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ASSESSING THE EFFECT OF THE KARS WETLAND ON FLOW ATTENUATION IN THE CAPE AGULHAS, SOUTH AFRICA

Submitted by

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Abstract

The Kars has a well-defined channel along the 62 km stretch from its sources in the Bredasdorp Mountains. After entering the Agulhas plain which has a very low gradient, this river changes into a triangular shaped wetland. This wetland is 7 km in length with no defined channel running through it. The wetland then discharges into another 7 km long channel that joins the Heuningnes River with its mouth at the Indian Ocean. The presence of the wetland causes frequent flooding which affects cultivated lands and a major highway linking towns on the coastal Cape Agulhas area with the rest of the country. Before this study, there was no monitoring of flows along the Kars River including water levels within the wetland. Consequently, the conditions leading to flooding of the wetlands were unknown. This study is aimed at understanding how the combination of local rainfall, Kars River inflow into the wetland, soil characteristics, and the morphology of the wetland influence flooding/inundation. The study monitored river inflows into and outflows from the wetland. A soil survey was conducted within the wetland using the augering method and an infiltrometer to determine soil type and infiltration rates. This was done to assess the hydrological characteristics of the wetland. Using the collected climate data and river flow data, a conceptual model was developed for predicting downstream outflows and possible flood events on a daily timescale. The results indicated that the Kars wetland comprises soil with high silt and clay content, and low infiltration capacity. The wetland causes flood attenuation and diffuse surface flows. Low infiltration rates result in ponding of local rainfall which can contribute to flooding.

Keywords: Flood Attenuation; Ungauged Catchment; Wetland; Wetland Delineation; Wetland Hydrology

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1. INTRODUCTION

1.1 Background

Natural resources within any country have to be managed sustainably in order to provide basic needs and services to humans. To manage these resources in a sustainable manner, there is a need for adequate information about the spatial and temporal dynamics of the availability of natural resources (Molobela and Sinha, 2011). A lack of adequate data leads to poor decision-making in resource management as well as infrastructure design. Hydrological data such as river discharge and rainfall are required for sustainable water resource management. These data include both the quantity and quality of water, and water usage within a given catchment, since water is managed at catchment level as recommended by ICWE (1992) and adopted globally as part of integrated water resource management (Global Water Partnership, 2000).

Wetlands play a vital role in catchment management as they regulate the flow of water through catchments (Bullock and Acreman, 2003). Wetlands provide ecosystem services for both humans and animals. First and foremost wetlands provide food and shelter for many different species of insects and animals. Promoting biodiversity is an important topic in conservation and many wetlands are regarded as hosting areas of high and unique biodiversity (Thorslund *et al*, 2017). The biodiversity of wetlands provides goods to humans such as reeds for thatching and fertile soils for farming. The abundant plant diversity acts as natural filters, improving water quality as well (Fan *et al*, 2012). As water flows through wetlands, plants trap and absorb pollutants in the water. Wetlands possess the potential to attenuate floods and prolong base-flows (Owen, 1995; Evenson *et al*, 2015). The most common notion regarding wetlands effect on flows is that wetlands act like a “sponge”, absorbing water (from floods) and slowly releasing the water ensuring that the river does not run dry or stay dry for a long period of time (Richardson and Vepraskas, 2001).

There are many different types of wetlands. Wetlands around the world have different water balance characteristics, different vegetation species and soil types. All wetlands have a dominant water source, which would either be groundwater or surface water. Wetlands are typically believed to occur in depressions but this is not always the case. Wetlands occur on slopes as well in the form of seep wetlands. These wetlands are groundwater fed wetlands, and occur along geological faults (Ollis *et al*, 2013). There are a number of problems which occur with the management of wetland areas. These arise as a result of gaps in knowledge regarding wetlands. These include knowledge regarding the biodiversity of the wetland, sustainability of resources (reeds) and behaviour of flow attenuation for specific wetlands (Belle, Collins and Jordaan, 2018).

Wetland specific studies should be done to increase the understanding of different types of wetlands, and provide information regarding their characteristics and importance. These studies should focus on the amount of resources a wetland provides sustainably, the extent to which these wetlands should be used for agricultural purposes, water purification of wetlands, biodiversity and lastly flood attenuation ability. These gaps in knowledge give rise to various challenges in the management of wetlands. These challenges include the creation of inadequate laws and policies, poor agricultural practices in wetlands, overexploitation of resources and also inadequate infrastructure development and planning for flood risks (Belle, Collins and Jordaan, 2018).

These problems occur at a global scale. There are many research papers which aim to understand wetlands and their characteristics. One of the biggest challenges facing the world is flooding. Flooding occurs everywhere. Wetlands occur almost everywhere on Earth. Therefore flood attenuation studies are important. Holden and Acreman (2013) reviewed 28 wetlands flood attenuation abilities in order to establish the relationship between wetlands and floods. Bullock and Acreman (2003) did a literature review of 439 published wetland studies to link wetland type with various hydrological processes. These reviews included studies conducted in the Americas, Europe, Africa and Asia. In both reviews it was found that most wetlands improve flood attenuation and the water quality of river flows but this is not true for all wetlands.

Flooding in this region is very unpredictable as rainfall can vary greatly over short distances. The level of soil saturation also plays a role in runoff which contributes to river flows. River water levels are also important in the prediction of flooding and establishing flooding thresholds. With a better understanding of how floods occur in a catchment and how a wetland attenuates floods, property damage can be mitigated, infrastructure development can be improved and loss of assets and life can be mitigated in the future.

1.2 Problem Statement

The problem which has to be addressed is the inadequate knowledge regarding the effect wetlands have on river flows in the Heuningnes catchment located in the Cape Agulhas (South Africa). This catchment was not monitored by the relevant organ of state and therefore the above problem cannot be addressed using existing data. It is therefore not known whether the wetlands in this catchment, and specifically the Kars Wetland, have the ability to reduce flood flows and prolong base flow. There is a lack of information regarding the baseline conditions of the Kars Wetland.

The climatic conditions over the wetland are not adequately understood. Thus, it is not known how much rainfall occurs in the area on an annual basis as well as evapotranspiration rates. The inflow and outflow points of the wetland are also poorly understood. The inflow point of the wetland is surrounded by dense reed vegetation, making it impossible to monitor the exact point of inflows. The outflow point of the wetland is dry for majority of the year, and it is unknown whether the wetland discharges at multiple points. The water budget of this wetland is not understood which makes it impossible to quantify inflows and outflows. The soil types of the wetland are unknown, and soil type can affect various hydrological processes such runoff and storage depending on the sand, silt and clay content.

The R319 road which runs between Bredasdorp and Struisbaai located in the Western Cape, South Africa, floods on an irregular basis. This road cuts through the Kars Wetland. The road has to be closed periodically in the winter due to the flooding during the rainy season. The conditions of the flooding are unknown and therefore have to be determined in order to assist in developing an early warning system.

This study aims to investigate effects that wetlands have on river flows in the Cape Agulhas region. It is largely assumed that wetlands reduce flood flows and increase flow duration. Information from this study can be useful for integrated water resources management

(IWRM) undertaken by the catchment management agency. Information from this will contribute to improved decision making such as early flood warning. It is therefore hypothesised that the wetland will reduce river discharge due to the gentle slope and lack of a defined channel and slowly releasing the flows over time. The extended flow duration would therefore also result in a large amount of water lost through the process of evapotranspiration (Shahin, 2002).

1.3 Aim and Objectives

Aim:

The aim of this study is to contribute to the understanding of how lowland wetlands affect hydrological processes in the Cape Agulhas region.

Objectives:

1. To establish the morphological, vegetation and soil characteristics of the Kars Wetland to aid in understanding the wetland hydrology
2. To establish how the Kars Wetland affects the flow regime of the Kars River

1.4 Outline of thesis

Chapter one of the thesis will provide a basic background to wetlands as well as the aims and objectives to the study. Chapter two is a review of literature on various aspects regarding wetlands and river flows. This chapter aims to provide more insight into the topic for better understanding. Chapter three outlines the methodologies used to complete the study. Chapter four provides the results on wetland morphology, vegetation and soil. Chapter five provided results on the climatic conditions of the study area. Chapter six provides results on the modelling, which aims to predict river flows through the wetland and Chapter 7 concludes the findings of the study.

2. LITERATURE REVIEW

2.1 Introduction

There are a number of different aspects that need to be discussed to assess how wetlands affect river flows. This chapter will provide the necessary information required to investigate wetland morphology, soils and the effect wetlands have on river flows. Understanding how hydrological research is done in ungauged catchments is a valid starting point. Identifying wetlands as a hydrological feature through wetland delineation is a key process in this study that will also be discussed, as well as the various classification factors that aid in classifying a wetland to understand some of the characteristics that the wetland might have. Hydrological modelling and water budgets are another aspect of this study which will be discussed further in this chapter.

2.2 Hydrological studies in ungauged catchments

Ungauged catchments are found all over the world, however they are far more commonly found in Sub-Saharan Africa (Mul, 2009) due to the lack of long term hydrological data, which introduces uncertainties in determining the river flow characteristics and implementing sustainable water resources management measures.

Studies conducted in ungauged catchments require a large amount of primary data for full catchment assessment and monitoring. A catchment monitoring system for collecting data on weather elements and river flows is required. Climate variables such as rainfall and temperature should ideally be monitored at fifteen minute intervals, whereas river water levels can be monitored at an hourly time interval. River discharge measurements can be recorded bi-weekly or weekly depending on weather conditions. The short term data record is then used as inputs for models. Hydrological models are used to predict floods and droughts, future water availability and for engineering purposes such as bridge and dam development (Kokkenen *et al*, 2003).

An ever growing human population has resulted in an increase in water demand for domestic and agriculture uses (Mul, 2009). This calls for the need to explore other water sources such as those occurring in ungauged catchments.

2.3 The value of rivers in the catchment

Rivers can be classified as perennial or non-perennial / ephemeral. Perennial rivers flow all year round, while non-perennial rivers are seasonal or only flow during certain parts of the year. Perennial rivers can dry out during extreme droughts. Non-perennial rivers typically flow for less time than they are dry (Rossouw *et al,* 2005).

From an environmental stand point, the importance of river flows is related to the ecological requirement to sustain the natural environment. This refers to the sustainability of both the animal population as well as the vegetation. Rivers are also important for nutrient transport (Brusca *et al*, 2017). Estuaries are known to be areas of high biodiversity especially for aquatic species, due to the nutrients supplied by the rivers (Brusca *et al*, 2017; Duval and Colby, 2017). Rivers serve as a water source for riparian vegetation (Shen *et al*, 2017). Floods typically provide water to vegetation on floodplains and surrounding areas and therefore contribute to the sustainability of the ecosystems.

Agriculture is a particular sector that benefits from river flows. Farms typically take up large areas of land which are often located along side or near rivers. Therefore the water demand for agriculture is quite high. However agriculture is only one sector. Another sector that benefits from river flows is fisheries (Duval and Colby, 2017). It was found that fisheries productivity increased with increased river flows. This in turn could be related to the nutrients supplied by the river (Brusca *et al*, 2017). Increased nutrients in the estuary may attract more aquatic life.

Rivers are important for the supply of water for domestic use. However river flows have to be quantified accurately (Anderson *et al*, 2017). Globally, flooding has become a growing concern as floods are occurring more frequently with greater intensity, and therefore accurate quantification of river discharge is important for infrastructure design as well as to serve as an early warning system (Anderson *et al*, 2017; Billi and Fazzini, 2017).

2.4 The value of wetlands in the catchment

The role of wetlands in the catchment has gone unrecognised or was poorly understood for a long period of time, but has recently been considered a key factor influencing hydrology and sustainable economic growth in terms of food production for local populations (Kotze, 2005). Wetlands can occur anywhere in the catchment. Wetlands are defined as a "transitional zone between aquatic and terrestrial environments", meaning an area that has characteristics of both aquatic and land ecosystems (Collins, 2005; DWAF, 2007).

Wetlands occur on plateaus, hillslopes and plains (Savenije, 2010). Wetlands occur where surface water or groundwater gathers and saturates the soil which may lead to shallow inundation on the earth's surface for a short period of time or permanently in some cases. This is highly dependent on the water source and topography (Bullock and Ackerman, 2003). Regardless of topographical location, wetlands provide a number of direct and indirect benefits (Table 2.1). (Kotze and Breen, 1994; Kotze *et al*, 2005; Collins, 2005).

The direct benefits of wetlands include a water supply for domestic use, agriculture, tourism and recreational activities (Collins, 2005). Wetlands directly benefit humans economically, which is why wetland conservation has been an important part of IWRM goals and management practices. The indirect benefits of wetlands include a series of hydrological benefits, biodiversity and biochemical cycling (Kotze *et al*, 2005). These benefits include water purification, flood attenuation, sustained base flow, groundwater discharge and recharge, and erosion control.

Water that flows out of a wetland area should be of a better quality than water that entered the wetland. This is due to sediment trapping which is a key function of a wetland (Yang *et al*, 2016; Shoemaker *et al*, 2017). The sediment trapping is a trade-off of the attenuation of river flows and runoff from rainfall. As the flows slow down, deposition of suspended material takes place. The flow attenuation ability of a wetland is a vital function of a wetland which has various benefits. This allows wetlands to attenuate flood flows which could cause a large amount of damage not only to a downstream human population, but also contribute to environmental degradation (Watson *et al*, 2016). The attenuation regulates flow out of the wetland so that base flow and evapotranspiration occurs over an extended period of time.

Table 2.1 Typical ecosystem services provided by wetlands (Collins, 2005)

Category	Examples
Provisioning	- Food supply (e.g rice) - Materials (e.g thatching reed) - Medicines (e.g extracts from plants)
Regulatory and Maintenance	- Flood control - Water quality regulation - Biodiversity regulation
Cultural and Recreational	- Religious practices - Fishing - Bird watching - Water sport activities

2.5 Wetland classification and delineation

2.5.1 Classification of wetlands

An important part of understanding wetlands is being able to identify and classify wetlands in the catchment. By understanding what type of wetland is located in the catchment, it would be possible to predict what type of hydrological processes occur in that wetland and which of those processes are dominant. There are various ways of classifying wetlands.

One of the earliest wetland classification systems, Classification of Wetlands and Deepwater Habitats of the United States, was developed by Cowardin *et al* (1979). This classification system was developed as a result of a fragmented and poorly implemented classification system (FGDC, 2013). The system developed by Cowardin *et al* (1979), required three factors for the positive classification of wetlands. These include hydrophilic vegetation, hydric soils and wetland hydrology (inundation) (Cowardin *et al*, 1979).

The Classification of Wetlands and Deepwater Habitats of the United States arguably relied to a large extent on vegetation species and cover (Brinson, 1993). Therefore Brinson (1993) developed an alternative classification of wetlands. This classification system differs from that of Cowardin *et al* (1979) because there is less focus on vegetation, and instead a large factor in wetland classification is placed on the hydrogeomorphic setting (e.g valley bottoms and floodplains) and dominant water sources.

Topography is one of two factors for classifying a wetland (Bullock and Ackerman, 2003). Bullock and Ackerman (2003) favoured the classification system by Brinson (1993) that classified wetlands as depression, floodplain or slope wetlands. The second factor for classifying wetland type is the dominant water source. This creates two types of wetlands which are groundwater dependent and surface water dependent wetlands (Brinson, 1993; Bullock and Ackerman, 2003). This classification system has five distinct wetland types which are groundwater depression wetlands, groundwater slope wetlands, surface water depression wetlands, surface water slope wetlands and floodplain wetlands. This classification system was used in a case study to investigate hydrological functions of wetlands on a global scale. This system may be effective for identifying wetlands however it is not a commonly used method for classification in South Africa. This may be because South Africa does not have wetland systems such as swamps.

The Classification System for Wetlands and other Aquatic Ecosystems in South Africa, developed by the South African National Biodiversity Institute (SANBI) is the standard method of classifying a wetland in South Africa (Ollis *et al*, 2013). This method of classification is more suitable for the study area than the method used in Bullock and Ackerman (2003) because it classifies wetlands on regional setting, landscape setting, hydrogeomorphic unit (HGM), hydrological regime (perennial or non-perennial) and descriptors (soils and vegetation).

The structure of the Classification System for Wetlands and other Aquatic Ecosystems in South Africa is as follows:

Level 2: Regional setting identification

Level 3: Landscape setting identification

Level 4: Hydrogeomorphic unit identification

Level 5: Hydrological regime identification

Level 6: Wetland descriptors

The first step in this method would be to identify the regional setting of the wetland which is known as Level 2 classification. This is the general geographical location in South Africa. There are twenty two regional settings based on the classification system by the Department of Water and Sanitation (DWS) of which the Cape Agulhas area is located in the South Coastal Belt region (Ollis *et al*, 2013). Level 3 classification calls for identification of the landscape setting, which refers to valley floor, plain, slope and bench (hilltop, saddle, and plateau). This relates to the topographical setting of the wetland as used in the system by Bullock and Ackerman (2003). Level 2 and 3 of the classification system is known as wetland/aquatic ecosystem context which refers to the basic geographic location within South Africa in terms of vegetation, climate and geological patterns (eco-regions) as well as whether the wetland occurs on a slope, valley floor or plain.

Level 4 of the classification system is the identification of the HGM (Ollis *et al*, 2013). The HGM unit describes the wetland system, its sources of water and the processes that are likely to occur in that wetland. There are seven HGM units that are described. These include rivers, a floodplain wetland, channelled valley-bottom wetland, unchannelled valley-bottom wetland, depression wetland, seep wetland and a wetland flat. This method differs from Bullock and Ackerman (2003) in that this method takes into account various water sources as opposed to the dominant water source classification used by Bullock and Ackerman (2003).

Floodplain wetlands are located adjacent to river channels. These types of wetlands usually occur on the plains, where there is a gentle slope. These wetlands were formed through alluvial depositional processes during flood events. These wetlands typically have geomorphological features such as oxbow lakes, point bars and levees (Ollis *et al*, 2013). Water enters these wetlands through over-spill from the river and rainfall. The movement of water through these wetlands can be both horizontal (flowing with the river channel gradient) and vertical (groundwater recharge and discharge) through the soil column. Groundwater may be a source of inflow in these wetlands, however the groundwater influence is not always present in these wetlands.

Valley-bottom wetlands are located on flat areas on the valley floor. They are often connected to an upstream or adjoining river channel. The wetlands are sites of sediment accumulation that serve as temporary storage sites, similar to floodplains. However deposition from the river is not as important in these wetlands (Ollis *et al*, 2013). Therefore few depositional features are present in valley-bottom wetlands. There are two types of valley-bottom wetlands. Channelled valley-bottom wetlands which have a defined river channel flowing through the wetland, and unchannelled valley-bottom wetlands, which lacks a defined river channel flowing through the wetland. Channelled valley-bottom wetlands receive inputs from the river that flows through it, overland flow from the valley slopes and in some cases groundwater. Unchannelled valley-bottom wetlands receive inputs from overland flow from the valley slopes and groundwater (Ollis *et al*, 2013).

Depression wetlands are located in topographical depressions. The depth of these wetlands increase with distance from the perimeter to the centre. These wetlands may have a river flowing into, or out of, them, however; they are mostly characterised by a closed contour shape. Some depression wetlands are so flat that it can be easy to classify these wetlands as floodplain flats or wetland flats (Ollis *et al*, 2013). Looking at the wetland over a large area may reveal the pan-shaped nature of these wetlands. Inflow into depression wetlands are surface inflow, groundwater inflow and overland flow. Groundwater and channelled surface water may not always be present. Depression wetlands can be classified as exorheic (inward draining) or endorheic (outward draining). Endorheic depression wetlands lose water through evaporation and infiltration only, whereas exorheic wetlands can lose water through diffuse surface flow or subsurface flow (Ollis *et al*, 2013).

Seep wetlands are located on gentle to steep sloped areas. They are generally found on valley slopes and do not extend onto the valley floor. Movement of water and material is in one direction. Seep wetlands are characterised by their association with geological features, such as areas where groundwater discharge takes place (Ollis *et al*, 2013). Inflows into a seep wetland is primarily through groundwater discharge and rainfall. Outflows are usually in the form of evapotranspiration and channelled outflow, which may not always be present.

A wetland flat is not connected to a nearby drainage system and occurs in a flat topographical area. This HGM type describes wetlands in a flat area such as a plain, disconnected to a drainage network and where the dominant inflow of water is through precipitation. Movement of water in these wetlands are usually vertical, and if horizontal movement of water occurs, it will be diffuse overland flow. Inflows into this wetland is precipitation and groundwater. Outflows are usually through evapotranspiration and infiltration (Ollis *et al,* 2013).

2.5.2 Wetland description

Wetland description or Level 6 of the classification process is a procedure aimed to identify vegetation types, soil types, climate patterns and hydrological regimes in terms of river flows and groundwater influences (Ollis *et al*, 2013). This procedure is applied in the field by physically identifying soils and vegetation to determine whether the ecosystem is a wetland or not. There are three factors which have to be evaluated in order to determine whether the investigated ecosystem is a wetland or not, and also to determine its spatial extent. These are hydrology (inundation or saturated soils), vegetation (hydrophilic) and soils (hydric). The presence of one of these above mentioned factors will be enough to classify a wetland. Recently the addition of remote sensing has improved the wetland classification.

Hydrology

The driving force of all wetlands is water (DWAF, 2008). The wetland hydrology (the movement of water through a wetland) has to be observed to determine whether or not an ecosystem can be classified as a wetland. According to the National Water Act of South Africa “the water table is usually at or near the surface, or the land is periodically covered with shallow water" (DWAF, 2008). South Africa is largely classified as a semi-arid country. Therefore most wetlands in South Africa are likely to be non-perennial (Melly *et al*, 2017). Relying on hydrology to classify wetlands in South Africa would be insufficient. Wetlands in South Africa may be wet during the rainy season, however in the dry season they may almost disappear, making them hard to identify based solely on hydrology (Melly *et al*, 2017).

Soil

Water may not always be obvious in the environment, in that a wetland is not always inundated. Therefore in order to determine whether the correct hydrological conditions are present in the ecosystem, soils are considered to be an important indicator of a wetland. This means that the soils are saturated sufficiently during the year. When soils are saturated for long periods of time, anaerobic conditions occur in the soil (DWAF, 2008). Once anaerobic conditions occur, the soils develop two characteristics. These characteristics are mottling and gleying (Ollis *et al*, 2013). These conditions do not always occur together. Gleying is characterised by the formation of a grey or blueish-grey colour in the soil. This occurs from the dissolved iron oxides in the soil from extended saturated conditions. Mottling occurs through the same process as gleying. The dissolved iron oxides are deposited in patches from a fluctuating water table. These are observed to be red, brown spots or strips in the soil profile (DWAF, 2008). If one of these characteristics are identified, the soils can be classified as hydric (hydromorphic) soils. Soils have the ability to restrict movement of water. Soils with high clay content can prevent groundwater from rising to the surface if they occur below the surface as perches (Melly *et al*, 2017). These conditions lead to rainwater saturating the surface soil layer. Soil texture can be determined using the hydrometer method, sieving method or the settling tube analysis method *(*Thiede *et al*, 1976).

Vegetation

The anaerobic conditions in soils create conditions that restrict certain vegetation from growing in the wetland. Vegetation that grows in hydric soils are known as hydrophilic (water loving) plants (Ollis *et al*, 2013). There are various species that occur in wetlands which include grasses, sedges and reeds. The identification of hydrophilic vegetation has been considered a key indicator in describing and classifying a wetland as these vegetation types only thrive in wet conditions (Kotze *et al*, 2005).

Normalised Difference Vegetation Index

Remote sensing has become a valuable tool for conducting scientific research, especially in areas that are difficult to access. Remote sensing has therefore also been included in wetland studies by various researchers and organisations such as the Wetland Status and Trends Unit in the United States of America, through the use of satellite imagery and remote sensing software (e.g. ArcGIS) to monitor wetland health and track wetland losses (Young and Dahl, 1995). One remote sensing technique that is very useful in delineating and describing a wetland is the Normalised Difference Vegetation Index (NDVI) (Huang *et al*, 2014; White *et al*, 2016). The NDVI allows a user to determine the response of vegetation to moisture. This is done by measuring the reflected radiation of the vegetation. NDVI is essentially a measurement of vegetation health. Actively growing plants absorb more red light than those that are stressed. Wetlands have a lot more moisture in the soil than normal terrestrial ecosystems, therefore wetland vegetation will be distinct from these other land areas when seen on the NDVI image (Davranche *et al*, 2014). NDVI has been used in various different studies related to vegetation health, such as wetlands, agriculture and even land degradation studies (Yengoh *et al*, 2014).

Normalised Difference Water Index

Another tool which can be used to delineate and describe a wetland is the Normalised Difference Water Index (NDWI). Instead of analysing vegetation response such as the NDVI, the NDWI depicts moisture content and more specifically open water features (McFeeters, 1996; Huang *et al*; 2014). This allows a user to identify areas of open water such as oceans, rivers, dams, pools in river beds and even swimming pools in urban areas (McFeeters, 2013). NDWI is a vital tool for delineating and describing a wetland as wetlands have higher moisture content than the surrounding terrestrial environments (Davranche *et al*, 2014). Therefore a wetland should ideally be a distinct feature in an NDWI image, either shown as an area of high moisture or in some cases as open water due to the inundation of the wetland. It may not always be as simple as that, as some wetlands may remain indiscernible from the surrounding terrestrial environment as water in a wetland is not always above the earth's surface or exposed in view of the satellite due to vegetation cover (Wolski *et al*, 2017). However changes in water content of leaves can be monitored using the Modified Normalised Difference Water Index (MNDWI) as well as identifying open water bodies (Du *et al.*, 2016). This can be used in conjunction with the NDWI in an attempt to monitor wetland inundation and flow pathways.

2.6 Effects of wetlands on river flows

There have been a large number of studies conducted to determine effects of wetlands on river flows (Bullock and Acreman, 2003; Zhou et al, 2017). These studies are done in order to assess wetland dynamics and the flood attenuating abilities of wetlands. Wetlands can affect river flows in a number of different ways (Acreman and Holden, 2013). Wetlands are said to behave like "sponges" in that they "absorb flows in wet seasons and release flows during the dry seasons" (Bullock and Acreman, 2003).

Wetlands can reduce flows, increase flows or have no effect on river flows at all (Bullock and Acreman, 2003). In most cases wetlands reduce floods (Thorslund *et al*, 2017; Zhou *et al*, 2017). The wetland conditions at the time of peak flow are important in flow attenuation. These conditions include topography, landscape location, soil moisture, soil type, vegetation type and density and slope (Acreman and Holden, 2013). If the wetland soil is dry, the flow would be absorbed by the wetland until the soil is saturated. This reduces the peak flows. Soil type also plays a role in attenuating floods. A soil with high porosity such as sand would be much better at attenuating floods than soils high in clay content. This is because the porosity of clay soils is low, and therefore act as a semi-permeable or even impermeable layer for water to pass through (Bullock and Acreman, 2003; Acreman and Holden, 2013).

Steep slopes generally promote increased runoff rates and reduced infiltration rates of soils. Therefore an increase in runoff aids in flooding conditions. Gentle slopes and plains are ideal for flood attenuation. These areas allow water to flow slowly, allowing for increased infiltration time, while also contributing towards diffuse flow, increasing flow time (Acreman and Holden, 2013). Peak flows will also be reduced and flow duration will increase (Lininger and Latrubesse, 2016). Vegetation type and density have a similar effect (Kadykalo and Findlay, 2016). Forested areas have been found to have no effect on flood attenuation, whereas wetlands, with shrubs and grasses tend to have good flood attenuation abilities. This is because forested areas have trees which are tall and not closely packed together, whereas shrubs tend to be smaller and have a higher density creating a good barrier for flow at ground level.

Wetlands can increase floods if the soils are saturated prior to the flood wave or if high intensity rainfall occurs over clay dominated catchments. Wetlands can also increase floods by releasing stored water or if the water table rises above the earth's surface. There is a trend that wetlands in upland areas increase flood frequency (Kadykalo and Findlay, 2016), because wetlands in these areas are known to be draining wetlands. These wetlands typically discharge water which contributes to runoff and flow of nearby rivers.

Kadykalo and Findlay (2016), Acreman and Holden (2013), Lininger and Latrubesse (2016) and Thorslund *et al* (2017) all agree with the findings by Bullock and Acreman (2003) which states that eighty percent (80%) of floodplain wetlands reduce floods. There are very few statements which show that wetlands increase floods (Bullock and Acreman, 2003). However it has been found that wetlands do increase floods, mostly wetlands in headwater regions. The study found that nineteen percent (19%) of wetlands (including wetlands in Africa, Europe, Asia and America) have shown to have no significant effect on river flows (Bullock and Acreman, 2003).

2.7 Modelling the effect wetlands have on river flows

One of the most cited and commonly mentioned services of wetlands is flow augmentation, which is the ability of a wetland to slow flows down and release the water over an extended time period (Kadykalo and Finlay, 2016). The ability to predict river flows is important in terms of planning for supply as well as disaster management. River flow modelling has been done in many different areas of the world. The main goal of modelling is to predict an outcome and forecast the most likely future conditions and scenarios.

Modelling is a useful tool. It allows a user to predict future events using current data. It is not always feasible to go into the field and manually record river flows and water levels. Therefore with a small data record, a model can predict events without the need for constant monitoring. Monitoring should be done in conjunction with modelling to evaluate the modelled outcome with the real life observations to assess the model performance.

There are many different types of models which can be used to predict river flows. Some models consist of seven to ten different parameters, whereas others will only require three or four parameters. An increase in parameters generally means an increase in complexity, due to the increased amount of processes that may need to occur. However, the most complex model is not always the best model (Devi *et al*, 2015). It is always best to use or develop the simplest model that is capable of doing the job. The more parameters that a model has, the more this increases the risk of over parameterisation of the model. This may result in a model that does not perform well or results in a model that performs well for the wrong reasons, such as producing accurate predictions with unrealistic input data or parameters.

The SWAT (Soil Water Assessment Tool) analysis tool is a physically based model. It is a continuous-event hydrological model that is used in GIS format. This model predicts stream flow in catchments with wetlands (Martinez-Martinez *et al*, 2014). It can also determine the impact of land management practices on water, soil and agricultural chemical yield. This is classified as a complex model as uses nine input parameters. A model with this complexity would require large data inputs or estimations in order to predict stream flow over time accurately. The accuracy of the model will decrease with an increasing number of estimations or assumptions, as these would not be precise or measured inputs. This model should ideally be used in catchments that have an extensive data record. The SWAT model performs well for long term predictions and is commonly used in the agricultural sector (Devi *et al*, 2015).

Another model which can predict stream flow and lake levels is the Variable Infiltration Capacity (VIC) model. This is a semi-distributed land surface model (Grimson *et al*, 2013). The VIC model uses a grid format coupled with a water budgeting approach. This model can be used to monitor flows of both surface and subsurface water. It has been successfully applied mostly in the northern hemisphere catchments with wetlands, as well as in African subtropical lakes. The VIC model performs well in moist environments (Devi *et al*, 2015). This too is a complex model which requires seven parameters.

There are a lot of models which have been developed over the years. The above mentioned models are only a few. Some commonly used models include MODFLOW and SWIM. The Soil and Water Integrated model (SWIM) is also a complex model. This model can provide a range of different outputs such as stream discharge, crop yield and nutrient concentrations. This model can integrate wetlands and riparian zones into a river basin (Hatterman *et al*, 2006). MODFLOW is used to predict flow through an aquifer (Karay and Hajnal, 2015). MODFLOW can be used in modelling the groundwater component of wetlands, such as in floodplains (Jolly and Rassam, 2009).

The development of a conceptual model is another way of understanding a catchment. This type of model is ideal for studies with short data records or unique landscape features and land uses. Villa and Tobon (2012) developed a conceptual model to determine water budgets of a catchment during the wet and dry seasons. The model performed adequately and only required four parameters. A similar approach was taken by Savenije *et al* (2010), through the development of the FLEX-topo model. This approach divided the catchment into three different classes based on topography, namely; plateau, hillslope and wetland. Each class has its own conceptual model and parameters. The wetland conceptual model has four parameters. The FLEX-topo model also allows for customisation. The model can be altered to represent the catchment in the best way possible. These types of models have proven to be very effective. Another popular and effective rainfall-runoff model is the Hydrologiska Byrans Vattenafelning (HBV) model (Devi *et al*, 2015). This is a simple model designed to predict runoff in catchments using climate data, and it also incorporates snow.

2.8 Summary of key concepts

Wetlands are important hydrological features in the catchment. Wetlands have to be protected as they provide a range of ecosystem services. These include increased water quality benefits as well as being biodiversity hotspots.

There are various different types of wetlands. These have to be studied and understood as each wetland type has its own hydrological properties. This is why wetlands have to be classified and studied. This will improve water resource management decision making.

Wetlands may or may not have a connection to groundwater. Each wetland type is different. Groundwater may be the main source of water for a depression wetland whereas a floodplain wetland may not have a connection with groundwater at all. The lack of knowledge about wetlands has led to a misconception that all wetlands are connected to groundwater.

Wetlands have different soil types or soil characteristics than surrounding landscapes. Wetland soils may have higher clay and silt concentrations. They will also typically display signs of frequent saturation such as mottling or gleying.

One clear difference between a wetland and its surrounding terrestrial environment is the vegetation type present on the land. Wetlands have vegetation types that thrive in hydrated soils and in soils with very little oxygen levels. This vegetation type is called hydrophilic vegetation.

Wetlands have the ability to reduce the risk of flooding. Wetlands absorb the river flows and release it slowly over time. However this is not true for all wetlands.

The FLEX-topo model (Savenje, 2010) is very simple and effective model that can be used to predict flows through a wetland. This model can describe the flood attenuating ability of the wetland and in some cases predict flood events.

3. METHODOLOGY

3.1 Introduction

This chapter describes the methods used in order to complete this study. It describes the general approach to the research study. The general study area is described, which is then followed by the characterisation/ description of the wetland. The criteria for site selection is described as well as data collection methods for weather and river flow. Lastly, the hydrological modelling procedure is described.

This study was done by monitoring river stages of the Kars and Poort Rivers upstream and downstream of the Kars Wetland in order to determine the effects of the wetland on river flows. This was done to assess whether the Kars Wetland attenuates floods and sustains base flows. The rivers were monitored from April 2016 to June 2017 in order to achieve a full wet and dry cycle of the area.

A water balance analysis of the Kars Wetland was also conducted in the study in order to determine the contributions of precipitation, surface water inflow, wetland storage evapotranspiration and surface water outflow. Lastly, the flow characteristics of the Kars River were also evaluated to describe the wetlands effect on peak flows, time to peak and recession flow behaviour.

3.2 Study area description

This study was undertaken in the Western Cape Province of South Africa, specifically in the Heuningnes catchment in the Cape Agulhas region, the southernmost tip of Africa (Figure 3.1). This study was done on the Kars River, which is one of the two main tributaries of the Heuningnes River, with the other tributary being the Nuwejaars River (Bickerton *et al*, 1984). The Heuningnes Catchment was ungauged prior to this study.

The Kars River has its source in the Bredasdorp Mountains, and is joined by the Klein-Sout , Groot Sand, and the Poort Rivers. The length of the Kars River starting from its confluence with the Nuwejaars River to its most western source, near a farm named Fairfield, is seventy five kilometres (75 km) (Bickerton *et al*, 1984).

The Kars Wetland is located just downstream of Nacht Wacht Farm (Figure 3.1). The wetland spans from the road R316 to the road R319, with a separate section on the western side of the road R319 as well. This is approximately eight kilometres (8 km) in length from the R316 to the R319 road and has a total area of 13 km². There is no defined river channel within the Kars Wetland. There are two artificial drainage ditches that run for short distances on the outskirts of the wetland to move water out of the wetland and away from the farm lands (Bickerton *et al*, 1984).

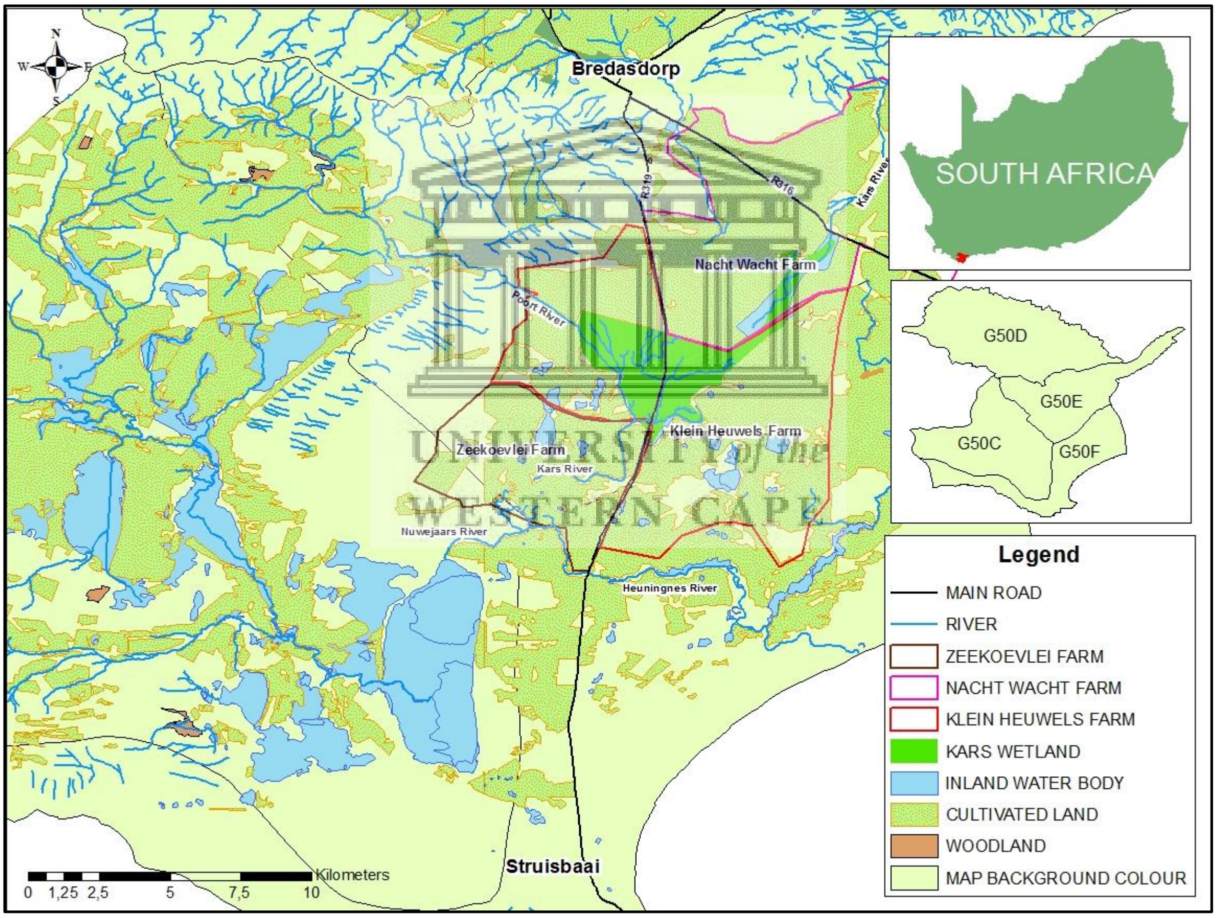

Figure 3.1 Study area map of the Heuningnes Catchment

3.2.1 Geology

The geology in the upper part of the Kars River catchment is dominated by Table Mountain Group sandstones, quartzite and shales of the Bredasdorpberge (Figure 3.2). In the undulating northern area of Bredasdorp, the geology is mostly made up of Bokkeveld Shales. The lower part of the catchment is mostly made up of coastal limestone and calcified sand (Bickerton *et al*, 1984). The Kars Wetland is located in an area dominated by the Bredasdorp geology group (Kraaij *et al*, 2009).

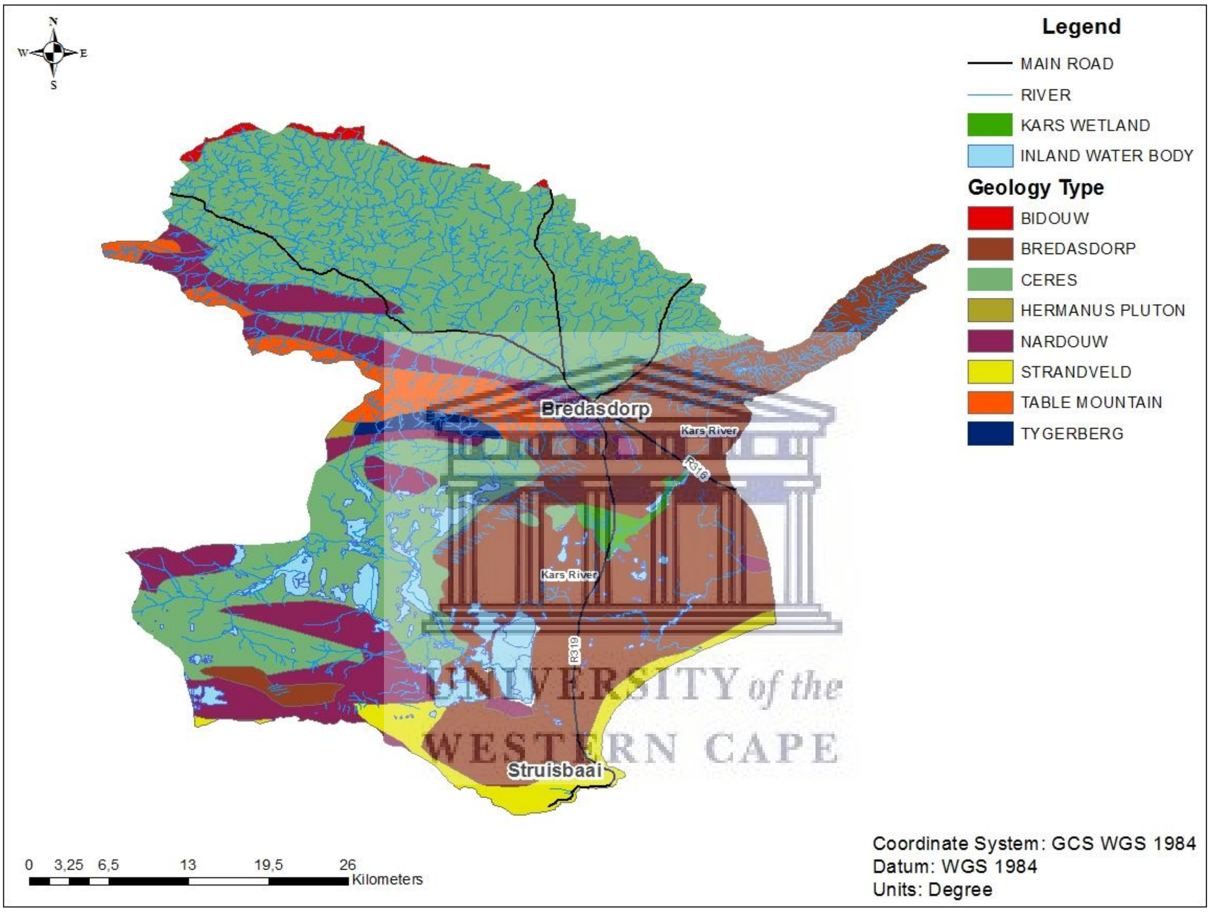

Figure 3.2 Geological map of the Heuningnes Catchment

3.2.2 Vegetation and land-uses

The study has mountain areas which are dominated by pine trees and invasive Acacia species. The *Acacia saligna* and *Acacia longifolia* also dominate a large portion of the riparian areas along the Nuwejaars River, and along the Poort River tributary of the Kars River. The portion of the Kars Wetland located next to the Poort River has Acacia sp. The Kars River and Poort River tributaries also contain reeds such as phragmites species. The Kars Wetland is located in the middle of farm land, so the surrounding areas all have grasses and/or crops.

Agriculture is the dominant land-use activity in this area (Figure 3.1). Therefore most of the farm lands produce grains or grasslands for livestock grazing. The wetland area contains a mixture of shrubs, sedges and grasses. There are marsh plants which grow in very saline conditions. These are a key indicator for the presence of hydric soils. The section of the Kars Wetland along the Poort River contains some Acacia sp.

3.2.3 Climate

The Western Cape Province is subject to warm dry summers and cold wet winters (Barrable *et al*, 2002). The rainy season occurs between May and September. The Western Cape receives between 400 and 750 mm of rainfall per year, with some mountainous regions receiving rainfall ranging between 1000 and 2000 mm per year (Barrable *et al*, 2002). The Western Cape contains vegetation from both the Fynbos biome as well as the Succulent Karoo (Kraaij *et al.*, 2009). These vegetation types are well adapted to arid and semi-arid conditions.

The Heuningnes Catchment receives between 400 and 600 mm/yr of rainfall, with an average yearly catchment rainfall of 447 mm/yr (Bickerton *et al*, 1984). The rainfall is mostly cyclonic with some orographic rainfall occurring in the upper reaches of the catchment.

3.2.4 Slope and drainage

The Kars wetland is situated on the Agulhas Plain, which is flat. Rainfall also tends to pond on the surface, which indicates that the slope is not significant in the area. Using the change in height over distance from the point where the Kars River discharges into the wetland to the point where the Kars River reforms at the R319 road, the slope was estimated to be 0,001° with a difference in height of 1 m over a distance of 930 m.

Drainage in the wetland is difficult to determine. Within the wetland there are two main drainage channels present on the edges of the wetland which are artificial. These drainage ditches were dug by farmers in order to remove water from the wetland, because when it rains over the wetland the water tends to pond. This ponding can be present for weeks at a time, depending on location and climate. The ponding is a result of slope and soil characteristics.

3.3 Wetland characterisation

The following methods were used to determine various characteristics of the Kars Wetland. Remote sensing methods were used to determine inundation temporal variations. The identification of vegetation was done to establish the presence of hydrophilic vegetation.

3.3.1 Remote sensing methods for wetland description

The Normalised Difference Vegetation Index (NDVI) was used to relate vegetation health to water availability and evapotranspiration (Glenn *et al*, 2008). This process involves reorganisation of various wavelength bands of a digital image to project desired information, which in this case would be to identify actively growing (healthy) vegetation in and around the wetland. This was done because wetlands typically would have higher soil moisture concentrations than the surrounding environment, which means that vegetation within the wetland would show a different reaction than the vegetation outside of the wetland. The NDVI image would then illustrate the wetland area by highlighting areas of increased vegetation response to soil moisture. Images of the study area were analysed both in the dry season and in the wet season.

In this study Sentinel-2 satellite images were used due to the short revisit time of 10 days, accessibility and reasonable spatial resolution. These images are multispectral containing a total of 13 bands in the visible, near infrared and short wave infrared part of the spectrum. These images have bands with a spatial resolution of 10 m, 20 m and 60 m. NDVI images with a spatial resolution of 10 m can be created. NDWI images with a spatial resolution of 10 and 20 m can be created. Bands 3, 4, 8 and 11 were used in this study.

Band 3: Green (10 m)

Band 4: Red (10 m)

Band 8: Near Infrared (10 m)

Band 11: Shortwave Infrared (20 m)

The NDVI is given by:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \tag{3.1}$$

Where: NIR = Near infrared

Red = Red band

A lot of wetlands are characteristically inundated with water for various periods of time during a year. Some are inundated throughout the whole year whereas others are inundated for a few weeks in a year. The Normalised Difference Water Index (NDWI) was used to identify all open bodies of water in the study area (Gao, 1996). It has been used to determine the spatial extent of wetland inundation. NDWI is given as follows:

$$NDWI = \frac{(NIR - SWIR)}{(NIR + SWIR)} \tag{3.2}$$

Where: NIR = Near Infrared radiation

SWIR = Short wave infrared radiation

The modified NDWI was also used to improve identification of open water bodies, flow pathways and presence of flood flows, and is hereby referred to as MNDWI. This MNDWI is given as follows:

$$MNDWI = \frac{(GREEN - NIR)}{(GREEN + NIR)} \tag{3.3}$$

3.3.2 Vegetation identification

The types of vegetation (grasses, sedges, shrubs and trees) were identified in the wetland. Relying on wetland inundation or having the water table at or near the surface is not a reliable means for wetland classification, because firstly there is no way of knowing whether the water table is near the Earth's surface without augering or drilling and the wetland in question may be a seasonal wetland where the water table is only at or near the Earth's surface for a short period of time during a year. South Africa experiences highly variable rainfall from year to year, resulting in an ever fluctuating water table, and during the dry season the water table rarely reaches the earth's surface. Therefore identifying the vegetation present in wetlands is an important indicator for wetland classification. These are known as hydrophilic vegetation. Vegetation identification was done while in the field. Pictures of the vegetation were taken and classified using literature and field guides of South African vegetation such as Gerber *et al* (2004), Van Ginkel *et al* (2011) and Manning and Goldblatt (2012).

3.3.3 Soil surveying

The purpose of the soil survey was to determine whether hydric soils are present in this area and also to determine their spatial extent. This will give an indication of the wetland boundary. This forms part of the wetland delineation and classification procedure. Soil samples were taken at selected sites from the surface and subsurface for analysis in the laboratory for soil texture composition. Other soil characteristics such as gleying and mottling assist in wetland characterisation. Identifying gleying and mottling was done while sampling the wetland soils. Soil colour and presence of mottling were recorded.

Soil sampling procedure

Soil samples were collected along eight transects. Transects were roughly one kilometre apart. Three sampling sites were selected along each transect, one site located at the start of each transect, one site located midway of each transect which is generally in the middle of the wetland, and another site near the end of the transect. Three sites per transect were due to resource constraints. The wetland area was densely vegetated with grasses and sedges, and therefore samples were only taken at sites where the soil was exposed as much as possible to minimise sampling of organic material. This means that the soil sample should contain mostly soil (sand, silt and clay) and a minimal amount of leaves and sticks, to achieve a proper representation of the soil. Infiltration rates of the surface soils were also measured at each sample site using a mini-disk infiltrometer.

Soil samples were collected using the auger method (Figure 3.3) (van Beers, 1958). At each site, a surface sample and another subsurface sample were collected. Surface samples were collected from the surface to a depth of up to five centimetres, while subsurface samples were collected at a depth of one meter where possible. During the augering process, observations were recorded describing the colour changes of the soils at various depths, mottling and vegetation types.

Figure 3.3 The soil sampling procedure using an auger in the Kars Wetland

Soil texture analysis

The soil texture was determined using the settling tube analysis method (Flemming and Thum, 1978). This was also done to determine whether there may be a clay layer in the subsurface. This method uses Stoke's law in order to separate different particle sizes based on settling time. A known quantity of soil is needed to use this method. 20 g of soil was placed into a 600 ml beaker. This soil consisted of soil and organic matter. The organic matter had to be removed from the mixture. This was done by adding hydrochloric acid (HCl) and hydrogen peroxide (H_2O_2) to the 600 ml beaker. 20 ml of hydrogen peroxide was added to the soil and heated on the sand bath in a fume cabinet until an exothermic reaction occurred. The process was repeated again after the initial reaction stopped. Once the second reaction stopped, 4 ml of hydrochloric acid was added to remove any remaining organic matter. The samples were then filtered and transferred from the filter paper to the 1000 ml settling tube (Figure 3.4). The settling tube was filled to 500 ml with water, and then 10 ml of dispersion solution was added in, and then the settling tube was filled up to the 1000 ml mark.

Two samples of 25 ml was drawn from the settling tube after it was shook thoroughly to disperse the soil evenly until the soil was in suspension. Using Stokes law it was determined that sand settles below the 10 cm mark after 32 s. Therefore the first sample was taken at 32 s. After eight hours, silt settles below the 10 cm mark which is when the second sample was taken. The first sample contains silt and clay, whereas the second sample only contains clay. The weight of the sampled soils after drying was recorded and multiplied by forty to estimate the silt and clay fraction of the soil sample. The soil type was determined using the soil texture triangle (Ditzler *et al*, 2017).

Figure 3.4 illustrating the drainage of hydrochloric acid from the soil samples

3.4 Weather data collection

Throughout the study weather data were collected *in situ* with the use of two weather stations (HOBO US30). One weather station was located at Napier, and the other was located at Vissersdrift Farm. Each weather station records data on a fifteen minute time interval. The data include rainfall, solar radiation, wind speed, wind direction, atmospheric pressure and relative humidity. This data was necessary to understand the climatic conditions of the study area and rainfall data was used as input data to the conceptual model.

3.5 River flow data collection

There are five different criteria which were used to select sites for flow measurement based on the World Meteorological Organization (WMO, 2010) guidelines. These criteria are stated as follows:

(i) The river must be straight for at least ten times the width of the channel both upstream and downstream of the cross section.

(ii) All flows must be contained within the river channel.

(iii) The river must have a stable bed and river banks to enable derivation of a reliable rating curve.

(iv) The river must be free of aquatic vegetation that will interfere with flow velocity measurements.

(v) The river must be free of tidal or river confluence influences.

Three river monitoring sites were selected for this study. One site was selected at a weir located on the farm named Nacht Wacht, which is four kilometres to the east of Bredasdorp, and upstream of the R316 road which runs from Bredasdorp to Arniston. This site is located upstream of the Kars Wetland. The second site was located on a farm named Klein Heuwels. This monitoring site is on the Poort River, which was a small tributary that feeds into the Kars River. This site is located just downstream of the Kars Wetland. The last site is located on the farm named Zeekoevlei, and is located on the lower Kars River just before the Kars River discharges into the Heuningnes River.

3.5.1 River monitoring site description

Kars River at Nacht Wacht Farm Weir

The Kars River has a broad-crested weir (Figure 3.5), which is 40 m wide and the height from the river bed was 3. 6 m. The weir is slightly damaged and has a crack in the wall and some chipped sections in the concrete at the top of the wall. The measured height of the wall from the logger position is 2, 65 m.

Figure 3.5 Weir at Nacht Wacht Farm which acts as a broad crested flow measuring weir

Poort River in Klein Heuwels Farm

This site is located just downstream of the Kars Wetland, on the Poort River, in Klein Heuwels farm. It is not easy to find sites that satisfy all five criteria for flow measurements. This was true for selecting sites in the Heuningnes catchment. Most river sections in this catchment do not satisfy all of the criteria, mostly by having vegetation within the channels.

The site selected on the Poort River, is straight for about 40 m before a small bridge, whereby flow is regulated through culverts, and then straight for 30 m after the bridge, where the flow measurements were taken. There is some vegetation within the channel. The channel bed and banks are stable. The soil in this area is high in silt and clay. Grasses and small aquatic plants do occur in the river channel in the upstream section of the river upstream of the bridge (Figure 3.6).

Figure 3.6 Vegetation in the Poort River

Kars River in Zeekoevlei Farm

The site selected on the lower Kars River is located in Zeekoevlei Farm (Figure 3.7). The lower Kars River is straight for more than ten times the width of the channel, has a stable bed and banks. All flow is contained within the river channel. The channel has a trapezoidal form. Note that the channel was modified to facilitate drainage of flood flows.

Figure 3.7 Lower Kars River is straight with some vegetation in the channel

3.5.2 Installation of river water level loggers

A six meter polyvinyl chloride (PVC) pipe was attached to an old gauge plate on the side wall of the weir (Figure 3.8). An OTT logger was placed inside the PVC pipe which was measured and adjusted so that the logger was one meter above the river bed. The crest of the weir was used as a stage datum and therefore corresponding to a water level of 0 m. On the other side of the weir wall in Figure 3.8, a box was mounted into the wall to house the logger cable and downloading port (Figure 3.9).

Figure 3.8 Installation of the OTT water level logger which was attached to a gauge plate on the side wall of the weir at Nacht Wacht farm

Figure 3.9 The housing box for the data logger download port fixed to the weir wall

On the Poort River, the PVC pipe was inclined on the river bed and bank which was anchored with two metal rods knocked into the river bed (Figure 3.10). To install the data loggers in the lower Kars River a one meter hole was augured into the river bed during the dry season (Figure 3.11). A three meter (PVC) pipe was placed into the hole and anchored with metal rods, so that two meters of the PVC pipe was exposed. Perforations were cut into the pipe to allow water to flow through. The logger was placed inside the PVC pipe to the depth that matched the length of the exposed PVC pipe and tied down.

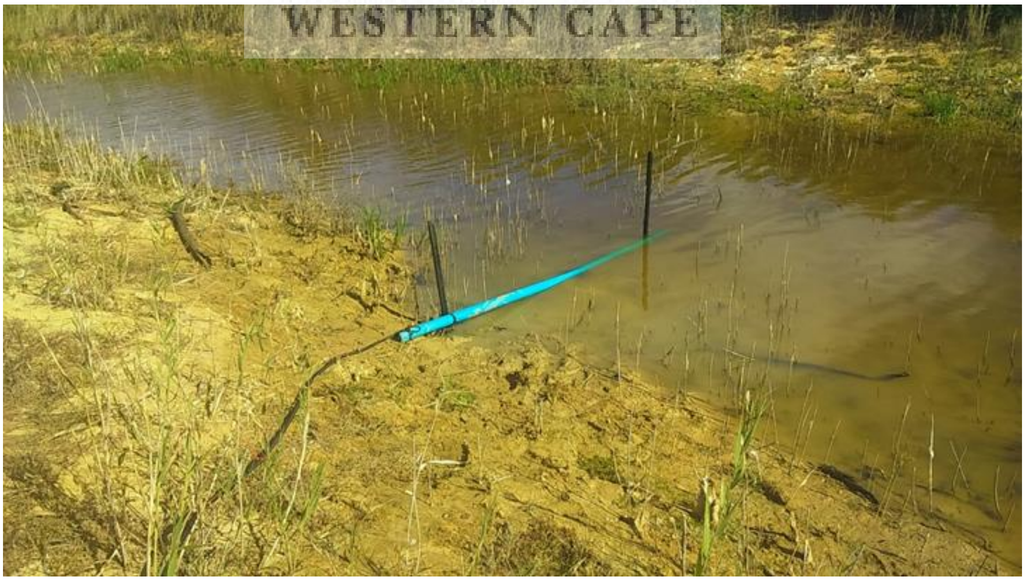

Figure 3.10 OTT logger was placed in the PVC pipe in the Poort River at Klein Heuwels farm

Figure 3.11 Installation of the PVC pipe into which the OTT water level logger was placed on the Lower Kars River at Zeekoevlei farm

3.5.3 River discharge measurements

River discharge was measured using an OTT MF-pro electromagnetic current meter (Figure 3.12). Discharge measurements were done once every two weeks and after large rainfall events.

The width of the river channel had to be measured first. The width of the river taken at the highest points of the riverbanks was also recorded at the start of the study. Once the width of the river channel was known, the channel was divided into three or four segments. One velocity measurement was done in each segment.

Discharge was calculated using the mean section method. There are three methods which are used in measuring velocity of a channel. These are the one point, two point and three point methods (WMO, 2010). The one point method refers to taking one river velocity measurement at each sample point at sixty percent (60%) of the depth of the channel. The two point methods requires two measurements of velocity at each sample point, one measurement at twenty percent (20%) of the depth and one measurement taken at eighty percent (80%) of the channel depth. The three point method requires three velocity measurements at each sample point, one measurement at 20%, 60% and 80% of the channel depth respectively. River discharge was calculated in cubic meters per second (m^3/s). Velocity was measured using all three methods depending on flow depth.

The discharge measurements were also used for the development of rating curves for these channels. Both channels were trapezoidal and had stable river beds and banks. Rating curves are an essential tool used by hydrologists to accurately estimate river discharge (Q) using depth (H). Under stable conditions there would be a constant Q-H relationship, which will then allow the estimation and prediction of discharges which cannot be physically measured such as those discharges during flooding conditions.

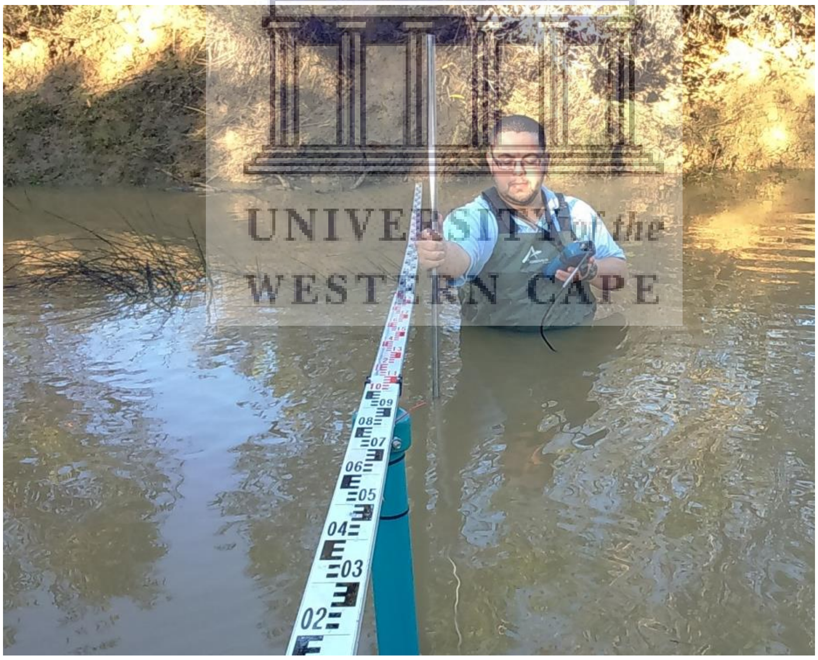

Figure 3.12 Using the OTT electromagnetic MF-pro current meter in measuring river flow discharge

The discharge measurements were used to derive rating curves for the Poort River in Klein Heuwels Farm and the Kars River in Zeekoevlei Farm in order to estimate river discharge based on water depth.

3.6 Water balance analysis

The water balance of the wetland was derived using data on river inflows and outflows. The inflows included Precipitation (P(t)) and River Inflows (Qi(t)) measured at the weir located on Nacht Wacht farm and on Poort River on Klein Heuwels farm. Outflows include Evapotranspiration (ET(t)) and River Outflows (Qo(t)) specifically river discharge of the lower Kars River at Zeekoevlei farm. The water budget of the Kars Wetland was determined using a simple water budget model as follows:

$$S(t) = Inputs - Outputs$$

$$S(t) = \big(P(t) + Qi(t)\big) - (ET(t) + Qo(t))$$

(3.4)

Where: S(t) = Storage (m^3/day)

P(t) = Precipitation (m^3/day)

Qi(t) = Surface water inflows (m^3/day)

ET(t) = Evapotranspiration (m^3/day)

Qo(t) = Surface water outflows (m^3/day)

Note that t = daily time step interval. Groundwater inflows and outflows have not been included in the water balance due to lack of resources and time. There are no boreholes in the Kars Wetland study area.

3.7 Kars Wetland Model

The Kars Wetland is a floodplain wetland based on the Classification System for Wetlands and other Aquatic Ecosystems of South Africa (Ollis *et al*, 2013). The most important characteristic regarding this wetland is the lack of a defined river channel within the wetland, the flat topography and ponding during the wet season.

A conceptual model was used in order to investigate the wetland effect on the Kars River flows. A modified FLEX-topo model proposed by Savenije (2010) was used during this study. Figure 3.13 illustrates the proposed conceptualisation.

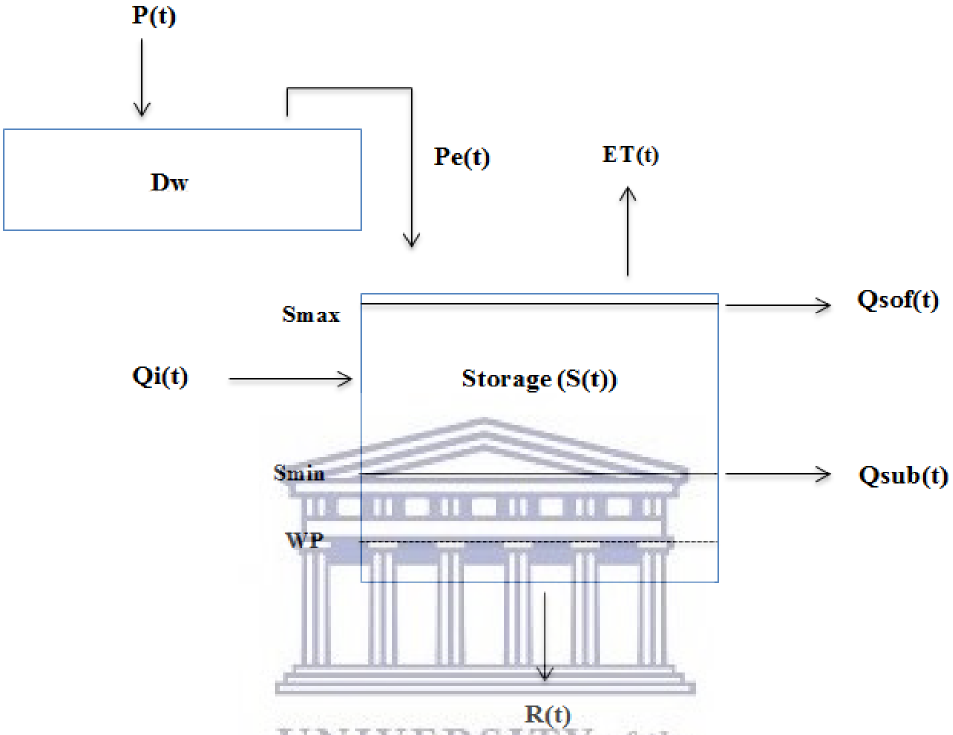

Figure 3.13 Conceptual model of the Kars Wetland

The above conceptualisation of the wetland requires six parameter estimations based on prior experience or literature (Savenije, 2010). These parameters include a number of storage thresholds for the subsurface reservoir (Smax and Smin), interception threshold (Dw), wilting point (WP) and groundwater recharge (R). Smax is the maximum amount of water the wetland can store before saturated overland flow occurs, and Smin is the minimum amount of water storage required in the wetland for discharge to occur downstream of the wetland. Dw is an interception threshold for water. This is to simulate the interception of rainfall by vegetation present within the wetland. The wilting point (WP) is the soil water content below which soil evapotranspiration does not occur, and cannot be removed from the soil by vegetation, or processes such as recharge (R) and reference evapotranspiration (ET).

From Figure 3.13 each box (reservoir) can be thought of as a bucket. Precipitation adds to the wetland if it exceeds the interception threshold (Dw) and flow out of the wetland occurs when Smin and Smax is exceeded. Precipitation is one of the inflows to the wetland system. Precipitation does not equal effective precipitation (Pe) in this model as seen in Wolski *et al* (2006) and Fenicia *et al* (2008). Instead the Flex-topo model approach by Savenije (2010) was used to account for interception losses of rainfall. Effective precipitation is given by:

$$Pe(t) = \max\ (P(t) - Dw; 0) \tag{3.5}$$

Where: Pe(t) = Effective rainfall (m^3/day)

P(t) = Rainfall (m^3/day)

Dw = Interception threshold (m^3)

The other hydrological input to the system is surface water inflows (Qi(t)). This refers to flows of the Kars River which discharges into the wetland. The discharge was measured at the weir on Nacht Wacht Farm. Once the flow enters the wetland it becomes diffuse because there is no longer a defined channel for the Kars River. ET(t) was calculated using the Penman-Monteith method (Allen *et al*, 1998) as shown in equation 3.6.

$$ET(t) = \frac{0.408\Delta(Rn-G)+\gamma\frac{900}{T+273}u_2(e_{s-}e_a)}{\Delta+\gamma(1+0.34u_2)} \tag{3.6}$$

Where: ET(t) = Evapotranspiration (mm/day)

Rn(t) = Net radiation at crop surface (MJ. m^2. day)

G(t) = Soil heat flux (MJ. m^2 day)

y = Psychometric constant (kPa)

T(t) = Air temperature (°C)

u_2(t) = Wind speed (m.s)

es(t) = Mean saturated vapour pressure (kPa)

ea(t) = Actual vapour pressure (kPa)

Δ = Slope of vapour pressure curve (kPa °C)

All meteorological variables required in the Penman-Montieth equation were obtained from the weather station on Visserdrift Farm located 8 km from the Kars Wetland.

The minimum storage (Smin) is the amount of water required for discharge to flow to the downstream part, and is estimated using wetland area and soil depth. The flow that occurs at Smin is regarded as "slow flow" and can be thought of as initial overland flow combined with through flow in the top layer of soil (below the surface), hereby termed (Qsub) and is given as:

$$Qsub(t) = \alpha(S(t) - Smin)^{\beta} \tag{3.7}$$

Where: Qsub(t) = Subsurface flow (m^3/day)

S(t) = Storage of subsurface reservoir (m^3)

Smin = Minimum storage threshold (m^3)

α = Model parameter

β = Model parameter

The last threshold is the maximum storage (Smax). Flow that occurs at Smax represents saturation excess overland flow (SOF). This is flow that occurs exclusively on the surface when the soil is completely saturated. A runoff coefficient (Cw) is given to the subsurface reservoir to calculate SOF (Fenicia *et al*, 2008). Cw is given as follows:

$$Cw = 1 - \left(1 - \frac{S(t)}{Smax}\right)^{\beta} \tag{3.8}$$

Where: Cw = Runoff coefficient

S(t) = Storage in subsurface reservoir (m^3)

Smax = Maximum storage threshold in subsurface reservoir (m^3)

β = Constant

Therefore:

$$Qsof(t) = Cw.Pe(t) \tag{3.9}$$

Where: Qsof(t) = Saturation overland flow (m^3/day)

Cw = Runoff coefficient

Pe(t) = Effective rainfall (m^3/day)

The last process that occurs within the subsurface reservoir is groundwater recharge (R). The wetland area has a high silt and clay composition, which is why the influence on groundwater discharge is not considered in the model. Clay and loam soils do not easily allow water to flow through (van der Wal, 2010). Some flow may occur but this was considered to be small in comparison to other fluxes, however recharge is considered to be a small outflow pathway.

A basic recharge estimate was incorporated in the conceptual model. For clay-silt loam soils, recharge is estimated at five percent of storage (DWAF, 2004). Therefore recharge is estimated at five percent (5%) of storage at all times. This is regarded as qualified estimates based on various studies regarding soil types and recharge rates including recharge estimation methods used by van Tonder and Xu (2001). Recharge also has a constraint where recharge only occurs when S(t) is greater than WP. With recharge factored into the model the final total outflow is given by:

$$Qsim(t) = Qsof(t) + Qsub(t) \tag{3.10}$$

Where: Qsim(t) = Simulated discharge (m³/day)

Qsof(t) = Saturation excess overland flows (m³/day)

Qsub(t) = Subsurface flow (m³/day)

The conceptual model as described above has seven parameters to be calibrated. These are Dw, WP, R, Smin, Smax, α and β. The calibration of each parameter was done using a trial and error approach. The storage parameters (Smin and Smax) were first estimated based on the wetland area and depth of soil. The other two parameters (α and β) were calibrated. These parameters were estimated in such a way as to maximise the correlation coefficient between the observed and simulated flows. The parameters were also estimated to minimise the root mean square error. To achieve this, the following objective function was used:

$$minimise \sum_{i=1}^{n} (Qobs(t) - Qsim(t))^2 \tag{3.11}$$

Where: Qobs(t) = Observed discharge (m³/day)

Qsim(t) = Simulated flow (m³/day)

Minimisation was done using the genetic algorithm that is part of the Solver tool in Microsoft Excel.

After a model was run, there is a need to validate the accuracy of the model and to establish a relationship between observed values and estimated values. The validation was done using correlation analysis. These techniques attempt to establish the relationship between observed and predicted values. The output is a coefficient of determination which is an r^2 value that ranges from 0 to 1. The correlation coefficient has an r value which ranges from -1 to 1.

4. SOIL, VEGETATION AND MORPHOLOGICAL CHARACTERISTICS OF THE KARS WETLAND

4.1 Introduction

This chapter will provide information about wetland delineation which is included in the first research objective. This includes processed satellite imagery (NDVI, NDWI and MNDWI), soil texture analysis and infiltration rates as well as vegetation identification. There are no previous studies done on this wetland so this study aims to establish baseline information which can later be used to investigate possible future changes.

4.2 Delineation of the Kars Wetland using satellite imagery

Satellite imagery was used to determine the size of the wetland. A wetland may change size between the wet and dry seasons. Satellite imagery was also used to determine whether the wetland could be a distinguished feature from the surrounding agricultural fields. Satellite imagery was also used to provide information to determine whether the Kars Wetland is a seasonal wetland or not.

4.2.1 Normalised Difference Vegetation Index

The NDVI was estimated using Sentinel 2 images for 3rd April 2016 and 11th August 2016. Sentinel 2 covers the area very often which is appropriate to use in time series studies, and the above mentioned images were used because the images were clear of clouds, the wetland was covered completely in the image and the image dates were selected because April falls within the dry season just before the wet season starts in June. August was selected because it is at the end of the wet season. Figure 4.1 shows the NDVI of the Kars Wetland during the dry season.

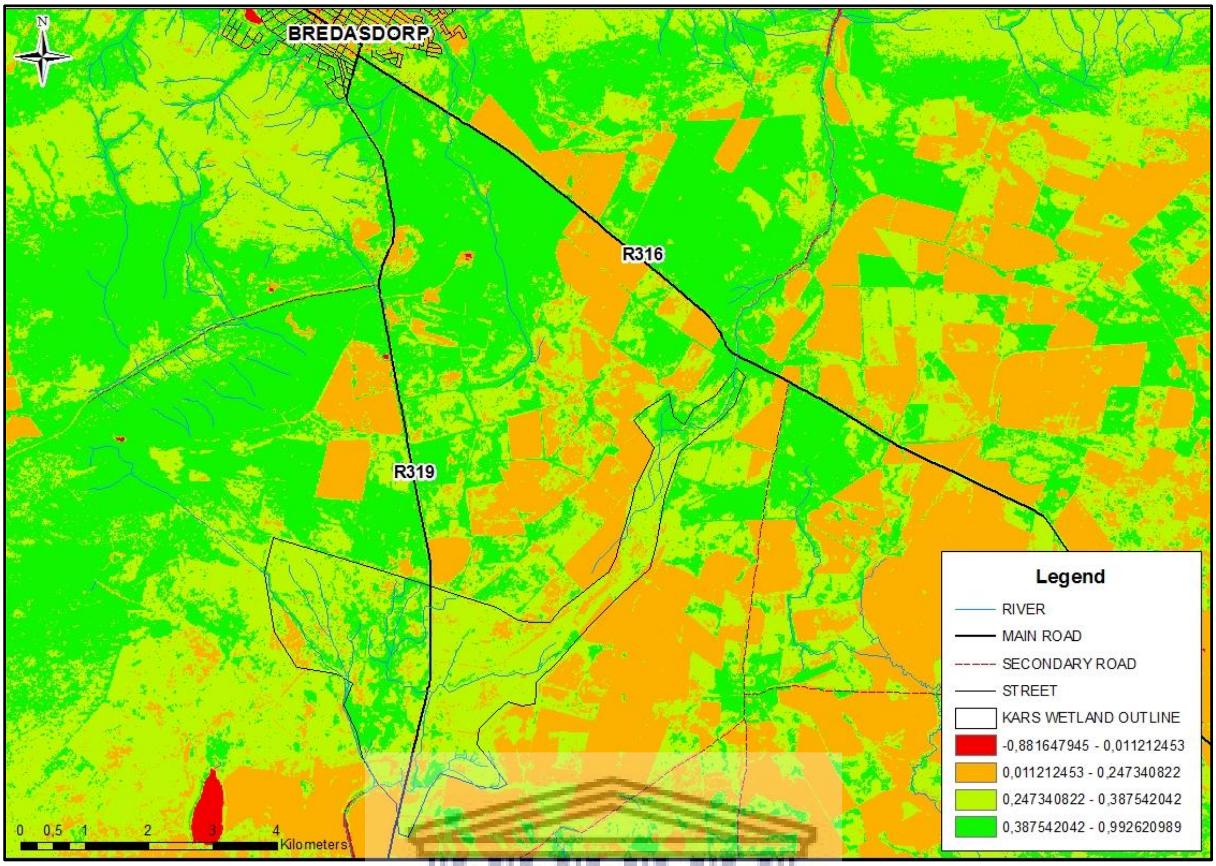

Figure 4.1 NDVI image of the study area during the dry season on 3rd April 2016.

The above image shows that most of the area has a NDVI value between 0.38 – 0.99 and NDVI between 0.24 – 0.38 which indicates high to moderate moisture levels in this area based on the vegetation response. NDVI values less than 0.247 suggest dry areas. NDVI values less than 0.0 corresponds to open water sources.

Figure 4.2 shows the vegetation response of the study area during the wet season. Cultivated lands which had low NDVI values (< 0.25) during the dry season, have high NDVI values (> 0.35) during the wet season. This shows an increase in moisture in the area due to the higher vegetation response. There are pools of water within the Kars Wetland. The shape of the Kars Wetland is discernible (NDVI = 0.25 – 0.39). There had definitely been an increase in the amount of water in the area based on the two images, and the vegetation showed a clear response to this increase in water. The higher NDVI values are indicative of increase soil moisture based on vegetation response.

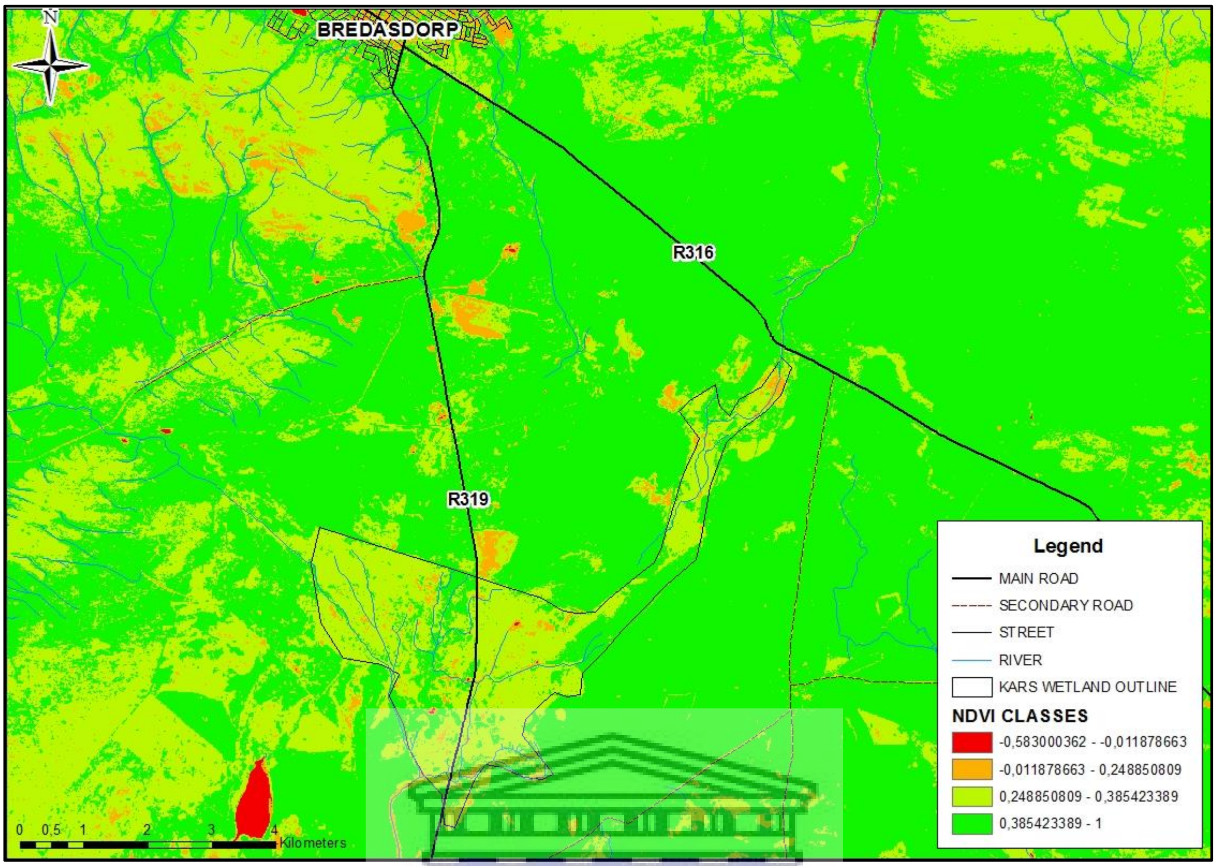

Figure 4.2 NDVI image of the study area during the wet season on the 11th August 2016.

4.2.2 Normalised Difference Water Index

The NDWI differentiates between the surface water bodies, moisture on the soil and the dry land surface on 3rd April 2016. Surface water bodies have NDWI values of 0.5 – 1 (Figure 4.3), wet soils have an NDWI value of 0.2 – 0.5, dry soils and built up areas have NDWI values of 0 – 0.2 and dry areas have NDWI values of -1 to 0. Isolated farm dams are identifiable using NDWI. A confusion matrix was used to test the accuracy of the NDWI. The NDWI proved to have an accuracy of 92 percent (%).

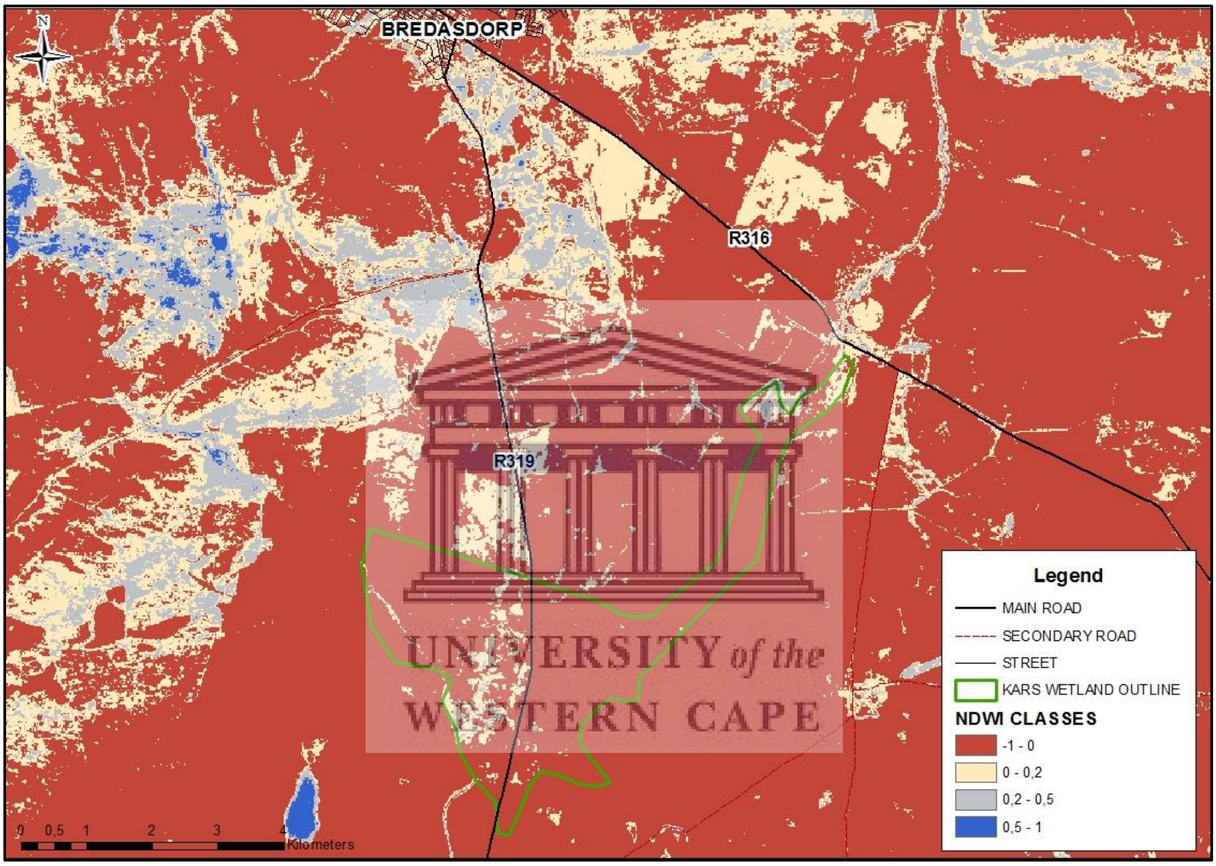

Figure 4.3 NDWI image of the study area during the dry season on 3rd April 2016.

Figure 4.4 shows that on 11th August 2016, there was an increase in areas with surface water bodies (NDWI = 0.5 – 1) and soil moisture as opposed to Figure 4.3. In Figure 4.4 most of the moisture is located around the wetland area. Varkvlei is shown to be full, and discharging water to surrounding areas. Some of the cultivated land is classified as open water bodies. This is because these areas had a spectral response of 0, 5 or more which is indicative of water. The Kars Wetland is not very noticeable in this image, however it has increased in moisture substantially compared to Figure 4.3.

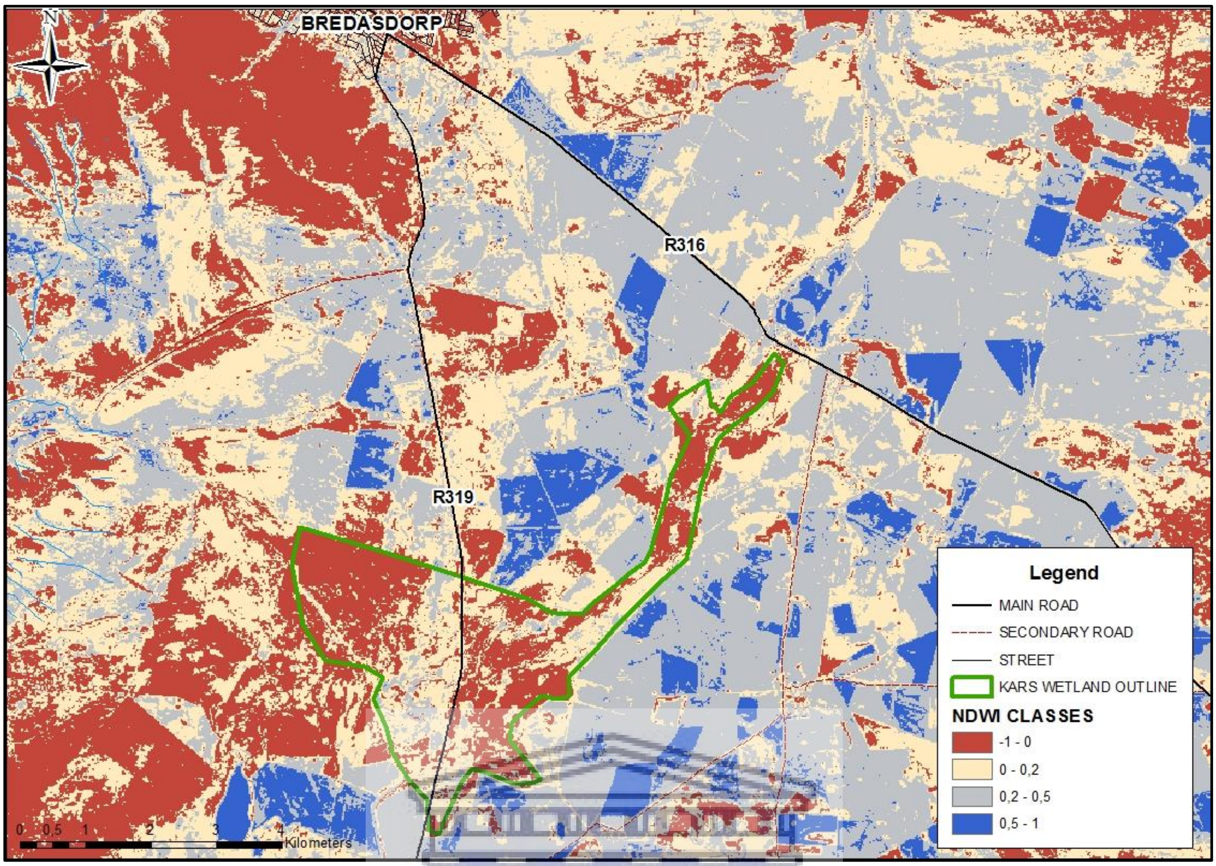

Figure 4.4 NDWI image of the study area during the wet season on the 11th August 2016.

4.2.3 Modified Normalised Difference Water Index

Figure 4.5 (3rd April 2016) illustrates surface water bodies in the study area with MNDWI values of -0.10 – 0.30 for shallow water and 0.30 – 1.00 for deeper water, wet soil has MNDWI values of -0, 25 to - 0,1 and dry soil has MNDWI values from -1.00 to -0.25. Varkvlei is clearly illustrated as a large open water body in blue. A confusion matrix was also used to identify the accuracy of the MNDWI. The MNDWI proved to have an accuracy of 87 percent (%) making it less accurate than the NDWI.

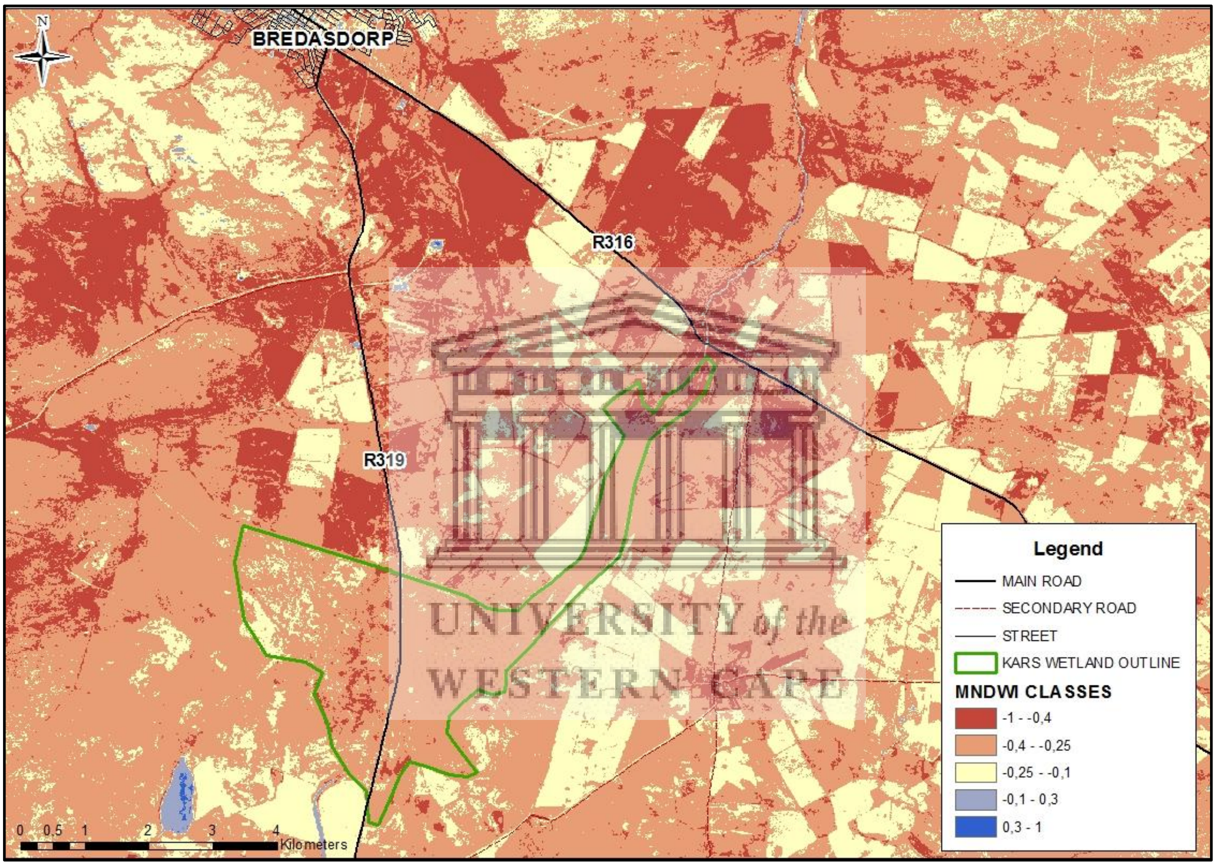

Figure 4.5 MNDWI image of the study area during the dry season on 3rd April 2016.

Figure 4.6 (11th August 2016) shows the MNDWI results of the wet season in the study area. There two key observations that need to be noted when compared to Figure 4.5. The first that there are more open water bodies identified during the wet season image than there are in the dry season. However, the second observation that has to be made is that the overall moisture level of the study area during the wet season image is higher than that of the dry season image in Figure 4.5. There are a larger number of dry areas in Figure 4.6. The Kars Wetland is discernible.

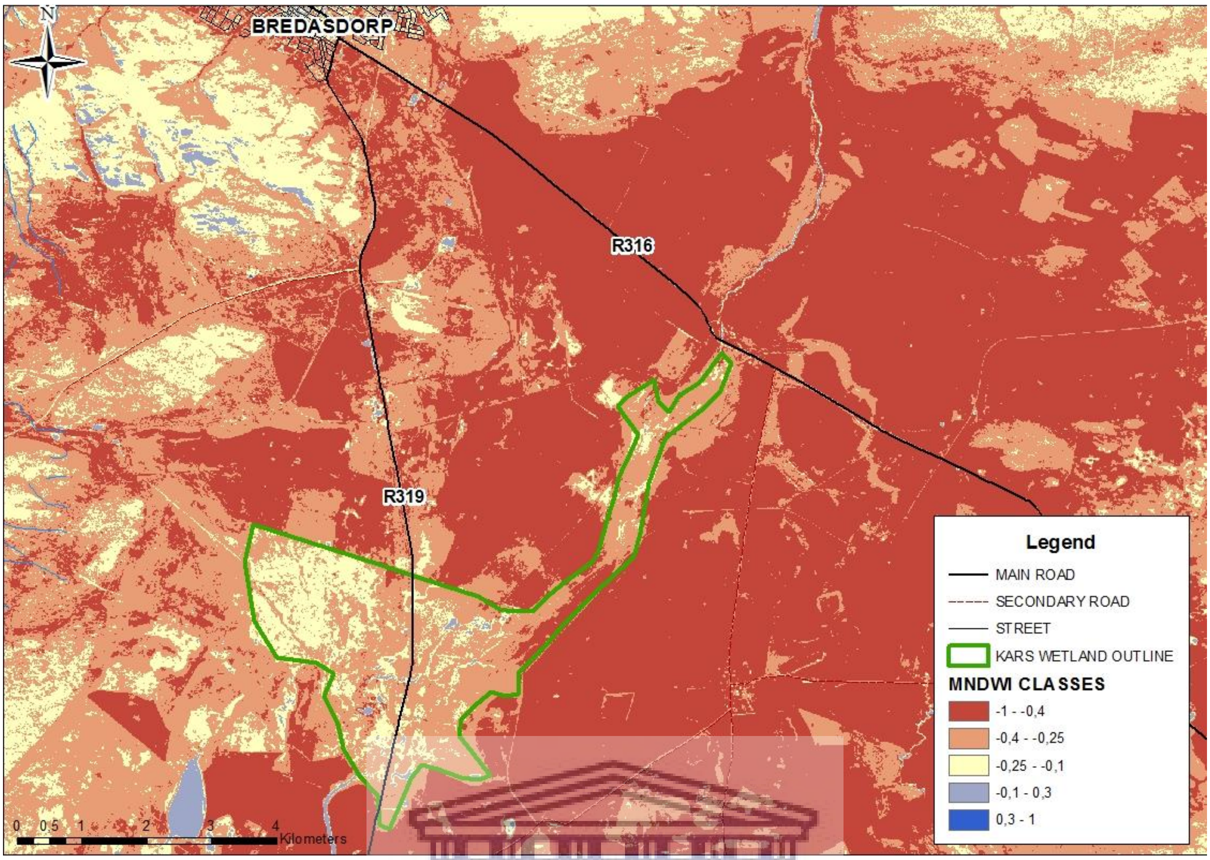

Figure 4.6 MNDWI image of the study area during the wet season on 11th August 2016.

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4.3 Vegetation of the Kars Wetland

The vegetation identification involved using a field guide (van Ginkel *et al*, 2011) and *in situ* observations to establish locations of dominant vegetation types. At the upper point where the Kars River discharges into the wetland, there is a dense population of reeds within the river and along the banks (Figure 4.7). These reeds were identified to be *Phragmites australis*. This species of reed is an invasive species and occurs throughout the Western Cape Province (Gerber *et al*, 2004).

The Kars Wetland contains mostly grasses, sedges and rushes (Figure 4.8 & 4.9). Figure 4.9 was derived using field observation notes as well as Google Earth imagery to create a basic vegetation type map of the wetland. These include grass species such as *Stenotaphrum secundatum* and *Spartina maritima* which are commonly found in marshy environments and can survive in saline conditions. A variety of sedges occur throughout the Western Cape Province, and some of the sedge species found in the Agulhas plain include *Bolboschoenus maritmus*, *Carex clavata* and *Cyperus congestus*. The rushes include *Juncus krausii*, and *Chondropetalum tectorum*. These rushes are known to occur in wetland environments. The Kars Wetland also has a population of *Acacia saligna* close to the Poort River.

Figure 4.7 *Phragmites australis* reeds at the start of the Kars Wetland at Nacht Wacht farm

Figure 4.8 Kars Wetland’s grassy terrain with some isolated rush vegetation

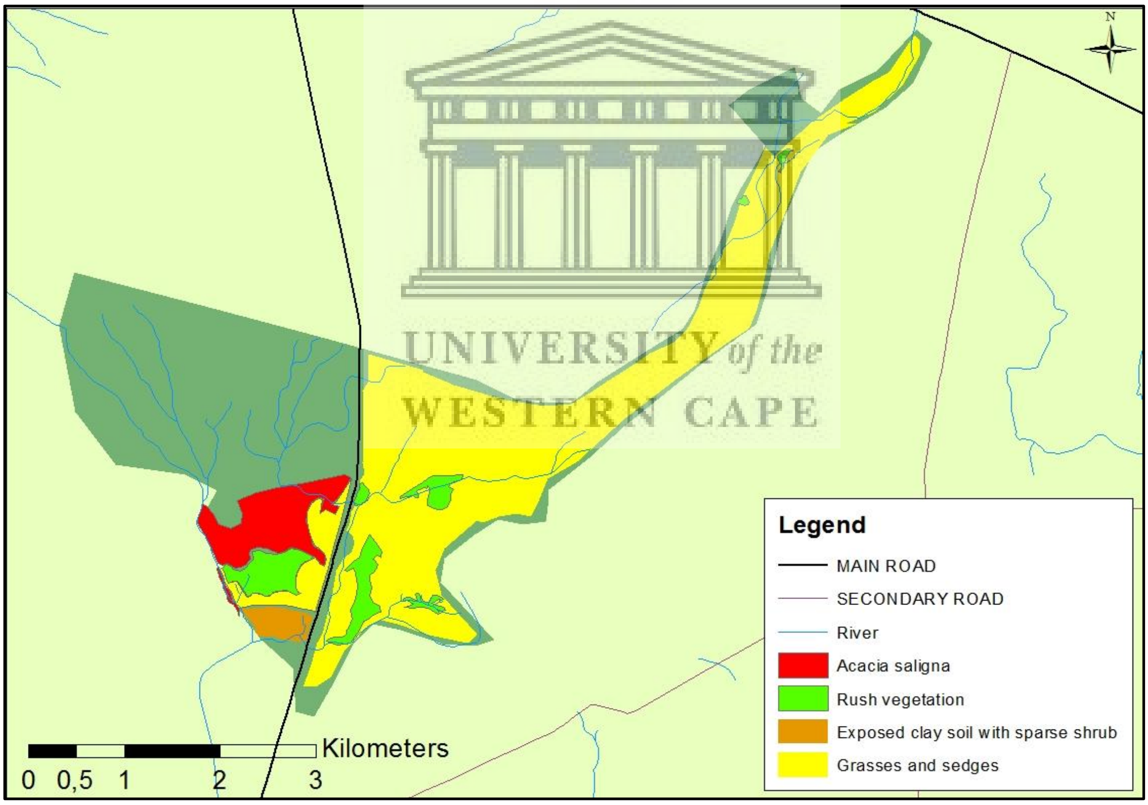

Figure 4.9 Basic map of vegetation distribution within the Kars Wetland based on field survey and Google Earth images

There are some tree species located on the eastern half of the Kars Wetland; however they do not occur in large enough populations to be mapped. It is important to note that the rush vegetation would likely cover a larger area of the western part of the Kars Wetland because the whole wetland could not be covered on foot. Vegetation identification was done along transects of the wetland.

Another observation that should be made is that *Acacia saligna* only occurs on the eastern part of the Kars Wetland. The exposed clay section with the clusters of shrubs as displayed on the map (Figure 4.9) was included because it is a unique feature of the wetland. There is no other section of the wetland such as this (Figure 4.10). The soil has a high amount of clay and shrubs occur in clusters. This vegetation type only occurs on this section of the wetland.

Figure 4.10 Exposed clay soil with shrub clusters on Klein Heuwels farm

4.4 Soil Survey of the Kars Wetland

A soil survey was done of the Kars Wetland in order to determine the spatial variation of soil texture as well as to determine the presence of hydric soils. This information will help to classify the wetland and also provide information which would help hypothesize the movement of water through the soil.

4.4.1 Soil profile observations

During the sampling process, as the soil was being augured, a general log was kept describing the soil colour, depth of colour change, the presence of mottling or gleying, surrounding vegetation and whether the water table was found within the top meter of soil. The soil sampling log can be found in Appendix 4.1. Some surfaces were found to have dark, hardened soils, whereas other sites displayed very light coloured soils which had a silty or clayey texture. What is very interesting from these observations is that cross sections two to six (Figure 4.16) all illustrated an orange to light brown soil layer found from about 30 cm depth up to 90 cm depth which was rich in clay and silt. These cross sections are located in the main parts of the wetland.

Another observation made was that mottling was present throughout the entire wetland area. With mottling found at all cross-sections of the wetland, it proves that these soils are saturated for long periods of time, which will lead to anaerobic conditions. Therefore it can be concluded that the soils in this area are hydric soils. This is also indicative of the flat nature of the Kars Wetland.

4.4.2 Soil texture analysis

The surface and subsurface soil samples were all analysed and plotted on soil type classification diagrams (Figure 4.11 and Figure 4.12). Figure 4.11 illustrates surface soil types and Figure 4.12 illustrates subsurface soil samples. This provides information regarding the variation of soil texture along transects and possibly across the entire wetland, in both the surface and subsurface. A general vertical change in soil texture can also be identified when the two diagrams are compared.

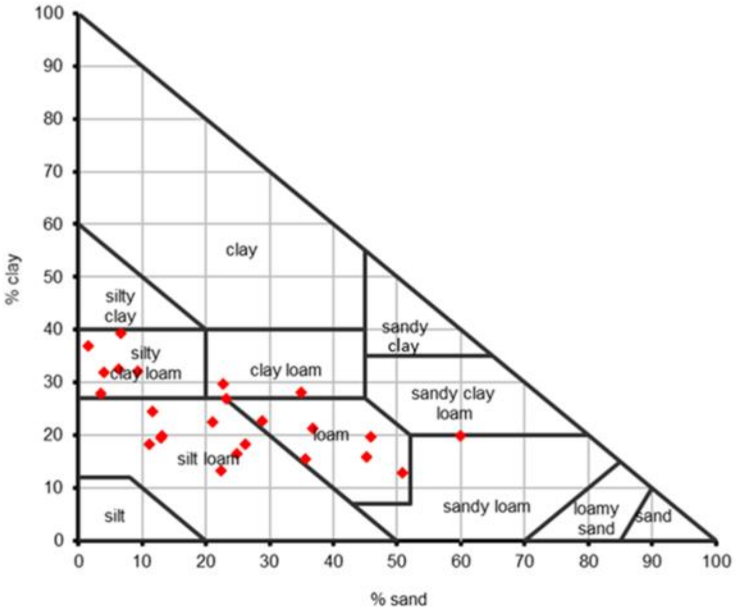

Figure 4.11 Variation of soil texture of surface soil of the Kars Wetland.

Figure 4.11 illustrates the variation in surface soil type across the entire wetland. Soils vary from a sandy loam soil, to loam soil, to a silt loam, a clay loam and even silty clay. The surface soils are dominated by loamy soils such as loam, silt loam and silty clay loam especially. Loamy soils are typical of wetlands and are also very common in agricultural areas.

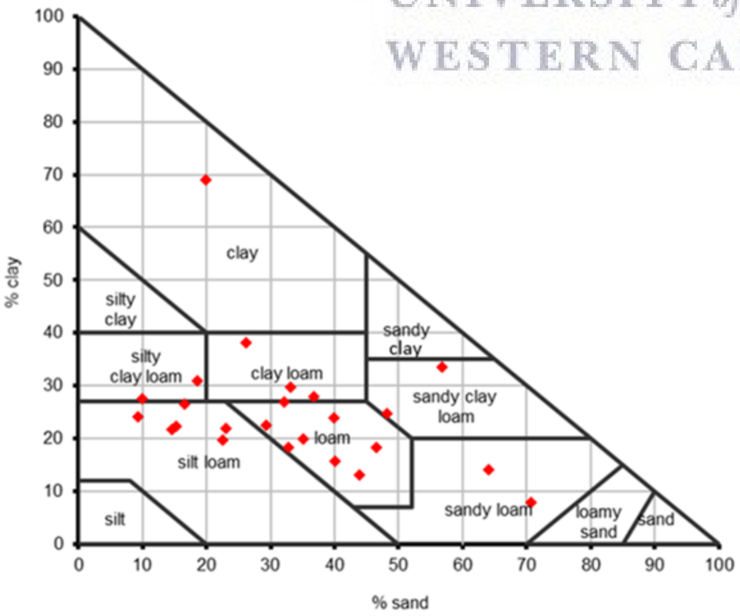

Figure 4.12 Variation of soil texture of subsurface soil of the Kars Wetland.

Soil texture varied from a dominant silt texture in surface soils and then increased in clay and sand content depending on location in the subsurface soils. The dominant soil texture is still loamy soil, spread mostly across loam and silt loam soil types. The sandy soils are consistently found near a flow path within the wetland (Figure 4.13 and 4.14).

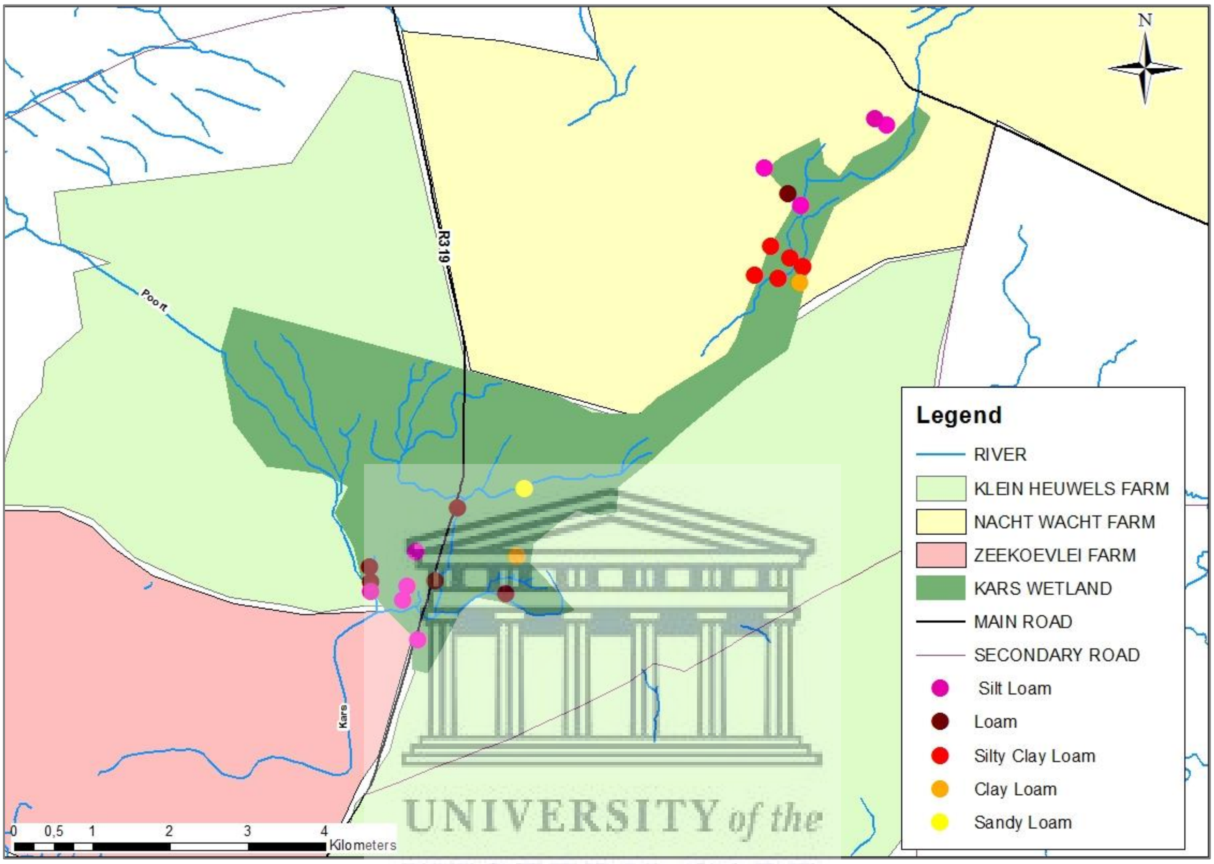

Figure 4.13 Spatial variation of texture of surface soils in the Kars Wetland

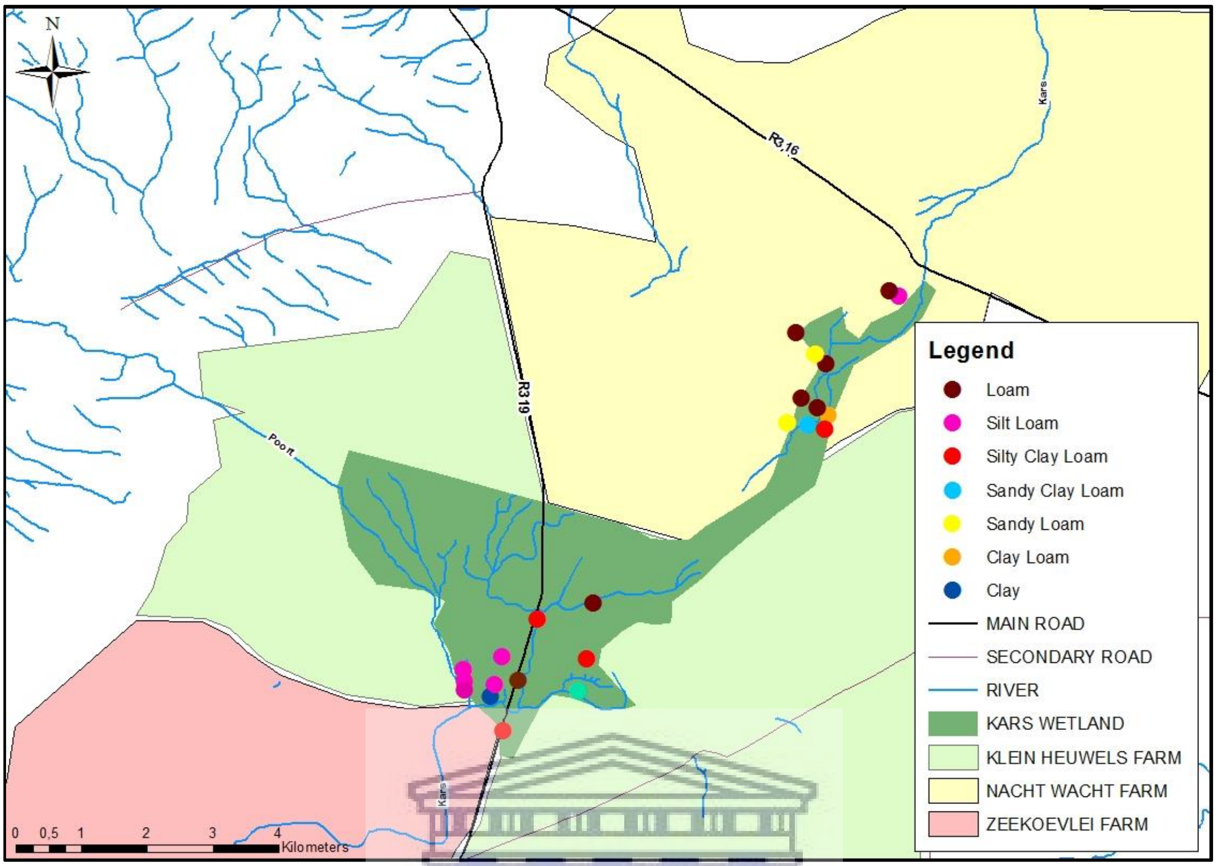

Figure 4.14 Spatial variation of texture of subsurface soils of the Kars Wetland

4.4.3 Soil infiltration rates

In addition to determining the soil type, the soil infiltration rates (Hydraulic conductivity) were also determined. This was done to determine the ability of the dry wetland soils to absorb and transmit water from the surface. The infiltration rates varied across the Kars Wetland (Figure 4.15). The units used to describe infiltration were centimetres per day (cm/day). Sites where the infiltration rates exceeded 40 cm/day, occurred mostly on the upper part within the wetland. There are also a number of sites that have infiltration rates of 10 cm/day or less. The infiltration rate sites are linked to the soil sampling sites as previously seen in Figures 4.13 and 4.14.

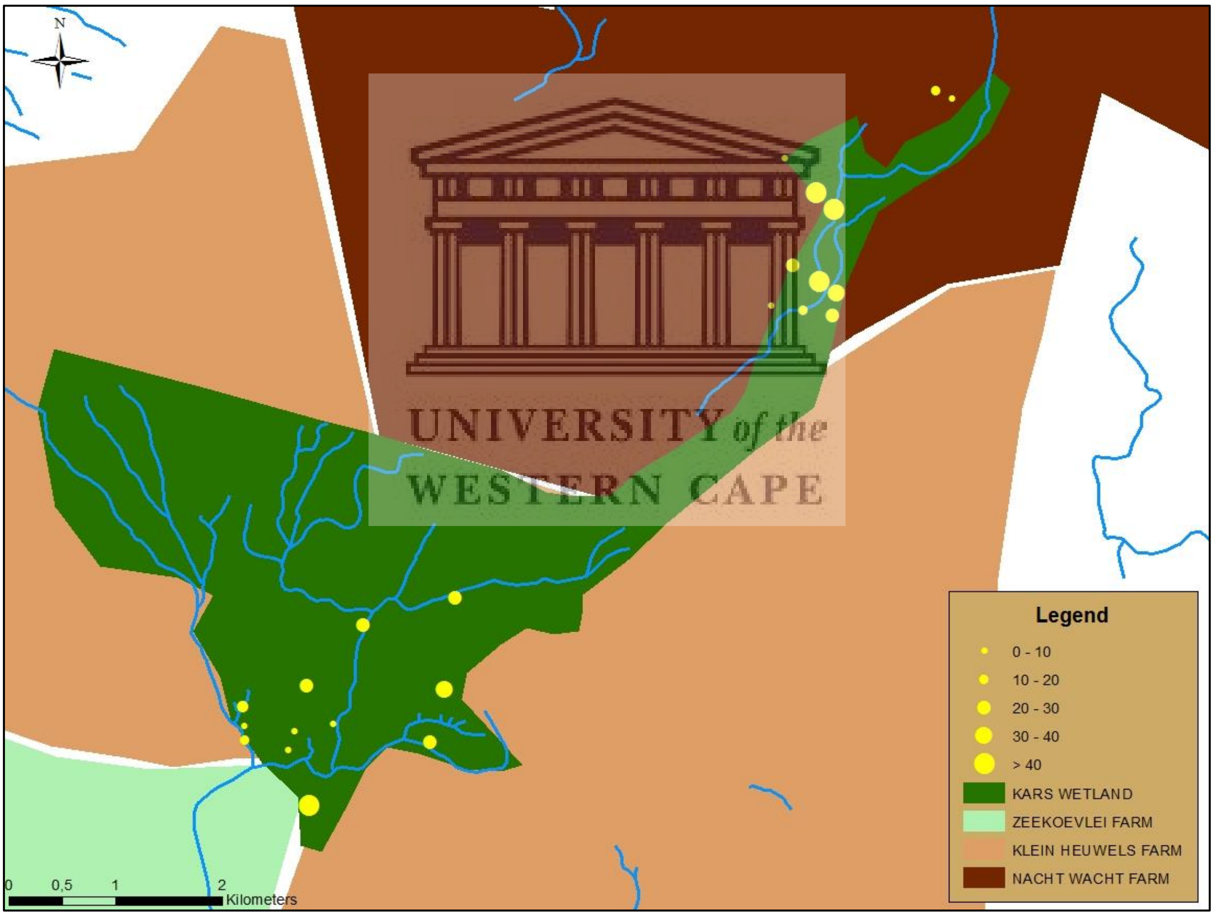

Figure 4.15 Map displaying the variation of infiltration rates (cm/day) across the Kars Wetland

From the infiltration rate data, 31 % of the sampling sites have infiltration rates of less than 10 cm/day. Furthermore 45.5 % infiltrate at rates slower than 20 cm/day and 72.2 % of the sites infiltrate at rates slower than 30 cm/day. Only 6 out of the 22 sites exceeded 40 cm/day.

4.5 Wetland morphology of the Kars Wetland

The cross-sections of the wetland were used to determine the morphological changes from one end of the wetland to the other as well as to identify flow paths within the wetland. This information helps to classify the wetland as a depression or flat. The cross-sections were constructed using a Differential Global Positional System (DGPS). The DGPS used was the Leica Zeno 15, which has an accuracy of up to 10 cm.

4.5.1 Wetland morphology

The wetland is narrow at the upper part (Figure 4.16), which is the point where the Kars River discharges into the wetland. The width at this point is 400 m. The wetland increases in width towards the downstream part till it reaches the R319 (Bredasdorp – Struisbaai road) and is triangular in shape as viewed from above. The width of the wetland at the downstream part is 3800 m. This is the point where the R319 road runs across the wetland. The wetland has another section on the west side of the R319 road. The only river that can be affected by this section of the wetland is the Poort River.

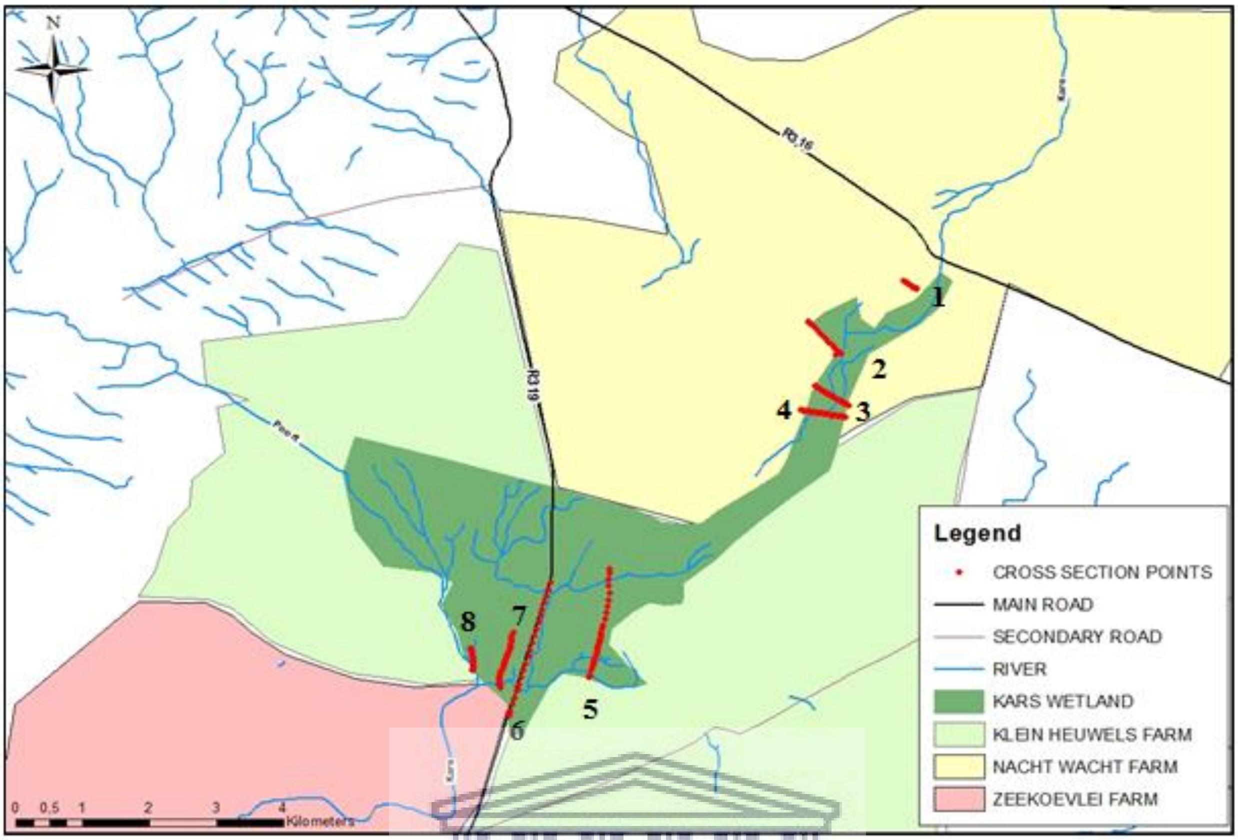

Figure 4.16 Map of Kars Wetland cross sections from cross section 1 on Nacht Wacht Farm to cross section 8 on Klein Heuwels Farm along the Poort River. Note: White areas on map have no meaning.

The morphology of the wetland is very flat and narrow at the upper part as previously stated, and wide at the lower part (Figure 4.17). Only the most representative cross-sections of the wetland are presented in Figure 4.17. And the cross-section locations are presented in Table 4.1.

The profile of cross section 3 of the Kars Wetland is the first full cross section of the wetland (Figure 4.17). The cross section starts on the lower start of a levee, which then drops down into the wetland. This is clearly a feature that was created by the farmers to separate the agricultural land from the wetland. There is a channel (drainage ditch) at the bottom of this levee. This is evident in the cross section as the lowest point in the cross section. However after the channel the wetland remains very flat. On the opposite side of the wetland there is another raised section of land.

Cross profile 4 started at the bottom of the levee on the agricultural land. The levee was not as high on this side and the decent was more gradual. This cross profile illustrates a lot more variation in form than the previous cross section. Around 100 m into the cross-section the cross-section shows a decent to 0 m (lowest point of the cross-section) which alludes to a flow pathway. This clearly resembles a channel within the wetland, however it was dry during the time the survey was conducted. At the 390 m point of the cross section there was another small channel found. This channel was smaller and also dry. After this the land remained flat and the cross-section ended at the foot of the other levee.

At the point where cross profile 5 was constructed there were no levees. The wetland also expanded in width. This cross section shows a lot of variation in elevation. The land on the southern part of the wetland is higher than the land on the northern side of the wetland, with a maximum difference in height of 4.5 m. The last observation to take note of is at the 646m point in the cross section. At this point the land rises by 2.4 m over a distance of 80 m and descends to the lowest point in the cross-section, which could be the point where the Kars River starts to reform.

Cross profile 6 is over 500m wider than cross profile 5, with a total distance of 2100 m covered. However there is much less variation in elevation in cross profile 6 than there is in cross profile 5. The only similarity between the two profiles is that the southern side of the wetland has a higher elevation. When constructing this cross section, there was a channel that occurred 429 m from the start of the cross section and ended at 432 m. This was not well represented in the channel, however this was the point where the Kars River re-formed and flowed through culverts under the R319 road.

Overall, it is difficult to locate the channels and flow paths within the wetland from the cross-sections. The easiest channels to identify would be the dredged channels at the start of the cross-sections 3 and 4.

Table 4.1: Locations of each cross-section for the Kars Wetland

Cross-Section	Start Coordinates		End Coordinates	
1	-34,58327°	20,10536°	-34,58438°	20,10710°
2	-34,58904°	20,09252°	-34,59337°	20,09657°
3	-34,59335°	20,09654°	-34,60093°	20,09788°
4	-34,60153°	20,09149°	-34,60255°	20,09744°
5	-34,63936°	20,06295°	-34,62403°	20,06564°
6	-34,64477°	20,05214°	-34,62602°	20,05776°
7	-34,64088°	20,05090°	-34,63300°	20,05273°
8	-34,63841°	20,04715°	-34,64030°	20,05083°

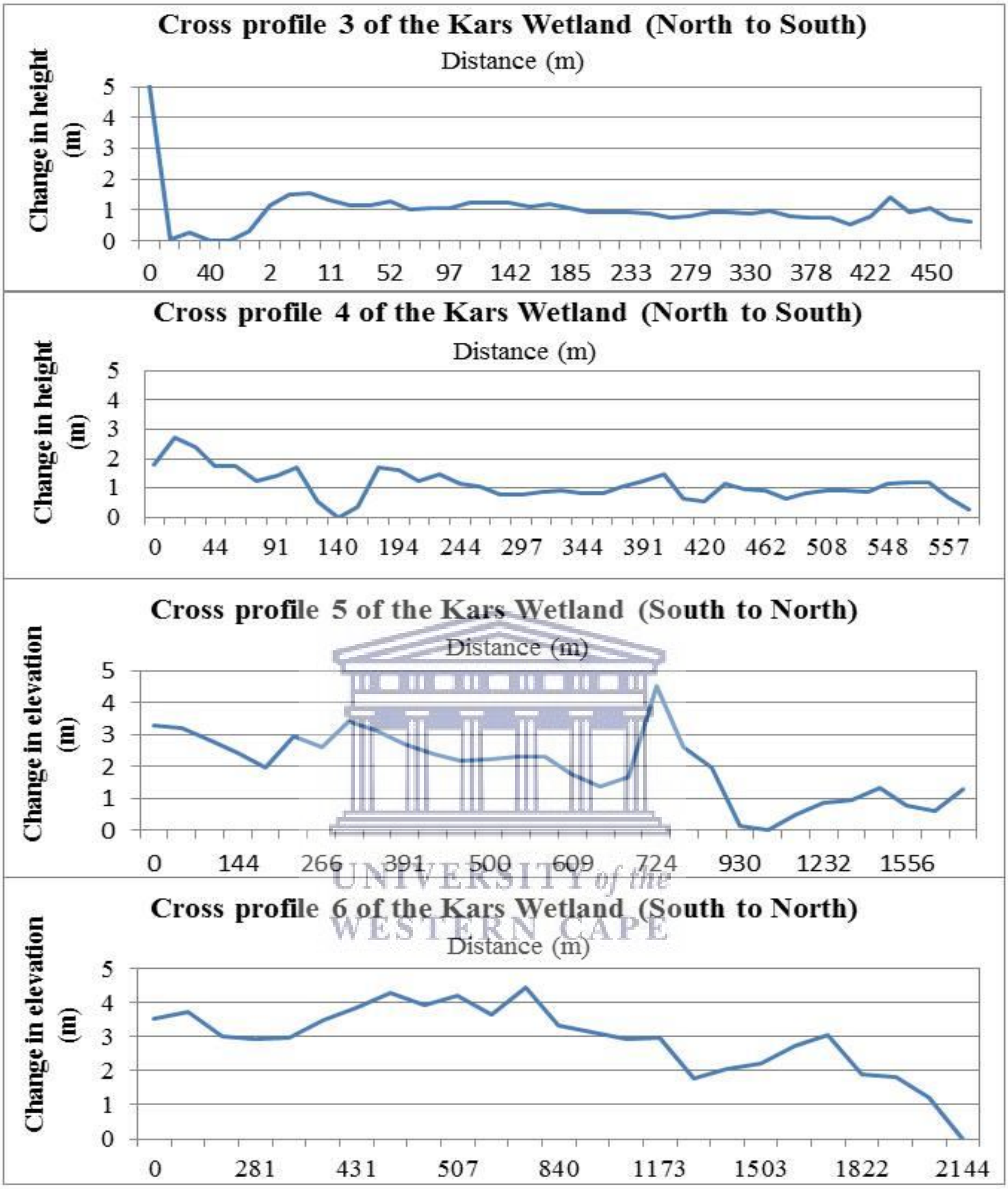

Figure 4.17 The most representative cross-sections of the Kars Wetland. Refer to Figure 4.16 for the locations of the cross-sections in the wetland.

4.6 Discussion

4.6.1 Remote sensing as a wetland delineating tool

During the dry season the wetland cannot be clearly identified using the NDVI. The NDVI image of the wet season provides a better image for wetland identification. In summer the surrounding area is dry and blends in with the wetland, however, in winter, the surrounding vegetation response to soil moisture is high whereas the Kars Wetland only has a slight increase in vegetation response. NDVI showed moderate results in delineating the wetland area, meaning that the wetland was discernible and NDVI could be applied in other areas with greater success

The NDWI images were used to identify the open water bodies and dry terrestrial environment. The idea of using the NDWI was to clearly illustrate the wetland shape, and distinguish it from the surrounding environment. This is especially true for the wet season. The NDWI image of the dry season shows how well the wetland blends in with the surrounding land. The wetland cannot be identified as a feature in this image. Varkvlei (as seen in the bottom left of the images) can be identified as an open water body. Looking at the NDWI image of the study area during the wet season there is a clear increase in water as shown by Varkvlei`s increase in size, inundated surrounding farm lands and most importantly by the inundated wetland soils within the Kars Wetland. The wet season NDWI does illustrate the wetland shape much better during the wet season than dry season. The NDWI image during the wet season shows that the fields on both sides of the R316 road are inundated with water which may cause this road to flood and cut the town of Arniston off from Bredasdorp. The area did not receive much rainfall during 2016 due to the drought but local flooding is a possibility during years with above average rainfall based on local knowledge.

The MNDWI was used to identify open water bodies and changes in moisture. The Kars Wetland could not be identified using MNDWI during the dry season. There is an improvement in identifying the Kars Wetland during the wet season. The wetland shape can be identified to an extent and the moisture changes are clearly visible from dry season to wet season. The MNDWI was not an effective method for delineating the Kars Wetland in terms of wetland identification.

The NDVI and NDWI were able to reveal wetland features. Another factor to take into consideration is the spatial resolution of the images being processed. In this case Sentinel 2 images, with a spatial resolution of 10 m and 20 m were used. Accuracy and feature identification will increase with images that have a better spatial resolution. It is important to note that the Western Cape Province experienced a period of drought during 2016 and 2017, which means that there was a reduction in the amount of inundated areas during this time compared to times of normal rainfall and soil moisture levels. This means that better images can be created in future with normal rainfall conditions and increased spatial resolution of images.

4.6.2 Vegetation identification

The vegetation identified during this study proves that the area can be classified as a wetland. This is because of the presence of reeds (*Phragmites australis*) and rushes (*Juncus krausii*, and *Chondropetalum tectorum*). These vegetation types are synonymous with wetland environments. They thrive in water and hydric soils. These vegetation types provide information that the wetland soils are saturated for a period of time in the year that is sufficient enough to support these vegetation populations.

With the use of field notes and Google Earth an adequate description of the vegetation distribution was done. An interesting observation to note is the rush vegetation types seem to occur near water sources such as rivers, pools and drainage ditches. This can be a result of these plants hydrophilic nature.

4.6.3 Wetland soils

The soil survey showed that the soil textures vary throughout the Kars Wetland. Certain parts of the wetland have sand deposits, other parts of the wetland had dry cracked hard clay, some parts are silty and others are very clayey. The exact composition of sand, silt and clay cannot be determined by a naked eye however the dominant material is easily identified by field.

Mottling was found throughout the wetland. This is due to the oxidised iron concentrations that accumulate in the soil as a result of the constant wetting and drying of the wetland. The constant wetting and drying of wetland soils results in chemical weathering of the parent material which causes increased concentration of minerals is soil. The presence of gleying and/or mottling is evidence that the soils in question are hydric soils. Hydric soils are a key indicator of a wetland.

The surface soils vary predominantly between Silty Clay Loam, Silt Loam and Loam soil types. This showed that silt is the dominant soil type or particle size for surface soils. Silt and clay does not allow water to pass through easily. With the Kars Wetland having an average infiltration rate that represents a clay loam soil type there are two assumptions that can be made. The first is that the Kars Wetland contains soils that are higher in clay and silt concentration. This leads to the second assumption which is that because the soils are higher in silt and clay, the infiltration capacity of the soils will not be as efficient as that of sand and sandy loam soils, which thereby results in reduced groundwater recharge rates and increased surface water ponding and runoff. This will play a role in localised flood events as well.

The increase in clay content with depth may allude to a clay layer deeper within the soil profile. The subsurface samples were taken 1 m below the surface. The soil profile below 1 m is unknown. Should there be a clay layer below 1 m within the soil profile, it can be said that this clay layer acts as a semi-permeable layer which restricts or retards the movement of water through the soil column. It may be that this clay layer results in the saturation of the surface soils as well as the ponding of water on the surface that is seen during the wet season, as rainfall water is stored in the upper layer of the soil column.

5. SPATIAL AND TEMPORAL VARIATION OF WEATHER AND RIVER FLOWS.

5.1 Introduction

This chapter describes the weather conditions of the study area in terms of temperature, solar radiation, relative humidity, wind speed, rainfall and evapotranspiration. Thereafter the channel descriptions as well as flow measurements and rating curves are presented for all three river flow monitoring sites. This information forms part of both research objectives, in that the climatic conditions and river flows around the wetland are explained, which is also information used in the modelling of the Kars Wetland and Kars River.

5.2 Weather conditions of the Kars Catchment

The weather of the Kars Catchment was monitored from June 2016 to May 2017. The Napier weather station is located far away from the Kars Wetland, but the Kars River receives water from tributaries from Napier. Vissersdrift weather station is located within 6 km of the wetland which is the primary rainfall data considered in the modelling.

5.2.1 Air temperature

The Cape Agulhas region has temperature patterns similar to Western Cape coastal regions with hot dry summers and cold wet winters. The hottest day for the year was recorded on the 18th January 2017 with a daily maximum of 37.0 °C and the lowest -0.7 °C was on the 17th July 2016 (Figure 5.1). Daily maximum temperatures varied mostly between 14.0 °C and 24.0 °C for the period of June 2016 to November 2016, and 19.0 °C and 29.0 °C for the period of November 2016 to April 2017. The daily minimum temperatures varied mostly between 4.0 °C and 14.0 °C during the June 2016 to November 2016 period, and varied mostly between 9.0 °C and 19.0 °C during the November 2016 to April 2017 period. There are considerable day to day variations in both maximum and minimum temperatures. In summer the maximum temperature varies mostly between 20.0 °C and 30.0 °C. The average minimum temperature in summer varies between 10.0 °C and 20.0 °C. In winter the average maximum temperature varies mostly between 15 °C and 25 °C. The minimum daily temperature will vary mostly between 5 °C and 10 °C.

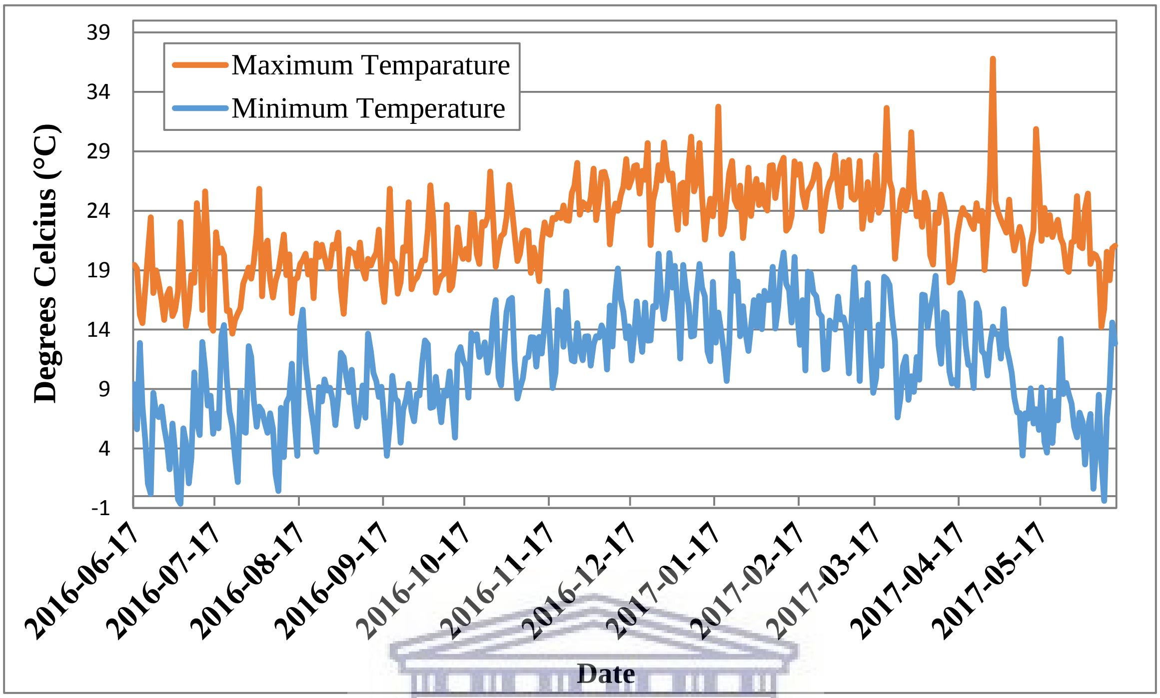

Figure 5.1 Minimum and maximum air temperature at Vissersdrift farm weather station for the period 17th June 2016 to 15th June 2017.

5.2.2 Relative humidity

The relative humidity of the Cape Agulhas region did not show major variations during the monitoring period (Figure 5.2). As expected the summer period from November 2016 to March 2017 had low relative humidity, with the minimum relative humidity averaging 55% during this period. During the winter period from June 2016 to September 2016 the relative humidity ranged mostly between 50% and 80%. The day to day variation in relative humidity varied much more in winter than it did in summer.

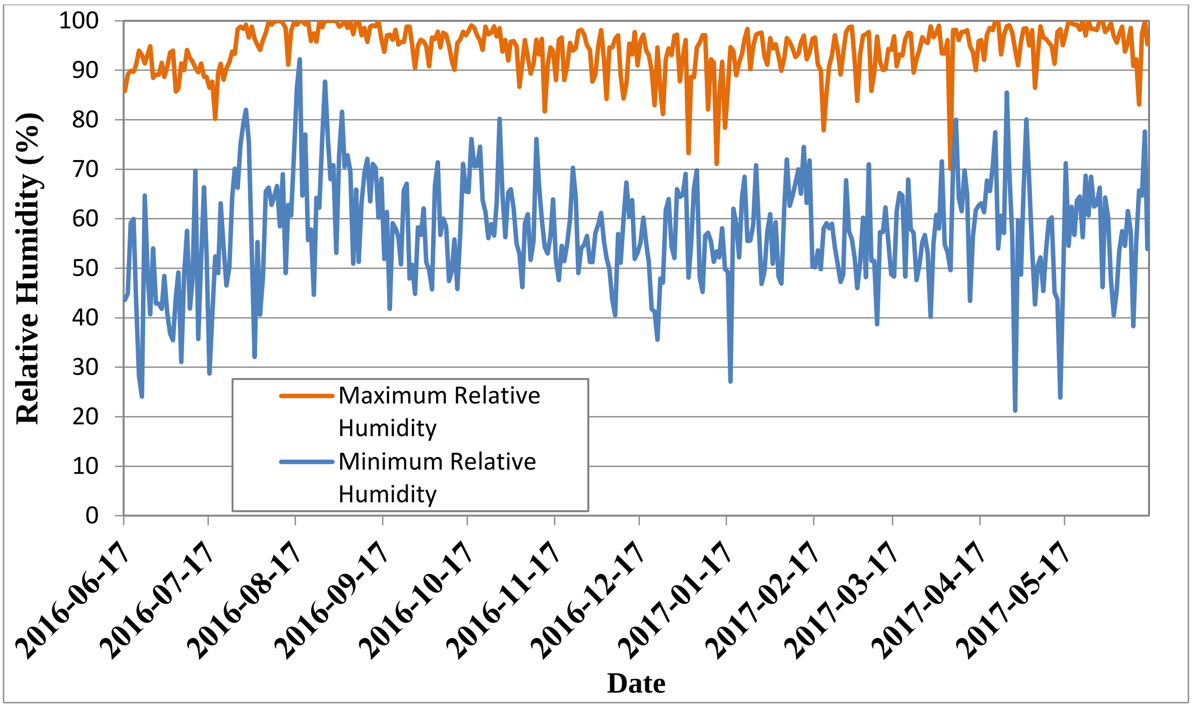

Figure 5.2: Daily minimum and maximum relative humidity at Vissersdrift Farm weather station for the period 17th June 2016 to 15th June 2017.

5.2.3 Solar radiation

The solar radiation of the Cape Agulhas region shows a strong seasonal trend (Figure 5.3), with the highest values occurring during December and January (summer) and the lowest during June and July (Winter). The highest recorded solar radiation was 35.5 MJ/day on the 25th December 2016 and the lowest was 1.5 MJ/day 17th June 2016. There was considerable variation of solar radiation from one day to another. For instance in summer, a day receiving 10 MJ/day can be followed by a day with 35 MJ/day. The day to day variations are lower during the winter months. The range of solar radiation in winter is generally between 5 – 12 MJ/day.

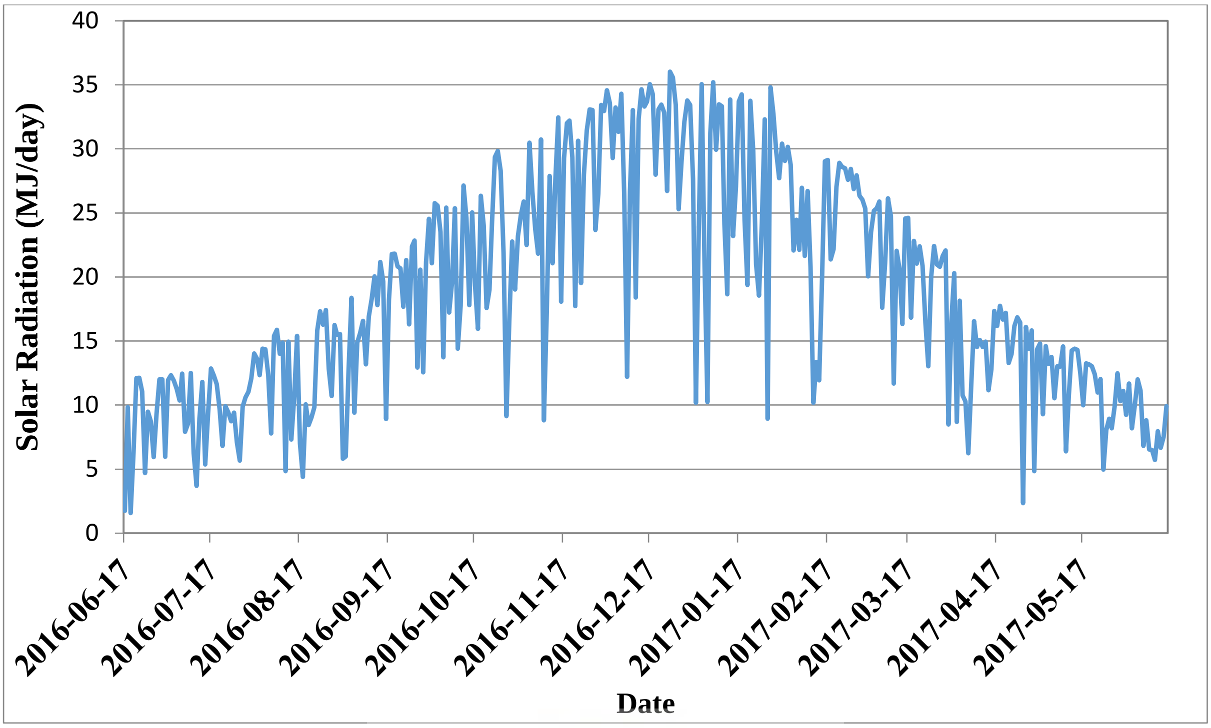

Figure 5.3: Daily solar radiation at Vissersdrift Farm for the period 17th June 2016 to 15th June 2017.

5.2.4 Wind speed

The wind speed in the Cape Agulhas region measured at Vissersdrift Farm was highest during June 2016 and July 2016 (Figure 5.4). The fastest wind speed recorded was 12, 6 m/s (45 km/h) on the 1st July 2016. From the 24th July 2016 to 15th June 2017 the wind speed did not exceed 5, 7 m/s (20 km/h). Wind speed was highest during the winter months than in the summer months.

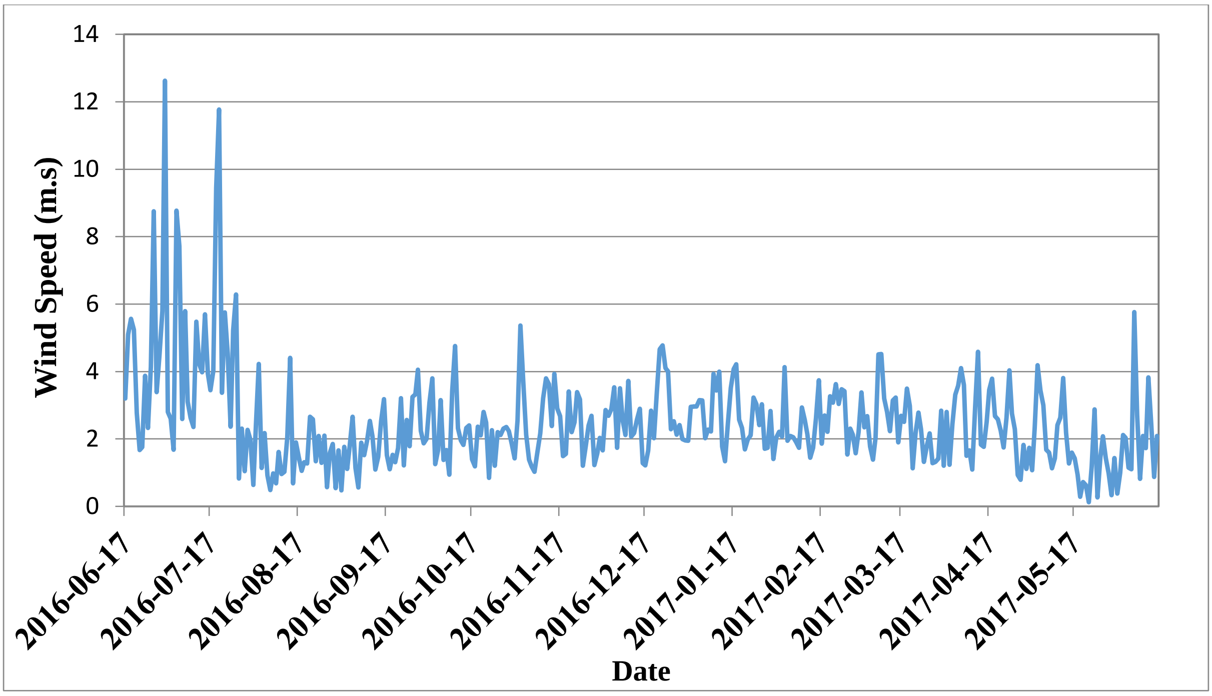

Figure 5.4: Daily wind speed at Vissersdrift Farm for the period 17th June 2016 to 15th June 2017.

5.2.2 Evapotranspiration

Daily reference evapotranspiration rates varied from 2 – 4 mm/day between June - October 2016 and April – May 2017. In summer, between November 2016 and March 2017 the rates ranged between 6 – 8 mm/day. The maximum rate of evaporation was 9.9 mm/day on the 18th January 2017, and lowest recorded evaporation rate was 0.9 mm/day on 26th April 2017. The total annual evaporation was 1469 mm for the year, which is greater than the 414 mm of rainfall received. Table 5.1 presents the total monthly evaporation rates. During winter the monthly evaporation rates ranged from 65 mm to 95 mm. During the summer months the monthly evaporation rates ranged between 132 mm and 213 mm. There is also a high day to day variation in evapotranspiration rates, where a day that evaporates 6 mm/day can be followed by a day that evaporates 2 mm/day. However, there is a clear seasonal trend with evaporation rates.

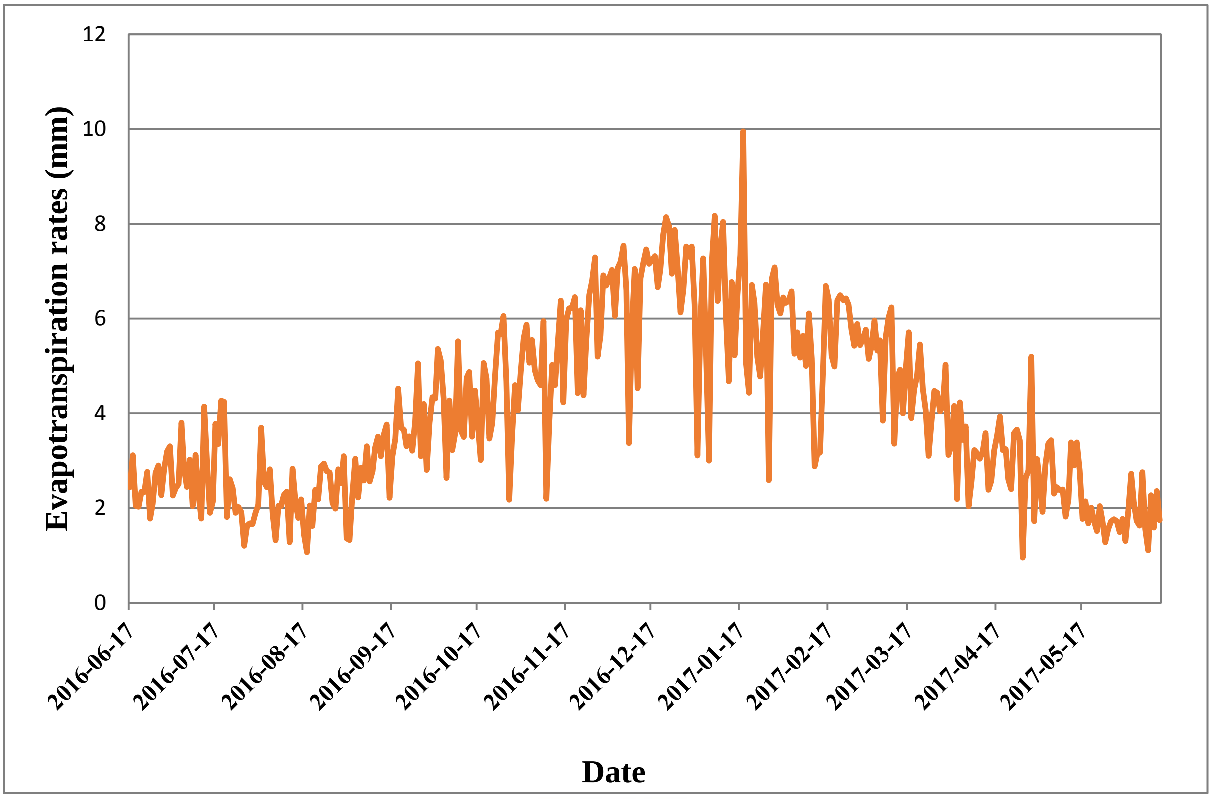

Figure 5.5 Potential evapotranspiration rates at Vissersdrift Farm weather station.

Table 5.1 Monthly evaporation rates of the Cape Agulhas

Month	Total evaporation (mm)	Month	Total evaporation (mm)
June 2016	65	December 2016	213
July 2016	79	January 2017	188
August 2016	70	February 2017	156
September 2016	95	March 2017	147
October 2016	132	April 2017	93
November 2016	162	May 2017	69
Total Evaporation (mm):		**1469**	

5.2.3 Rainfall

Monthly rainfall data (1909 – 2016) was provided by the farm owner of Zeekoevlei Farm. The 2016 rainfall data were compared to this long term record to assess whether the 2016 rainfall was below or above average (Figure 5.6).

Figure 5.6 shows that at Vissersdrift Farm, rainfall was below average for seven of the twelve months. Some of the Kars River's tributaries start in Napier. Napier's rainfall data record does not include the months of July and December 2016, as the weather station was accidently switched off during downloading. However Napier only received more rainfall than the average during March. May, October and November was much drier compared to the average for both weather monitoring sites.

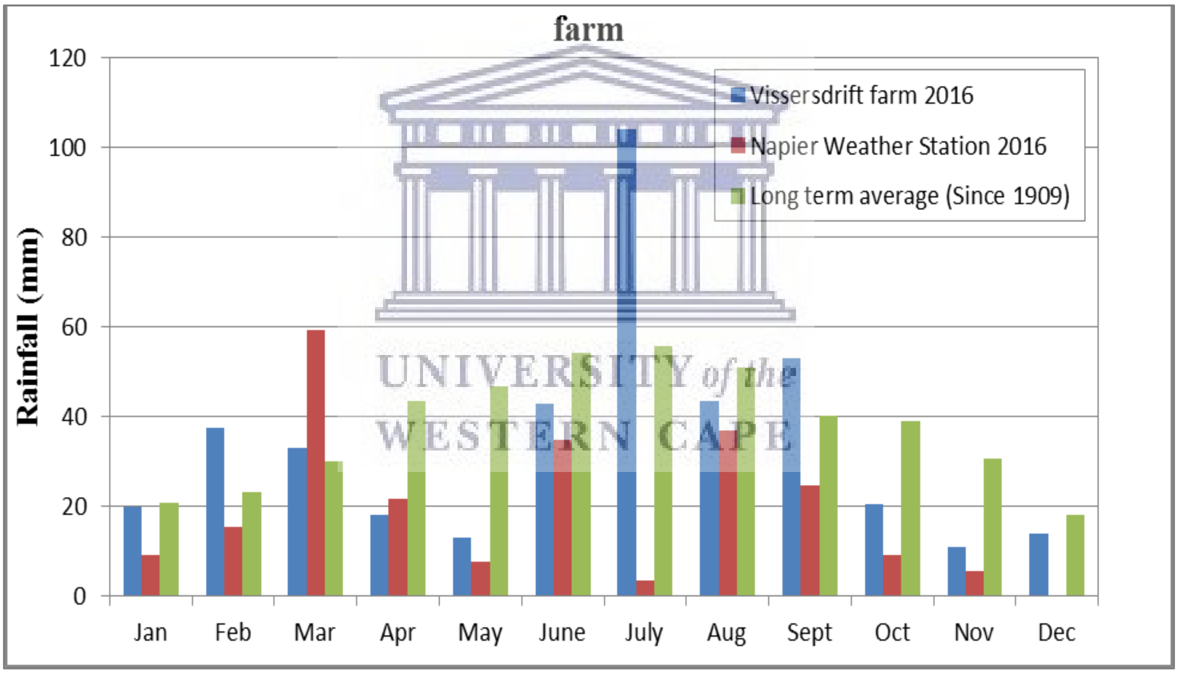

Figure 5.6 Comparison of 2016 rainfall to long term average at Zeekoevlei farm

The long term annual average rainfall at Zeekoevlei Farm based on the provided data is 454 mm/year. The total rainfall received at Zeekoevlei Farm in 2016 was 410 mm. Therefore the area received less than average rainfall during 2016.

The total rainfall for June 2016 to June 2017 at Vissersdrift Farm is 414 mm/yr. The Cape Agulhas region receives on average between 400 mm and 600 mm per annum. June and early July 2016, had rainfall ranging between 10 mm and 13 mm/day (Figure 5.7). On the

25th July 2016 20 mm/day of rainfall was recorded, and on the 26th July 2016 70 mm/day of rainfall was recorded. This storm contributed 21% of the total annual rainfall. After the major rainfall event in July 2016, there are only five rainfall events which exceeded 10 mm/ day.

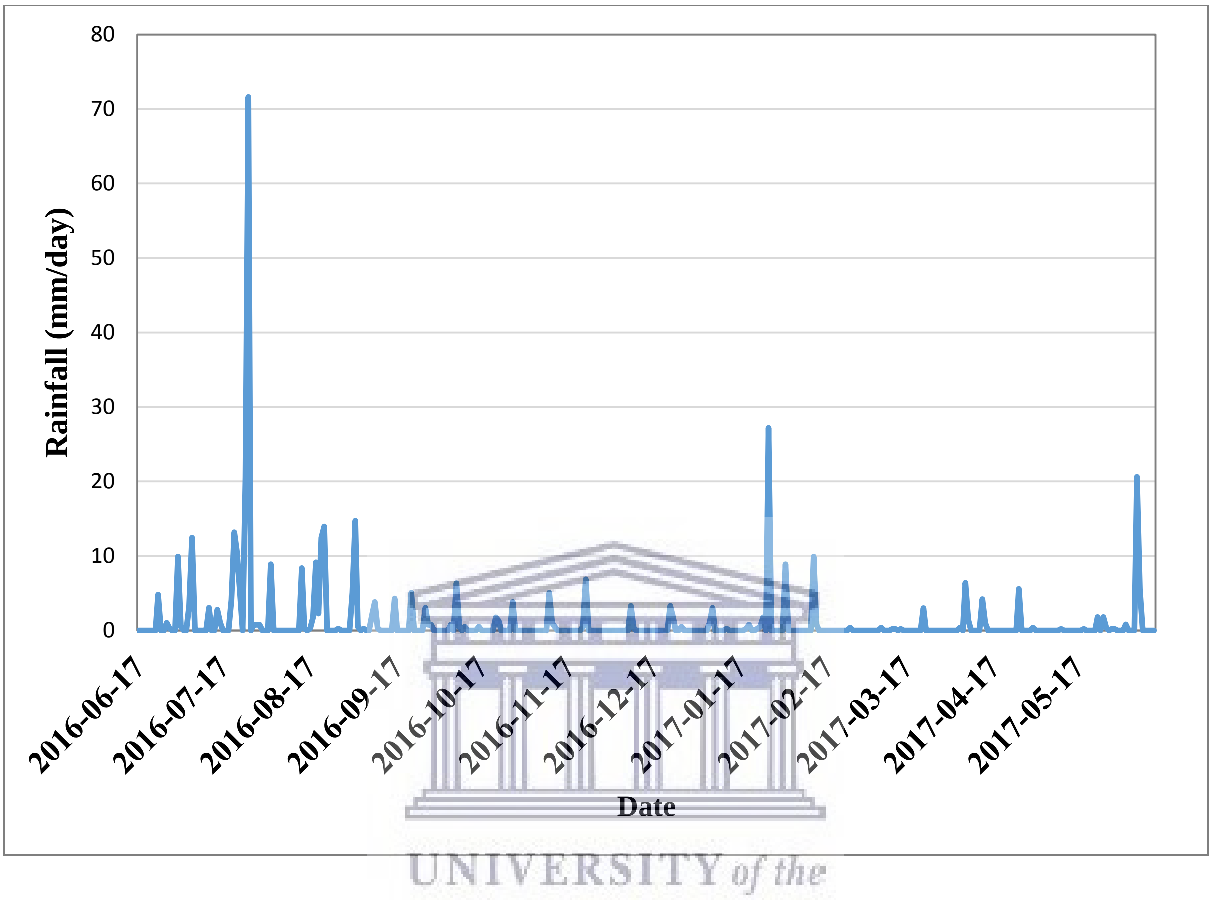

Figure 5.7 Daily rainfall record at Vissersdrift farm weather station

In Napier, only four rainfall events exceeded 10 mm/day during 2016 (Figure 5.8). The two largest rainfall events were recorded were 15.4 mm/day and 17.6 mm/day. July and December 2016 rainfall values are not known. The sum of the recorded rainfall for Napier (without July and December) is 217 mm/yr, which is 200 mm below the total annual average for the region.

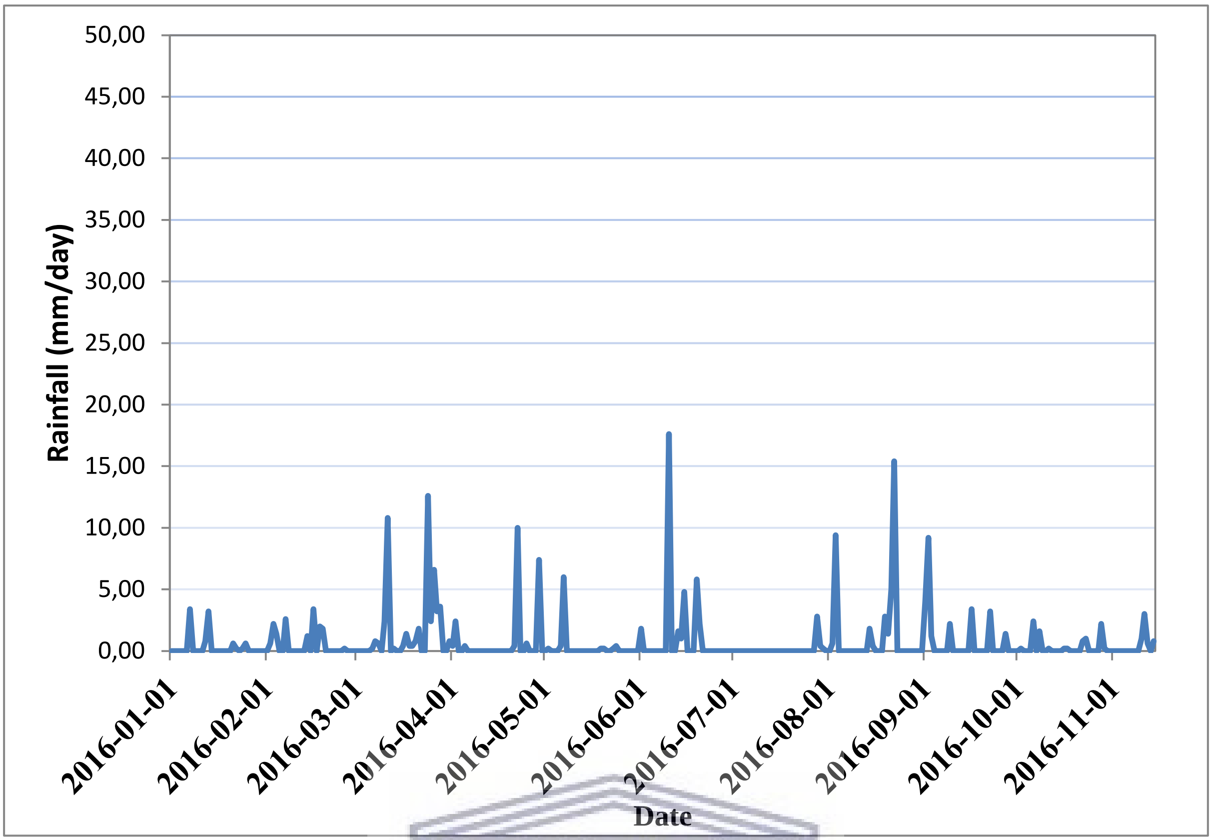

Figure 5.8 Daily rainfall record at Napier Weather Station during 2016

5.2.4 Flow measuring sites

The weir flow measuring site is located furthest north. The flow measuring site located on the edge of the wetland is the Poort River site and the site located furthest south is the Lower Kars River site on Zeekoevlei Farm.

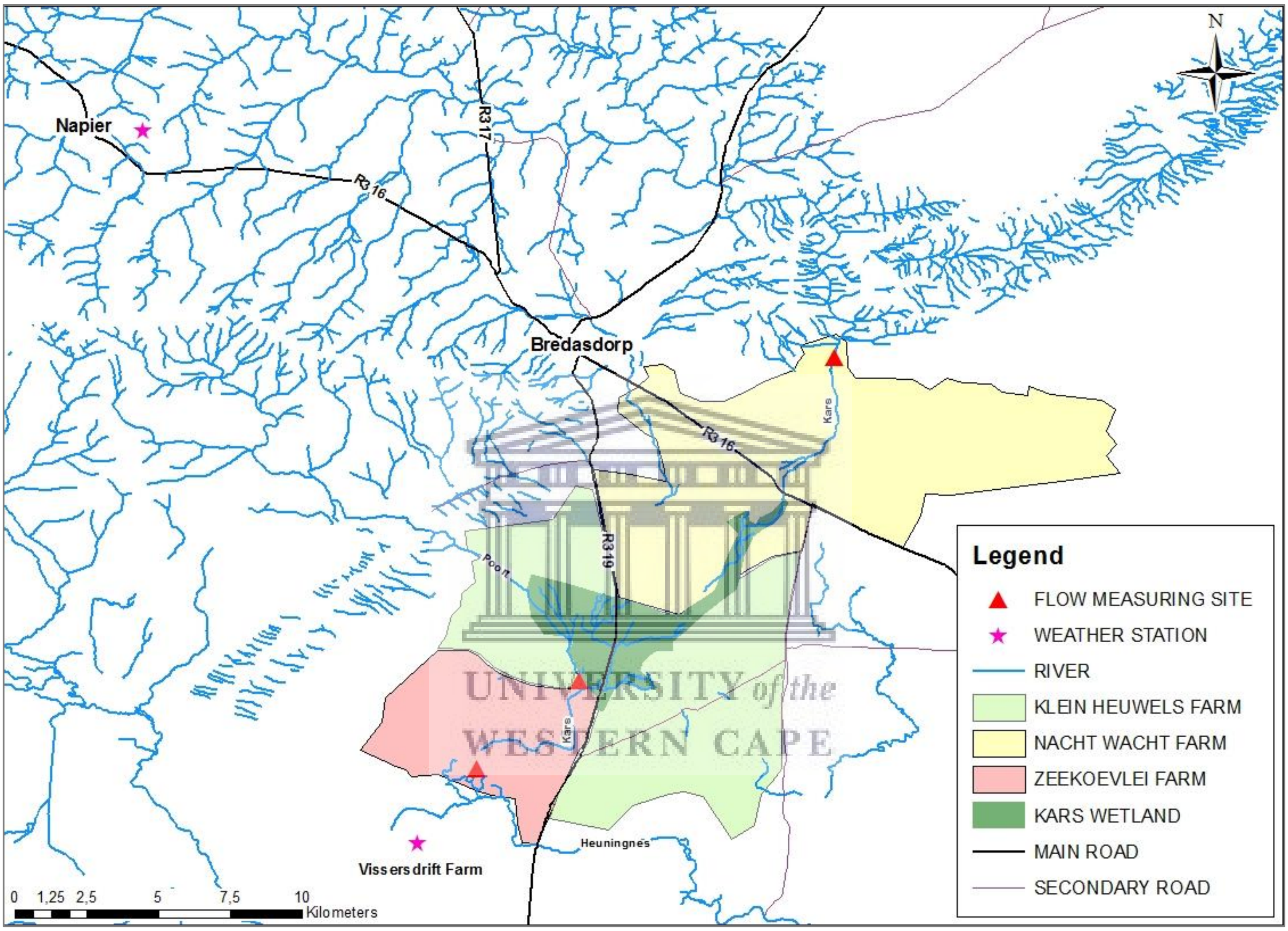

Figure 5.9 Map of flow measuring sites and weather stations in the Kars Catchment

Upper Kars River Weir at Nacht Wacht Farm

The river has a u-shaped channel incised in shale and contains gravel and sand, with trees, shrubs and reeds growing on the banks. The weir was used to estimate river discharge with depth by using the broad-crested weir equation.

Poort River (Klein Heuwels farm)

It can be seen that the Poort River channel is a regular u-shaped channel (Figure 5.10). The bank-full stage is 1.3 m. The river banks contain clay soil and on top of both river banks there were young *Acacia saligna* trees growing.

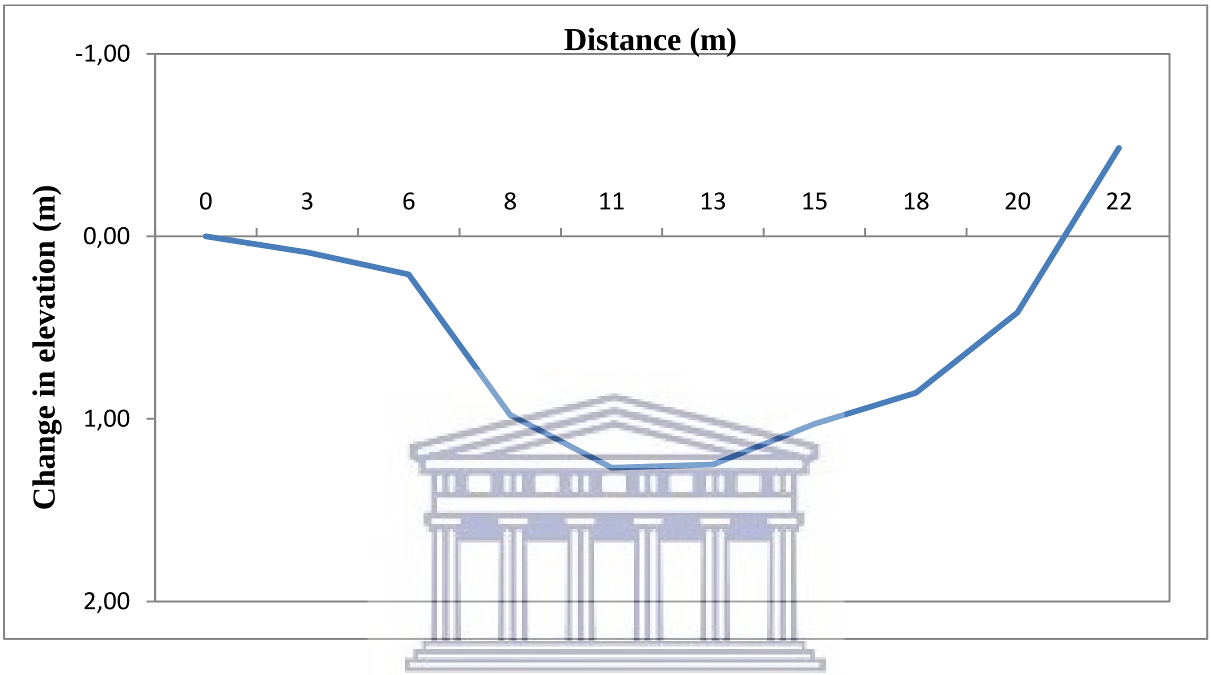

Figure 5.10: Cross profile of the Poort River at Klein Heuwels farm

Lower Kars River (Zeekoevlei farm)

The Lower Kars River profile (Figure 5.11) has a well-defined channel. The bank-full stage is 2.6 m. Grass covers the river bank and bed.

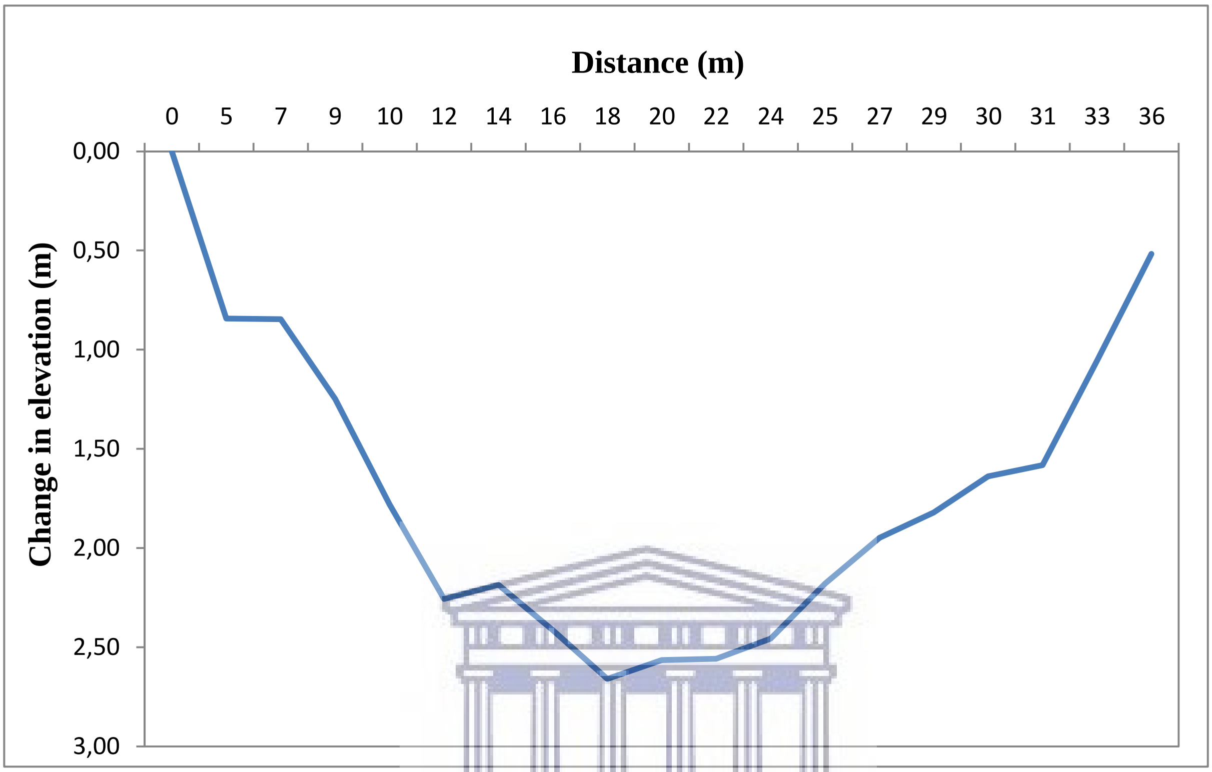

Figure 5.11 Cross profile of the Kars River at Zeekoevlei farm

5.3 River flows

5.3.1 Rating Curves

For the Upper Kars River section at Nacht Wacht Farm, the broad crested weir equation (Bos, 1989) was used to estimate river discharge and is given as follows:

$$Q = Cd.Cv.\left(\frac{2}{3}\right)\left[\left(\left(\left(\frac{2}{3}\right) * g\right)^{\frac{1}{2}}\right) * \left(b * h^{\frac{3}{2}}\right)\right] \tag{5.1}$$

Where: Q = Discharge (m³.s)

Cd = Discharge coefficient

Cv = Velocity coefficient

g = Gravity acceleration (m.s)

b = Width of the weir (m)

h = Water level above weir wall (m)

Cv was estimated using an area ratio of the wetted area for the measured head and the wetted area of the control section of the weir (Bos, 1989). A graph of area ratio vs Cv values was also provided in Bos (1989) for estimation of Cv values. The Cv value estimated in this study was 1.1. The Cd value was estimated using a correction function to the energy head (H) (Bos, 1989). In this study the Cd value was estimated as 0.9, and the equation is given as:

$$Cd = v^2/2.g \tag{5.2}$$

Where: Cd = Discharge coefficient

v = Velocity (m/s)

g =Gravity acceleration (m/s)

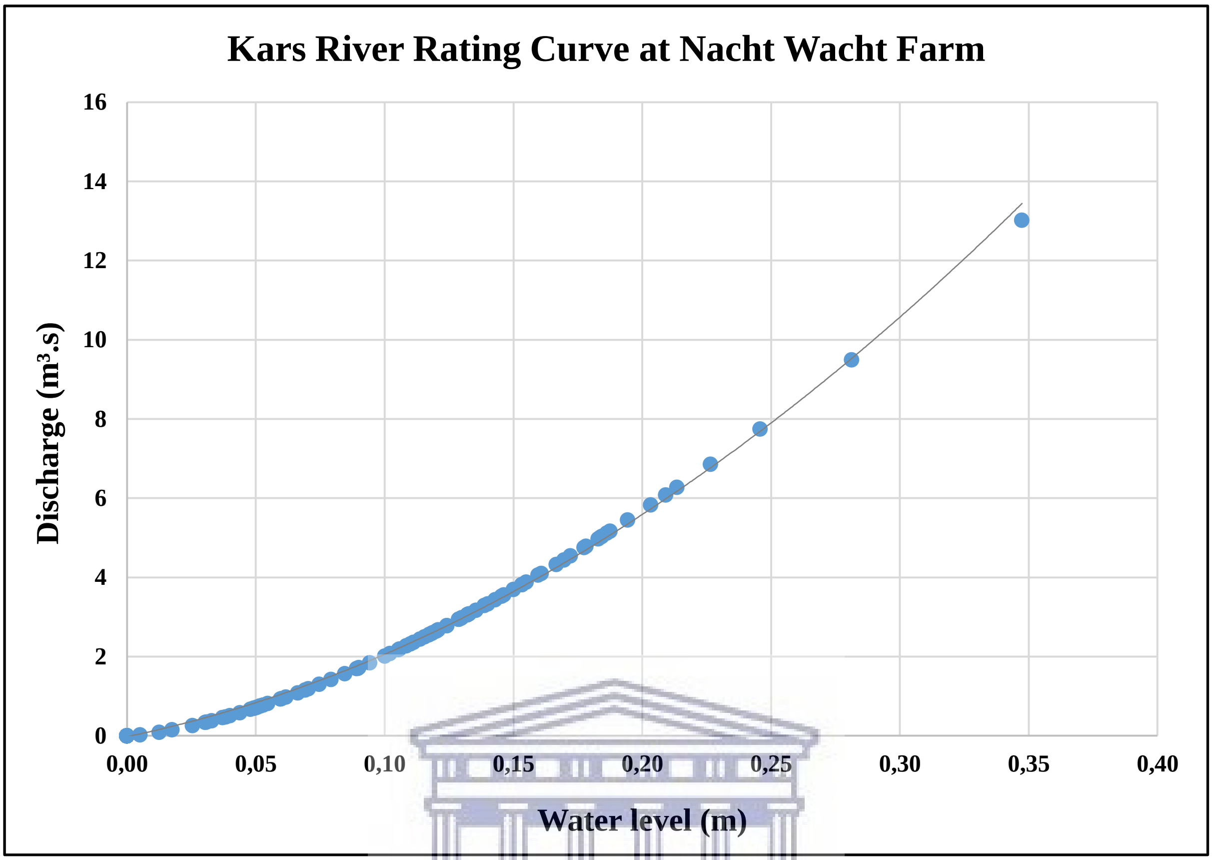

Figure 5.12 Weir rating curve at Nacht Wacht farm

The rating curve for the Nacht Wacht Weir (Figure 5.12) was created using the broad crested weir equation. Discharge measurements were conducted bi-weekly throughout 2016 using the electromagnetic current meter at Poort River and Lower Kars River sites. Seven discharge measurements using the electromagnetic current meter were made on the Poort River in 2016. The measurements were using to derive a rating curve (Figure 5.13) for this flow measuring station. Five measurements were recorded at the lower Kars River flow measuring station, and a rating curve (Figure 5.14) was derived for this station as well. Ideally there should have been twelve or more measurements covering the full range of discharge magnitudes to derive a rating curve. Due to the dry conditions in 2016, only five measurements were possible at the Kars River flow measuring station and seven at the Poort River measuring station. Measurements did not extend to bank-full stage. Due to the limited number of discharge measurements, the level of confidence in the accuracy of the rating curves derived are moderate.

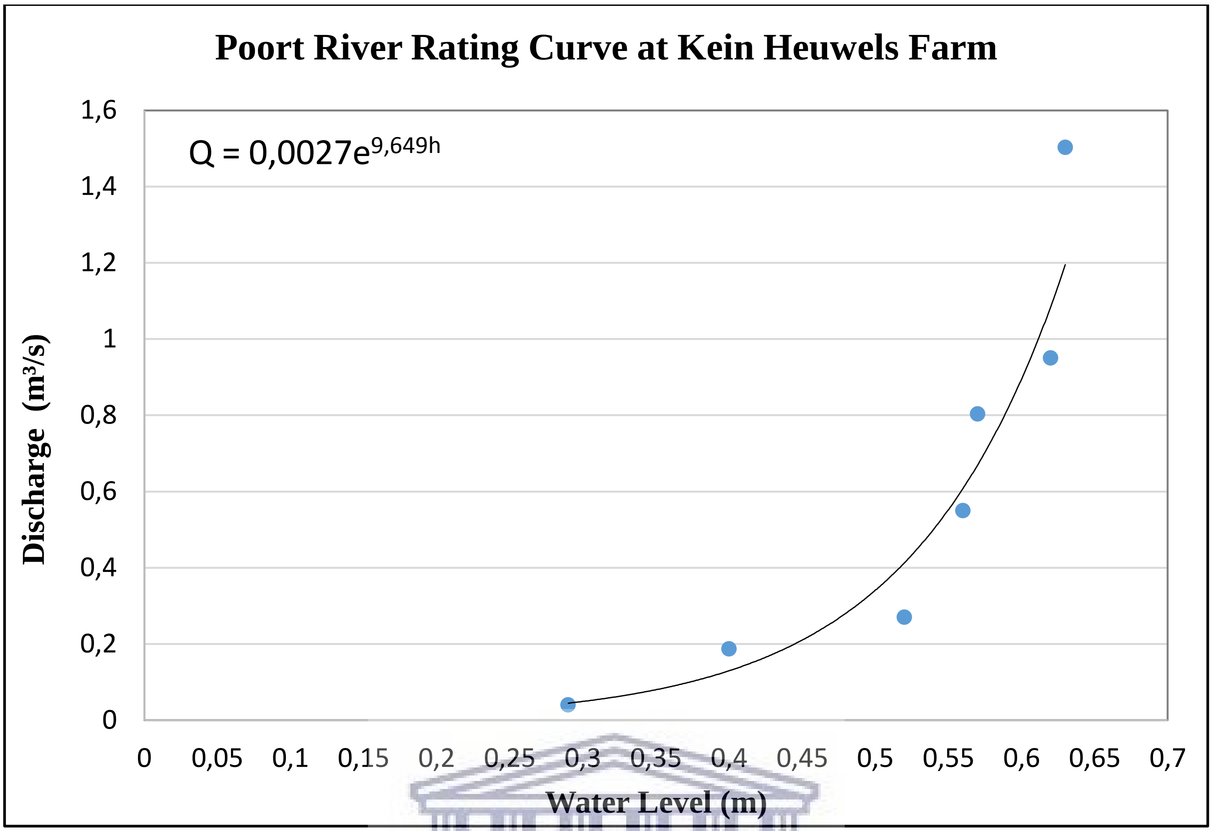

Figure 5.13 Rating curve of Poort River at Klein Heuwels farm

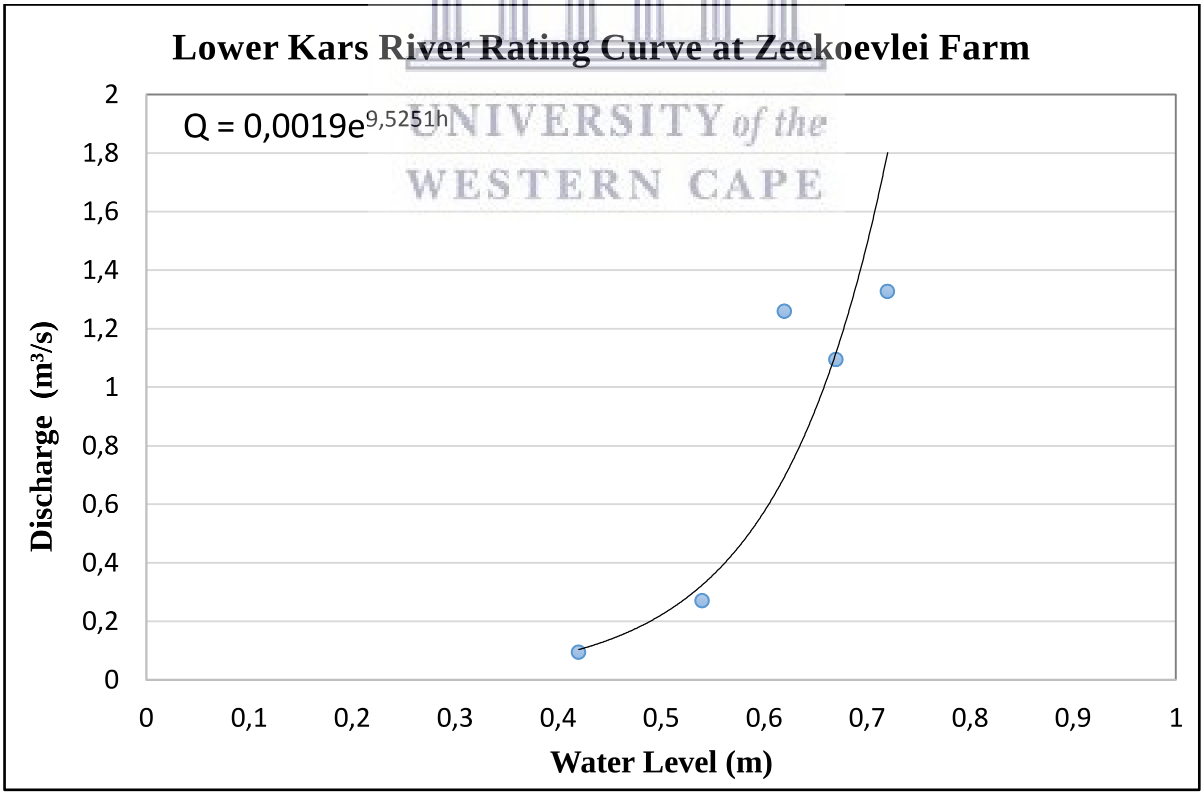

Figure 5.14 Rating Curve of Lower Kars River at Zeekoevlei farm

To improve discharge estimation, the Manning's formula for open channel flow estimation was applied to both the Poort River and Lower Kars River flow measuring stations. Using Manning's equation, a rating curve was derived for each site which predicts discharge (Q) for every stage height (h). The relationship of stage height (h) to flow area (A), and stage height (h) to hydraulic radius (R) was also described for both sites. Manning's formula is given as:

$$Q = \frac{A}{n} \, . R^{\frac{2}{3}} . S^{\frac{1}{2}} \tag{5.3}$$

Where: Q = Discharge (m^3/s)

A – Cross-sectional area of flow (m^2)

n – Manning's coefficient

R – Hydraulic radius (m)

S – Slope

The Manning's coefficient (n) selected for the sites was 0.032 which describes a straight dredged and uniform channel with grass and some weeds. This n-value is representative of both sites. Due to the depressions along the Poort River, flow estimation was improved by modifying the slope (S) for stages less than 0.5 m. A slope of 0.00003 was applied to stages less than 0.5 m and a slope of 0.0001 was applied to stages greater than 0.5 m. As previously stated, the study area is very flat, as it occurs within the Cape Agulhas Plain. Therefore a greater slope gradient was applied to higher flows, as with increased stage height, the energy gradient of the water flows would be higher. A slope of 0.0003 was applied to the Kars River for water levels greater than 0.5 m and a slope of 0.00005 was applied for water levels less than 0.5 m.

The Poort River rating curve derived using Manning`s equation (Figure 5.15) overestimates discharge when compared to the measured discharge values. However, the estimated discharge values are realistic values and can be estimated using the equation displayed on the graph. The R^2 value of 0.957 is evident of a good relationship between the equation and Manning's estimations.

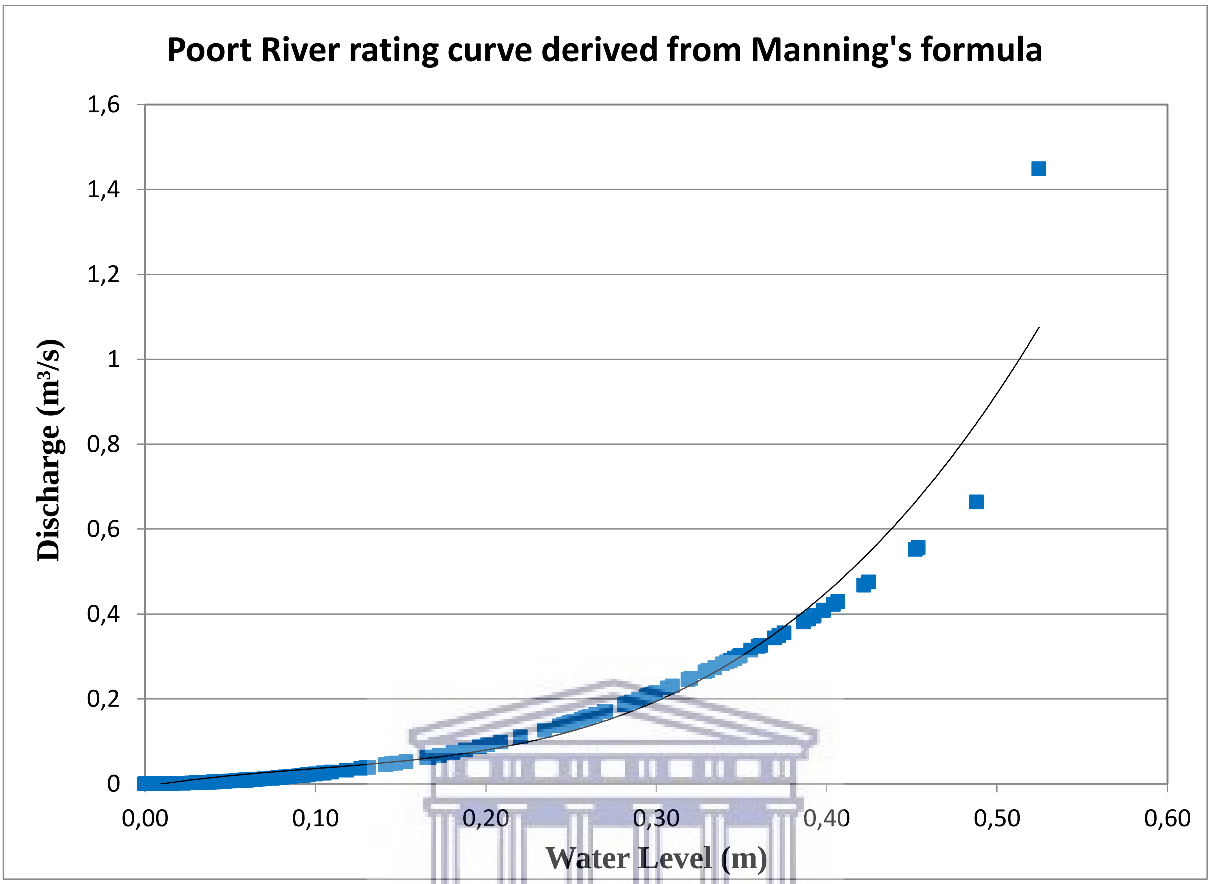

Figure 5.15 Manning’s estimation of flow discharge for the Poort River at Klein Heuwels Farm

The rating curve derived using Manning’s formula for the Kars River (Figure 5.16) also overestimates discharge when compared to the measured discharge measurements. However, the estimated discharges are realistic as they vary slightly above the measured discharges. Discharge estimates from the Manning’s formula are more accurate for water levels above 0.5 m. The observed abrupt increase in discharge around the 0.5 m water level mark is indicative of the river cross-section. The river has a step, where the width of the river changes drastically with a small change in height, which allows more discharge to occur.

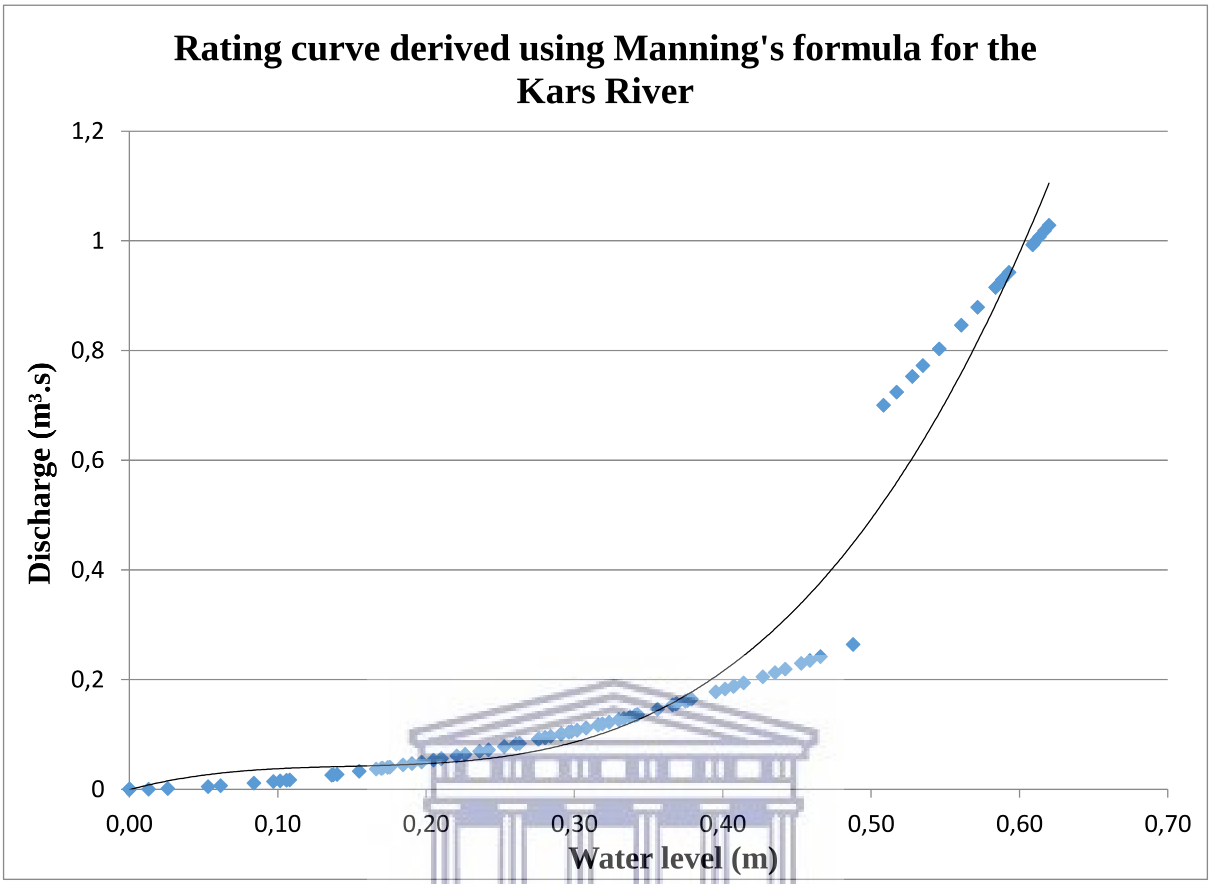

Figure 5.16 Manning’s estimation of flow discharge for the Kars River at Zeekoevlei Farm

5.3.2 Temporal variations of river flows

The Poort River started flowing before the Kars River (Figure 5.17). The Poort River's water level starts at 0.17 m because that's the date that the logger was installed and the Poort River already has some water in it. The Lower Kars River started flowing before the Upper Kars River. This could be because Varkvlei may have discharged water into the Lower Kars River. At all three monitoring sites there are three distinct peaks in flow or water level.

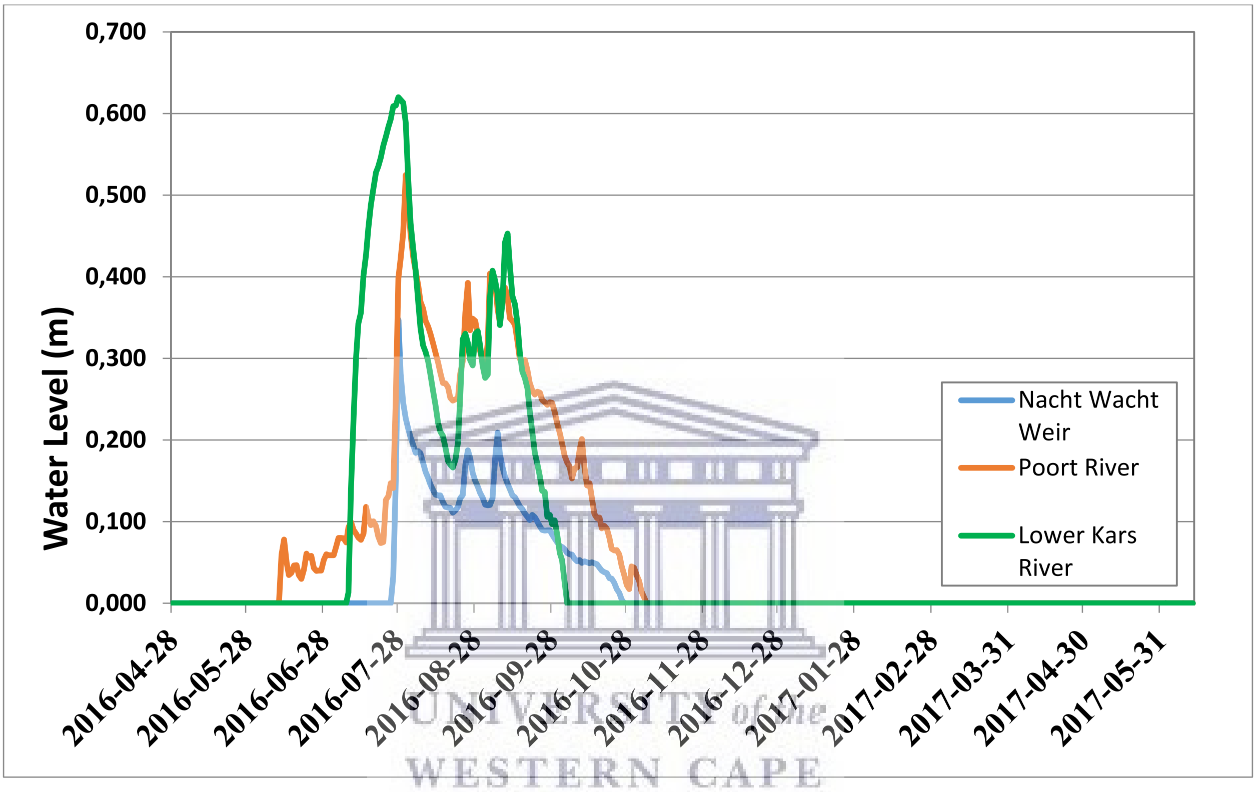

Figure 5.17 Daily water level changes of the Kars River and Poort River

Flows over the weir across the Kars River in Nacht Wacht Farm commenced on 27th July 2016. Peak discharge occurred on the 27th and 28th July 2016. Peak discharge was estimated to be 1.01 Mm³/day on the 28th of July 2016. After the initial peak, there are two other peaks in discharge which occurred on the 25th August 2016 and on the 6th September 2016. Total discharge for the Upper Kars River for the year was estimated to be 19.93 Mm³. Flow occurred from the 27th July 2016 to the 26th October 2016.

The Poort River had a peak discharge of 0.037 Mm³/day on the 24th July 2016. The Poort River discharged a total of 0.57 Mm³ of water between 28th April 2016 and 30th June 2017. Similarly to the Upper Kars River, the Poort River also displayed two distinct peaks in discharge. The peaks in discharge of the Poort River occurred on the 18th August 2016 and 28th August 2016.

This is the most downstream flow monitoring site, however flow started on the 8th July 2016. Peak daily discharge for the Lower Kars River was 0.099 Mm³/day recorded on the 30th July 2016. After the initial peak, there are four more peaks in discharge. The first two occurred on the 23rd August 2016 and 28th August 2016. The last two peaks in discharge occurred on the 4th September 2016 and the 9th September. The total discharge for the monitoring period was 4.6 Mm³.

5.4 Discussion

5.4.1 Climate conditions

The Heuningnes catchment is subject to hot dry summers and cold wet winters. Temperatures therefore will be expected to be highest during December, January and February. The lowest temperatures therefore are expected during June, July and August. These trends were observed and are characteristic of semi-arid climates.

Relative humidity varied constantly. However one key observation was that the relative humidity varied more during the colder months (May – August), and the highest recorded relative humidity were also recorded during these months. The variation may be greater during this time period because this is the wet season.

The solar radiation over the study area showed the same seasonal trend as the temperature. Higher values are recorded during summer and lower values are recorded during winter. Temperature and solar radiation are related. There are more sunny days during summer which is why we see the seasonal trend.

Wind speed over the study area showed interesting results. During June and July of 2016 the wind speeds reached 12 m/s, around the time of the 25th July 2016 storm, and ever since then remained between 0 and 6 m/s. It could be that there have been no real windy days or severe storms since the one in July 2016.

5.4.2 Evapotranspiration

Evapotranspiration (ET) is closely linked to solar radiation. The relationship is directly proportional. Higher solar radiation results in higher Et rates and lower solar radiation results in lower ET rates. This trend was observed in Figures 5.1 and 5.2. The average evapotranspiration rate was 3,6 mm/day, which is a reasonable estimated rate of evapotranspiration. ET rates over the Kars Wetland are relatively high. Coupled with erratic or below average rainfall, this could result in short flow times of rivers, reduced groundwater recharge (if any) and more importantly result in a less water storage for agriculture use. The study area presents perfect conditions to high ET rates. These include open plains with minimal vegetation, windy conditions and high daily temperatures (solar radiation).

5.4.3 Rainfall

Rainfall in the Heuningnes catchment occurs mostly in winter. As Figure 5.4 illustrated, on average most of the rainfall occurred during June, July and August. On the 25th July 2016 a cold front hit the Cape Agulhas causing high rainfall over the course of two days. This rainfall event caused flow to occur in the Upper Kars River which contains the weir. The rainfall event also caused flow in the rest of the catchment, where some locations along the Nuwejaars River and some bridges along local roads where completely flooded. Comparing Figures 5.4, 5.13 and 5.14, it was seen that the river responded almost immediately to the rainfall event, releasing large volumes of water from the weir, meaning that the Kars River had a quick runoff response to heavy rainfall.

The total rainfall for the year of 2016 was 414mm. This is just below the average annual rainfall in the catchment of 447mm (Bickerton et al, 1984), where 72mm fell over the 26th and 27th July 2016. The years 2016 and 2017 had very little rainfall. The Western Cape region of South Africa was experiencing a drought. Rainfall over the region has been below average for a number of years, and the rainfall pattern in the Heuningnes Catchment shows a similar trend. Napier did not have a lot of rain during 2016. This may be an important factor in why the river only flowed for three months.

5.4.4 River profiles

The Poort River has a cross profile which is skewed to one side. The water would flow more on one side of the channel, and this would like result in higher erosion rates on the favoured river bank. Channel velocity would be higher on one side than the other. Looking at the longitudinal profile of the Poort River, it was seen that there are two clear depressions or pools in the Poort River. These pools would reduce flow velocity of the Poort River and would aid in the deposition of suspended material. In terms of flow measurement, these are not ideal conditions in which to measure river flow velocities, however in reality it is very difficult to find suitable sites, which meets all the characteristics of a good flow measuring site. The Poort River is such a case. The Upper Poort River is infested with reeds, which makes it impossible to measure river flows in that location. Therefore this was the only section of the river that was suitable enough to measure river discharge with a current meter.

The profile of the lower Kars River at Zeekoevlei farm as illustrated in Figure 5.8 is that of a stable channel. In reality this section of the Kars River is a trapezoidal river channel with stable river banks. River flows are uniformly distributed across the channel. The shape of this river channel however is artificial. It was excavated in the 1940's by the land owner, in an attempt to drain water off of the property much faster, as flooding was an issue in this area during that time period. The result of the excavation was this trapezoidal channel shape with stable banks and very little vegetation. This channel is ideal for measuring river flows with a current meter. It is a long straight river section with stable banks and has little to no vegetation present within the channel. The longitudinal as illustrated in Figure 5.9 shows that the river reach does not have any significant pools or depressions. Therefore the velocity of the river flow was not adversely affected by the river bed.

A channel profile was not constructed for the Upper Kars River site as it was located at a weir. The water was dammed at this point, and could reach a depth of up to 2,5 m. The current meter method was not applied to this site, and therefore did not need to meet flow measuring characteristics for this method.

5.4.5 River flows

The rivers in the Heuningnes catchment are mostly classified as ephemeral or non-perennial. These rivers usually flow only during the wet season. The Kars River and the Poort River follow this trend.

The Lower Kars River section was the first to start flowing. This raises the question as to where this water came from. Some of this water could be from direct surface runoff from surrounding farmlands, as there were a series of rainfall events early in July 2016. Groundwater is an unlikely source purely based on the water levels of the river and catchment conditions (slope and soil). Based on the river water levels over the course of 2016 and 2017 it is evident that the river levels rise and drop quickly, which shows the groundwater is not sustaining any flows.

The Kars River flowed for three months in 2016 and it didn’t flow until July 2017. No persistent pools were observed in the rivers and none of the farm owners have seen any evidence of groundwater on their land (based on discussions held with land owners). Based on satellite imagery; Varkvlei contains water throughout the year. It dried up roughly in October 2017; however the Western Cape Province was experiencing a severe drought during this period of time. When Varkvlei is full of water, it discharges water into the lower section of the Kars River, which may partly explain why the lower Kars River started flowing first. Varkvlei is very close to this monitoring site as well. The Lower Kars River discharged a total of 4,69 Mm³ of water into the Heuningnes River. Surrounding farmlands could be filling up Varkvlei through overland flows, and the excess water gets discharged into the Lower Kars River.

The Poort River was the second river to flow in 2016. The source of the Poort River is the south facing slopes of the Bredasdorp Mountains. Rainfall in the mountainous areas is usually higher than that in the lower lying areas. The Poort River contributed 0.57 Mm³ of water from April 2016 to June 2017. This is an insignificant amount compared to the surface water contribution of the Upper Kars River.

The Upper Kars River was the last river section to starting flowing. This is because all the water from the Upper Kars River tributaries is dammed on the farm Nacht Wacht by the large weir. Once the water level reaches a depth of 2,65 m, the water spills over and starts to discharge into the Kars Wetland. The Upper Kars River was the largest contributor of water into the Kars Wetland. The Upper Kars River discharged a total of 22,14 Mm³ of water into the wetland from April 2016 to June 2017. Once the Upper Kars River started flowing into the wetland, it was this water source that kept the Lower Kars River flowing, and eventually feeding into the Heuningnes River.

6. WATER BALANCE ANALYSIS AND WETLAND MODELLING

6.1 Water balance analysis

Using the daily flows of each flow measuring station, the rainfall from the Vissersdrift weather station and the daily ET estimations, the total sum of each inflow and outflow point can be calculated for the study period and a water balance analysis can be created (Table 6.1)

Table 6.1: Inflow and Outflow of water in the Kars Wetland system from June 2016 to May 2017

Inflows	**Volume (m^3)**	**Volume (%)**	**Outflows**	**Volume (m^3)**	**Volume (%)**
Poort River	657 504	2. 5	**Lower Kars River**	4 618 250	18
Upper Kars River	22 141 610	87	**Et**	20 467 973	80. 5
Rainfall	2 593 755	10. 5			
Total	25 392 869	100	**Total**	25 086 223	98. 5

This water budget was therefore aimed at examining the influence of surface water within the wetland system. The flow graphs of the Kars River showed that the Kars system may be a runoff system, due to the short duration of river flows and rapid response to rainfall. A runoff system is a catchment where rivers respond immediately to rainfall events and river flows decline fairly fast if no rainfall occurs consistently.

It can be noted that the Poort River does not contribute a large amount of water to the Kars River. This is because some of the Poort River flows are diverted further upstream into Varkvlei, which is why Varkvlei remains filled with water all year round as observed in satellite imagery.

Rainfall contributed 10.5 % of the total water inflows into the wetland. The area received 414 mm of rainfall from June 2016 to June 2017. This is within the annual average of 400 mm – 600 mm per year. However 21 % of the total rainfall amount fell over the course of two days in July 2016 and rainfall during the study period were recorded below average for eight out of the twelve months. It should be noted that the Western Cape Province was in a period of drought. Therefore rainfall may have a larger influence outside of the drought. This can be determined with continued catchment monitoring.

The greatest contribution of water into the wetland was surface water inflow from the Upper Kars River which discharged over 22 Mm^3 of water into the wetland, which amounts to 87 % of the total inflows. In the Kars River system, 18 % (or 4.6 Mm^3) of the inflow water leaves as surface water flow and flows into the Heuningnes River. This is approximately one fifth of all the water that entered the system. ET losses amounted to 20.4 Mm^3 of water or 80.5 % of the total outflows. This makes ET the dominant outflow process of water in this wetland system. Lastly in comparison to the total inflows and total outflows, there is a difference of 2.5 %. This 2.5 % is the amount of water that cannot be accounted for in this water balance analysis.

6.2 Model parameters and estimations

As stated in Chapter 3, there are various parameters needed to run the model. Some parameters such as ET are derived using an equation and others need to be estimated. Table 6.2 shows the parameters that have been estimated in this study along with the values used.

Table 6.2 Estimated model parameters used in this study

Model Parameter	Values
Wetland Area	7.5 Mm^2
ET Area (Wetland Area + River Areas used in Et calculation)	10 Mm^2
Smax	4 Mm^3
Smin	1.7 Mm^3
α	0.1
β	0.947
Dw	1 mm

Wetland area and ET area were estimated using satellite imagery. Wetland area refers to the estimated maximum size of the wetland only, whereas ET area includes the wetland area as well as the surface area of the river sections. ET area was only used in calculating the volume of water lost through ET and this area is larger to account for water loss from the rivers as well.

6.3 Hydrological modelling of the Kars River

The observed river outflows were monitored at the Lower Kars River site. It can be seen that the observed river flows occurred before the simulated river flows (Figure 6.1). The simulated flows only start after the major rainfall event of 72 mm that occurred during July 2016. The peak discharges of the observed and simulated river flows are almost similar, with a difference of only 2000 m³. The second peaks in observed and simulated river discharges were far apart. The observed discharge was in the region of 54 000 m³, whereas the simulated discharge was in the region of 75 000 m³. The model therefore overestimates discharge by 21 000 m³ at this point. The third peak in observed and simulated discharges was closer together. The observed discharge was in the region of 73 000 m³, and the model simulated a discharge of 79 000 m³. There is an overestimation of 6000 m³ at this point. The tail end of the model simulates flows that are comparable with the observed flows. Thereafter no flow has occurred in the catchment up to the last monitored day on the 14th June 2017.

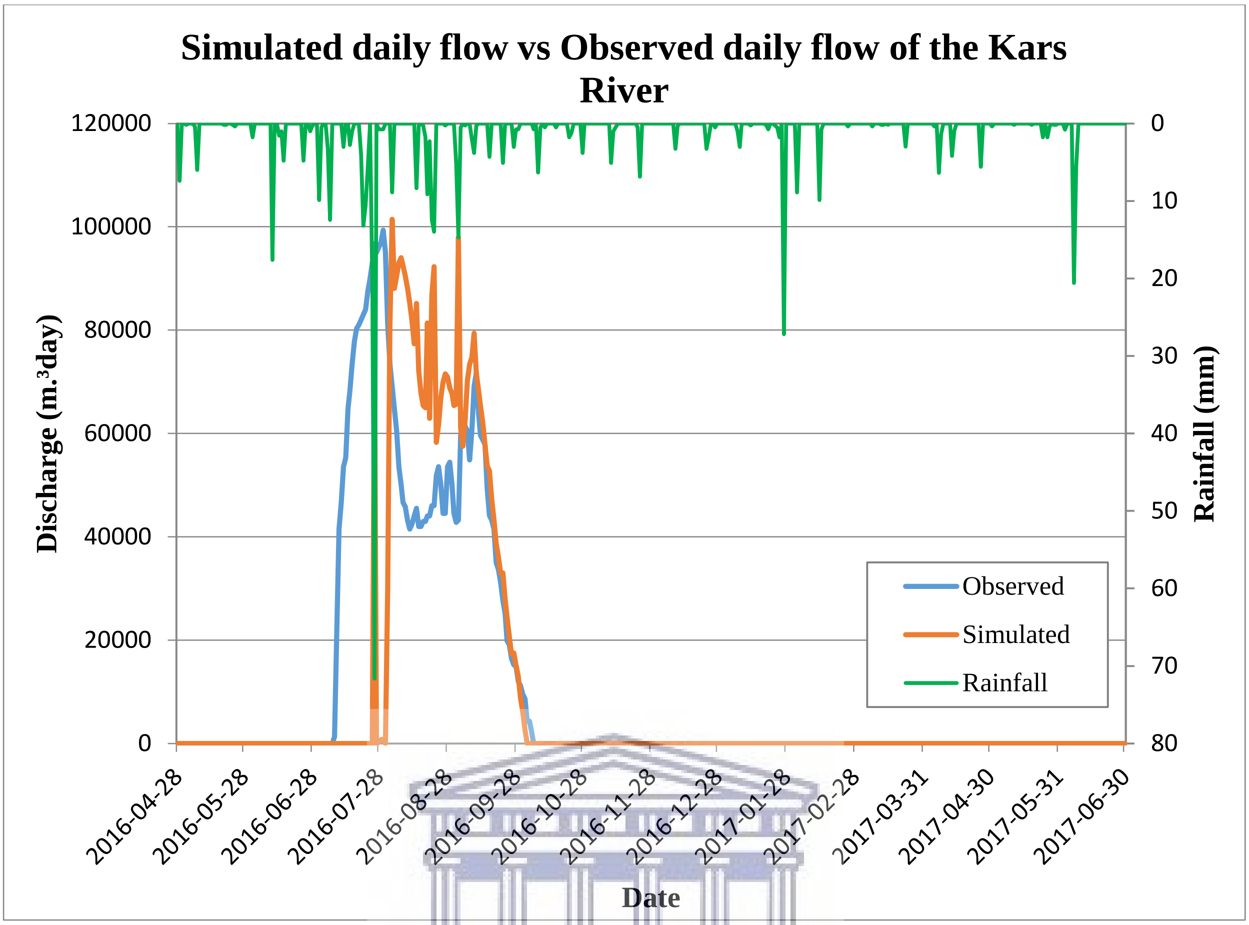

Figure 6.1 Observed river flow versus the simulated river flows of the conceptual model

The model predicted values were highly variable to the observed values (Figure 6.2), in that there is an obvious underestimation in flows (the delay in flow between Lower and Upper Kars River) and then once flow is predicted, it is overestimating flows. The relationship is not linear. However from Figure 6.2, the R² value of 0.47 indicates a weak correlation between the observed and simulated values. The RMSE value for the study period was 0.191, which indicates that there is a close relationship between the observed and simulated flows. It is important to note that these were the values derived after model calibration and optimisation.

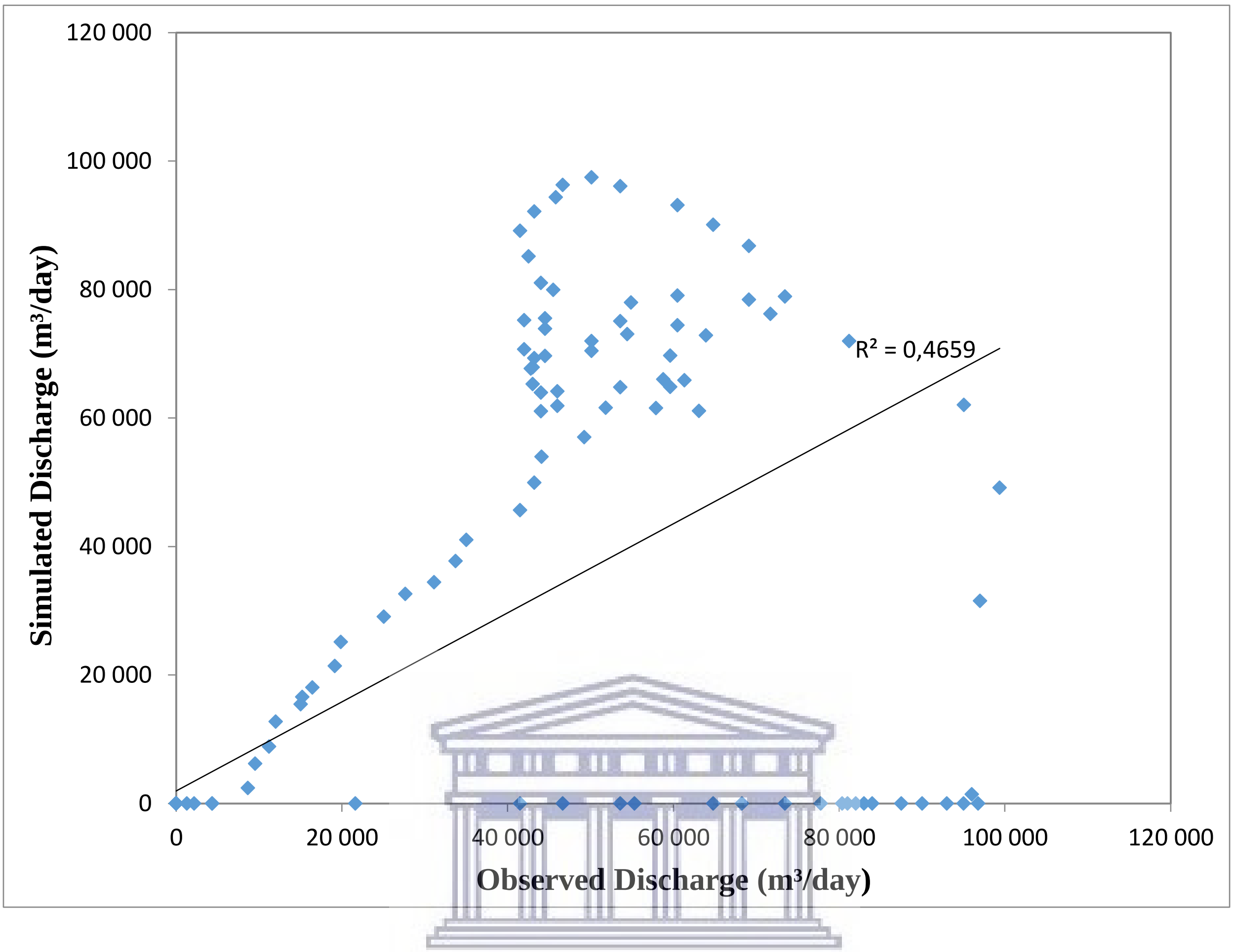

Figure 6.2 Observed vs simulated discharge regression analysis

6.3 Discussion

6.3.1 Water balance

The water balance illustrates some important observations. The first observation is that the Poort River does not contribute a large amount of water to the Kars River at the Poort River monitoring site. The total contribution was 2.5 % of the total inflows. The contribution of the Poort River is low because further upstream of the monitoring site the water is diverted into Varkvlei. Satellite imagery revealed that Varkvlei contained water all year round during 2016. The Poort River would be the only source of water to Varkvlei, other than precipitation and possible groundwater discharge. Precipitation is an unlikely source, because rainfall was not high during 2016 and the surface area is relatively small. In addition to this, similar sized vlei's or pans in the area did not manage to sustain water all year round. Though it is unknown, groundwater is also considered to be an unlikely source of water to Varkvlei. This is because in the water balance analysis over 98 % of the inflows were accounted for in the outflow pathways (surface water outflow and evapotranspiration). This indicates that groundwater may not be a major contributor to the surface water flows as some of the water that is unaccounted for would be stored in the soil, reducing the possibility of groundwater discharge. Therefore a combination of precipitation and river inflows from the Poort River must be sustaining Varkvlei.

There are a lot of catchments around the world where rainfall is the dominant source of water to a wetland or river system. However the Kars system is not one of these systems. This may also be a result of the drought that affects the Western Cape province of South Africa. Rainfall has been below average for a while in many regions within the province; however the Cape Agulhas has received 414 mm/year which is within the 400 mm to 600 mm/year range that is estimated to fall annually in this area. It must be stated that 72 mm of the 414 mm fell over the course of two days. If that particular event did not occur, the total rainfall for the year would have been well below the average rainfall amount. The amount of farm dams in the area serve as an indicator to show how important it is to store rainfall. This catchment is described by locals as a runoff catchment. Once it rains, the water flows into rivers, and causes floods in certain areas and bank erosion in others (mostly in the upper catchment). The catchment was modelled and conceptualised based on this assumption. The hydrograph illustrating the flows of the various river monitoring sites proves this concept as well. It shows that spikes in river flows occur shortly after a rainfall event.

Of the 25 Mm^3 of water that entered the catchment, only 4.6 Mm^3 of water left the Kars River as surface water outflow. This water discharges into the Heuningnes River and flows downstream towards the estuary. This is a sizeable contribution to the Heuningnes River considering the Kars River is a non-perennial river. Roughly one fifth of the total inflows into the wetland system leave as surface water outflow providing freshwater and nutrients to the Heuningnes estuary.

The dominant outflow process of water was evapotranspiration (ET). This was estimated using the Penman-Montieth method. The average ET rate for the Kars Wetland was 3.6 mm per day. The flat topography of the Agulhas Plain, windy conditions and the hot summer climate resulted in high ET rates as previously shown in Chapter 5. The dominant loss of water through ET makes the Kars Wetland similar to the Okavango Delta as in Wolski *et al* (2005), which may be a trend for Southern African wetland systems. In the broad review of wetland studies by Bullock & Acreman (2003), it was found that many wetlands around the world follow the same trend, including some studies from the Southern African region.

Only 1.5 % of the water was not accounted for in the water balance. This means that over 380 000 m^3 of water cannot be accounted for. However this is a small amount of water. There are two possible explanations. The first is that the wetland may be storing the water in the soil. Wetlands are known to act like a “sponge” and store water within the soil to release it over time. The second explanation is that the water was stored by the wetland and recharged the groundwater table. Groundwater was not monitored during this study. Therefore it is possible that the remaining 1.5 % of water recharged the underlying aquifer. Additionally both processes could have occurred whereby some of the water was stored in the wetland and some of the water percolated down to recharge the aquifer. Bullock & Acreman (2003) have found studies which support both theories, however further studies are required to test these theorie on this particular wetland.

6.3.2 Hydrological Modelling of the Kars River

There are six observations which illustrate the models ability to predict river flows. The first observation is that the observed river flows occurred before the predicted flows. This is because the model relies on upstream river flows to make predictions. From the hydrograph it was seen that the Lower Kars River started flowing before the Upper Kars River. The water budget also reveals that the Upper Kars River is the dominant water source of the Kars Wetland. Therefore the model only predicted flows once the Upper Kars River started flowing which is why the model predicted flow after the observed flows. Varkvlei discharges water into the Lower Kars River when it is full, and from the satellite imagery, Varkvlei was seen to have contained water all year round. Therefore to improve the model, Varkvlei should be monitored to establish exactly where its water comes from and how much water is stored in the reservoir. Once this is known, the model can be altered by including a separate reservoir for Varkvlei, and possibly reducing the prediction error at the beginning of the model.

Once the model started predicting flows, the peak discharges of the model were similar. This shows that the model predicted a reasonable discharge when compared to reality. The second peak in discharge was not similar at all. The model overestimated flow by a large margin. This may have been a result of the delayed start in flow predictions by the model, as the time for water loss was shorter than that of the observed flows until the next major rainfall event. The model had ten days less time to lose water, so it lost water too slow or the volume of water lost was too little over this period. Time should not be a big factor at this point as both river sections would have been flowing for a while. This is proved at the third peak in discharge, where the model and observed discharges are fairly similar with a small overestimation of 6000 m^3 by the model. This is an adequate over estimation of discharge. Looking at the tail end of the model, both the observed and the predicted flows decreased at the same rate and the predicted discharge at each point is similar to the observed discharge. Overall with further monitoring and the inclusion of Varkvlei into the monitoring system, the model should perform much better.

The regression analysis showed an R^2 value of 0. 47 which indicated a weak relationship between predicted and observed values. The RMSE of the modelled and observed flows showed that there is an adequate relationship between the variables. However, with further monitoring of the Kars River and the inclusion of Varkvlei into the model, the predictive variability of the model will be reduced improving model performance.

The high variability of the models predicted values are a result of the inclusion of runoff plots and estimated discharge of Varkvlei based on rainfall and Varkvlei's area. The inclusion of Varkvlei and local runoff estimations into the model formed part of the model optimisation. This was done in an attempt to reduce variability in model predictions. However this was not very successful because there was no data available on Varkvlei's depth, water level fluctuation patterns and discharge conditions. The only success that this technique brought into the model was to reduce the time between observed and predicted flow by one day, which was negligible. The estimated Varkvlei and local runoff discharge resulted in the various short increases in discharge prediction which lead to some overestimations in prediction. The lack of long term data, and the use of data collected during a drought period creates uncertainties in catchment observations in terms of flow and weather conditions, which creates uncertainty in model predictions.

This topographical approach to modelling by Savenije (2010) is a conceptual approach, which will require more testing in various other catchments over many more years to come before it can be an established method of modelling. However, based on limited data, the model performed to an acceptable level in providing a basic prediction of flows through a wetland and should be considered as the first approach to modelling when data records are short and not very detailed.

7. CONCLUSION

7.1 Characterising the Kars Wetland

In conclusion the Kars Wetland was found to be a seasonal floodplain wetland using the method by Ollis *et al* (2015). The wetland has one point of inflow, the Poort River adding flows just below the wetland and one point of outflow. There is no defined river channel running through the Kars Wetland, however along the outskirts of the wetland there are two drainage ditches that were artificially constructed by land owners in order to remove water from the land as fast as possible to avoid flooding of the neighbouring cultivated lands. There are small flow paths within the wetland, however these do not run through the whole length of the Kars Wetland. The area in which the Kars Wetland occurs is very flat.

During the summer months, the wetland is almost indiscernible from the surrounding environment. This is because the wetland occurs between farm lands that are often cultivated as grassland for livestock. Grasses are commonly found within the Kars Wetland. Almost all the water that was stored in pools and in the soil from the winter has evaporated by mid-summer as temperatures can reach up to the high thirties. The Cape Agulhas region is an area that experiences winter rainfall. This area receives on average between 400 mm and 600 mm of rainfall annually. Therefore the Kars Wetland and the Kars River receive water from rainfall mostly between June and August. At this point the Kars Wetland changes from the indiscernible wetland to a very distinct wetland environment. It no longer has dry soils, but instead has lands that are ponded with water. The clear contrast of the wetland between winter and summer is evidence that this is a seasonal wetland and also shows how important rainfall is to the Kars Wetland.

The wetland soils are largely responsible for the occurrence of ponding. The Kars Wetland has a range of different soil types however the most dominant soil texture is silt. The average texture concentration for the soil was sixty percent silt, thirty percent of clay and ten percent of sand. Water does not infiltrate into these soils easily, the pore sizes and space within these soils are small and not interconnected, and therefore the water ponds on the surface. The inundation of the wetland is a result of the wetlands soils as well as the flat topography of the area. Evaporation was a major process of water loss for the Kars Wetland. This is characteristic of wetlands in areas with high summer temperatures. The soils survey aimed to provide information about the area to determine whether the soils were hydric soils or not. Two observations that indicate hydric soils are the presence of mottling and gleying. Both mottling and gleying were observed in many areas of the wetland which provided sufficient information indicating that the soil receives water on a regular basis to change the oxygen concentration of the soils.

The Kars Wetland contains several different species of vegetation. An accurate vegetation census was not done in this study, however key vegetation types were identified to provide information on whether the Kars Wetland is an actual wetland or not. These vegetation types are hydrophilic plants. The Kars River as well as the Poort River on various sections contains a number of plant species which occur in the water. These include reeds such as *Phragmites australis*. The Kars Wetland contains mostly grasses, sedges and rushes. These species are known to occur in wetland areas and therefore serve as an indicator that this is a true wetland area as these plants prefer hydric soils.

The hydrology of the Kars Wetland proves why it is a seasonal wetland. Firstly rainfall occurs seasonally as previously mentioned. Rainfall is not the dominant water source for the Kars Wetland. The dominant water source of the Kars Wetland was surface water flows from the Kars River. The river has to reach a stage height of 3.65 m (point at which the weir is full) before it can flow over the weir and eventually discharge water into the wetland downstream. The Kars Wetland is dominated by surface water. The extent to which groundwater is involved in the wetland hydrology is not known. With over 98,5% of the water accounted for within the water balance analysis, which may be an influence of groundwater. Groundwater was assumed to have little impact in the wetland hydrology of the Kars Wetland due to the silt and clay concentrations in the B-horizon of the wetland soil. Evaporation was the dominant process of water loss. This is much like the Okavango Delta. This may potentially be a trend in Southern African wetlands.

7.2 Determine the effect of the Kars Wetland on the Kars River flow regime

One of the objectives of this study was to determine the effect that the Kars Wetland has on the Kars River flows. This objective has been achieved. The Kars River was monitored for a period that extended over a year and a half, which during this time provided hydrological information over one wet season and two dry seasons. In an ideal situation, two wet seasons would have been preferred but due to the draught of the Western Cape this was not possible. However, there was enough information to conclude that the Kars Wetland does augment the flows from the Kars River.

With the lack of a defined river channel within the wetland, the river flows enter the wetland area, and diffuse overland flow occurs. This increases the residence time of flow within the wetland, which therefore also increases the evaporative losses. Roughly only one fifth of the upstream volume reaches the downstream river section.

The data showed that there was a delay in flows of five to six days between upstream and downstream monitoring points. With real time monitoring of the upstream river flows, flood warnings can be provided to the downstream population to reduce the risk of loss of life and property damage. This would require a hydrological model capable of predicting river flows downstream. This study attempted to develop such a model using limited information.

It can be concluded that the hydrological model developed in this study performed to a satisfactory standard in that it predicted a similar peak discharge, showed a similar trend in flows and the tail end of the model was very accurate using limited data inputs. It can also be concluded that there are some improvements that need to be made to create a model that would truly be acceptable of acting as an early flood warning system.

Overall the wetland has been described and the hydrological behaviour of the wetland was determined. This study has provided a sufficient baseline of the Kars Wetland and the Kars River, and the knowledge base will only improve in the future as further in-depth studies are conducted of the intricate environmental processes.

7.3 Recommendations

There are a few recommendations for further research on the Kars Wetland and Kars River. These include:

- Assess the effect of groundwater in the Kars Wetland hydrology. This would provide a detailed account of the hydrogeological properties of the area which has not been established yet. It would be interesting to determine whether the clay layer has a significant effect on recharge or not.

- Monitoring of Varkvlei and determine its influence on the Kars River. The contribution of Varkvlei to the Kars River could not be determined during this study and therefore a study into this would improve on the current findings and understanding of the system.

- Improve the hydrological model by continuous river flow monitoring and including Varkvlei and groundwater data. This study would round off the project as a whole, allowing a solid baseline study of the area which can be used for water resource prediction and aid in the local areas decision making on water resource management.

Appendix

Table 4: Soil sampling log created in the field

Site	Surface description and vegetation type	First layer of soil and depth	Second layer of soil and depth	Third layer and depth	Mottling or Gleying present
1.1	Hard surface, compacted and sandy. grasses present, one or two trees	Top layer was dark brown sandy clay (0-15cm)	Soft brittle silt/clay texture. (15-40cm)	Lighter brown soil (50cm depth) with mottling. Sand still present up to 80cm.	Yes
1.2	Hard surface, dark brown in colour, some salt marsh present.	Dark sandy clay soil texture. 0-15cm depth.	lighter soil colour, some mottling present, soil harder from a depth of 70cm.	n/a	Yes
2.1	Hard clayey surface. Grey in colour. Not a lot of vegetation at this site. Some sedges and grasses in surrounding area.	(0-45cm) grey, Silty clay soil. Small stones in soil.	45cm - Orange brown clayey soil with small stones present. Mottling found in this layer.	n/a	Yes
2.2	Same as site 2.1	Sandy silty soil. Grey in colour. Stones present in soil. Compacted soil. (0-30cm)	(30-45cm) Orange brown clayey soil with gravel.	(45-70cm) Orange brown clayey soil with no gravel. Mottling present. (70cm +/) seemed to be more sandy.	Yes
2.3	Seems to be a dry river / channel bed. Cracked surface.	(0-20cm) Sandy texture	(20-70cm) Orange brown clay. Dense or solid. Struggled	n/a	Yes

			to auger deeper.		
2.4	Sandy cracked bed. Grasses and sedges in area.	(0-35cm) Sandy texture with some silty/clay evidence.	(35-50cm) Orange silty layer with mottling present.	(50-90cm) Brown clay	Yes
3.1	Sandy surface. Reeds and grasses present.	(0-25cm) Dark colour soil, roots present, sandy texture.	(25-45cm) Change to orange brown clay with mottling.	(50-90cm) Dark brown solid/dense clay, with some sand.	Yes
3.2	Sandy surface, Sedges and grasses dominant vegetation cover.	Mostly a mix between sand and silty soils. (0-35cm)	(35-60cm) Orange brown clay	(60-90cm) hard dense clay layer.	Yes
3.3	Cracked channel bed.	(0-20cm) Light brown Silty texture.	(20-50cm) Orange clayey soil with mottling.	(50-80cm)light brown clay with mottling. Almost grey in colour. (80cm +) Silty with some sand	Yes
4.1	Dark soil. Rich in organics	(0-35cm)Dark brown soil, some silty material.	(35-90cm) Light brown soil. Clayey texture.	n/a	not specified
4.2	Hard top layer, grey in colour.	(0-30cm) Hard grey sandy clay	(30-45cm)Orange brown silty. Mottling in this layer.	(45-90cm) Clay content increased	Yes
4.3	Channel bed.	(0-25cm)Organic with silt and sand.	(25-45cm) Orange clayey soil. Flakey and brittle. Mottling present.	(45-90cm) Same orange soil layer, but very hard.	Yes

6.1	Hard surface with grasses as the surrounding vegetation.	(0-35cm) Hard layer, but sandy and silty in texture.	(35-60cm)Orange clayey soil. Mottling present.	(60cm-90cm) Mottling colour was red.	Yes
6.2	Hard surface layer. Sedges were dominant vegetation.	(0-30cm) Hard compact sandy layer.	(35-40cm) Soil is slightly more silty.	(40-90cm)brown to orange grainy clay texture with mottling.	Yes
6.3	Hard surface as in 6.2 and surrounding vegetation was mostly sedges.	(0-30cm) Hard sandy soil material.	(30-45cm) Increased silt or clay texture with mottling present.	(+45cm) Soil was too hard to auger through	Yes
7.1	Hard sandy surface with sedges.	(0-15cm) Sandy soil.	(15-45cm) Soil was to hard to auger further	n/a	not specified
7.2	Hard surface, with salt marsh surrounding the sample site.	(0-15cm) Hard sandy clay texture	(20-30cm) Flakey clay	(30-60cm) Hard clay, with mottling present, could not auger deeper.	Yes
7.3	Sedges are dominant vegetation here.	(0-15cm) Brown clayey soil.	(20cm) colour change in soil to light brown / orange	(50-80cm) orange clayey soil with mottling.	Yes
8.1	Hard clayey topsoil. Sparse shrubs are the dominant vegetation.	(0-40cm) Hard silty soil. Greyish surface soil colour.	(40-90cm) light brown soil. Hard. Mottling present.	n/a	Yes
8.2	same as site 8.1	(0-45cm) Silt layer. Dense and compact.	(45-90cm) Light brown silty clay layer. Mottling present.	n/a	Yes

8.3	Hard silty clay surface. Sedges and grass dominant vegetation.	(0-40cm) Hard silty soil layer.	(40-90cm) Clayey soil but feels a little grainy. Mottling present.	n/a	Yes
9.1	Hard sandy surface with sedges and grasses.	(0-25cm)Soft sandy surface.	(25-70cm) Dark grey clay soil. 70cm light grey soil.	n/a	not specified
9.2	Hard clayey surface with salt marsh and shrubs. Closest to a river.	(0-25cm) Hard silty sand.	(25-90) Light grey soil. Saturated soil at 90cm	n/a	not specified
9.3	Same as 9.2	(0-25cm) Clayey texture. Light brown.	(25-90cm) Clay light brown or grey in colour. Mottling present. Soil saturated at 90cm.	n/a	Yes

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