scale were ascribed to publications depending on the geographical extent of the research. The number of publications and type of publication (journal article, thesis, report), was summarized. For the purpose of this research, the review provided support/validation for the social values/mapping identified in Section 8.2.3.

8.2.2 Social value mapping of wetlands

The use of participatory mapping and interviews are qualitative methods that can provide insight to which ecosystems society values within a spatial context (Lynam *et al*., 2007; Raymond *et al*., 2009; Ruiz-Frau *et al*., 2011; Chan *et al*., 2012; Klain & Chan, 2012; Plieninger *et al*., 2013; Palomo *et al*., 2014; Wolff *et al*., 2015). The qualitative approach identifies what is of value to the stakeholder and understanding why it is of value, and provides an understanding of the potential demands for ecosystem services (Chan *et al*., 2012; Wolff *et al*., 2015). The mapping activity illustrates the spatial range of ecosystem benefits, and can be as basic as drawing in the soil; using large sheets of paper in sketch mapping; using georeferenced maps or aerial photographs in scale mapping (Rambaldi *et al*., 2006; Corbett, 2009). The main aim of the mapping activity was to assess the values assigned to wetlands by exploring which wetlands stakeholders regarded as providing regulating and cultural benefits.

8.2.2.1 Sampling of stakeholders

The stakeholders identified for the research included landowners, the manager and the farmers within the NWSMA. As a section of the Soetendalsvlei is managed by South African National Parks (SANParks) and Cape Nature, it was important to include officials from these organizations in the survey. The municipality, local government and institutions that have a mandate relating to resource use and conservation within the Nuwejaars catchment were also enlisted for the research. Based on the preselected criteria, the sampling method used in the initial selection of stakeholders was purposive sampling. Brown & Fagerholm (2015) suggests that this method allows better population representativeness. The stakeholders were informed about the nature of the study. Stakeholders were contacted via electronic mail, personal communication and/or via telephone and a brief explanation of the research was given. The stakeholders were informed of the study, and once the stakeholder agreed to participate in the research, the place and time of the interview was finalized. The researcher adhered to the Code of Research Ethics of the University of the Western Cape and the anonymity of the stakeholders was ensured. Based on the Memorandum of Understanding with the Breede-Gouritz Catchment Management Agency (BGCMA) and the Nuwejaars Wetlands Special Management Area (NWSMA) general permission was granted to conduct research within the study area.

8.2.2.2 Interviews and participatory mapping

Semi-structured interviews and mapping were conducted either at the place of work, or at the home of the stakeholders. According to Wolff *et al*., (2015, p166) "participatory approaches can capture the heterogeneity of human desires, values and preferences, which are crucial for understanding human demand". Although the participatory mapping approach is context and landscape (local) specific, it generates valuable primary and credible data which can serve as baseline information for efficient management of the wetlands in the relevant catchment (Ramirez-Gomez *et al*., 2015).

The main question to the stakeholder was: which wetlands provide ecosystem benefits? A printed georeferenced A0 map with an approximate ratio scale of 1:100 000 of the Nuwejaars catchment was used for the participatory mapping. The use of different colour marker pens in assigning and drawing regulating (brown) and cultural (green) benefits associated with wetlands on the map were explained to each of the stakeholders. When drawing each of the above-mentioned benefits the stakeholders were urged to use the available markers to write any specific comments; values; ideas or feelings they associate with the relevant wetlands. Polygons and circles were the dominant shapes used to spatially represent the wetland ecosystem services. Where stakeholders allowed, the interview was recorded. Interviews lasted from 45 minutes to approximately 60 minutes. The mapping exercise with all the stakeholders took place from March 2015 to March 2016.

8.2.2.3 Data analysis

After each interview the annotated map of the stakeholder was assigned a number for identification. A photograph was taken of the map and stored as a jpeg file. Each jpeg file was georeferenced and spatial representations were digitized for wetland ecosystem services and threats for each stakeholder. The wetland type was identified for each ecosystem service. The spatial extent of benefits provided for the different wetland types were summarized for all stakeholders. The iterative process of interviews and interview transcription during the research process allowed key themes to emerge from the data.

8.2.2.4 Limitations of the participatory mapping approach

The participatory mapping was conducted in 2015 and 2016, when data collection from the Living Lab was still in process, and no substantial data analysis had been completed. In retrospect, the results and interpretation of results from the Living Lab could have been incorporated into the participatory approach. The scale of the map used in the participatory approach did not allow the identification of small wetlands. Not all stakeholders participated in the participatory mapping exercise as they were reluctant to draw on the map. However, the textual information resulting from the interview were valuable to the research.

8.3 Results

8.3.1 Scientific value of wetlands within the "Living Laboratory"

A total of 40 research publications between 2014 and 2019, and explicitly related to wetland properties, functions, benefits and/or values in the Nuwejaars catchment were reviewed (Table 8.2). Research publications were mainly theses (45%), reports (40%) and journal articles (15%). The spatial scale of the research was primarily at a hydrogeomorphic scale (i.e. 14 of the 39 studies), and mainly on floodplain wetlands, valley-bottom wetlands and depressions. Most of the sites were located along the Nuwejaars floodplain and the depression wetlands in the lower catchment. The majority of sites for scientific investigations were located within the Nuwejaars Wetlands Special Management Area (NWSMA) and Agulhas National Park. Findings related to wetland ecosystems are incorporated into Section 8.3.3.

Research conducted at the catchment scale were mainly related to hydrologic studies, with a focus on water regulation and water storage (regulating ecosystem services). Theses research related to catchment hydrology used the monitoring sites of the Living Laboratory (Figure 2.6). Publications related to data derived from the instrumentation of the "Living Laboratory" account for 48% of all publications. To assess "Finding 'new' water to address conflicting and competing water demands in the Nuwejaars catchment, Cape Agulhas" (WRC Report No 2324/1/18), Mazvimavi (2018) quantified the benefits of water consumption for agricultural use based on a water balance and landuse assessment, review of water licences and crop water requirements and provides data and information on ecosystem services related to water provision.

Table 8.1 Publications related to wetland-related research conducted within the Nuwejaars catchment (2014 – 2019)

Spatial scale	Description of Ecosystem Properties/Social-Economic factors	Methods	EF	ES	Reference	P
National	Cultural services and benefits from birds (in South African National Parks, including Agulhas National Park)	Field data collection on bird communities; Survey	HP	C	**1.**Cumming & Maciejewski (2017)	J
National	Developing wetland distribution and transfer functions from land type and soil data to support wetland identification and delineation	GIS analysis of secondary data; case study	SR	R C	**2.**Job et al., (2019)	R
Region & Wetland types	Characterizing wetland plant communities and assessing change over time	Topo & aerial photo analysis; Data collection: Total dissolved solids and major ions of wetlands; plant identification		P	**3.**Ramjukadh (2014)	T
Region	Influence of habitat on density and population estimates for Agulhas long-billed lark (Overberg Region)	Bird counts & citizen-science data. Correlation with habitat variables	HP	P	**4.**De Kock & Lee (2019)	J
Region	The risk of sediment and nutrient inputs on a landscape scale is assessed using secondary data. No available water quality data to validate results in the Nuwejaars catchment (Water purification:WP)	Landscape scale analysis (secondary data); scores developed to identify hotspot areas	WP	R	**5.**Malherbe *et al.*, (2019)	J
Region	Value of nature to landowners in Overberg region	Interviews with landowners	N/A	C	**6.**Cresswell (2016)	T
Overberg Region	Overberg district municipality wetland report (2017) – aimed at improving and enhancing ecosystem management	Descriptive summary of biodiversity wetlands; governance, management	N/A	C	**7.**Robinson (2018)	R
Fynbos region	Comparing wetland properties over time by comparing results of a survey conducted by Silberbauer and King in the 1980s	*In situ* water quality; vegetation characteristics; invertebrates		P R	8. Malan et al (2015)	R
Catchment	Land use and land cover influences water yield (Results are included in research conducted by UWC postgraduate students – references indicated with *)	Hydrocencus; Landuse/cover. Water use estimated for number of livestock & area of cultivated crops (*in situ* data)	WPr FP	P	**9.**Mazvimavi (2018)	R
Catchment	Evapotranspiration (ET) for forests/high density woodlands have highest ET during summer, cultivated dryland lowest ET in winter. Results indicate that MOD 16 underestimates ET. MOD 16 has the potential to map shallow groundwater	ET assessed using MOD 16 ET data, validated with *in situ* data from a similar catchment.	WPr (ET)	P	**10.**Ndara (2017)*	T
Catchment	Characterization of shallow coastal aquifer. Shallow groundwater (3 – 10m) influenced by topography. Low transmissivity of Table Mountain sandstone and unfractured Bokkeveld shales. Hydrochemical analysis indicates connectivity between aquifer and river. Conceptual models of groundwater flow relevant to understanding aquifer-river interaction.	Resistivity survey, slug test, *in situ* water level data from rivers, boreholes and piezometers. Environmental stable isotopes, water quality analyses	WR	R	**11.**Manyama(2017) **12.**Kinoti (2018) **13.**Banda(2019) **14.**Mokoena(2019)*	T T T T

Catchment	No relationship between occurrence of invasive alien vegetation and hydrochemistry of water. Decrease in cultivated land due to establishment of Agulhas National Park	Land use/cover change, *In situ* water quality data	WR	R	**15.**Apedo (2015)	T
Catchment	Measured transpiration by *Acacia longifolia* in riparian/floodplain wetlands is 3.5 mm/day, and 1.4 mm/day on hillslopes in Spanjaardskloof. Transpiration by invasive alien vegetation along floodplain wetland dependent on water storage in shallow soil layers. Hillslope invasive alien vegetation may use groundwater. Invasive alien vegetation in the Nuwejaars catchment use 20.5 Mm^3 of water	*In situ* data: sap flow, soil water content, and climate data. Soil water model	WPr	P	**16.**Mkunyana (2018)* **17.**Mkunyana et al., (2019)	T J
Catchment	Birding (2015 – 2019) description of sites, bird presence recorded	Citizen science data, descriptive information	HP	P	**18–23.**De Klerk (2014 - 2019)	R
Region HGM units	NFEPA Wetland Groundtruthing	*In situ* data; soil and vegetation sampling and description		P	**24.** Fisher et al., 2017	R
NWSMA	Annual report by the Nuwejaars Wetlands Special Management Area	Report with descriptive information on activities	HP	P C	**25-27.**NWSMA (2017 - 2019)	R
Estuarine zone	Ecological status of estuary and Soetendalsvlei assessed. Linkages between estuary and Soetendalsvlei.	Baseline description and health assessment	WR WP	P R	**28.** AEC(2018)	R
Estuarine zone	Mouth management recommendations for the Heuningnes	Hydrodynamic modelling, floodline delineation	WR	R	**29.**SMEC(2017)	R
Nuwejaars Floodplain	Large pools & oxbow lakes in floodplain. Pools have max depth of 2 m. Sandy loam and loam soil dominant surface soils. Average infiltration rate is 55 mm/day. Storage capacity of Nuwejaars wetland is 6.55 Mm^3	*In situ* data: soil texture, infiltration rates; rating curves; mapping vegetation. Development of a water budget	WR WS	R	**30.**Mehl (2019)*	T
Nuwejaars Floodplain	Medium grained sandy loam soils have low hydraulic conductivity, cause ponding. Daily stream flow strongly correlated to catchment rainfall. Precipitation, overland flow and evapotranspiration influence the water budget. Influence of groundwater exchange not included (Elandsdrift/Wiesdrift)	Modelling: Pitman & ACRU; Soil analysis; validate using *in situ* data.	WR WS	R	**31.**Mandlazi (2017)*	T
Floodplain wetland	Pools in the Nuwejaars floodplain vary over time. Area of pools strongly influenced by temperature	Assess proxies to extract water. Correlation with *in situ* climate data	WS WR	R	**32.**Seaton (2019)*	T
Floodplain, valley-bottom, depression wetlands	Ecosystem properties influence opportunities for water and harvestable provision, water quality enhancement benefits, flood attenuation, tourism, recreation and education & research. Anthropogenic activities impacts wetland functioning. Wetlands provide benefits to society. Habitat provision important for birding, and tourism. Geese have negative impact on agricultural yield.	Interviews & scores (WET-EcoServices)	N/A	C	**33.**Williams (2018a)	T

Valley-bottom wetlands	Cut-and-fill processes assessed for valley-bottom wetland (Pietersieliekloof) dominated by *Prionium serratum* (palmiet). Road crossings and clearing of invasive alien vegetation have an impact on erosion of palmiet wetlands. A change in catchment hydrology and sediment supply has reduced wetland resilience.	*In situ* data: sediment analysis, radiocarbon dating. Long and cross profiles, historical image analysis	SR	R	**34.**Mamphoka (2019)	T
Valley-bottom; Floodplain wetlands	Gully erosion and headcut migration rates in Palmiet wetlands (Pietersielieskloof, Jan Swartskraal) linked to morphodynamic characteristics and soil properties. Morphodynamics characteristics could serve as indicators in identifying wetlands susceptible to headcut migration are identified for wetland restoration intervention.	Morphodynamic characteristics assessed by *in situ* data and analyzing soil samples; image analysis of headcuts	SR	R	**35.**Williams (2018b)*	T
Valley-bottom wetland	Wetland rehabilitation by Working for Wetlands to improve water security and habitat provision. Unchannelled valley-bottom peat wetlands degraded by multiple stressors: landuse, invasive alien vegetation, draining and road crossing. Development of chute-drop structures maintained wetland connectivity.	Descriptive account	WR HP	R P	**36.**Nieuwoudt *et al.*, 2018	J
Floodplain wetlands	Carbon content of dark soil layers at three floodplain wetland sites have a mean carbon content lass than 2.5%. Opportunities for "generating carbon credits through wetland restoration" seems limited.	Soil analysis and organic carbon using Walkey-Black method	CR	R	**37.**Mills & Hunter (2018)	J
Floodplain wetland, Estuary	Salinity levels due to tidal exchange assessed. Increased salinity in the Heuningnes River due to tidal influence and low flows from the Nuwejaars/Soetendalsvlei	Bathymetric survey, *in situ* water and salinity levels, models	WR	R	**38**.Van der Ende (2015)	T
Depression	Water storage capacity of Voëlvlei estimated at 6 Mm^3	Bathymetric survey	WS	R	**39**.Seaton (2016)*	T
Depression wetlands	Water surface area of 7 depression wetlands varies over time (1989 – 2016)	Water surface area determined using proxy. Correlation with rainfall	WS	R	**40.**Fortune (2018)	T

Ecosystem Function (EF): HP: Habitat Provision; WPr: Water provisioning; WP: Water purification; FP: Food production; WS: Water storage; WR: Water Regulation; SR: Soil Retention; CR: Climate regulation
Ecosystem Service (ES): P: Provisioning/Supporting; R: Regulating; C: Cultural Publications (P): J: Journal; T: Thesis; R: Report

Findings by Mazvimavi (2018) show that wetlands provide important provisioning ecosystem services within the agricultural landscape. Dryland cultivation and pasture production are the dominant users of green water (i.e. water in the soil after precipitation, and used by plants) with an estimated use of almost 20% of the mean annual rainfall. 59% of the 61 registered users of water, abstract from the river (within the floodplain wetlands) and 26% of the users abstract from springs, with water mainly used for crop irrigation (Figure 8.1).

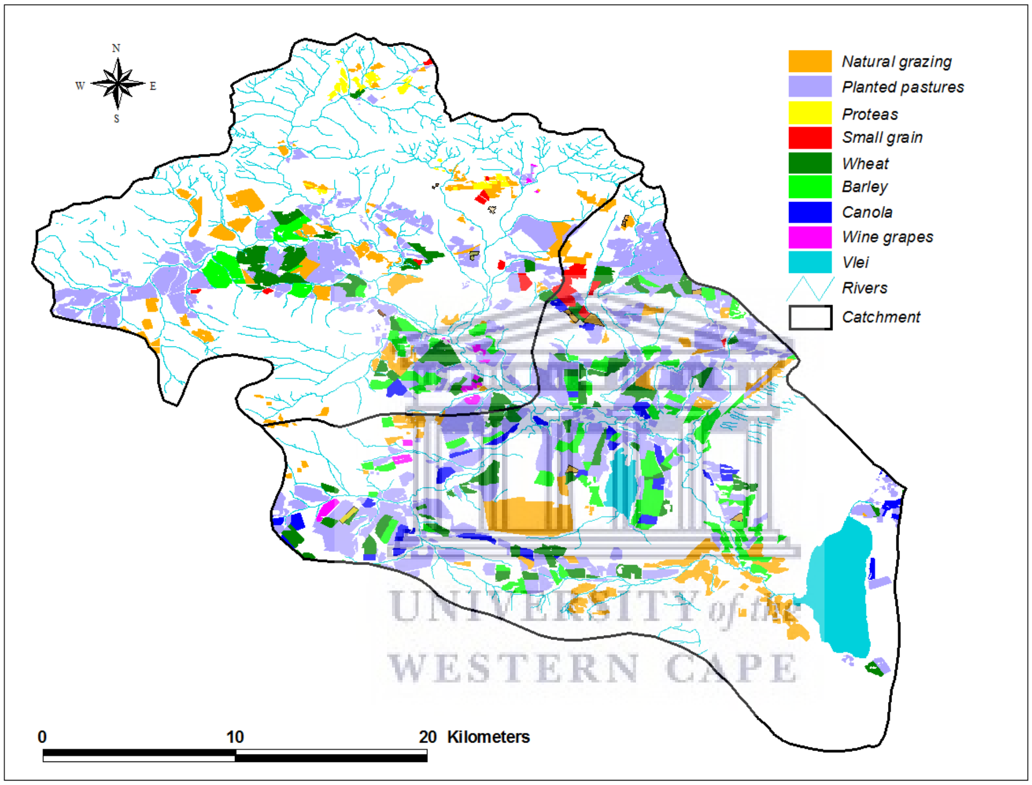


Figure 8.1 Land use in the Nuwejaars catchment (source: Mazvimavi, 2018)

8.3.2 Social value mapping

8.3.2.1 Stakeholders

Fourteen stakeholders were interviewed. The stakeholders interviewed included 3 farmers and a manager from the NWSMA; 2 wetland consultants; 3 Cape Nature officials; 3 SANParks officials, an Overberg district municipal official and an official from the Department of Agriculture (Landcare). The mapping was only completed by 2 NWSMA members; 2 officials from SanParks and 2 officials from CapeNature. One of the stakeholders who declined to participate in the mapping exercise found the absence of management boundaries confusing, while other stakeholders did not provide a reason.

8.3.2.2 Benefits identified by stakeholders

The floodplain wetlands, valley-bottom wetlands, seeps and depressions were identified for their regulating services, such as sediment retention, water quality amelioration/purification, streamflow regulation and water storage (Figure 8.2 and Table 8.2). All stakeholders identified at least 2 regulating ecosystem services for depression and floodplain wetlands. A SanParks official was the only stakeholder who mapped seeps as providing flow regulation. Regulating ecosystem services were spatially the most abundant benefit, with all wetland types identified as providing flow regulation.

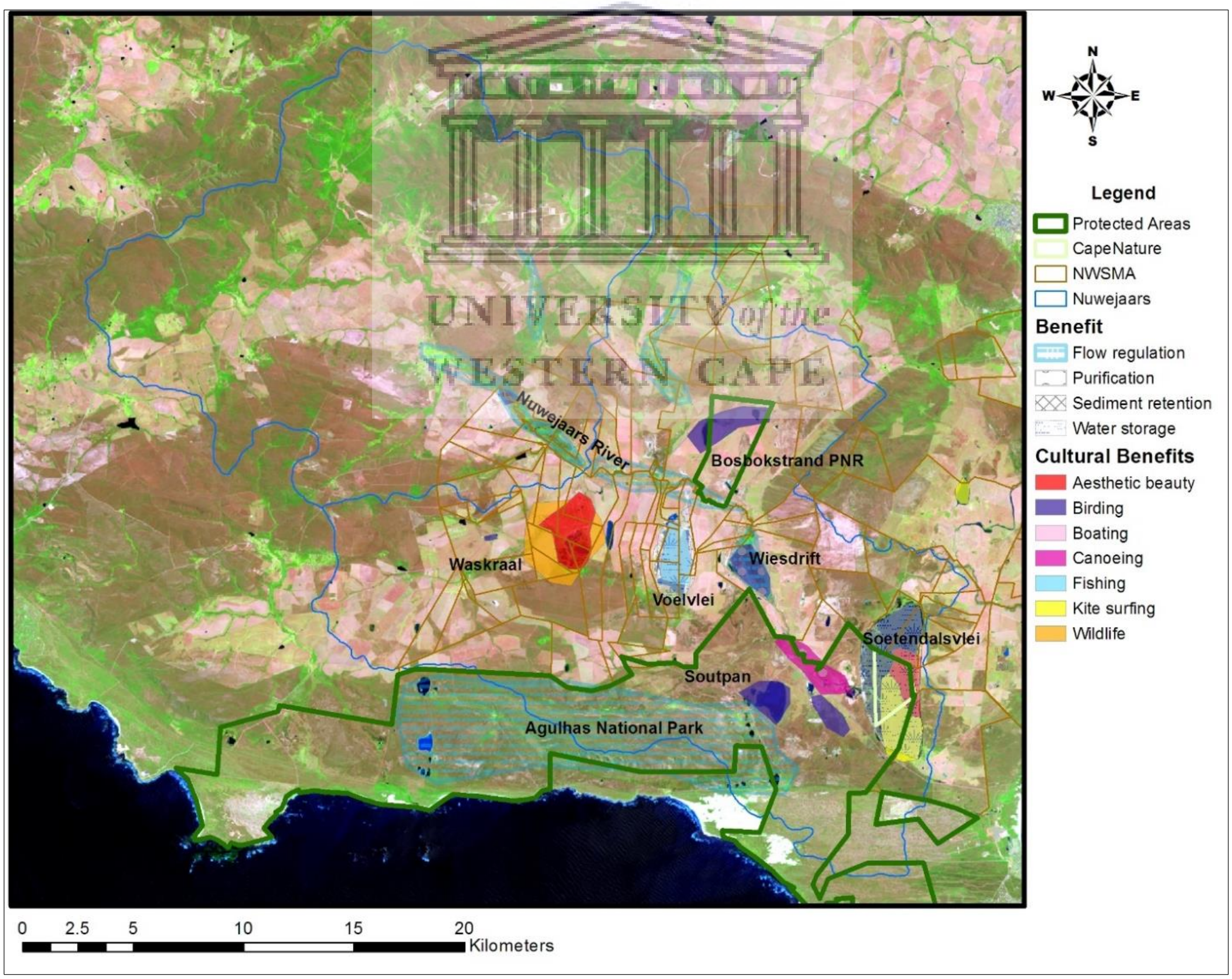


Figure 8.2 Wetland benefits identified by stakeholders in the Nuwejaars catchment

Recreation in the form of birding, wildlife, fishing, kite surfing, canoeing and boating are popular activities known to provide cultural benefits in the Nuwejaars catchment (Figure 8.2). All wetland types, except seeps, were identified as providing multiple cultural benefits. For example, Soetendalsvlei provides benefits such as boating, fishing, birding, kite surfing and aesthetic beauty. Waskraal provides habitat for wildlife (such as the hippopotamus) and aesthetic beauty, with access regulated by the NWSMA. Birding was the most common benefit mapped by all stakeholders. Kite surfing is reserved for the private landowners adjacent to Soetendalsvlei; while canoeing was identified by SanParks. As most wetlands are located on private property, access to cultural benefits is limited for the general public/community, with permission needed from the landowners. Access to wetlands managed by SANParks and CapeNature (such as Soetendalsvlei) are controlled by the relevant authority.

Table 8.2 Identified benefits from different wetland types (areal coverage of benefits included)

Ecosystem Benefits	Depression	Seeps	Floodplain wetland	Valley-bottom	Areal coverage (km^2)
Regulating					
Purification	X		X	X	8.5
Water storage	X				19.0
Flow regulation	X	X	X	X	26.2
Sediment retention	X				15.9
				Total area	**80.4 km^2**
Cultural					
Boating	X				2.4
Fishing	X			X	4.9
Birding	X		X	X	14.5
Kite surfing	X				7.1
Canoeing	X		X		3.7
Wildlife	X				10.8
Aesthetic beauty	X		X	X	8.3
				Total area	**51.7 km^2**

Floodplain, valley-bottom and depression wetlands were identified as providing more than one regulating service. The Nuwejaars floodplain from Elim to the inflow at Soetendalsvlei was identified by all stakeholders as providing at least two or more regulating benefits. Based on research conducted in the Nuwejaars catchment, the ecological properties of the Nuwejaars floodplain wetlands allows for the storage of water and flow regulation (Mandlazi, 2017; Mehl, 2019) while shallow groundwater discharges along the Nuwejaars floodplain wetlands and also contributes to flow regulation (Banda, 2019).

The various benefits of wetlands, and the threats to the functioning of the wetlands are recognized by stakeholders in the catchment. The impact of invasive alien vegetation along the Nuwejaars River and its tributaries causes soil erosion (Nieuwoudt *et al*., 2018; Mamphoka, 2019), increases evapotranspiration and influences water storage in shallow soil layers (Mkunyana, 2018; Banda, 2019; Mkunyana *et al*., 2019). To enhance the benefits of wetland functioning, the clearing of invasives are undertaken by farmers, the Working for Wetlands and conservation organizations, with support from government. According to one of the farmers '*when you get rid of these water thieves you can see the flow downstream*'. According to the NWSMA, the clearing of invasives along the Nuwejaars floodplains also contributes to increased biodiversity. Coordinated bird counts are being conducted along the Nuwejaars floodplain wetlands to assess how the clearing of the invasives influence avian diversity (NWSMA, 2019).

8.4 Discussion

Given the complex and dynamic relationship of society with wetlands over time and space, the aim of this chapter is not to provide a comprehensive overview of this relationship (as that is beyond the expertise of the researcher). The main aim was to provide some insight to how society is intricately connected to the water balance dynamics of wetlands, and the biodiversity it supports.

8.4.1 Scientific value of wetlands

The Nuwejaars catchment has a history of scientific value related to wetlands and biodiversity. Cleaver & Brown (2005) provide an annotated bibliography of 74 publications (from 1965 to 2005) related to the properties and characteristics of wetlands, fauna and flora, and highlights the threats to wetland ecosystems in the Nuwejaars catchment. The economic value of biodiversity has been assessed by Conradie & Garcia (2013) and Turpie *et al*., (2003). Malan *et al*., (2015) report on scientific investigations which reflect the "trajectories of change in wetlands" in the Fynbos Biome from the 1980s to 2014, and highlight the water quality, properties of vegetation and invertebrates of the various wetlands on the Agulhas Plain and the benefits the wetlands provide. van Wilgen *et al*., (2016a) make reference to scientific research and knowledge, and how that knowledge influenced conservation measures in the Cape Floristic Region between 1945 and 2015. Bioregional planning and the designation of state-protected areas such as the Soetendalsvlei Nature Reserve (farm/erf 276) in 1977 and the Agulhas National Park in 1989 (van Wilgen *et al*., 2016a) was supported by scientific knowledge generated of the Nuwejaars catchment. Scientific value can thus contribute to decision making and policy development (Friess *et al*., 2020).

However, while scientific value may provide much support for policy development at the broader/national scale, the implementation of these policies can cause conflict at a local scale (Kepe *et al*., 2005) or there may be limited implementation/integration of these policies in everyday management practices (Ntshotsho *et al*., 2015). This is particularly the case when local stakeholders (such as local government, NGO's and community members) are not engaged at all levels of decision making or policy development. According to Ntshotsho *et al*., (2015, p142) to ensure that scientific value has practical 'value', it should be "user-inspired and user-relevance science". For example, given the importance of birding and biodiversity areas in the Nuwejaars catchment, avifauna monitoring is collaboratively undertaken by relevant organizations including the NWSMA. Findings from De Kock & Lee, (2019) on the impact of agriculture on the habitat preferences and food sources for Agulhas Long-billed larks (a near threatened endemic bird) within the Overberg provide insight to how farmers can maintain biodiversity on their farms (NWSMA, 2018). With wetlands known to provide a habitat for various birds on the Agulhas Plain, citizen scientists collecting avifauna survey data become advocates for nature (Harrison, 2020), such as supporting wetland rehabilitation (De Klerk, 2018). Where scientific knowledge and evidence is co-created, publicly available and informs everyday adaptive management practices, there is much opportunity to enhance ecosystem services and conserve biodiversity.

The significance of this present review of the scientific value of wetlands highlights the importance of scale. With most of the research conducted at a hydrogeomorphic scale, the knowledge contributes to a better understanding of processes at a catchment scale, and knowledge of wetlands in general. For example, the groundtruthing of the NFEPA wetlands is collaboratively effected by SANParks and CapeNature since 2013 which contributes knowledge of aquatic ecosystems in the Nuwejaars catchment and contributes to the South African National Wetland Inventory (Fisher *et al*., 2017). Publications related to wetland functioning from 2014 to 2019 (Table 8.2) were mainly related to regulating ecosystem services, with a focus on water regulation, water storage and soil retention. These publications are aligned to the research objectives of the WRC Report No 2324/1/18 for "finding 'new' water to address conflicting and competing water demands in the Nuwejaars Catchment", and supports the mission of the Water Research Commission (WRC) to become a "global water knowledge node". The scientific value advances the general understanding of wetland functioning (Phillips & Madlokazi, 2011) and is relevant to specific stakeholders at the local scale. The scientific value of wetlands is relevant for the Agulhas National Park (SANParks, 2020) and Heuningnes management plans (SMEC, 2017); and specifically contributes to understanding the connectivity of wetlands in the Nuwejaars catchment.

The scientific value also "strengthens and supports" policy such as the Spatial Development Framework and Integrated Development Plans at municipal level for the Overberg District Municipality (Robinson, 2017; Overberg District Municipality, 2018). To the NWSMA, the scientific value informs the environmental management plan, and is important "to answer these many questions that are being raised by farmers" (NWSMA, 2019, p14). Informed decision-making requires data and knowledge, and according to one of the stakeholders, "*we need to monitor…. that is the problem*". Given that the Nuwejaars catchment was ungauged prior to 2014, the need for hydrological data and information is relevant, and with continued hydrological monitoring and research planned until November 2024 (given the extension of the MOU between the NWSMA and UWC), longer term data will strengthen knowledge generation. However, as highlighted by many researchers, given the dynamic and complex interactions between ecosystems and society, research on social perspectives related to wetlands are needed (Phillips & Madlokazi, 2011; Scholte *et al*., 2016; Boerema *et al*., 2017). An understanding of cultural ecosystem services provides insight to the varied and complex values which motivate participation in private conservation (Chan *et al*., 2012; Fish *et al*., 2016; Scholte *et al*., 2016). While financial incentives may promote private conservation participation, Selinske *et al*., (2015) found that conservation value, place attachment (i.e. strong emotional bond with the land) and social learning (i.e. seeking to learn about biodiversity and how to best to manage land; and to be part of a larger movement to protect nature) were the three highest ranked factors motivating participation in private biodiversity stewardship programmes in the Western Cape Province in South Africa. According to Comberti *et al*., (2015, p249) in agricultural communities where there is a high dependence on the natural landscape for livelihoods, "landscapes are often integral to their cultural identity".

Given that most wetlands are located on private property, the scientific value of wetlands in the Nuwejaars catchment (between 2014 and 2019) are mainly located outside the national protected area of the Agulhas National Park. Findings demonstrate that enabling conditions which promote scientific value is related to collaboration and research support at multiple scales (Smit *et al*., 2017). Within the Nuwejaars catchment, collaboration with local organizations such as the NWSMA, SANParks and CapeNature are vital as the three organizations collectively manage 68% of wetlands in the Nuwejaars catchment (G50B and G50C). Of particular significance, is that data and research findings generated within and by the "living laboratory" are shared, and opportunities are created where stakeholders can engage and interact (Mazvimavi, 2014; NWSMA, 2018, 2019). Smit *et al*., (2017) quantified scientific value (termed intellectual value by including scientific, education and staff capacitating) in South African National Parks, and suggest that positive feedback occur between scientific value and provisioning and regulating ecosystem services. Increased scientific knowledge informs adaptive management and policy which results in improved management of ecosystems (Ntshotsho *et al*., 2015; Smit *et al*., 2017). There is thus much opportunity to continue collaborative engagement and research in the Nuwejaars catchment, and to understand ecosystem response to management strategies within such a diverse landscape.

8.4.2 Wetland ecosystem services in the Nuwejaars catchment

Within agricultural landscapes, such as the Nuwejaars catchment, there is a high dependence on natural resources, and thus provisioning services such as water, arable land and grazing are prominent (Mazvimavi, 2018). Negative impacts associated with agricultural activities were, in turn, associated with conversion of wetlands for agricultural use, the construction of dams, the negative impacts of infrastructural development, drainage ditches, overgrazing and the growth of invasive alien vegetation (Sampson, 2021). There is thus much opportunity to manage agricultural activities for sustainable development. Within agricultural landscapes, management strategies to enhance ecosystem services, may not necessarily increase biodiversity conservation, and thus identifying synergies and potential tradeoffs, are important (Macfadyen *et al*., 2012). One management strategy, the removal of invasive alien vegetation, has benefits for both biodiversity and ecosystem services (Le Maitre *et al*., 2014). Due to the consumptive use of water by invasive alien vegetation in the Nuwejaars catchment (Visser, 2001; Ndara, 2017; Mkunyana, 2018; Mazvimavi, 2018; Mkunyana *et al*., 2019), the clearing of invasive alien vegetation particularly along the floodplain wetlands, increases available water storage and flow (Mehl, 2019), and enhances freshwater flow to the estuarine zone (SMEC, 2017). The clearing of invasives also increases the available and suitable habitat for select birds and so increases biodiversity (Mangachena & Geerts, 2017; NWSMA, 2019). In the Nuwejaars catchment, where threats related to agricultural activities pose a risk to water quantity and quality, and ultimately the integrity and optimum functioning of wetlands (Cleaver & Brown, 2005), an understanding of the trade-offs and synergies, particularly within a variable climate, is required to enhance decision making that will effectively promote wetland conservation and biodiversity. Recognizing that wetlands provide various ecosystem services, particularly within an agricultural landscape, and that the uses and values of these wetlands change over time and space, requires integrated and adaptive/evolving management approaches.

Findings from this research showed that benefits of regulating ecosystem services related to water storage, flow regulation and water quality amelioration were similarly perceived by farmers, conservation and government authorities. These findings were supported by empirical research conducted by Mazvimavi (2018). The natural resources and environment are also intricately linked to cultural ecosystem services, as communities and farmers have a ‘special’ bond to the land (Bouahim *et al*., 2015; Cresswell, 2016; Smith & Sullivan, 2014). The cultural benefits most commonly mapped in this research were related to wildlife, recreation and aesthetic beauty. However, the many informal discussions with the community in the Nuwejaars catchment has shown that there is a rich and diverse cultural value that is intricately connected to the history of the landscape and the people. The importance of the cultural value of the landscape was also found through using in-depth interviews with communities in the Nuwejaars catchment (Conradie, 2010; Creswell, 2016).

The floodplain, valley-bottom and depression wetlands, located within the agricultural and state protected landscape of the Nuwejaars catchment thus provide multiple ecosystem services, also referred to as “ecosystem service bundles” (Egoh *et al*., 2008; Raudsepp-Hearne *et al*., 2010; Turpie *et al*., 2010; Bouahim *et al*., 2015; Ament *et al*., 2017). Given the importance of protecting the biodiversity within agricultural landscapes (Cole *et al*., 2000; Jones *et al*., 2000; Malan *et al*., 2015) the partnerships established between the NWSMA, state and conservation organizations provide a platform for wetland conservation. For the NWSMA the development of ecotourism within agricultural landscapes are seen as a means of generating financial security, employment and environmental sustainability (Child, 2010; NWSMA, 2018). In view of the impacts of climate change, the diversification of agricultural activities promotes the multi-functional use of wetland ecosystems (Soy-Massoni *et al*., 2016).

The mapping of the benefits as perceived by stakeholders generally identified the more prominent wetlands, such as Soetendalsvlei, Voëlvlei, Waskraal and the floodplain wetlands of the Nuwejaars catchment. A concern for the ‘missing wetlands’, the smaller wetland systems in the Nuwejaars catchment which are often overlooked, was identified by a conservation official. While the significance of small-scale wetlands in providing ecosystem services have been established (Blackwell & Pilgrim, 2011), they have either not been accurately reflected in the National Wetland Inventory or they are perceived as wetlands of less value. Continued wetland mapping will thus provide relevant data that can inform land use activities in the catchment.

Given that the NWSMA, CapeNature and SanParks have scientific personnel, and that partnerships exists among these institutions, as well as with other government, civil and citizen science organizations, there is much opportunity for learning, knowledge sharing and engagement. While Franco & Luiselli (2014) found that shared ecological knowledge of wetland hydrological functions declined spatially from the wetland areas where people live, the findings from this study suggests that shared knowledge, given enabling conditions, can spatially extend beyond the individual wetland boundaries. Shared knowledge within a community can contribute to collective action to the benefit of biodiversity and ecosystem services (Stenseke, 2009; Speelman *et al*., 2014).

8.5 Conclusion

Wetland ecosystems provide benefits related to provisioning, regulating and cultural ecosystem services. The floodplain, valley-bottom and depression wetlands provide bundles of ecosystem services, related to water regulation, water storage, water quality amelioration, and cultural benefits related to wildlife, recreation and aesthetic beauty. The wetlands also provide scientific value, where enabling conditions promote opportunities for the increased generation of scientific knowledge. Management strategies for increasing the species diversity of birds in the Nuwejaars Wetlands Special Management Area is informed by citizen science and scientific knowledge, and illustrates the importance of enhancing opportunities for collaboration amongst diverse stakeholders. Where shared knowledge and informed decisions are underpinned by scientific evidence, collective and adaptive management strategies, can enhance the benefits of wetland ecosystems.

CHAPTER 9

GENERAL SUMMARY, DISCUSSION AND RECOMMENDATIONS

9.1 Introduction

The main aim of the research was to improve the understanding of the spatial and temporal availability of water and storage of a depression wetland in a semi-arid climate, and to relate these to ecosystem functions. As wetland ecosystems are intricately connected to society, a secondary aim of the research was to understand how wetland ecosystem functions, within a changing climate and landscape, provide benefits to society. This chapter summarizes the key findings presented in Chapters 3 to 8 in relation to the objectives identified in Chapter 1. Theoretical and practical implications of the findings are discussed, and research limitations and opportunities for future research are also highlighted.

9.2 Summary of key research findings

9.2.1 Assessing the influence of rainfall variability and anthropogenic activities on wetland dynamics/properties - Objective 1

Understanding how landscapes have historically responded to a variable climate and anthropogenic influences, provides insight to the complex factors that influence (present) wetland functioning (Chapter 3).

Within the ungauged Nuwejaars catchment the monthly rainfall data for three stations from 1930 to 2018 provided an understanding of the spatial and temporal variability of rainfall. Mean annual rainfall within the upper catchment (611 mm/annum) is generally higher than the lower catchment (466 mm/annum). Catchment rainfall during autumn and winter account for almost 60% of the annual rainfall, and influences the temporal inundation of wetlands (Chapter 4). Rainfall in the upper catchment is an important source of surface runoff and inflow to the water balance of the Soetendalsvlei (Chapter 6), and thus any change affecting the rainfall-runoff process will influence the water balance of the lake. One of the objectives of Chapter 3 was therefore to assess rainfall variation using the Mann-Kendall trend analysis, as well as the Standard Precipitation Index (SPI) for detecting extreme wet and dry periods. The monthly, seasonal and inter-annual rainfall in the Nuwejaars catchment is highly variable, with significant *very wet* (floods) and *very dry* (drought) periods from 1930 to 2018. While there was no significant evidence of rainfall trends in the

Nuwejaars catchment, the frequency, magnitude and intensity of extreme rainfall periods is important to consider. Between 2011 and 2018, three consecutive and extreme dry-wet-dry periods were observed in the Nuwejaars catchment. The characteristics of the relatively recent extreme drought (2016 – 2018) is similar to the drought of 1925 to 1932 and 1969 to 1977. These extreme droughts, with a 24-month SPI value exceeding -2.0 caused the desiccation of Soetendalsvlei. The utility of the SPI in understanding the influence of rainfall variability on wetland inundation has been demonstrated in this and other studies (Zhang *et al*., 2015; Nsubuga *et al*., 2019).

Historical aerial photographs for 1938, 1961, 1973, 1989 and 2014 were assessed to determine the land use and land cover change within Soetendalsvlei, and the immediate surrounding landscape. It is evident that human activities and decisions have transformed the natural land cover of vegetation and wetlands for agricultural land use from 1938 to 1989. The benefit of wetlands, to landowners, is observed through the conversion of floodplain wetlands and flats into agricultural fields, and the storage of excess runoff from the drained wetlands into depressions. The impacts on Soetendalsvlei is evident with the decrease in open water and increased growth of macrophytes along the shoreline, attributed to the inflow of nutrients and sediment from the catchment, particularly via the Nuwejaars River and a drainage ditch. By 1989 the property area of Soetendalsvlei was subdivided into 9 erven, with the centre of the lake provided with protected wetland status by CapeNature, and the surrounding lake owned by farmers. Between 1989 and 2014, with the proclamation of the Agulhas National Park and the establishment of the Nuwejaars Wetlands Special Management Area (NWSMA), conservation planning and initiatives had direct impacts on the natural land cover and the use and management of water resources. The rehabilitation of wetlands, clearing of invasive alien vegetation and occurrence of fallow fields are evident. The transformation of the land use/land cover within the 76-year period is influenced by complex, dynamic and interrelated anthropogenic and natural drivers which span political, legislative, socio-economic and environmental factors.

9.2.2 Characterizing the spatial and temporal variation of flooding - Objective 2

With no access to *in situ* hydrological data for the Nuwejaars catchment prior to 2015, satellite imagery from the Landsat archive was processed using the Modified Normalized Difference Water Index (MNDWI) to assess the spatial variation of flooding. High resolution aerial photographs and a terrestrial *in situ* survey of the lake shoreline were used for identifying the optimal threshold for extracting surface water. The MNDWI, with a threshold of zero, had the highest overall accuracy of 93%. Using the MNDWI with a threshold of zero, Landsat images were processed to generate a time series of inundation maps from 1989 to 2019. The frequency of flooding of wetlands within the catchment varies over time and space, with depression wetlands having a higher frequency of inundation. The 30-year time series of the extent of surface water inundation for Soetendalsvlei, a freshwater coastal depression, shows no significant trend of flooding, but displays significant monthly, seasonal and annual variation that is influenced by rainfall variability. A significant positive correlation (R^2 = 0.60) between the 18-month Standard Precipitation Index (SPI) and inundation for Soetendalsvlei illustrates the importance of rainfall and antecedent precipitation/storage, but also suggests that inundation may not only be influenced by rainfall variability. The characterization of the hydroperiod for Soetendalsvlei, shows permanent, seasonal and intermittently flooded areas that establishes lateral hydrological connectivity within the wetland. The hydroperiod, together with the diverse properties of vegetation, characterizes functional units which supports diverse habitat assemblages.

There is a significant positive correlation (R^2 = 0.75) between the *in situ* daily lake level (measured from 2015 to 2017) and inundation derived using the MNDWI. With the increased spatial, temporal and spectral resolution of remotely sensed data, and improved/new techniques to extract water, the enhanced detection of water from remotely sensed data can only improve the monitoring and understanding of wetlands. The outcome of this study supports the use of the MNDWI as a proxy for monitoring the lake water level of a shallow lake in a semi-arid area. Where no previous hydrological data available exists for lakes and wetlands, the integration of *in situ* and remotely sensed data can provide a retrospective description of hydrological data. In light of climate variability and its impacts, changes in land use, and future water resource developments earmarked for this catchment, this research provides baseline information which may be useful to water and conservation managers.

9.2.3 Wetland morphology, processes and functions - Objective 3

Knowledge of the morphology of a wetland contributes to wetland classification and provides an improved understanding of the physical properties that influences ecosystem and hydrological functioning. The morphometric characteristics of Soetendalsvlei were derived from a bathymetric and terrestrial survey, remotely sensed data, and the daily monitoring of water levels and wind characteristics over a two-year period. The shallow, asymmetric-shaped lake is influenced by the inflow of water and sediment, the growth of vegetation and the impact of wind. While the resistivity survey provides evidence of shallow groundwater, the consistent monitoring of groundwater levels is needed to improve the understanding of the surface-groundwater interaction influencing this lake and the aquatic ecosystems. The hypsographic curve for Soetendalsvlei provides the unique volume-area-depth relationship to support the estimation of the daily water balance of the lake (Chapter 6). The structure/capacity to store approximately 20 Mm^3 of water in this lake, is an ecosystem function that is dynamic in time and space (Chapter 4), and provides opportunities for the provision of ecosystem services. One of the ecosystem services, the regulation of water flows, was quantified by developing the lake stage-outflow rating curve. The rating curve reflects a non-linear relationship, with surface outflow from the lake to the downstream Heuningnes River estimated when the lake level is 1.66 m. The timing of surface outflow, to the Heuningnes estuary, as a function of lake storage, highlights the importance of understanding the processes that hydrologically connect the coastal lake within/to the estuarine functional zone.

9.2.4 Establish the seasonal variation of storage and influences on wetland functions and processes - Objective 4

Data from the "Living laboratory" and knowledge of the hypsographic curve was used to develop a conceptual model of the hydrological behavior of the Soetendalsvlei. The daily water balance model was developed from 2015 to 2017 by estimating precipitation and evaporation to/from the lake and surface inflow from the catchment. Groundwater exchange to/from the lake was assumed as zero, and surface outflow was simulated using a 2-segmented rating curve. By applying a 1-day time delay of surface inflows due to flow regulation by upstream floodplain wetlands, the simulated lake level, with R^2 = 0.99, compared well with the *in situ* lake level. Surface runoff from the Nuwejaars catchment is the dominant inflow of water storage in Soetendalsvlei. Surface outflow will only occur when the threshold water storage of 9.5 Mm^3 is exceeded, after which the pattern of surface outflow closely simulates the inflows. Total evaporation exceeds inflow to the lake during summer, and is dependent on the surface water availability. Evaporation is the dominant outflow when lake storage is below the threshold for surface outflow.

To assess how a change of surface inflows and antecedent storage capacity may influence lake storage and surface outflows, a one-factor scenario analysis was applied to the water balance model. Simulations illustrate that once catchment surface inflows are reduced to 5.1 Mm^3, no surface outflow from the lake will occur. The simulations also highlight the importance of high rainfall events in reducing the water residence time in the lake. The residence time not only has implications for the environmental conditions of the lake, but to the downstream estuary as well.

The water balance model has advanced the understanding of the relative contribution of the water balance components to the variation of storage for Soetendalsvlei, and highlights the need for continued hydrological monitoring. A better understanding of surface and subsurface flow of the entire catchment, and the interaction between subsurface water, floodplain wetlands and the lake is required to refine the water balance model for Soetendalsvlei.

9.2.5 Understanding how wetlands, within a variable landscape and climate, provide ecosystem services and benefits to society - Objective 5

The ecosystem services approach was the guiding framework to understand the value of wetlands to society. Habitat provision, scientific value and the social value of wetlands were assessed for the Nuwejaars catchment. Habitat provision provides insight to the environmental conditions of the Nuwejaars catchment. Species abundance and richness were assessed using available avifauna data which is available from the Animal Demography Unit at the University of Cape Town. On a landscape scale the lower Nuwejaars catchment supports a higher number of bird species than the upper catchment. The mosaic of wetlands, agricultural fields and protected landscapes provide diverse habitats and available food in the lower Nuwejaars catchment. The highest species were observed in the Soetendalsvlei pentad. The integration of bird counts with wetland inundation for Voëlvlei and Soetendalsvlei demonstrated the importance of the hydroperiod in influencing bird richness and diversity. Soetendalsvlei and Voëlvlei are important sites for habitat provision, with species diversity also influenced by drought conditions. Continued monitoring, given climatic variability, is essential.

The scientific value of the Nuwejaars catchment was assessed for the period 2014 to 2019, to coincide with the establishment of the "Living Laboratory". The scientific value of wetlands was assessed by reviewing the number of publications related to functions, processes, benefits and values of wetlands, and the spatial distribution of study sites within the Nuwejaars catchment. Given that most wetlands are located on private property, the scientific value varies spatially, with the Nuwejaars Wetlands Special Management Area (NWSMA) contributing significantly to scientific knowledge. Enabling conditions, such as financial support, stakeholder engagement and collaboration, clear protocols and accessibility, are important considerations in realizing opportunities for scientific value of ecosystems.

Findings from participatory mapping and interviews conducted with stakeholders in this study, show that floodplain, valley-bottom and depression wetlands provide multiple benefits related to regulating and cultural ecosystem services. The regulating benefits identified by stakeholders were related to water storage, flow regulation and water quality amelioration. The capacity of the wetlands to provide these regulating benefits are supported by empirical research conducted in the catchment. The cultural benefits most commonly mapped in this research were related to wildlife, recreation and aesthetic beauty.

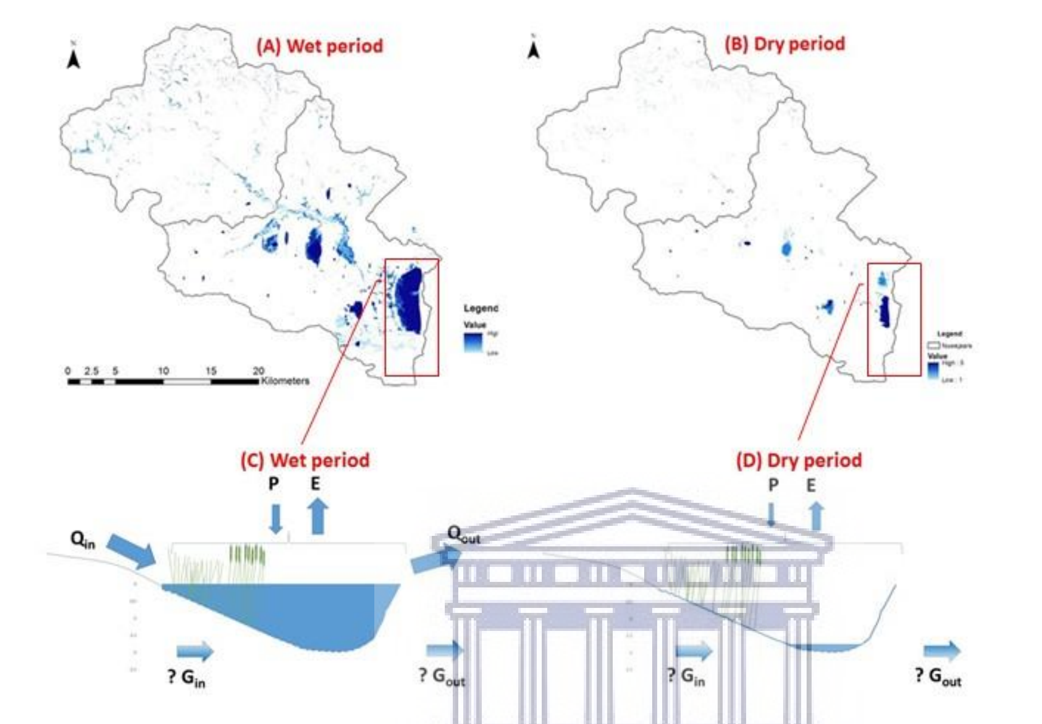
The diverse wetlands in the Nuwejaars catchment provide bundles of ecosystem services. Ecosystem services are enhanced through adaptive management strategies, with the clearing of invasive alien vegetation providing multiple benefits. Protecting the natural environment within an agricultural landscape, is regarded as important for increased farming productivity (NWSMA, 2018). In a landscape where wetlands are protected by various management authorities, the collaboration and interaction of stakeholders to promote monitoring, co-create knowledge and collectively identify and enforce appropriate management strategies, is essential for wetland conservation.

9.3 Discussion of key findings

9.3.1 The spatial and temporal variation of water and storage in depression wetlands

Assessing and understanding the dominant processes controlling the variation of water and storage in depression wetlands, given the *in-situ* hydrological data constraints, requires a hybrid approach (Gal *et al*., 2016). The relevance and applicability of the remote monitoring of wetlands using freely available satellite images and water extraction techniques has been widely demonstrated in providing valuable data and information (Politi *et al*., 2016; Buma *et al*., 2018; Bredin *et al*., 2019) particularly when validated by high resolution data and *in situ* data.

Using a hybrid approach, findings from this research (Chapters 3 to 6) demonstrate the daily (Figure 5.7), monthly (Figure 4.12), seasonal (Figure 4.11) and annual (Figure 4.8), variation of the water storage for Soetendalsvlei. The quantification of the dominant processes controlling the daily water storage of Soetendalsvlei shows that surface runoff from the catchment is the main inflow, except during dry periods (Figure 9.1). This was evident with the presence of surface lake water during the extremely dry period from 2017 to 2019 when rivers ‘ran dry’, thus challenging the initial assumption that groundwater exchange for Soetendalsvlei was zero.



Ecosystem function: Wet period	Ecosystem Services	*Ecosystem function: Dry period*
Positive change in storage Abstraction of approximately 1 Mm³/yr	Water provision (agriculture)	Negative change in storage No abstraction from the lake
Surface outflow with 1-day lag time $Q_{out} = \alpha_1 (V_t - V_{min})^{\beta 1}$	Flow regulation	No surface outflow $Q_{out} = 0$
High species diversity due to increased habitat and food availability	Habitat provision	Low species diversity due to a decline in diverse habitats and food availability
Opportunity for scientific investigation	Scientific value	Opportunity for scientific investigation

Figure 9.1 Conceptual understanding of the water balance of Soetendalsvlei during wet and dry periods and functions for select ecosystem services

The permanent inundation of the south pool of Soetendalsvlei and at the inflow of the Nuwejaars River to the lake during the extremely dry period from 2017 to 2019, may be due to groundwater discharge or surficial recharge in the lower catchment. According to Mazvimavi (2018) and Visser (2001), shallow unconfined primary aquifers, consisting of alluvial sands, are found along banks and floodplains of the Nuwejaars River, with the subsurface flow maintaining rivers and wetlands during dry periods. While the geologic substratum of the Malmesbury and Bokkeveld shale results in low hydraulic conductivity, the presence of faults may also cause localized surface discharge in the catchment (Mazvimavi, 2018). What was also evident from the monitoring of the water level of the Heuningnes River downstream of Soetendalsvlei, was that river flows were not solely maintained from surface overflow from the lake (Figure 5.9B). A possible explanation for this is that Soetendalsvlei may function as a throughflow-lake, where groundwater flows into the lake along one section, while discharge takes place along a different section of the lake (Figure 9.1 C and D). The groundwater exchange between the lake and surrounding aquifer may thus not be zero, but may vary, depending on factors affecting surface and subsurface flow conditions at the local and regional scale (Boyle, 1994; O'Driscoll & Parizek, 2008; Zacharias & Zamparas, 2010). The management of wetlands in the Nuwejaars catchment should thus consider both surface and groundwater resource use in the catchment. The current water level monitoring of surface and groundwater resources in the Nuwejaars catchment will thus provide much insight to the surface-groundwater exchange, over time and over space, between the lake, and the contributing surface and subsurface flows.

The findings presented in this research are cognizant of the limitations, sources of error and uncertainty in assessing the surface water and water storage of Soetendalsvlei (as discussed in the methods section for each of Chapters 4 to 6). The findings should thus be interpreted with these limitations in mind. However, with certainty, the findings from this research demonstrate the importance of wetland processes in understanding wetland functions within a variable climate. The temporal and spatial variation of catchment inundation and water storage for Soetendalsvlei (Figure 9.1 A and B) demonstrates the importance of inflows and outflows (Figure 9.1 C and D), during wet and dry periods. Inflows during wet periods are mainly surface runoff from the catchment. This was demonstrated with the significant positive correlation (R^2 = 0.60) of wetland inundation with the Standard Precipitation Index (SPI) (Figure 4.16); and the response of daily lake water levels to the cumulative catchment rainfall (Figure 6.5). A comparison of the lake surface water area derived from the daily water balance model (Chapter 6) and inundation using remotely sensed data (Chapter 4) show a significant positive correlation (R^2 = 0.88) for the period January 2015 to mid-2017 (Figure 9.2).

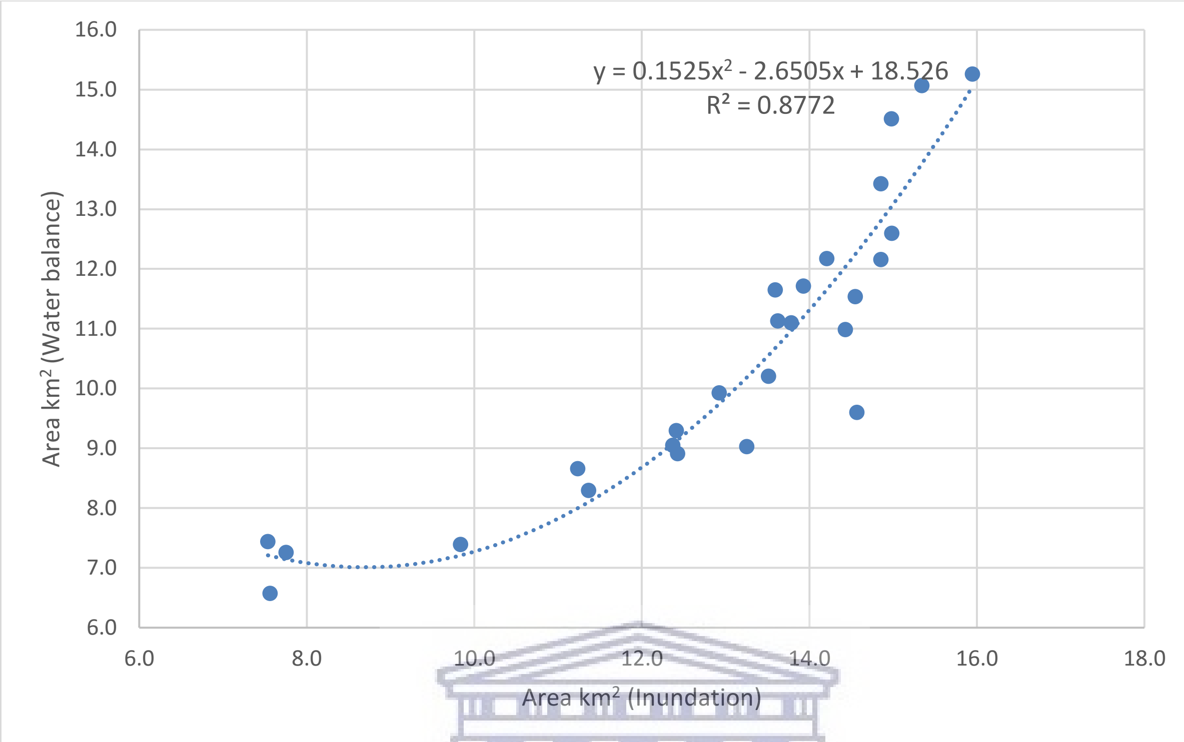


Figure 9.2 Correlation of the flooded area of Soetendalsvlei determined by remotely sensed data using the MNDWI and the daily water balance model

Given the capacity for water storage, the occurrence of emergent vegetation in the lake and the geographic location of the lake within the fluvial system, the importance of shallow depression wetlands in regulating flow through a "fill-and-spill" process have been demonstrated (Spence, 2000; Maherry *et al*., 2016). With surface overflow or "spill" to the Heuningnes River only occurring once a critical storage threshold is reached, Soetendalsvlei acts as a 'barrier lake' (Allanson, 2001). The retrospective approach using remotely sensed data, shows that overflow from Soetendalsvlei to the Heuningnes River between 1989 and 2017 only occurred 26% of time (Figure 5.11).

Of significance to the timing and magnitude of the "fill" process of the lake, are the upstream wetlands (Mandlazi, 2017; Mehl, 2019; Seaton, 2019). The regulating impact of wetlands upstream of Soetendalsvlei is reflected in the use of the segmented rating curve and the 1-day delay of surface inflows in the daily water balance model (Section 6.3.2). The wetlands in the lower Nuwejaars catchment are diverse, with each wetland playing an important hydrological function in the catchment (Winter, 2001; Maherry *et al*., 2016). The “fill-and-spill” and regulating impact of the wetlands thus exhibit surface flow connnectivity during the wet periods. Connectivity to groundwater flow is evident with permanent inundation of the wetlands during the dry periods.

Key findings from Chapters 4 to 7 provide insight to the thresholds and conditions which influences how the lake functions (Figure 9.1 and 9.3). Of significance in the understanding of wetland processes is how the morphology of depressions, with changing inundation, influences the characterization of the hydroperiod. While these findings may seem apparent, incorporating vegetation descriptions to spatially ‘visualize’ how interactions with a changing water level provides for various habitat assemblages, is valuable (Figure 9.3).

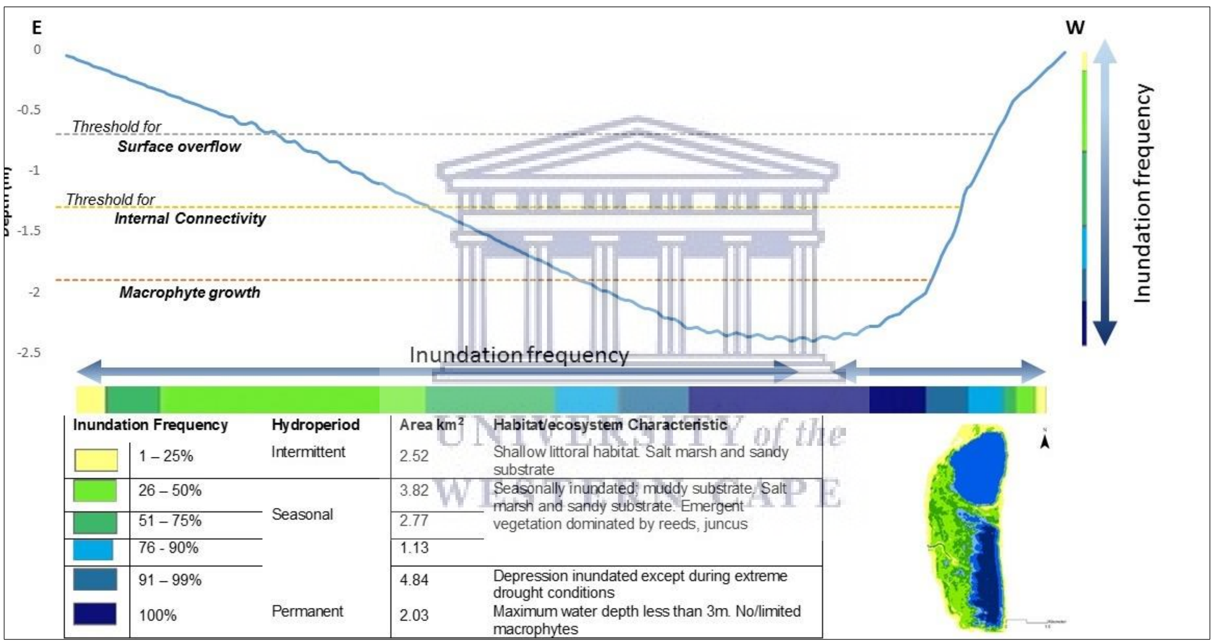


Figure 9.3 Vertical and horizontal gradients of water depth, inundation frequency and the corresponding habitat characteristics

While morphology is generally described by absolute values of depth, the interpretation of the spatial heterogeneity and complexity of shallow depressions can be described or illustrated as “functional shallowness” (Padisák & Reynolds, 2003), “gradients of water depth” (Crisman *et al*., 2005, p381) or as illustrated in Chapter 4, as gradients of wetness. These vertical and lateral gradients of wetness represent complex interactions associated with morphology and vegetation, which continually influence the properties of habitats and the availability of resources (Keddy & Fraser, 2000). The variation of inundation was significant in explaining the abundance and diversity of birds for both Soetendalsvlei and Voëlvlei. Monitoring that is currently being undertaken at Voëlvlei has not only provided insight to how diversity may change in response to climate variability, but also to management measures undertaken by the NWSMA (NWSMA, 2019).

9.3.2 Wetlands as complex social-ecological systems

The properties of the Nuwejaars wetlands are a reflection of the social and biophysical processes that have shaped these ecosystems over various time scales. Findings from this research has emphasized that wetlands in the Nuwejaars catchment can be regarded as complex social-ecological systems. The integration of the findings from this research, with research conducted in the Nuwejaars catchment, and in similar agricultural/protected environments will be discussed in relation to characteristics of complex social-ecological systems.

Systems are dynamic across spatial and temporal scales

What is evident from this research is that systems are dynamic. The system, whether at a hydrogeomorphic or catchment scale, or at an erf or special management area scale, is shaped by complex and interrelated factors. What is also important to consider is that interactions occur across these various spatial scales, and also over time. In South Africa, these interactions (and in most cases the product or results of these interactions) are further complicated with the legacy of Apartheid policies, which is still evident on the contemporary landscape.

Political decisions, policies and management protocols made at international and national level, have an impact on the management of site-specific wetlands (Cumming *et al*., 2017). Within the Nuwejaars catchment, the identification of the critical biodiverse areas on the Agulhas Plain in the 1980s, and the conservation planning for the landscape, involved various national and provincial stakeholders. Limited engagement with local stakeholders in the conservation planning of the Agulhas Plain was identified as a key issue when developing a shared vision for biodiversity conservation (Conradie, 2010; van Wilgen *et al*., 2016a). What is evident about complex systems, is that the response of a system to change, takes time. This was particularly evident for Soetendalsvlei where, over time, the private ownership of specific erfs or land parcels, was converted to state protected areas. Currently the 9 erfs dividing Soetendalsvlei is co-managed by national, provincial and local stakeholders. The importance of scale is also evident where wetlands, such as Voëlvlei and Soetendalsvlei, provide a habitat to various Southern African resident and Palearctic bird species. Species richness and diversity is influenced by wetland inundation, which varies over time and space in the catchment. Management strategies, such as the clearing of invasive alien vegetation and wetland rehabilitation, at the local wetland and catchment scale are relevant in improving habitat provision, and so enhancing the global directive for enhancing habitats for waterbirds.

Tradeoffs, synergies and feedbacks

Sampson (2021) provides a quantitative catchment analysis of the agricultural-related impacts on the various wetland types in the Nuwejaars catchment. What is evident from the catchment-scale analysis (Sampson, 2021) and the findings from Chapter 3, is that there are tradeoffs. Increasing food security has resulted in the direct conversion of wetlands, and the loss of ecosystem services associated with these wetlands.

Also associated with land use change are the indirect impacts on the downstream aquatic environment. As the "mirror" of the Nuwejaars catchment, the growth of emergent vegetation in Soetendalsvlei increased by 138% between 1938 and 2014. The increase in the growth of aquatic emergent vegetation in lakes and wetlands have been associated with increased agricultural activities within catchments (Russell, 2003; Papastergiadou *et al*., 2007; Pilgrim *et al*., 2015). The occurrence and properties of the emergent vegetation in wetlands have been associated with the increased provision of regulating ecosystem services (Turpie *et al*., 2010; Sieben *et al*., 2018) and habitat provision (Ma *et al*., 2010b).

With the establishment of the state and stewardship conservation areas in the agricultural landscape, the negotiation of tradeoffs was in the interest of biodiversity conservation (Dennis Moss Partnership, 2004; Child, 2010; Conradie, 2010). According to McShane *et al*., (2011), tradeoffs between conservation and development requires some "hard choices" and decisions that needs to be assessed regularly. The management plans of the NWSMA needs to be aligned to ensure sustainable development, and the conservation of biodiversity within an agricultural landscape. Partnerships of the NWSMA, CapeNature and SanParks with various organizations, provide beneficial environments in which certain monitoring activities informs management strategies. This is particularly important in the Nuwejaars catchment, as the cumulative impacts of agricultural activities, impacts of invasive alien vegetation and climate variability can have negative effects on wetland ecosystems (Jackson *et al*., 2016). Win-win results have been demonstrated with the clearing of invasive alien vegetation, where improved water flow and increased bird species richness has been recorded (Mazvimavi, 2018; NWSMA, 2019).

Thresholds

The hydrologic functioning of coastal lakes, which can be described by attributes such as change in storage, connectivity, timing, lag times and thresholds, is dynamic over time, and is influenced by the unique geographic and catchment characteristics (Brauman *et al.*, 2007). Findings from this research highlights the hydrologic functioning of the Soetendalsvlei (Figure 9.3), and characteristics which describes this lake as, and as part of, a complex social-ecological system. Knowledge of wetland inundation was relevant in describing bird species richness and diversity. Findings from this research also showed that the species response to wetland inundation could be explained by functional traits of waterbirds. By integrating different environmental datasets (such as Chapter 7), the value of citizen science avifauna data becomes more than an "early warning system" (Barnard *et al*., 2017), but a guideline for effectively monitoring strategies for waterbird conservation.

Knowledge of the threshold for storage overflow is important for the integrity of the estuarine ecosystem of the Heuningnes, and highlights the importance of managing the catchment in an integrated manner.

Resilience

Land use change in the Nuwejaars catchment has resulted in the loss and degradation of wetland ecosystems (Cleaver & Brown, 2005; Jones *et al*., 2000; Malan *et al*., 2015; Sampson, 2021). As the 'mirror' of the Nuwejaars catchment, the ecological condition of the Soetendalsvlei has remained the same, or possibly improved between the 1980s and 2015 (Malan *et al*., 2015). While the areal extent of wetland inundation exhibits significant annual and seasonal variation, there is no significant trend of wetland inundation between 1989 and 2019. The sedimentation in the Soetendalsvlei within the last century (Gordon *et al*., 2012) and evidence of the proliferation of emergent vegetation in the lake suggests a change (a possible decline?) in the storage capacity of the lake. With no previous bathymetric data for Soetendalsvlei, these suggestions cannot be validated. What was significant between 1938 and 2019 was the desiccation of the northern depression of Soetendalsvlei during the extreme drought periods. The permanent inundation of Soetendalsvlei South is indicative of the importance of groundwater flow for the lake. Despite the impacts of rainfall variability and land use change (1938 to 2014), Soetendalsvlei still provides various ecosystem services, and displays the characteristics of a resilient wetland system. As the hydrological functioning of Soetendalsvlei is intricately connected to the functioning of the upstream wetlands (in terms of regulating flow) and groundwater flow, the resilience of Soetendalsvlei is tightly coupled with the catchment conditions.

An integrated and multi-disciplinary approach is imperative when managing complex systems such as wetlands (Biggs *et al*., 2015; Parrott & Quinn, 2016; Biggs *et al*., 2017). Enabling conditions "that bring diverse people together" with different knowledge, roles and strengths to better understand complex social-ecological systems, and collectively develop or adapt management strategies, can promote a sustainable and ecologically resilient landscape (Biggs *et al*., 2015; Parrott & Quinn, 2016, p14). As one of the stakeholders stated, '*there is no one individual entity that will make a success of wetland conservation, if it is not done as a collective'*.

9.3.3 "Living Laboratory"

With the limited capacity of government institutions for long-term monitoring, and significant gaps in data, information and knowledge on aquatic ecosystems (Skowno *et al*., 2019), the construct of a "Living Laboratory" is to support long-term monitoring and scientific investigation that can enhance knowledge of wetlands and water resources, and inform adaptive management (Toucher *et al*., 2016; Zingraff-Hamed *et al*., 2019). Insights to the successful establishment of a "Living Laboratory" in Cathedral Peak research catchment in the high-lying, sparsely populated Drakensberg region South Africa (Toucher *et al*., 2016) and the urban Isar River floodplain in Germany (Zingraff-Hamed *et al*., 2019) both advocate for stakeholder collaboration across various scales and disciplines, and the fostering of partnerships. Lessons learnt from the establishment of the "Living Laboratory" in the Nuwejaars catchment is that the process is dynamic, requires time and commitment, a willingness to share and learn, and to collaboratively identify common goals or objectives that ultimately support shared or overlapping visions.

According to the Memorandum Of Agreement (MOA) between the Institute for Water Studies at the University of the Western Cape (IWS-UWC) and Breede-Gouritz Catchment Management Agency (BGCMA), the approach in establishing the ungauged Nuwejaars catchment as a "Living

Laboratory" was aimed at "bringing together people, providing research and training opportunities, enabling technologies and know-how and, in a broad sense, providing collaboration infrastructures to facilitate development and innovation". The Nuwejaars catchment, as a "Living Laboratory" consists of a network of landowners, communities, public institutions, non-governmental organizations, research institutes, tertiary institutions, citizen scientists and other relevant stakeholders bringing about conditions that create opportunities to generate knowledge of scientific value (Table 8.1).

To adequately address the objectives of this research required the participation and engagement of the researcher in, and with, the "Living Laboratory". This research was part of the larger research project "Finding 'new' water to address conflicting and competing water demands in the Nuwejaars catchment, Cape Agulhas" (WRC Report No 2324/1/18) awarded to the Institute for Water Studies at the University of the Western Cape (IWS-UWC) (Mazvimavi, 2018). In adhering to the protocol of hydrological monitoring (WMO, 2008), and to the formal and informal agreements with relevant partners, the site selection and installation of equipment (to address objectives 2, 3 and 4 of this research) were successfully completed with support from various stakeholders (Figure 9.4). Given the various MOA's of the IWS-UWC with stakeholders in the Nuwejaars catchment, the IWS-UWC shared available data and information with the "Living Laboratory".

There are various stakeholders of the "Living Laboratory", with each stakeholder having their own network of partnerships (examples include Figure 3.11 and 9.4), and so, contributing diverse interests, skills, data and knowledge of wetland ecosystems. For example, access to data and knowledge of avifauna in the Nuwejaars catchment are enabled by, amongst others, citizen scientists (Harebottle, 2020; Harrison, 2020) and personnel of the Agulhas National Park (SanParks), De Mond Nature Reserve (CapeNature), NWSMA, Birdlife South Africa, Overberg Crane Group, Agulhas Plain Birding Project, the South African National Biodiversity Institute and the Animal Demography Unit at the University of Cape Town. Given the available (and not always accessible), diverse environmental data and knowledge generated of the Nuwejaars catchment, there is support to foster research collaborations (Grenfell, 2020) and integration amongst the "silos of knowledge", which can contribute to the integrated knowledge and "data management and sharing imperatives" identified by the National Biodiversity Assessment" (Skowno *et al*., 2019, p187).

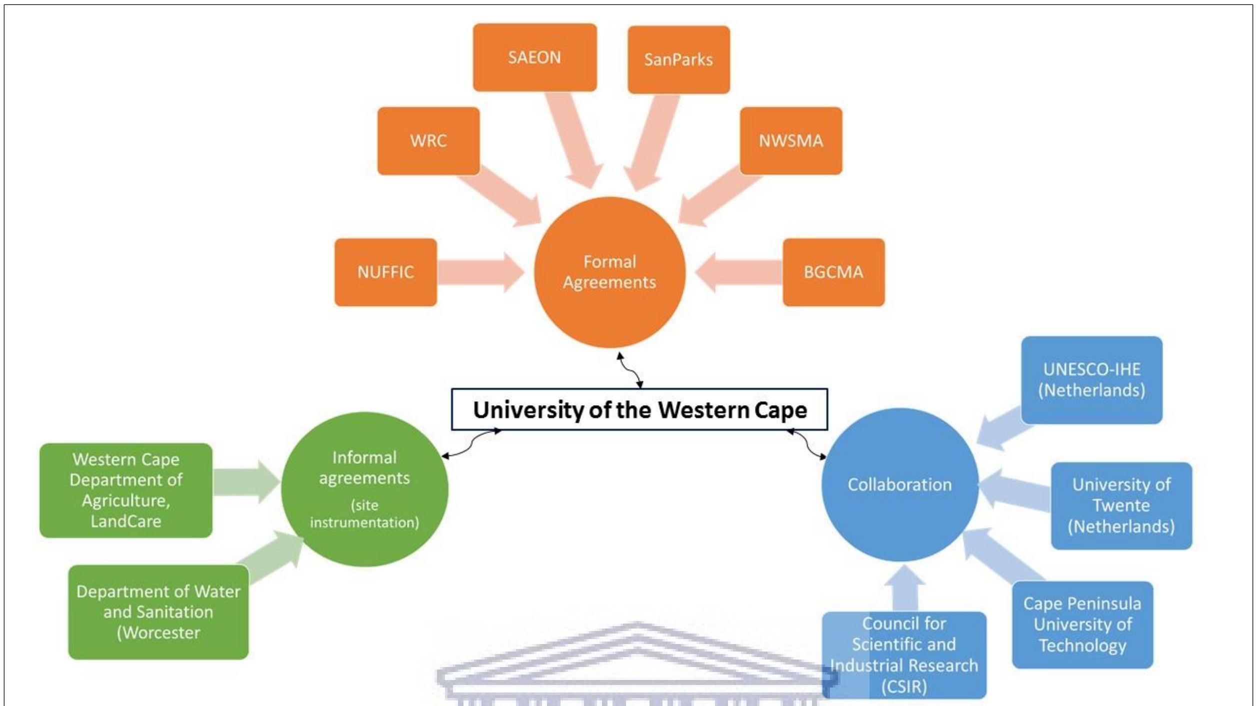


Figure 9.4 Organizations affiliated with the Institute for Water Studies at the University of the Western Cape in enabling the establishment of the catchment hydrological monitoring system in the "Living Laboratory" (2012 – 2015)

Further investment in the "Living Laboratory" is required to document and assess the dynamic organizational structure and the various roles and responsibilities of the stakeholders in generating and managing the available data and knowledge. With available hydrological, biophysical, climate and environmental data available for the Nuwejaars catchment, a coordinated approach to further identify data and knowledge gaps in the "Living Laboratory" is essential. By integrating multiple sources of relevant data on wetland ecosystems (such as the integration with avifauna data in Chapter 7), there is much opportunity to enhance our understanding of these complex systems. The challenge is then to incorporate this knowledge and understanding to better assess feedbacks, synergies and tradeoffs for the conservation of wetlands and in enhancing wetland ecosystem services (Xu *et al*., 2018; Skowno *et al*., 2019).

9.4 Research limitations and opportunities for future research

Continued, coordinated and integrated hydrological, biophysical and ecological monitoring is essential for an improved understanding of wetland ecosystem services. One of the main limitations of this study was access to consistent groundwater data to better understand the lake-subsurface water interaction over time. Continued monitoring of groundwater levels around Soetendalsvlei and in the Nuwejaars catchment; increased flow measurements to improve the flow rating curves and monitoring of the ungauged subcatchments in the Nuwejaars catchment is essential to improve our knowledge of the water balance of Soetendalsvlei.

The determination and calculation of the morphology of Soetendalsvlei can be updated with a repeat bathymetric survey, particularly of the western shore which is inundated with vegetation. Monitoring which is not 'invasive' within such a sensitive ecosystem needs to be further explored. The morphology of coastal lakes are not static, and is influenced by the deposition of sediment from the catchment, vegetation dynamics (e.g. stabilization effect; vegetation die-back etc.) and conditions (such as wind and waves) which cause the resuspension and movement of sediment within the lake. This has implications on water quality and the ecological conditions of the lake. Further research is needed to explore sediment transport from the Nuwejaars River, and sediment processes and movement within the lake.

While the morphology and frequency of inundation provides some insight into the capacity to provide ecosystem benefits, additional data on plant species composition and their functional traits will enhance our understanding of "the effectiveness of the wetland in providing a range of different ecosystem services" (Sieben *et al*., 2018, p448). Specific information such as plant height, above-ground biomass, stomatal conductance and specific leaf area of vegetation as a function of morphology, soil properties and depth to groundwater is needed to inform how Soetendalsvlei, as a complex system, provide ecosystem benefits (Sieben *et al*., 2018). This is particularly important where the distribution and composition of wetland vegetation changes over time (Russell, 2003). Specifically in Soetendalsvlei, the measurement of evapotranspiration from wetland vegetation is recommended to understand the influence on flow regulation (Sánchez-Carillo *et al*., 2004; Dye *et al*., 2008; Parsons & Vermeulen, 2017). Measurements should be conducted over a sufficient time-period so as to incorporate the variable climatic conditions and the influence of plant senescence on evapotranspiration (Parsons & Vermeulen, 2017). The available *in situ* evapotranspiration measurements will also improve the conceptual water balance model for wetlands (Maherry *et al*., 2016), and is also useful when assessing the feasibility of remotely sensed data as a data source (Bredin *et al*., 2019).

While the integration of wetland inundation with avifauna data provide some insight to bird distribution, incorporating other relevant biotic (e.g. invertebrates, fish) and abiotic data (e.g. water quality, climate data) is recommended. Bird counts should be continued at Soetendalsvlei, with survey sites located at Soetendalsvlei North and Soetendalsvlei South. Water quality and ecological data should be continually collected and integrated with the available knowledge of lake morphometry and lake water level and/or inundation to establish how the ecological state of the lake changes over time. Given the varied factors influencing bird populations, more complex statistical analysis or modelling that combine relevant and site/area/region-specific factors may provide more meaningful results that explain favourable conditions for increased bird abundance and diversity (Pickens & King, 2014).

The complexity of social-ecological systems requires an in-depth, integrated and transdisciplinary research approach that will provide insight into how interactions, decisions and management strategies at multiple scales (of time, space and governance) influences ecosystem functioning.

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APPENDICES

Appendix A: List of bird species for Voëlvlei and Soetendalsvlei (based on CWAC counts)

Total: total number of birds counted during the survey period

Min: Minimum number of birds counted during a single CWAC count

Max: Maximum number of birds counted during a single CWAC count

Ave: Average number of birds counted during the survey period

Count: Number of times birds were observed during the survey period

Voëlvlei CWAC Count Period: January 2017 to October 2019 (11 counts)

Soetendalsvlei CWAC Count Period: February 2000 to January 2017 (13 bird counts)

	Voëlvlei					Soetendalsvlei				
Species	**Total**	**Min**	**Max**	**Ave**	**Count**	**Total**	**Min**	**Max**	**Ave**	**Count**
African Black Duck	3	3	3	3	1	26	1	16	9	3
African Darter	51	1	36	7	7	256	1	120	26	10
African Fish-Eagle	9	1	7	3	3	18	1	4	2	9
African Marsh-Harrier	2	1	1	1	2	22	1	13	6	4
African Oystercatcher	0				0	27	27	27	27	1
African Sacred Ibis	24	1	12	5	5	257	5	71	29	9
African Snipe	25	25	25	25	1	13	3	10	7	2
African Spoonbill	46	1	26	9	5	28	1	12	6	5
African Swamphen	0				0	15	1	7	4	4
Black Crake	0				0	7	1	3	1	5
Black Harrier	0				0	7	2	5	4	2
Black-headed Heron	0				0	23	1	5	3	8
Blacksmith Lapwing	194	1	104	19	10	182	3	35	17	11
Black-winged Stilt	438	11	145	63	7	41	1	18	8	5
Blue Crane	0				0	59	4	50	20	3
Cape Cormorant	0				0	40	1	35	10	4
Cape Shoveler	324	1	140	41	8	11	5	6	6	2
Cape Teal	132	5	64	22	6					
Cape Wagtail	233	1	79	21	11	102	2	23	9	12
Caspian Tern	0				0	17	1	8	3	5
Cattle Egret	41	1	31	14	3	151	1	65	19	8
Chestnut-banded Plover	0				0	2	2	2	2	1
Common Greenshank	25	25	25	25	1	3	3	3	3	1
Common Moorhen	0				0	34	4	15	9	4
Common Ringed Plover	226	15	88	45	5	28	4	12	7	4
Common Sandpiper	1	1	1	1	1	8	2	6	4	2
Curlew Sandpiper	53	2	44	13	4	48	12	21	16	3
Egyptian Goose	4064	5	1822	406	10	1552	4	503	119	13
Glossy Ibis	1	1	1	1	1	152	1	68	30	5
Goliath Heron	0				0	1	1	1	1	1

Appendix A: continued

	Voëlvlei					Soetendalsvlei				
Species	**Total**	**Min**	**Max**	**Ave**	**Count**	**Total**	**Min**	**Max**	**Ave**	**Count**
Great Crested Grebe	0				0	3	1	2	2	2
Great Egret	0				0	3	1	2	2	2
Great White Pelican	156	2	90	52	3	56	1	53	19	3
Greater Flamingo	1093	30	400	219	5	3	1	2	2	2
Greater Sand Plover	0				0	3	3	3	3	1
Grey Heron	15	1	5	2	8	38	1	11	4	10
Grey Plover	10	1	9	5	2	21	1	11	4	5
Hadeda Ibis	26	2	15	7	4	112	2	26	12	9
Hartlaub's Gull	0				0	2	2	2	2	1
Hottentot Teal	0				0	8	8	8	8	1
Kelp Gull	35	1	10	4	8	77	1	49	9	9
Kittlitz's Plover	699	8	218	70	10	115	1	62	16	7
Lesser Flamingo	103	5	58	34	3	206	56	150	103	2
Little Bittern	0				0	1	1	1	1	1
Little Egret	0				0	41	1	20	5	8
Little Grebe	5	5	5	5	1	29	5	11	7	4
Little Stint	9611	582	3986	1602	6	270	18	224	90	3
Malachite Kingfisher	0				0	2	2	2	2	1
Marsh Sandpiper	6	2	4	3	2	8	8	8	8	1
Osprey	0				0	3	1	2	2	2
Pied Avocet	600	13	168	120	5	7	7	7	7	1
Pied Kingfisher	0				0	15	1	5	3	6
Purple Heron	0				0	13	1	5	3	5
Red Knot	0				0	2	2	2	2	1
Red-billed Teal	310	3	102	44	7	7	2	5	4	2
Red-knobbed Coot	32	2	30	16	2	109	2	27	16	7
Reed Cormorant	18	2	10	6	3	146	1	41	12	12
Ruff	52	8	34	17	3	53	2	43	11	5
South African Shelduck	1634	2	1355	233	7	273	1	260	68	4
Spur-winged Goose	798	2	636	114	7	446	1	251	50	9
Three-banded Plover	155	1	108	22	7	91	1	29	9	10
Unidentified Ducks	249	49	200	125	2	1	1	1	1	1
Unidentified Waders	2250	50	2000	750	3					
Water Thick-knee	3	1	2	2	2					
White-breasted Cormorant	48	1	17	7	7	127	2	35	14	9
White-faced Duck	0				0	1	1	1	1	1
White-fronted Plover	1	1	1	1	1					
Wood Sandpiper	1	1	1	1	1	19	19	19	19	1
Yellow-billed Duck	643	2	227	64	10	466	2	192	58	8