DETERMINING THE HYDROLOGICAL FUNCTIONING OF THE PALMIET WETLANDS IN THE EASTERN AND WESTERN CAPE OF SOUTH AFRICA

Thesis submitted to Rhodes University in fulfilment of the requirements for the degree of Master of Science

By

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DECLARATION

By submitting this dissertation I declare that the entirety of the work contained therein is my own original work (except where acknowledgements indicate otherwise).

Signature

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19 March 2019

Date

ABSTRACT

Wetlands provide a range of supporting, regulating and provisioning ecosystem services, including hydrological benefits such as flood attenuation and sustaining base flows. Despite their value, wetlands are one of the most vulnerable ecosystems in South Africa. Palmiet wetlands in the Eastern and Western Cape are particularly threatened. Palmiet (*Prionium serratum*) is a robust perennial plant that is endemic to wetlands and rivers located in the sandstones and quartzites of the Table Mountain Group (TMG), in the Eastern and Western Cape as well as the Natal Group sandstones in KwaZulu-Natal. Palmiet is described as an ecosystem engineer because of its ability to alter its environment and create large valley-bottom wetlands. The Krom River is an important water source for the city of Port Elizabeth and there has been a decline in palmiet wetlands along the Krom River as a result of alien vegetation invasion, agricultural activity, and gully erosion. Working for Water has been clearing alien vegetation and Working for Wetlands has been installing rehabilitation structures in the Krom River catchment for a number of years. There are, however, serious knowledge gaps in the understanding of palmiet wetland structure and function, particularly in respect of the hydrological functioning of these wetland systems.

The aim of this study was to investigate the hydrology (surface and groundwater) behind these wetland systems. The investigation focussed on small-scale dynamics of the palmiet wetland system in order to increase general understanding of the surface water and groundwater processes of these wetland systems. Field work was concentrated on the Kompanjiesdrif and Krugersland palmiet wetlands in the upper K90A Krom River catchment. The investigation involved the installation of piezometers, water quality and stable isotope sampling and analysis, an Electrical Resistivity Tomography survey, and hydrological and mixing cell modelling. The results of the investigation indicate that the hydrological functioning of palmiet wetlands is closely linked with high sub-surface discharges typically associated with TMG aquifers. It is proposed that the palmiet wetlands are sustained by significant amounts of sub-surface water (both groundwater and interflow) moving through preferential flow paths in the alluvial fans and tributaries, which are in turn sustained by groundwater discharge from the surrounding sandstones and quartzites of the Nardouw Sub-group and Peninsula Formation.

The palmiet wetlands clearly retain a significant amount of water, leading to the maintenance of prolonged flows, and a larger baseflow. However, it is hypothesised that the occurrence of palmiet as the dominant species in these wetlands is due to the sustained low flows related to catchment geology and high hydrological connectivity between the catchment and the wetland that is enabled by flow paths that allow the free flow of water from the catchment to the wetland. It is further proposed that palmiet is possibly more reliant on a consistent water supply for its existence and survival than it is on acidic nutrient-poor water and soils as stated by other authors.

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1 INTRODUCTION

Wetlands are considered to be one of the most vital ecosystems on the Earth. They are known to regulate water supplies, prevent floods and droughts, as well as to cleanse polluted waters, recharge groundwater aquifers and provide important habitats for various floral and faunal species (Mitsch and Gosselink, 2007). Wetlands cover approximately 6% or 570 million hectares of the Earth's land surface and over the last century, 50% of wetlands have vanished (Silva *et al.,* 2007).

Despite their value, wetlands are one of the most vulnerable ecosystems in South Africa, with 65% of wetland ecosystems regarded as threatened (Nel *et al.,* 2011). As a result of the significant amount of wetland degradation, and the associated potential negative consequences for human wellbeing, large-scale wetland restoration has been initiated and has been ongoing for well over a decade largely through the Working for Wetlands Programme (Dini and Bahadur, 2016; DEA, 2018). Despite large investments by the State in wetland restoration, there are serious knowledge gaps in our understanding of wetland structure and function, particularly in respect of the hydrological functioning of these systems.

This lack of understanding means that many of these wetland restoration initiatives might be poorly designed, inefficient or may even be harmful (Barclay, 2016; De Haan, 2016; McNamara, 2018; Pulley *et al.,* 2018).

Palmiet wetlands in the Eastern and Western Cape are particularly threatened. *Prionium serratum* (palmiet) is a robust plant (with stems up to 2 m tall) that is endemic to the nutrient-poor Table Mountain Group (TMG) and Natal Group sandstones and grows in dense stands that impede river flow, forming wetlands. It is thus known as an ecosystem engineer (Boucher and Withers, 2004; Barclay, 2016; Sieben, 2016). Palmiet is also thought to control floods and improve the water quality of rivers (Munro and Linder, 1997). Rebelo (2012), determined that floods are more prevalent, and baseflows are less reliable, where the palmiet wetlands have been damaged or destroyed.

Discharges to wetlands from the TMG aquifers in South Africa are usually linked with seeps, wetlands, and mires at higher elevation (Sieben, 2000; Le Maitre *et al.,* 2002; Colvin *et al*., 2003). Groundwater discharges associated with the deep circulating TMG aquifers to lower lying wetlands have also been reported (Roets *et al.,* 2008a and 2008b). However, wetlands in TMG aquifers are varied in terms of hydrological functioning and are often misunderstood (Parsons, 2009), due to the complex and heterogeneous nature of the fractured rock aquifers. Roets *et al.* (2008a) detail the common hydrological properties of the TMG aquifers and mentions 'real and perceived groundwater discharges'. The contribution of interflow and groundwater to the low flows that support rivers and wetlands in the TMG is often difficult to differentiate, yet is very important, in terms of the effect groundwater abstractions can have on the flow regime, and therefore on wetland distribution, structure, and functioning.

Le Maitre *et al.* (2002) notes that there is a lack of knowledge on the hydrological functioning of groundwater dependent ecosystems in the Fynbos Biome (within the TMG). Various authors also highlight the need for further research into the water balance of palmiet wetlands and the contribution of groundwater discharges from quartzitic sandstones of the TMG to palmiet wetlands, as well as the role that these groundwater aquifers play in maintaining the wetlands (Job, 2014; Lagesse, 2017; Schlegel, 2017).

To understand the functioning of wetlands, it is necessary to have a multidisciplinary perspective of the geomorphological, hydrological and ecological factors that underpin and sustain wetland ecosystems. The main driver of wetlands is their hydrological regime. This refers to the frequency, depth, and duration of inundation. The hydrological regime results from interactions between rainfall and evapotranspiration, surface inflows and outflows, and groundwater discharge and recharge (Fretwell *et al.,* 1996; Mitsch and Gosselink, 2007; Ellery *et al.,* 2009; Jackson *et al.,* 2014).

The area that was the focus of this study is located in the upper Krom River catchment (K90A). Two largely intact and pristine palmiet wetlands were investigated. Working for Wetlands has built structures to protect these wetlands. The Krom River is a main water source for the city of Port Elizabeth, via the Churchill Dam. Wetland loss could potentially impact the river and dam through increased sedimentation and decreased flood control. Also, loss of baseflow or increased floods as a result of wetland loss could impact biodiversity and ecosystem services of the river.

This study has investigated the catchment hydrology using an integrated approach as surface water and groundwater interactions were thought to be significant within the upper Krom River catchment, and there was a strong possibility that the wetlands were groundwater dependent. Aspects of the hydrology such as aquifer storage, recharge, the source of the base flows and catchment response to rainfall, were examined to better understand the hydrological dynamics within the catchment.

This investigation focussed on improving the understanding of the smaller scale surface water and groundwater processes to increase general understanding and reduce uncertainty within modelling analysis both at smaller and at larger scales. The study was aimed at understanding how palmiet wetland systems work at a small scale in more detail (therefore in one study area), rather than completing a large scale investigation and risking too much uncertainty. The study thus tried to identify small-scale processes common to other palmiet wetlands.

1.1 Aims

The aims of this study are as follows:

1. Determine the surface and groundwater dynamics of the Krom River upper catchment (K90A).

2. Identify the relationship between the palmiet wetlands and hydrological functioning of the catchment.

In order to achieve the aim of the study the following research questions were explored:

1.2 Research questions

1. Does groundwater contribute to the hydrology of the Krom River wetlands?

2. If groundwater contributes to the wetlands how does it make this contribution?

3. What is the significance of any groundwater contribution to the wetlands?

4. What is it that supports the palmiet and enables it to exist and act as an ecosystem engineer?

5. How much does palmiet contribute to flow attenuation and reduction of siltation?

2 LITERATURE REVIEW

2.1 Wetland definition

Various definitions have been developed to describe wetlands. These vary from country to country, as is outlined in Mitsch and Gosselink (2007).

The Ramsar Convention definition encompasses all types of marine, estuarine and inland wetlands and defines wetlands as “areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres” (Ramsar Convention Secretariat, 2013:7).

For the purposes of this thesis the wetland definition provided in the South African National Water Act (NWA; No. 36 of 1998:18), which defines a wetland as “land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil”, will be used.

2.2 General wetland types

Wetlands can exist in a variety of landscapes, but tend to occur in areas with a lower elevation (where water may accumulate), or bordering rivers or lakes. Wetlands are, however, also found on hillslopes or other elevated areas. All wetlands, however, form in areas where water accumulates and is retained for a significant period (Winter, 1988).

Wetland types vary globally and are classified differently in various parts of the world. A list of the main types or classes of wetlands in four different countries, as well as the main types recognised by the International Ramsar Convention (Ramsar Convention Secretariat, 2013), is provided in Table 2.1 below. Section 2.6 describes South African wetland classification in more detail.

Table 2.1 Wetland types in the United States, Canada, Europe, South Africa and as listed by the Ramsar Convention (Mitsch and Gosselink, 2007; Silva *et al.,* 2007; Ollis *et al.,* 2013; Ramsar Convention Secretariat, 2013).

United States (Mitsch and Gosselink, 2007:260)	**Europe (Silva *et al.,* 2007:4)**	**Canada (Mitsch and Gosselink, 2007:269)**	**Ramsar Convention (Ramsar Convention Secretariat, 2013)**	**South Africa (Ollis *et al.,* 2013)**
"(1) coastal – • salt marsh, • tidal freshwater marsh, • mangrove, and (2) inland – • freshwater marsh, • peatland, • freshwater swamp, and • riparian ecosystems".	• "Marine and coastal wetlands; • estuaries and deltas; • rivers and floodplains; • lakes; • freshwater marshes; • peatlands; • man-made wetlands, such as canals and reservoirs".	• "bog, • fen, • swamp, • marsh, • shallow water marsh".	• Marine (includes coastal lagoons, rocky shores, coral reefs); • Estuarine (includes deltas, tidal marshes, mangrove swamps); • Lacustrine (linked to lakes); • Riverine (adjacent to rivers and streams); and • Palustrine (includes marshes, swamps, bogs).	Incorporates and distinguishes between marine, estuarine and inland aquatic ecosystems but only focusses on inland wetland systems and classifies them into the following types: • Floodplain wetland; • Channelled valley-bottom wetland; • Unchannelled valley-bottom; • Depression wetland; • Seep; • Wetland flat.

2.3 Wetland formation

Wetland formation is influenced by (amongst others) aspects such as geology, topography, hydrology, and geomorphology. These are described in more detail below.

2.3.1 Geology

Two types of sub-surface stratigraphy assist in wetland formation; firstly, the stratigraphy of the organic soils, and underlying fluvial silts and clays and secondly, the underlying geological formations. Generally the low permeability of the compacted, decomposed organic material as well as the underlying silts and clays (aquitards), commonly prevent the vertical movement of water through a wetland (Winter, 1988).

Groundwater can, however, flow through certain compacted peat layers. The permeability of peat is linked to the degree of decomposition of the peat, with amorphous peat being more permeable than fibrous peat (Wong *et al.,* 2009). Chason and Siegel (1986) conducted a study of the hydraulic conductivity (K) of peat in the Lost River Peatland, in northern Minnesota. This study indicated that humified peat can transport groundwater quite readily.

Wetlands also form where there are discontinuities in the stratigraphy of underlying geologic units (Figure 2.1). Groundwater may move upward as a result of the pinching out of permeable rocks, or where these permeable rocks have a different dip (slope of the rock surface) to the surrounding less permeable rocks (Winter, 1988 and Winter *et al.,* 1998).

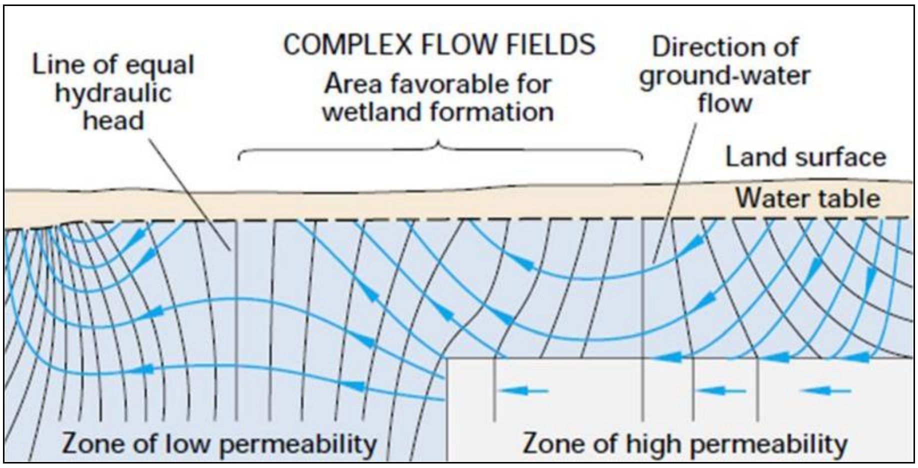


Figure 2.1 Formation of wetlands in areas with complex underlying geological conditions (Winter *et al.,* 1998).

Other examples of how geological conditions may influence wetland formation include the formation of wetlands in dolomitic areas, for example, where impermeable rocks push underground water to the surface as well as faulting and folding of impermeable rocks that force sub-surface water to the surface (Ellery *et al.,* 2009). Tooth *et al.* (2002) describes how geological controls (in the form of resistant dolerite outcrops) affect the formation of alluvial meanders and floodplain wetlands in the Klip River, South Africa. Winter (1999) provides various case studies illustrating the ways in which the local geology of an area can impact groundwater-surface water interactions and in turn the formation of wetlands.

2.3.2 Topography

Wetlands usually form in hollows or low-lying areas with a small gradient. Areas with a reduced gradient are typically characterised as having slow drainage and water can thus accumulate on the land surface, or within the soil for large periods of time. However, wetlands can also be found in areas with steep slopes (for example, embankments) where the water table intersects the land surface resulting in groundwater discharge near the bottom of the slope (Figure 2.2). Continuous groundwater seepage at this point will result in soil saturation and will allow the growth of wetland plants (Winter, 1988). Where there is a break in gradient of the water table, groundwater tends to flow up towards the land surface into the area with the lower gradient providing a constant source of water (Winter, 1988; Winter, 1999).

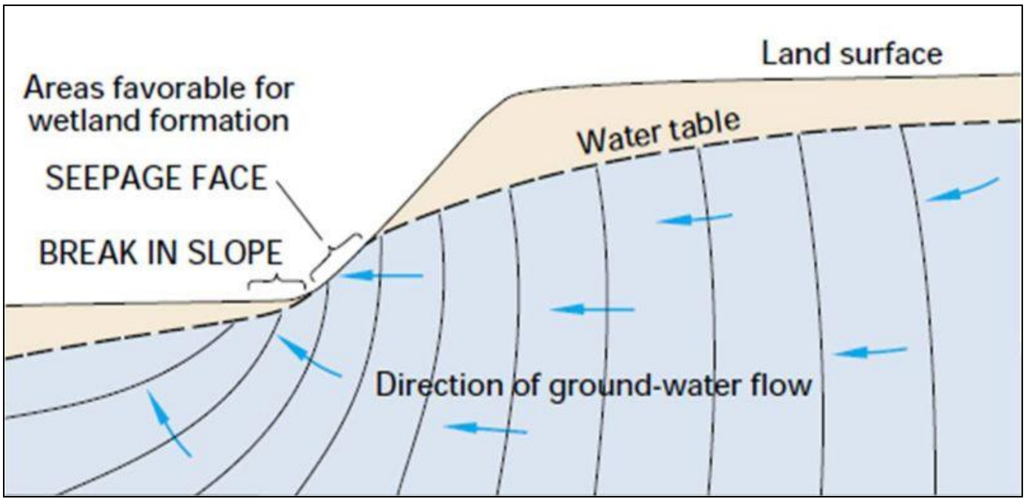


Figure 2.2 Formation of wetlands at a seepage face or break in slope (Winter *et al.* 1998).

2.3.3 Hydrology

According to Mitsch and Gosselink (2007), hydrology is possibly the most significant factor in the formation and maintenance of various types of wetlands and their processes. Even if the topographic and geological conditions of an area are suitable for wetland formation, the hydrological conditions must ensure that there is sufficient water to allow a wetland to form (Winter, 1988).

Wetland formation requires a persistent and sufficient water supply near the soil surface for an extended period of time to create anaerobic conditions in the rooting zone. Rivers and lakes have sufficient water supply to form anaerobic soil conditions, however, the water in these environments is often either too fast flowing or too deep to allow the growth of macrophytic plants. Wetland formation thus generally requires continuous saturation in shallow water (Ellery *et al.,* 2009).

Hydrological processes in wetlands

The main drivers of the hydrological cycle are precipitation and evapotranspiration (ET) with surface water flow, shallow sub-surface water and groundwater also being important components, as is illustrated in Figure 2.3. These components are discussed separately below. Wetlands constantly gain or lose water through the transfer of water from the atmosphere, streams, and groundwater and are generally found more commonly in cooler (with lower evapotranspiration) and wetter climates than in hotter areas (Fretwell, *et al.,* 1996; Mitsch and Gosselink, 2007).

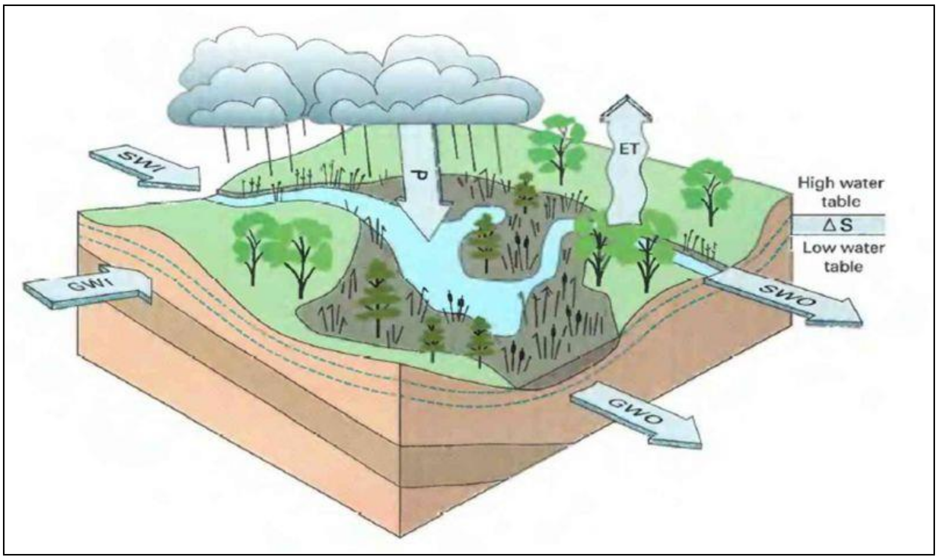


Figure 2.3. A simplified illustration of a wetland water budget. (P = precipitation, SWI = surface water inflow, SWO = surface water outflow, GWI = groundwater inflow, GWO = groundwater outflow, ET = evapotranspiration and ΔS = change in storage (Fretwell *et al.,* 1996)).

Precipitation

Precipitation (rain, snow, mist, etc.) can supply water to a wetland directly, in the form of precipitation falling on the wetland, and indirectly when precipitation is conveyed to the wetland via surface or groundwater runoff (Fretwell *et al.,* 1996). Wetlands are more likely to form in environments where precipitation is higher than evapotranspiration (Mitsch and Gosselink, 2007).

Evapotranspiration

Water is removed from wetlands or soil via evaporation and transpiration by plants. This combined loss of water is known as evapotranspiration (ET). This refers to actual ET. It is difficult to measure the rate of actual ET as this requires calculating the quantity of water transpired by plants over time. ET losses from wetlands are variable and depend on the plant species, plant density and the plant status (growing or dormant), as well as the availability of water in the wetland. Seasonal variations in ET are also linked to the water table position (height of the water table in relation to the land surface) and temperature. Daily ET rates depend on the available energy to evaporate water (lower at night and on cool days) (Fretwell *et al.,* 1996).

Potential evapotranspiration (PET) refers to the potential loss of water without any restriction imposed by the availability of water. PET is usually measured using evapotranspiration pans with an open body of water. When there is an ample water supply then actual ET rates will be equal to potential ET rates, but actual ET rates will decrease to below potential ET rates when the water supply is limited or declining (Beven, 2016).

Surface water

Wetlands receive surface water from upstream inflow, overland flow (incremental catchment runoff), interflow and groundwater discharge (Fretwell *et al.,* 1996; Parsons, 2004). Surface water outflow from a wetland is highest in the wet season or during floods. Streamflow from wetlands that mostly rely on groundwater input is usually evenly distributed during the year, compared to streamflow from wetlands that are mainly dependent on precipitation. This is due to groundwater discharge being more consistent than precipitation (Fretwell *et al.,* 1996).

Overland flow (Figure 2.4) takes place when the rainfall rate is higher than the infiltration rate resulting in surplus water that cannot penetrate the soil and ultimately flows over the land surface to lower elevations. Saturated overland flow takes place when the soil is saturated and inhibits precipitation from entering the sub-surface (Parsons, 2004). These are both determined by rainfall intensity and duration.

Interflow

A concept often ignored in wetland hydrology is interflow. Interflow is a significant element of the hydrological system as it often supports local aquatic ecosystems (Xu *et al.,* 2003). Interflow (or throughflow) can be defined as “water that infiltrates the soil surface and then moves laterally through the upper soil horizons towards the stream channels, either as unsaturated flow or, more usually, as shallow perched saturated flow above the main groundwater level” (Figure 2.4). Interflow is usually found in conditions where the lateral conductivity in the surface layers of the soil is higher than the total vertical hydraulic conductivity through the soil profile. Ideal conditions for interflow can also be found where a thin permeable soil layer occurs above impermeable bedrock (Ward and Robinson, 1990:220). The description of interflow provided by Ward and Robinson (1990) refers to interflow occurring in soil layers, but it does also occur in rock layers (Parsons, 2004; Hughes, 2010).

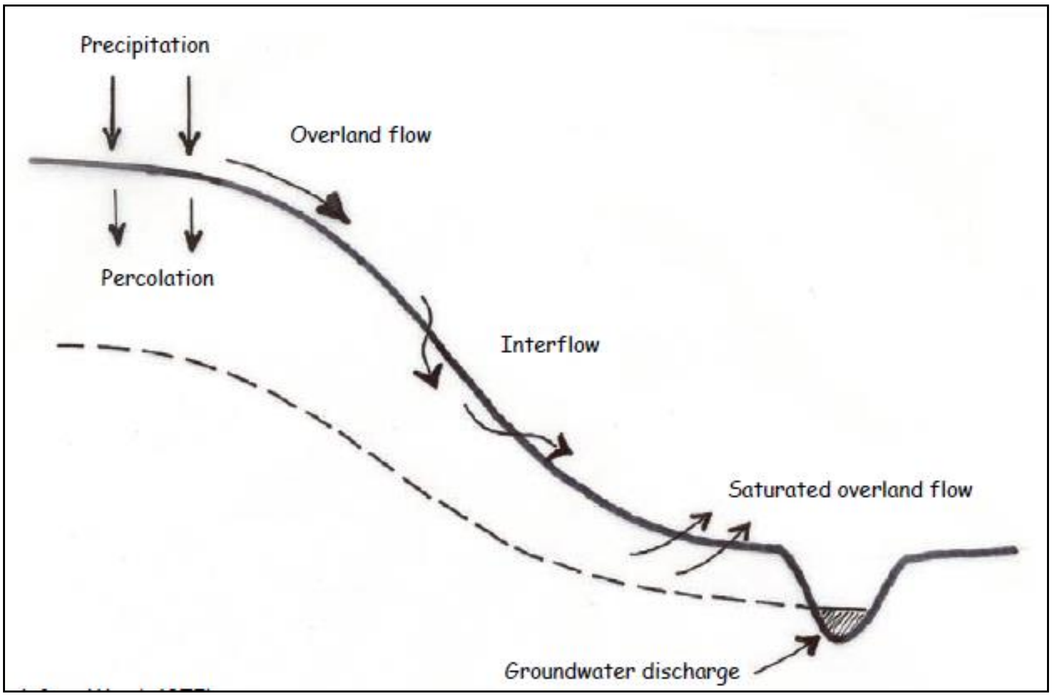


Figure 2.4 Illustration of the various runoff flow paths (Parsons, 2004).

Xu *et al.* (2003) illustrate various conditions in which interflow may occur in mountainous catchments in South Africa (Figure 2.5):

a. Impermeable soils preventing the downward movement of water;

b. Appropriate arrangement of fracture networks;

c. Partially saturated flow created by a perched water table; and

d. Preferential flow paths (created by roots, for example) in a soil horizon.

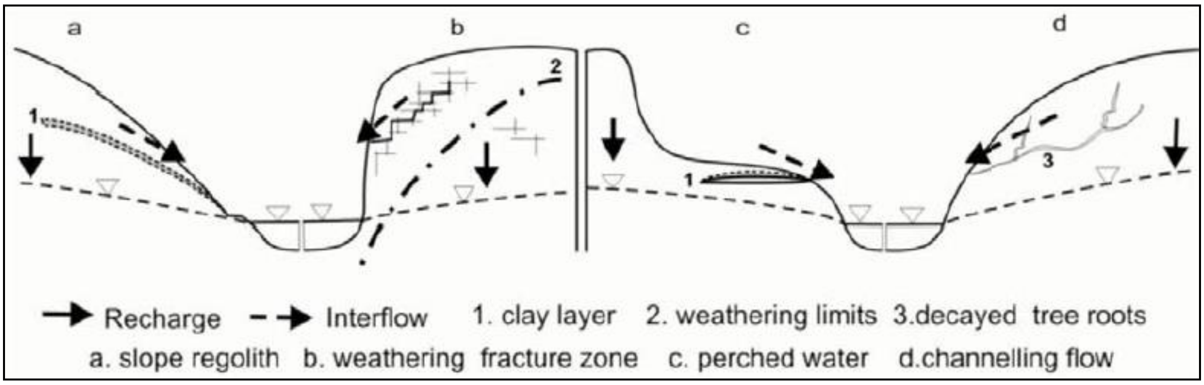


Figure 2.5 Conditions in which interflow occurs in mountainous catchments (Xu *et al.,* 2003).

Hughes (2010) provides examples of observations of interflow emerging as springs in fractured rocks in South Africa and highlights the importance of differentiating between interflow and deeper groundwater in hydrological investigations.

Groundwater

Water that exists below the land surface can be separated into the saturated and the unsaturated zone (vadose zone) (Figure 2.6a). The voids in rocks of the unsaturated zone are filled by air and water. The upper portion of the saturated zone is called the soil-water zone. This zone consists of roots, organic matter, animal burrows, etc. where soil water can be removed by plants or evaporation (Winter *et al.,* 1998). Groundwater includes only that water found in the saturated zone and not water that is stored in soil horizons or the unsaturated zone (Parsons, 2004).

The voids in rocks of the saturated zone (groundwater) are packed with water and the top surface of this zone is described as the water table. The depth to the water table can vary significantly but is often relatively small close to streams, lakes, and wetlands (Winter *et al.,* 1998). The capillary zone (or fringe) (Figure 2.6b) is located between the saturated and unsaturated zone (above the water table) (Parsons, 2004). In this zone, water attaches to rock particles and moves upwards against gravity. The water in this zone is under pressure which is lower than atmospheric pressure (i.e. “negative hydraulic pressure”) (Heath, 1983:4). Perched aquifers refer to a saturated groundwater body that is located over localised impermeable material above the unsaturated zone. Springs or seeps commonly form where water from these perched aquifers discharge at the surface (Parsons, 2004).

Variations in hydraulic head (pressure) are responsible for groundwater movement to the surface, or into surface water bodies (described as groundwater discharge). Wetlands are often groundwater discharge areas (often below springs), but can also be recharge areas depending on the topography, hydrogeology, climate, and soil of the area. Groundwater discharge into a wetland will affect the water chemistry of that wetland and groundwater recharge from a wetland will affect the water chemistry of the receiving aquifer. The source of water in a wetland (which affects the water chemistry) will also influence the plant growth in the wetland (Fretwell *et al.,* 1996).

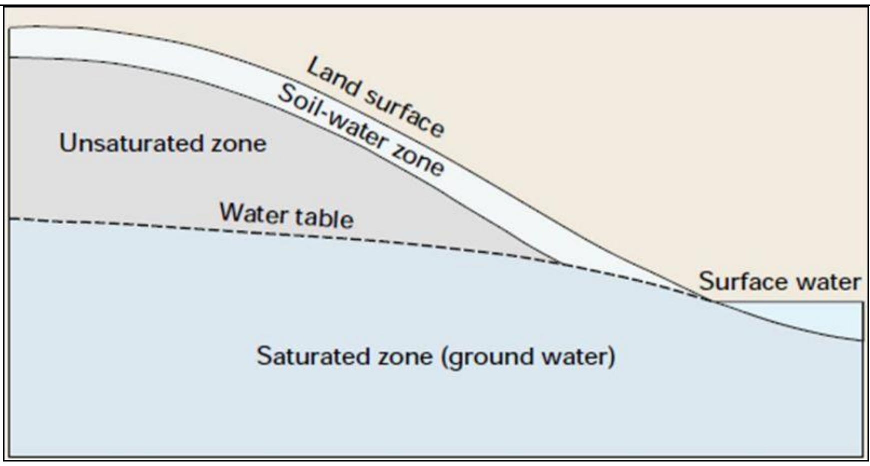


Figure 2.6a. Illustration of the unsaturated zone, water table and saturated zone (Winter *et al.,* 1998)

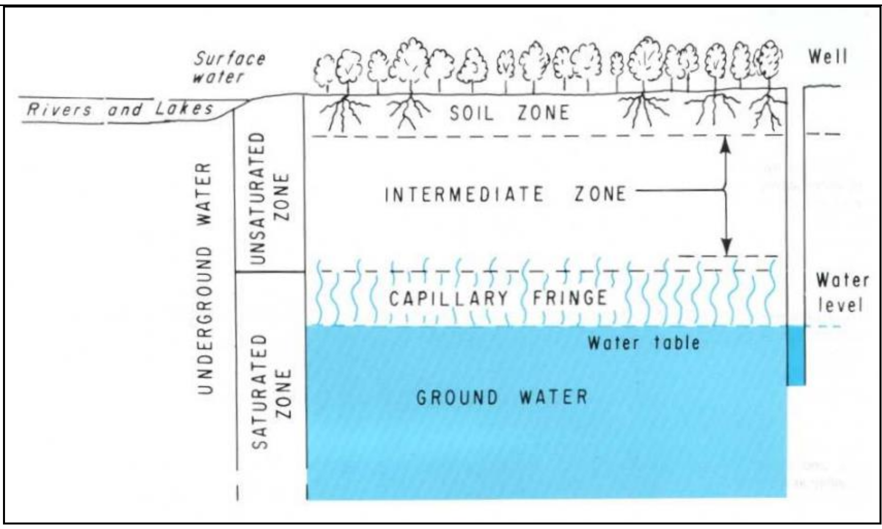


Figure 2.6b. Illustration of the capillary zone (or fringe) located between the saturated and unsaturated zone (Heath, 1983).

2.3.4 Geomorphology

Although hydrology has traditionally been considered to be the main factor influencing the formation and distribution of wetlands, the important role of geomorphology in wetland formation is increasingly being recognised (Ellery *et al.,* 2009; Tooth *et al.,* 2015; Pulley *et al.,* 2018).

The movement of mass involved in the formation and structure of a wetland can include tectonic activity (for example, the Okavango Delta in Botswana) and weathering, erosion, transportation and deposition of earth material by water, gravity and wind (Tooth *et al.,* 2015).

It has been recognised that wetlands tend to form in two main geomorphological environments; namely valleys with a relatively flat surface cross-section and areas that have a very gentle longitudinal gradient (Tooth *et al.,* 2002; Tooth *et al.,* 2004). Geomorphological factors affecting wetland formation in South Africa are discussed in section 2.4.3.

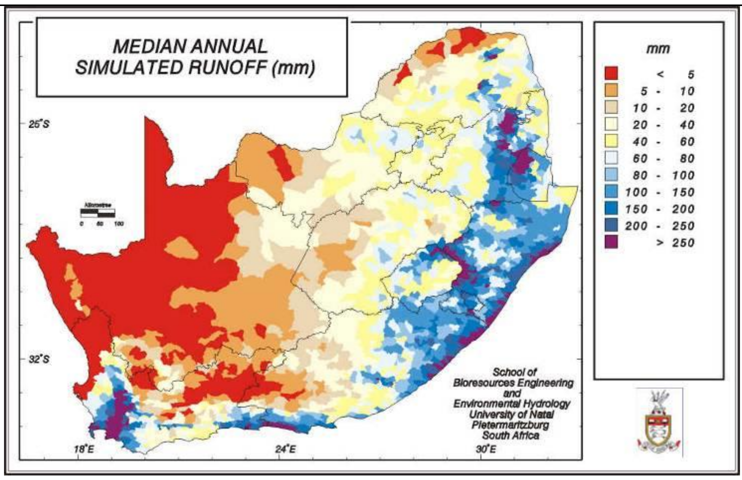
2.4 South African Wetland Formation

The regional distribution of wetlands in South Africa is linked to climate and hydrology, while locally geomorphological factors also influence wetland distribution. According to Ellery *et al.* (2009), wetland systems in South Africa do not easily compare with those in northern temperate regions. The following factors, according to Ellery *et al.* (2009), illustrate why South Africa should have few wetlands and peatlands should not exist at all:

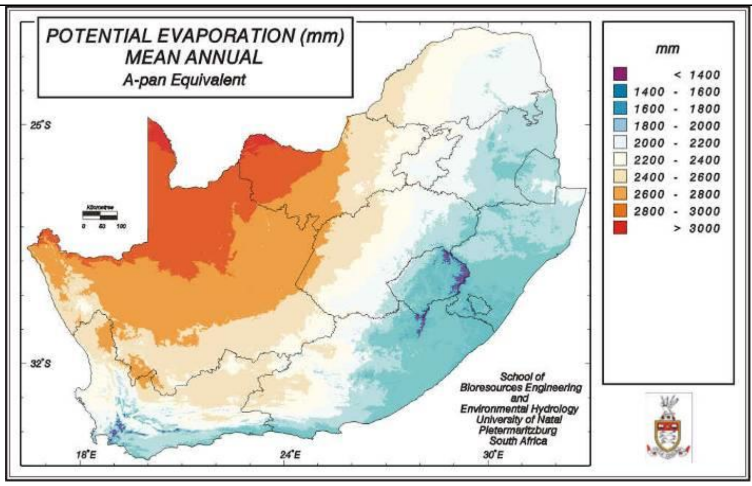
- The country has not been impacted by any recent significant tectonic activity;
- It is located at a high mean elevation and is, therefore, undergoing high rates of erosion;
- Recent glaciation has not played a substantial role in altering the landscape;
- The mean annual rainfall in South Africa is approximately half the world average mean annual rainfall;
- PET is high.

2.4.1 Climate

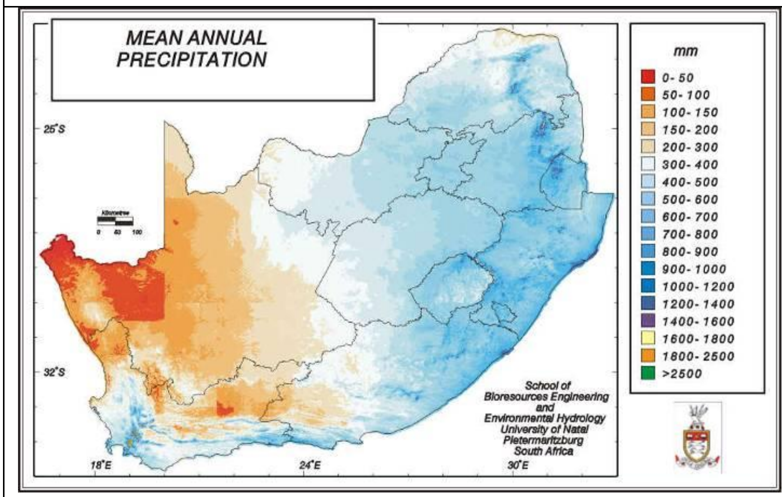
The mean annual rainfall in South Africa is about 497 mm which is significantly lower than the world average of 860 mm (Cowan, 1995). Inland wetlands depend on rainfall to provide water in the form of surface runoff or groundwater recharge. Water availability in the country is also dependent on atmospheric demand (PET being a good gauge of this) (Ellery *et al.,* 2009). In South Africa potential evaporation intensifies in the western portions of the country and rainfall is highest in the northern and eastern parts of the country (Figure 2.7). Mean annual potential evaporation lows are approximately 1400 mm in the Drakensberg and between 1600 mm and 1800 mm in the eastern and southern coastal areas. There is a southwest-northwest increasing trend resulting in highs that exceed 3000 mm per year in the northwest (Schulze, 1997). Based on these climatic patterns it is expected that the majority of wetlands should be concentrated in the northern and eastern portions of the country (Ellery *et al.,* 2009).



Median annual simulated runoff.



Mean potential evaporation.



Mean annual precipitation

Figure 2.7 Median annual simulated runoff, mean potential evaporation and mean annual precipitation maps for South Africa (Schulze, 2001).

2.4.2 Hydrology

The mean annual precipitation (MAP) in South Africa decreases in a westerly direction across the country. The KwaZulu-Natal Province receives the highest MAP (845 mm), while the Northern Cape receives the lowest mean MAP (202 mm) (Schulze, 1997). The downward moving limbs of the Hadley and Ferrel Cells cause a high-pressure zone to develop at approximately 30°S which creates anticyclonic conditions. Moisture-laden air tends to collect over the Indian Ocean and move westwards over the country. As this air hits the great escarpment in the east, rainfall ensues and declines as the air moves across the country in a westerly direction. Air masses originating from above the Atlantic Ocean also do not carry much moisture, as a result of the upwelling of the cold Benguela current, and this causes the west coast to be quite dry (Ellery et al., 2009).

Most of South Africa is semi-arid, with mean annual runoff only accounting for approximately 8.5% of mean annual precipitation (Whitmore, 1971). Runoff tends to be high in the Western Cape mountains, and in the eastern and southern portions of the country, while KwaZulu-Natal is the wettest province (Figure 2.7) (Schulze, 1997).

Due to the fact that the mean annual rainfall is quite low in South Africa, it is unlikely that many wetlands in the country depend predominantly on rainfall for water supply. Wetlands that are rainfall dependent are likely to be located in the Lesotho Highlands and in the eastern and southern coastal areas (high rainfall and low evaporation areas). Wetlands that depend largely on groundwater or hillslope seepage to form are usually small and located in areas where the water table is near the ground surface (KwaZulu-Natal and southern Cape coastal areas as well as in headwater areas). The majority of wetlands in the country are associated with rivers (Ellery *et al.,* 2009).

Processes that restrict water loss from a site (geological or geomorphological factors) are also important processes involved in wetland formation in the country. The endorheic pans in the semi-arid Kalahari and Orange Free State are examples of wetlands that formed due to a restriction of surface water loss. Seasonal pans in semi-arid regions of the country generally form as a result of underlying impermeable rocks which prevent sub-surface discharge from the wetlands (Ellery *et al.,* 2009).

2.4.3 Geomorphological controls on wetlands

Wetlands usually form in environments where the river transport capacity is lower than or equal to the load being transported by the river. Wetlands thus tend to mostly form in a setting that is non-erosional (i.e. is depositional) and can thus be considered to be a 'sediment sink'. The lack of capacity of water to erode has traditionally been seen as one of the most significant factors supporting wetlands. Erosion in a wetland may be due to anthropogenic impacts, but can also take place naturally "if the surface of a wetland is steepened longitudinally by prolonged sedimentation and ultimately exceeds a critical threshold of slope stability" or if there is a reduction in the amount of sediment being carried in runoff to the wetland (Ellery *et al.,* 2009:52).

Gully erosion is a particularly destructive form of erosion in wetlands and commonly affects valley-bottom wetlands. Schumm (1994) and Ellery *et al.* (2009) illustrate the process of gully erosion over time (initial incision of a channel, widening of the channel, sediment production, and aggradation) and how the land surface that has been subjected to gully erosion naturally stabilises again over time.

A number of models have been developed to explain wetland distribution and dynamics in South Africa. Tooth *et al.* (2002) proposes that the presence of resistant rocks (in the form of a sill or a dyke) amongst less resistant rocks can promote lateral erosion (and valley flattening) upstream of the resistant rock. This results in river channel migration and formation of floodplain wetlands. Grenfell *et al.* (2010) proposed that wetlands may form as a result of the blockage of a tributary (at the confluence with the trunk) by rapid sedimentary deposition of a large trunk stream and its floodplain.

2.5 Wetland Classification in South Africa

In South Africa wetlands have been classified according to a six-tiered system (Figure 2.8) (Ollis *et al.,* 2015).

Level 1 of the classification system distinguishes between marine, estuarine and inland systems. Level 2 describes the regional setting of the system (geology, vegetation types, soils, etc.) and level 3 describes the landscape unit or topographical position of the system in the landscape. Level 4 (the most important level in wetland classification) describes the various hydrogeomorphic (HGM) units, which are distinguished by landform, hydrological characteristics, and hydrodynamics (Ollis *et al.,* 2015). Level 5 describes the way that water behaves in the ecosystem (i.e. the tidal or hydrological regime) and level 6, which is optional, consists of descriptors for the HGM unit (i.e. details on geology, soils, salinity, pH, etc.) (Ollis *et al.,* 2015).

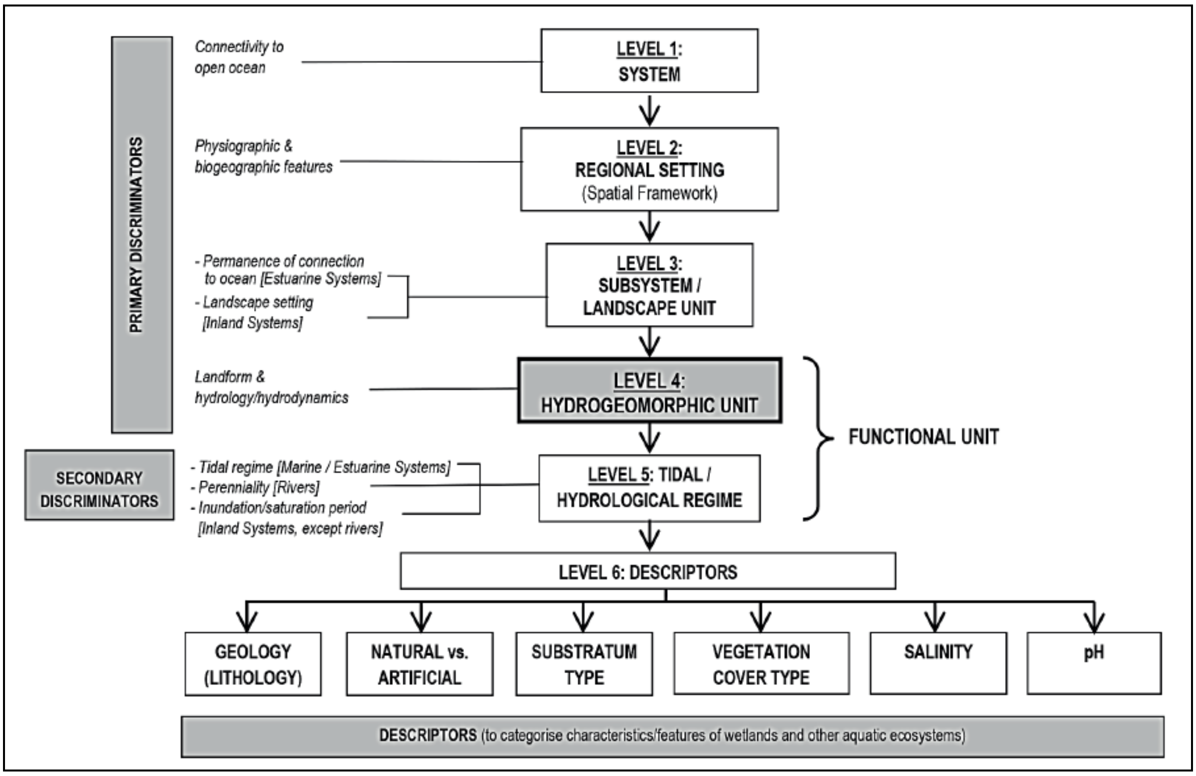


Figure 2.8 The classification system for wetlands and other aquatic ecosystems in South Africa (Ollis *et al.,* 2015).

2.5.1 Hydrogeomorphic units

The wetlands that are the focus of this thesis are inland wetlands and thus only inland wetlands will be described here (Figure 2.9). Six HGM units are described by Ollis *et al.* (2013; 2015) for inland wetlands**:**

Floodplain wetlands

Floodplain wetlands usually form on flat areas near or on a river channel and are typically periodically flooded when water overtops the river banks (Ollis, *et al.,* 2015). These wetlands are associated with point bars, scroll bars, oxbow lakes and levees (Ollis *et al.,* 2013). An example of a floodplain wetland is the Mfolozi floodplain of the Maputaland coastal plain (Ellery *et al.,* 2009; 2013). This wetland is about 19 000 hectares in size and is fed by the Mfolozi River and Msunduzi River (Ellery *et al.* 2009). Floodplain wetlands are usually bigger (>1800 ha) than valley-bottom wetlands and have gentler slopes (Ellery *et al.,* 2016).

Channelled Valley-Bottom Wetlands

Channelled valley-bottom wetlands form on valley floors with rivers traversing through them. Water is typically supplied to the wetland from the river itself (flooding or lateral seepage) or from the surrounding valley-side slopes (Ollis *et al.,* 2015). An example of this type of wetland is the Killarney wetland which drains into the Ntsikeni Vlei in KwaZulu-Natal (Cowden *et al.,* 2008).

Unchannelled Valley-Bottom Wetlands

These wetlands occur in a valley floor setting without a river traversing through it and are characterised by diffuse flows. Water is usually derived from upstream river channels and seepage from surrounding valley side slopes in the form of overland flow and interflow (Ollis *et al.,* 2013; 2015). An example of an unchannelled valley-bottom is the Goukou wetland in the Western Cape. According to Job (2014), the formation and persistence of this wetland is linked to water input from the surrounding quartzitic rocks of the Cape Supergroup as well as the palmiet plant which alters the river channel by reducing flows, trapping sediment and promoting diffuse flows through the wetland. The palmiet wetlands along the Krom River, which are the focus of this thesis, can also be described as unchannelled valley-bottom wetlands.

Depression Wetlands

A depression wetland typically forms in a topographic setting with closed elevation contours and which is quite deep in the centre (allowing water to accumulate). The bottom of the wetland may be flat (usually called 'pans') or rounded (Ollis *et al.,* 2015). Depression wetlands may be fed by streams (not always connected to them), groundwater and interflow (Ellery *et al.,* 2009). An example of this type of wetland is the Darling Pans in the Western Cape (Smith and Compton, 2004) as well as the Tevreden Pan in Mpumalanga (Ollis *et al.,* 2013).

Seep

A seep wetland forms on steep slopes where water flows unidirectionally downslope. The source of water feeding the seep is usually sub-surface water flowing downslope (Ollis *et al.,* 2015). Seeps form in areas where the landscape and geological conditions allow the discharge of groundwater to land or sub-surface interflow to seep downslope. Such conditions include areas where there is a break in slope of the groundwater table allowing discharge of groundwater to the surface or on slopes where an impermeable layer of rock or soil prevents the infiltration of surface water. The Oudebos wetland (near Kleinmond) and Drakenstein wetland (near Wemmershoek Dam) in the Western Cape are both seepage wetlands (without channelled outflow). Both seeps "are groundwater-fed wetlands located on relatively steep slopes that are characterised by diffuse, unidirectional, down-slope water movement." (Ollis *et al.,* 2013:79).

Wetland Flats

Wetland Flats form on a relatively flat landscape and are not sustained by river water. Water is mainly supplied from rainfall, except for wetland flats that are located on the coastal plain, in which case they may receive groundwater inputs (Ollis *et al.,* 2015). Examples of these wetlands can be found near Delareyville in the North West Province (Cloete, N., 2014).

The HGM unit classification described by Ellery *et al.* (2009) (Table 2.2) differs slightly from the system described by Ollis *et al.* (2013; 2015) in that it does not include ‘wetland flats’ and includes an additional wetland type, known as ‘fringe wetlands’, which are located on the edges of lakes.

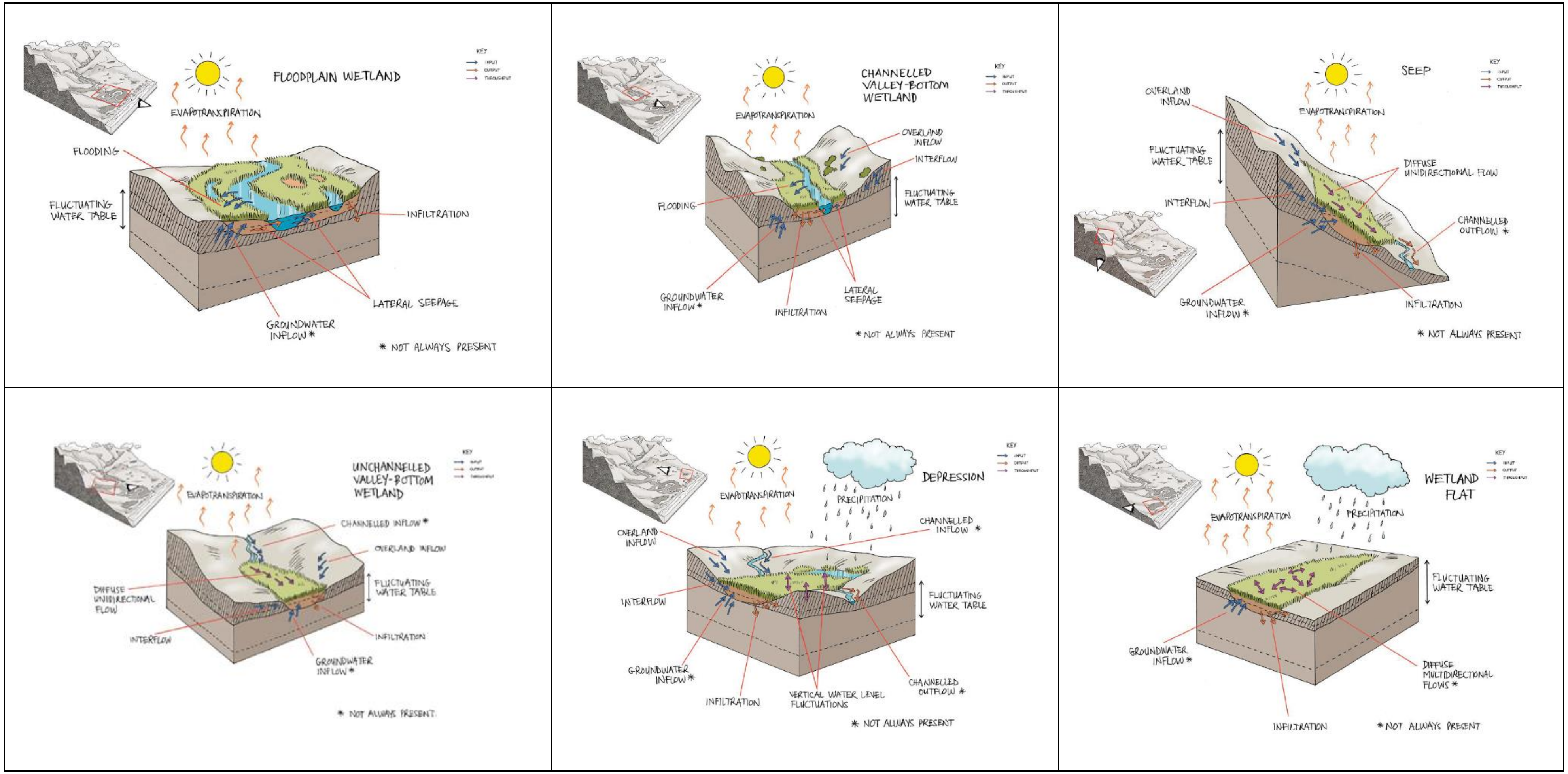


Figure 2.9   HGM wetland classification in South Africa (Ollis *et al.,* 2013).

Table 2.2. Wetland landform settings, adapted from Ellery *et al.* (2009).

LANDFORM SETTING	DEFINITION	HYDROLOGICAL COMPONENTS		
		Inputs	**Throughputs**	**Outputs**
Hillslope seepage not feeding a watercourse	Concave or convex slopes characterised by the colluvial (transported by gravity) movement of materials.	Predominantly groundwater and interflow or diffuse surface flow	Interflow and diffuse surface flow	Evapotranspiration and groundwater flow
Hillslope seepage feeding a watercourse	Concave or convex slopes characterised by the colluvial (transported by gravity) movement of materials. Outflow is typically by channel into the drainage network.	Predominantly groundwater and interflow or diffuse surface flow	Interflow and diffuse surface	Variable but usually by channel flow and evapotranspiration
Valley bottom without a channel	Valley bottom areas of low relief with no clearly defined stream and situated on alluvial fill.	Channel entering the wetland and adjacent hillslopes	Diffuse surface and sub-surface flow	Channel outflow and evapotranspiration
Valley bottom with a channel	Valley bottom areas with a well-defined stream channel but lacking characteristic floodplain features. Water inputs are mainly from adjacent slopes while the channel itself is typically not a major source of water for the wetland.	Channel flow and adjacent hillslopes	Diffuse flow on elevated valley bottom and channel flow	Channel flow and evapotranspiration
Floodplain	A riparian area of low relief characterised by the alluvial transport and deposition of material by a well-defined stream channel, which gives rise to characteristic floodplain features such as levees and oxbow lakes.	Primarily as channel overspill and/or tributary supply	Channel flow that during flood events becomes extensive diffuse surface flow	Channel flow and evapotranspiration
Depression (includes pans)	A basin-shaped area with a closed elevation contour that usually is not connected via an outlet to the drainage network.	Variable	Insignificant	Evapotranspiration
Fringe wetlands	Areas on the edge of open water provided by lakes, dams or estuaries.	Lake or estuary (tidal)	Diffuse surface flow	Lake or estuary (tidal)

2.5.2 Table Mountain Group lithology and aquifer properties

The Ordovician to Devonian aged Table Mountain Group (TMG) falls within the Cape Supergroup of rocks and runs from northwest of the Western Cape to northeast of the Eastern Cape. The TMG has a total thickness of >2000 m and is predominantly characterised by quartzitic sandstones, but also shale, diamictite, siltstone, and conglomerate. As a result of their age and exposure to mild regional metamorphism, the quartzitic sandstones have no primary hydraulic conductivity. However, due to factors such as structure and climate, they are one of the most significant fractured rock aquifers in the country. Groundwater is located in secondary openings formed by fractures, faults, and folds. The depositional environments of this group can be described as shallow marine, fluvial and glacial (Rosewarne, 2002a; Rosewarne and Weaver, 2002; Thamm and Johnson, 2006; Xu *et al.,* 2009).

According to Rosewarne and Weaver (2002), aquifers associated with the TMG are also known to occur in areas with large quantities of weathered and transported TMG sediment (i.e. alluvial fans and river channel deposits). In the Hex River valley, for example, two types of aquifers exist; namely the TMG/Bokkeveld fractured aquifer and the overlying alluvium aquifer. There is estimated to be around 16 million m^3 of storage available in alluvial fans that could serve as artificial recharge. About 7 million m^3/a could be recovered directly using alluvial boreholes or indirectly via seepage into the underlying TMG and Bokkeveld Aquifer (Rosewarne, 2002b).

2.5.3 Groundwater dependent ecosystems in the TMG

Colvin *et al.* (2007:3) define aquifer dependent ecosystems as “ecosystems which depend on groundwater in, or discharging from, an aquifer”. Vegetation that is endemic to the TMG rocks is referred to as fynbos and not much is known about the hydrological functioning of groundwater dependent ecosystems located in this biome (Le Maitre *et al*., 2002).

Figure 2.10 illustrates a typical example of groundwater flow paths and groundwater dependent ecosystems associated with the folded and faulted TMG. Groundwater discharge from the fractured rocks causes the formation of marshes and seepages at several locations along slopes, at breaks in slopes and in limited flatter settings. Colluvial and alluvial deposits which form from the quartzitic rocks give rise to streams which emerge and disappear as surface runoff (especially on alluvial fans which are common in valleys). Large regional fault zones offer storage for large quantities of groundwater (Colvin *et al.,* 2003).

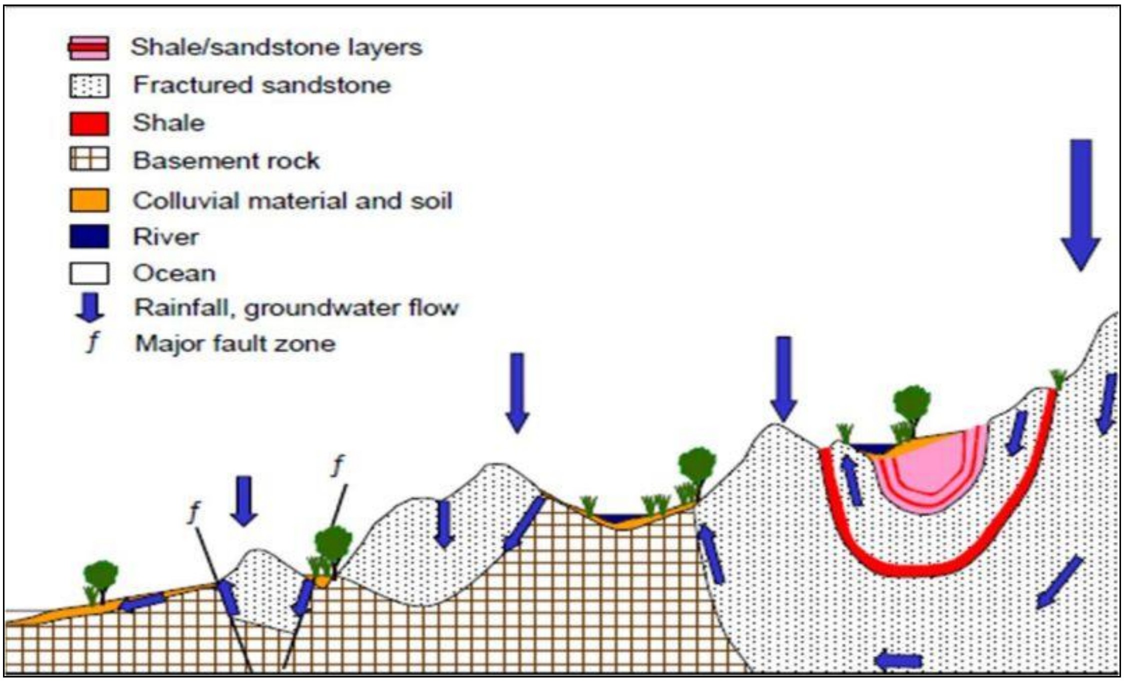


Figure 2.10 Typical groundwater flow paths and the location of groundwater dependent ecosystems in a faulted and folded TMG setting (Colvin *et al.,* 2003).

2.5.4 Wetlands and rivers associated with the TMG aquifer

Several studies have been undertaken to determine the link between groundwater discharge from the TMG aquifer and the surface water of rivers and wetlands (Roets *et al.,* 2008a; Roets *et al.*, 2008b; Parsons, 2009; Parsons and Vermeulen, 2017). These studies largely highlight the complexity associated with understanding the dynamics of these systems.

Roets *et al.* (2008a:78) developed a conceptual model to determine the input of discharges from the TMG aquifer to surface water flow in rivers and streams associated with the TMG. According to the conceptual model the contribution of groundwater from the TMG aquifer to surface water resources takes place in two principal environments known as the "TMG aquifer daylight-domain" and the "TMG aquifer surface water interface-domain" (Figure 2.11). The *TMG aquifer daylight-domain* (situated in recharge areas) contributes groundwater to the surface water flow in mountain and foothill streams (also includes interflow) and the *TMG aquifer surface water interface-domain* contributes groundwater to wetlands and other aquatic ecosystems located in lowland areas.

Local discharges in the TMG aquifer daylight-domain are likely limited to springs originating from locations in the TMG where faults intersect the shale (aquitard) layers. Regional discharges are probable in the TMG aquifer groundwater-surface water interface-domain and have an impact on wetlands, estuaries and marine ecosystems (Roets *et al.,* 2008a).

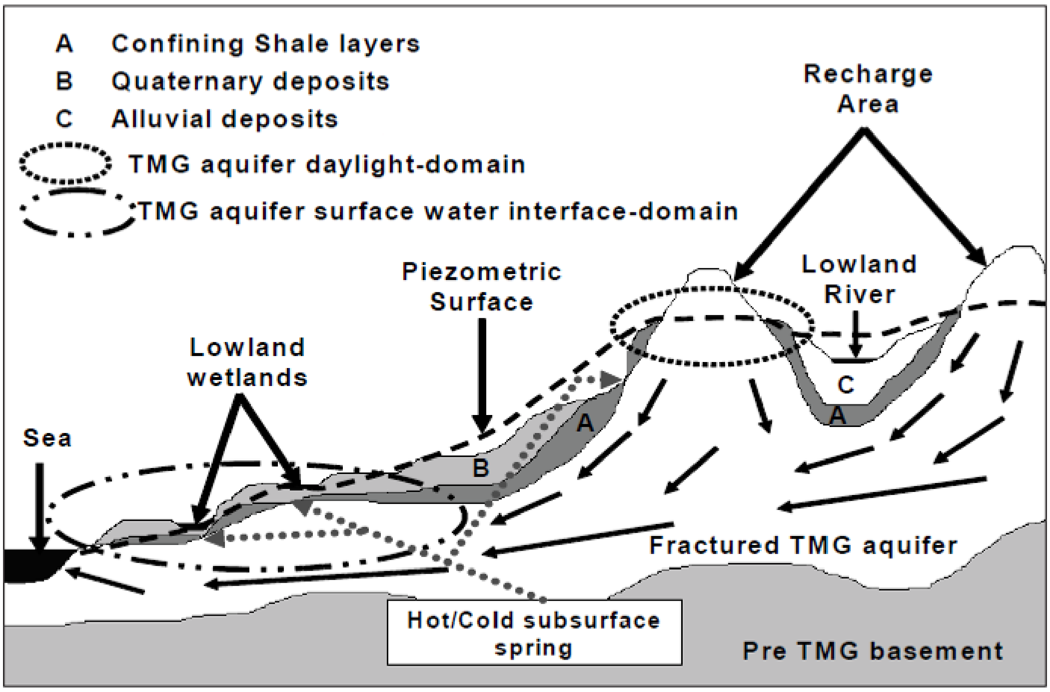


Figure 2.11 Illustration of the interaction between surface water and groundwater from the TMG aquifer proposed by Roets *et al.,* 2008a.

Roets *et al.* (2008b) completed a water quality study (pH, EC, Na^+, Fe^{2+}, and Cl^-) of two lowland wetlands (Groenvlei and Van Kervelsvlei) in the Southern Cape with the aim of illustrating that these wetlands are dependent on groundwater discharges from the TMG aquifer. According to Roets *et al.* (2008b), the water level and water quality data collected for these wetlands and the 3-dimensional interpolation of the water quality results clearly illustrates that Van Kervelsvlei receives direct TMG discharges and Groenvlei receives at least secondary TMG discharges from Van Kervelsvlei (Figure 2.12).

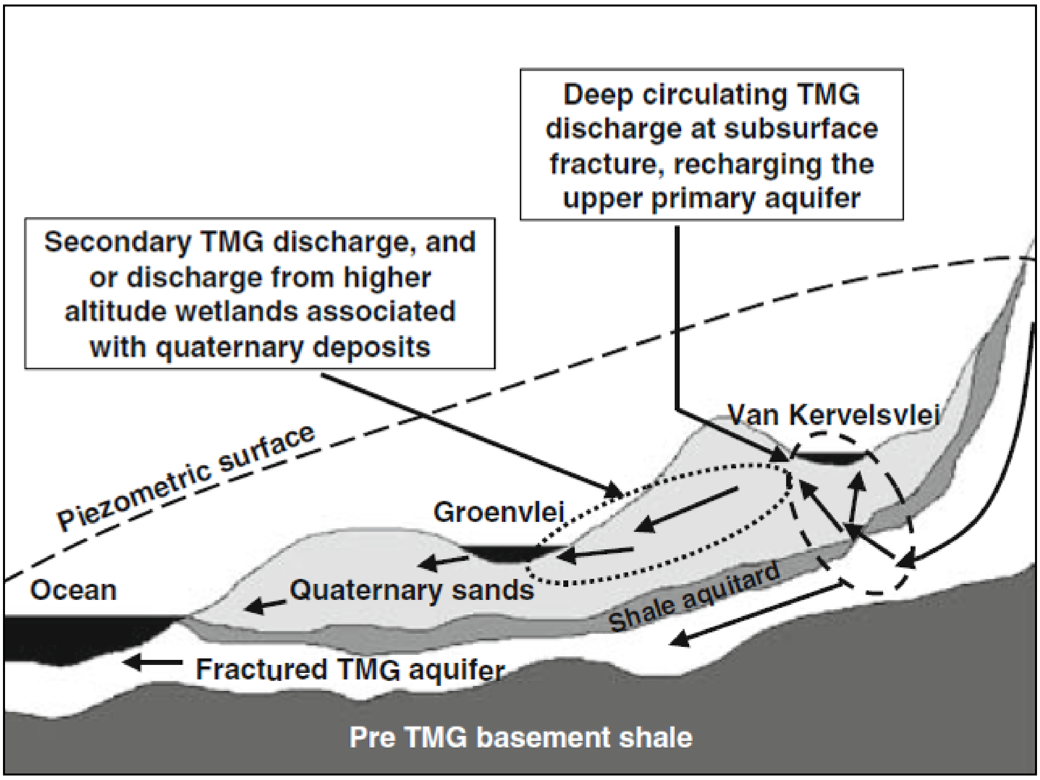


Figure 2.12 Cross-section illustrating the proposed TMG groundwater-surface water interactions at the Groenvlei and Van Kervelsvlei wetlands (Roets *et al.,* 2008b).

Parsons (2009), however, disagrees with the above mentioned TMG groundwater discharge model put forward by Roets *et al.* (2008b) for the Groenvlei and Vankervelsvlei wetlands. According to Parsons (2009), deep boreholes (up to 162 m deep) drilled in the vicinity of Groenvlei have recorded groundwater levels within 3.7 m of mean sea level. The fact that Vankervelsvlei falls within the same geological and geohydrological environment as the area where these boreholes were drilled indicates that water levels measured by Roets *et al.* (2008b) from piezometers at Vankervelsvlei are probably perched water levels. This contradicts any hydraulic relationship between Groenvlei and Vankervelsvlei proposed by Roets (2008b). Parsons (2009) also disagrees with the theory that the chemical character of these wetlands is characteristic of TMG aquifer water as the chemical character of coastal aquifers throughout the country coincides with that of TMG groundwater. According to Parsons (2009), Vankervelsvlei is more likely to be rainfall dependent. The impermeable base of the vlei, lack of a dry season (continuous recharge) and the presence of dense sedge vegetation (preventing evaporation losses) all promote a rainwater-fed theory.

An alternative model for the wetlands is presented by Parsons (2009) in Figure 2.13. According to this model, the unconfined primary aquifer system receives rainfall recharge that infiltrates through the vadose zone and down to the regional water table of the primary aquifer. Parsons (2009), estimates that the depth to the regional water table at Vankervelsvlei is about 145 m below ground level. Vankervelsvlei is solely rainfall fed while Groenvlei receives both rainfall and groundwater recharge and according to Parsons (2009), there is no hydrological link between the two wetlands. Parsons and Vermeulen (2017) further illustrate that Groenvlei is not endorheic in nature and that direct rainfall (estimated to provide 71.6% of inflow) and evapotranspiration are the main components of its hydrological regime (with groundwater performing a secondary function).

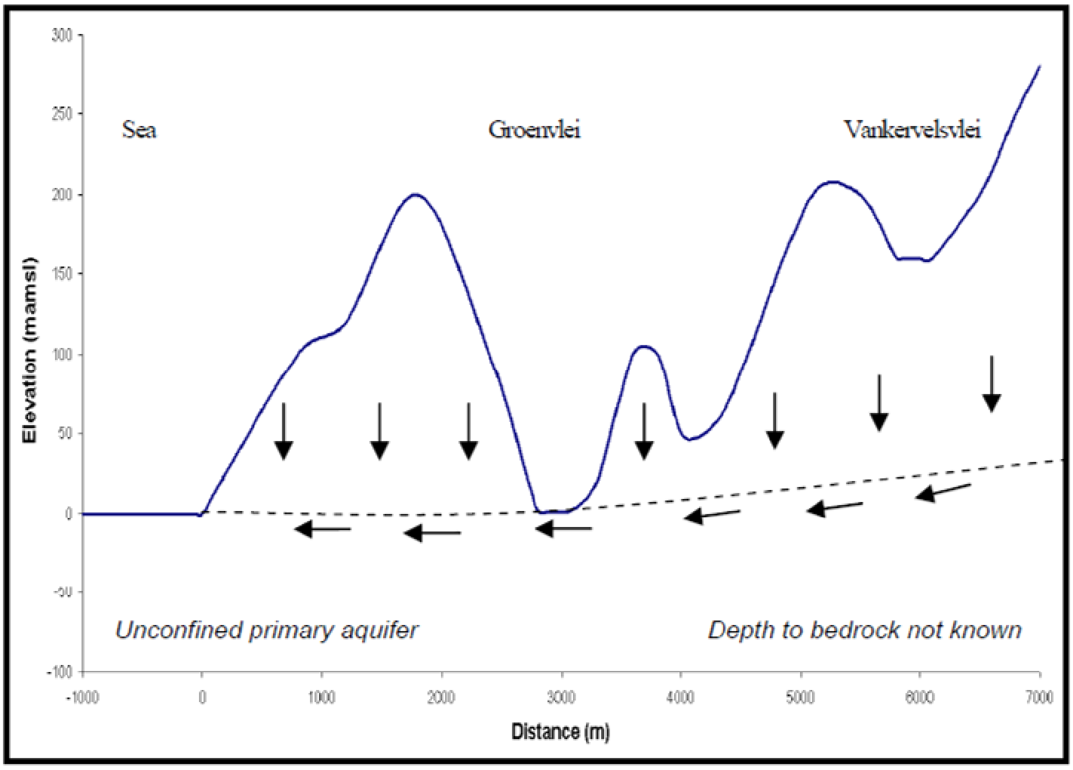


Figure 2.13 Conceptual hydrological model for the Groenvlei and Vankervelsvlei wetlands (Parsons, 2009).

These studies highlight the complexity associated with understanding the link between TMG aquifers and the surface water of rivers and wetlands.

2.6 Palmiet wetlands

2.6.1 Description of palmiet

Palmiet (*Prionium serratum*) is a hardy palm-like shrub that grows in the beds of rivers and within wetlands, with stems that grow up to 3 m high and flat, and narrow serrated leaves up to 1.2 m long (Figure 2.14 and 2.15). *Prionium serratum* was previously included in the family *Juncaceae* but due to its strange growth form, compared to *Juncaceae*, it was put into a new family, *Prioniaceae*. Palmiet is endemic to nutrient-poor rivers (usually on sandstone - most commonly Table Mountain Group (TMG) sandstone) in the Eastern Cape, KwaZulu-Natal (Natal Group sandstones) and the South Western Cape of South Africa (Munro *et al.,* 2001; Boucher and Withers, 2004; van Ginkel *et al.,* 2011; Munyai, 2013).

Palmiet has a thick system of fibrous roots that grow significantly deeper than other similar wetland plants (sometimes up to five metres deep). Its deep rooting system appears to play an important role in the ecosystem functioning of the plant and its ability to withstand heavy floods that are characteristic of the TMG geology (Munro and Linder, 1997; Sieben, 2016). Palmiet grows relatively fast, with a seedling grown (already a small replica of an adult plant) within 4 weeks of germination (Munro and Linder, 1997).

According to Boucher and Withers (2004), palmiet does not grow in saline conditions and does not thrive in shaded areas, but grows well in areas with direct sunshine. The plant survives fires, which actually seem to boost flowering and sprouting of the plant (Boucher and Withers, 2004). Pulley *et al.* (2017) studied the mineral magnetic properties of sediment within the Krom River palmiet wetlands and found that these wetlands had been subjected to (and survived) various fire events in the past.

Figure 2.14 Palmiet growing in the Krom River, Eastern Cape.

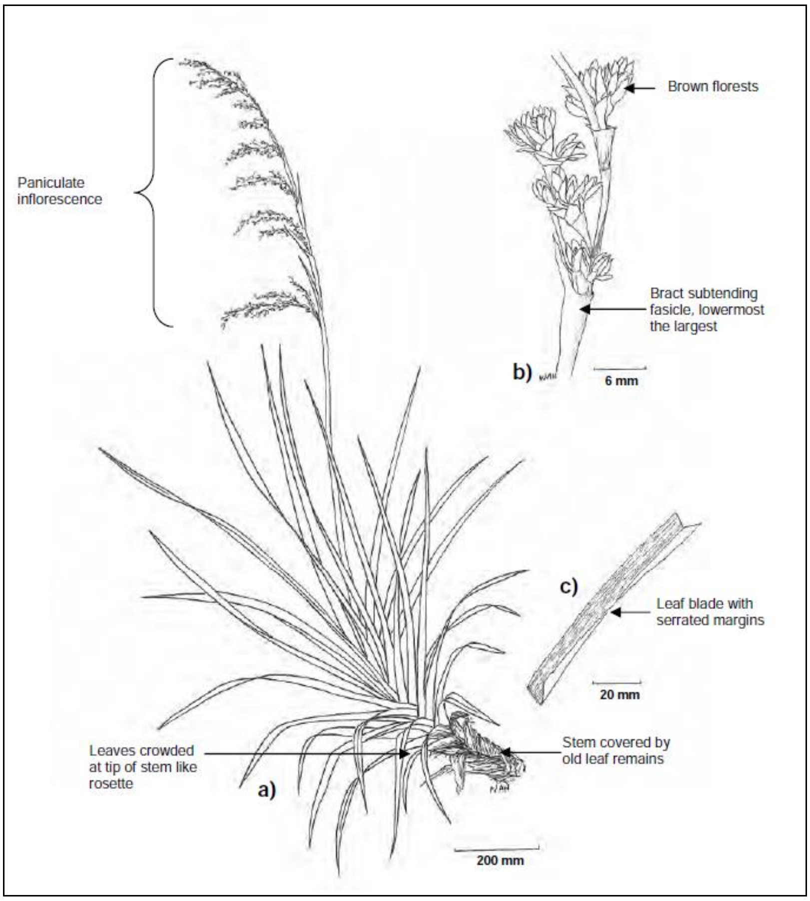


Figure 2.15 Illustration of the typical palmiet plant (a), palmiet inflorescence (b) and palmiet leaf (c) (van Ginkel *et al.,* 2011).

Palmiet wetlands are commonly underlain by thick peat beds (Rebelo, 2012; Job, 2014; Bekker, 2016; Pulley *et al.,* 2018) and provide important ecosystem services such as carbon sequestration, flood attenuation and water purification (Rebelo, 2017). Rebelo *et al.* (2018) illustrate that palmiet wetlands (in a pristine ecological condition) play an important role in purifying water by acting as a sink for pollutants derived from nearby agricultural activities.

Rebelo *et al.* (2017) examined four palmiet wetlands within the Cape Floristic Region of South Africa using multispectral imagery, aerial photographs, and the MaxEnt model to determine the extent of land cover changes within these wetlands over time. It was found that these palmiet wetlands had decreased in size by about 31% over the last 60-70 years. Rebelo *et al.* (2017:220) attribute the decline in palmiet wetlands in South Africa to "erosion, agriculture and alien plant invasion".

2.6.2 Palmiet and gully erosion

Intensive gully erosion is common in palmiet wetlands of the Western Cape (Job, 2014). While various authors attribute gully erosion in palmiet wetlands to human impacts, recent studies of the Krom River palmiet wetlands (in the Eastern Cape) by Lagesse (2017), Schlegel (2017) and Pulley *et al.* (2018) indicate that gully erosion may be a natural part of palmiet wetland functioning, and that human impacts only contribute to the speeding up of this natural process. According to Pulley *et al.* (2018) gullying forms an essential function in terms of removing excess sediment that builds up within the wetlands, particularly due to commonly found alluvial fans constricting wetland extent in the Cape Fold Belt region. This erosion is deposited downstream, laterally flattening the valley-bottom and decreasing the longitudinal slope, forming an environment fit for wetland formation downstream of the erosion point.

2.6.3 Palmiet as an ecosystem engineer and its effect on the hydrology of rivers

Sieben (2012) and Barclay (2016) describe palmiet as an ecosystem engineer since it alters its environment to support its own growth and it appears to play a significant role in the formation of valley-bottom wetlands. According to Jones *et al.* (1994:374) ecosystem engineers "are organisms that directly or indirectly modulate the availability of resources (other than themselves) to other species, by causing physical state changes in biotic or abiotic materials. In so doing, they modify, maintain and/or create habitats". Wetland plants generally affect the hydrology of their environment by binding and trapping sediments, altering water flow and creating peat (Mitsch and Gosselink, 2007).

The abundance of palmiet in foothill streams plugs the river resulting in the formation of a valley-bottom wetland. Palmiet's deep, substantial rooting system along with its clonal growth and ability to tolerate strong flood events are key traits that assist the plant to transform its own environment (Sieben, 2012).

It is suggested by Job (2014:66) that the distribution of the peatland in the Goukou River (Western Cape) is linked to the occurrence of palmiet and that the palmiet forms "a local base level and water ponding" in the river. The higher base level created by the palmiet results in a relatively constant water table and allows organic matter to accumulate (and exceed decomposition). Palmiet grows throughout the Goukou wetland and it is effective at collecting clastic sediment. During continued low flows in the Goukou River palmiet spreads out and extends into the river channel open water, restricting channel width, and densely filling up the river channel. By extending across the valley floor palmiet colonises the river, traps sediment and reduces flow. This process alters the flow in the river to a diffuse flow, allowing the accumulation of organic material and formation of a deep peat basin (Job, 2014). A similar process was also noted by Czegledi (2013) in a study of the Hudsonvale palmiet wetland on the Krom River and by Bekker (2016) in a study of the Tierkloof palmiet wetland along the Tierkloof River.

A study of a palmiet wetland in the Upper Krom River (Kompanjiesdrif wetland), by Barclay (2016), indicates that palmiet may have converted the braided to anastomosing stream at this site to an unchannelled valley-bottom wetland with diffuse flow by colonising gully beds and areas of open water. It was found that palmiet plays a role in naturally restoring eroded gullies along this river. In the investigation of this wetland it was clear that palmiet occupied three main habitats; namely, on near-flat valley-bottoms filled with organic and clastic sediment, on the bottom of gullies (recently infilled by sediment) and on open water.

The Kompanjiesdrif wetland has been subjected to various episodes of gully formation and infilling. Barclay (2016) indicates that palmiet has an impact on these gullies by filling them (trapping sediment in the gullies), colonising gullies that have been filled by alluvial fan sediment and encroaching into former gullies that are filled with water ('dammed' or 'ponded' up) and are obstructed downstream by alluvial fan sediment. Palmiet forms a tangled mat over the open water surface of these former gullies.

After an erosional gully develops, sediment (formed through headward erosion) accumulates as sandbars in the gully. These bars are colonised by palmiet which also traps clastic sediment and forms peat. The sandbars keep forming and are colonised by palmiet until the gully is ultimately filled (Figure 2.16).

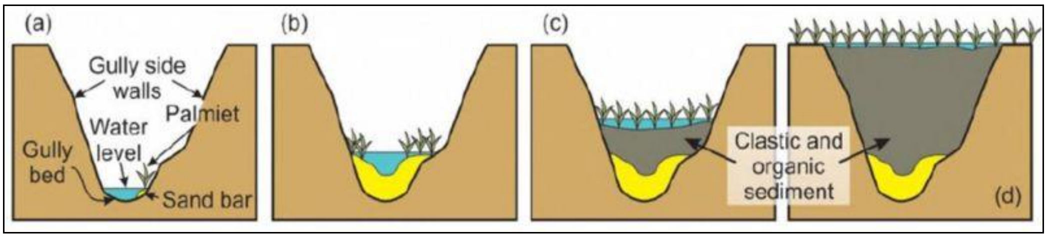


Figure 2.16 Illustration of palmiet colonising sedimentary bars, trapping sediment and forming peat in a gully (Barclay, 2016).

2.6.4 The water use of palmiet

According to Rebelo (2012), many riparian landowners consider palmiet to be a high-water user. Rebelo (2012) conducted a study on the water-use of palmiet using stomatal conductance measurements of a palmiet wetland in the Jonkershoek valley, Western Cape. Her study found that palmiet is a fairly low water-user, for a wetland plant. Microscope examination of palmiet leaves revealed that palmiet has developed sunken stomata (pores), which are more common in desert plants (and not wetland plants), to survive dry periods. These adaptations could permit palmiet to continue to survive and grow in wetlands even in very dry years. Rebelo (2012) also conducted a study of a palmiet wetland at Franschhoek and obtained annual ET estimates of 1526 mm (scintillometry), 1042 mm (MODIS) and 1623 mm (Landsat) for the plant. Agricultural Catchments Research Unit (ACRU) modelled ET estimates for palmiet in the Krom River are lower at 694.6 ± 21.46 mm per year, which is approximately 246.21 mm higher than natural fynbos, but approximately 200 mm lower than invasive *Acacia mearnsii* (black wattle) (Rebelo *et al.,* 2015). Although, the ACRU model wetland and riparian ET estimates are known to be low due to the way that the model allows for water availability in the rooting zone.

3 DESCRIPTION OF THE STUDY AREA

3.1 Location, catchment boundaries, and topography

The study area is located within a sub-catchment of the K90A upper Krom River catchment, approximately 20 km east of the town of Joubertina in the Eastern Cape Province of South Africa (33°52'41.04" S, 24° 3'6.83" E) (Figure 3.1). The Krom River is approximately 100 km long from its upper reaches to its estuary (at St Francis Bay). It is bounded by the Suuranys Mountains (+/-1050 m.a.s.l.) to the north and Tsitsikamma Mountains (+/-1500 m.a.s.l.) to the south. The Krom River provides the Nelson Mandela Bay Metropole with about 24% of its water via the Churchill Dam and sustains peatlands dominated by palmiet (Haigh *et al*., 2009; Rebelo, 2012).

Two palmiet (*Prionium serratum*) wetlands form the focus of this study and are located along the Krom River in a valley-bottom with an elevation that ranges from about 400 m.a.s.l. to about 350 m.a.s.l. (Figure 3.2). The upstream catchment area feeding these wetlands is 56 km^2, which is about 26% of the K90A quaternary catchment area.

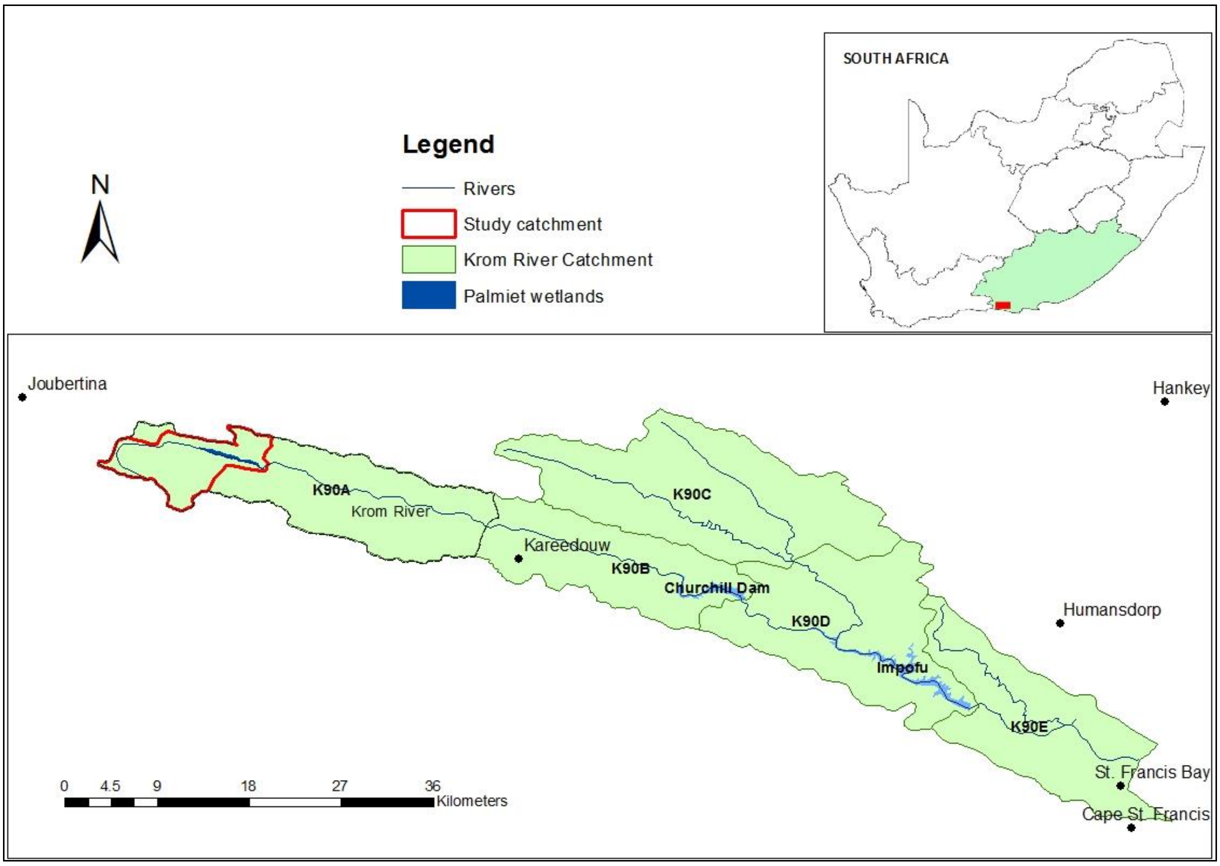


Figure 3.1 Locality map illustrating the study catchment (in red) within the K90A catchment.

Figure 3.2 Locality map illustrating the two palmiet wetlands that are the focus of this study.

3.2 Land cover, land use, and vegetation

The floodplains of the Krom River formed and accumulated sediments over millennia. Pulley *et al.* (2017) have dated sediments up to 7000 years old within the palmiet wetlands. The geomorphology of much of the Krom River has since been modified and the palmiet wetlands are threatened by erosion. According to Haigh *et al.* (2009), the palmiet wetlands in the K90A and K90B catchment have declined in size significantly since 1942.

According to Rebelo (2012), the land cover within the Krom River catchment has been transformed by orchard farming, over-grazing, road construction, and black wattle (*Acacia mearnsii)* infestation. Haigh *et al.* (2009), Rebelo (2012) and Nsor and Gambiza (2013) provide a detailed history of land use change in the Krom River catchment since the eighteenth century. Rebelo *et al.* (2015) calculated a decline of palmiet wetlands by 84% and riparian vegetation by 92% in the Krom River catchment (K90A and K90B) over the last century. Figure 3.3 illustrates the current land use in the study catchment.

The upper Krom River catchment is located within the fynbos biome and is characterised by sandstone fynbos, shale band vegetation and shale renosterveld (Rebelo *et al.,* 2006). The wetlands are dominated by palmiet (*Prionium serratum*) and also contain plant species such as *Miscanthus capensis, Juncus kraussi, Metalasia densa and Pennisetum clandestinum* (alien invasive grass) (Barclay, 2016). Alien vegetation (in particular black wattle) has invaded parts of the Krom catchment and palmiet wetlands. *Working for Water* and *Working for Wetlands* has been clearing black wattle along the Krom River since 1996 (Rebelo *et al*., 2013).

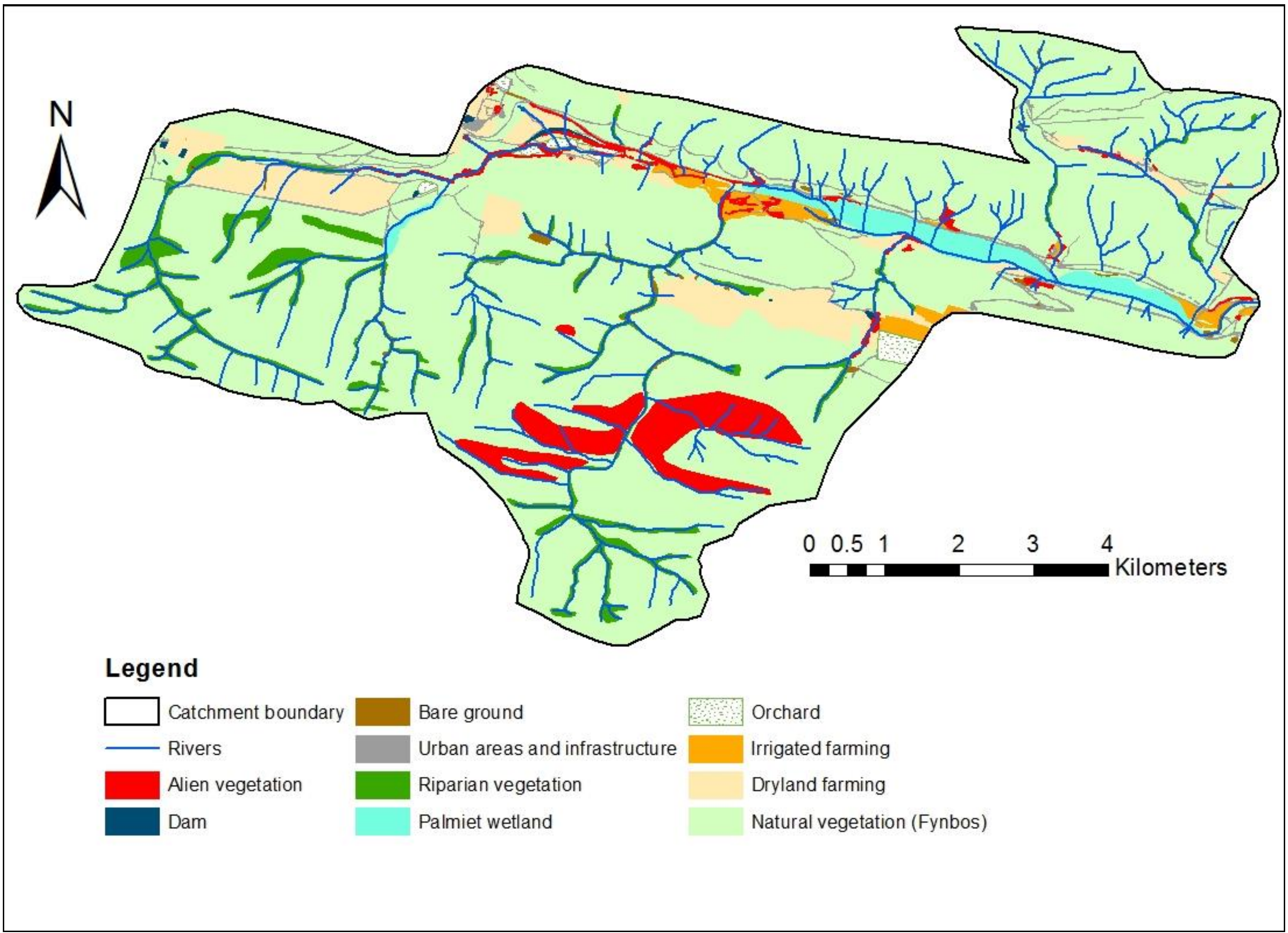


Figure 3.3 Land cover in the study catchment (land cover shapefiles edited from Rebelo (2012)).

3.3 Climate

The Krom River catchment experiences a bimodal pattern of rainfall, with spring (August to October) and autumn (February to April) receiving higher rainfall than the rest of the year (Nsor and Gambiza, 2013). Rainfall is unevenly distributed within the Krom River catchment, with higher rainfall occurring in the south and south-west of the catchment compared to the north and north-east (Haigh *et al.,* 2009). Rainfall also tends to increase from inland towards the coast (Bailey and Pitman, 2016).

The Water Resources 2012 database (Bailey and Pitman, 2016) has determined a mean annual precipitation (MAP) of 716 mm, mean annual evaporation (MAE) of 1400 mm and mean annual runoff (MAR) of 27 million m^3 in the K90A Krom River catchment. A local weather station (located at Twee Riviere – 13 km from the study site) has recorded a MAP of 346 mm and a MAE of 1095 mm (based on an average of 7 years of data, which included a severe drought).

3.4 Geomorphology and hydrology

Floods are common in the Krom River catchment (which is expected in a steep mountainous Cape Fold Belt environment) with significant floods having been recorded in 1931, 1965, 1981, 1996, 2001, 2006, 2007 and 2012 (McNamara, 2018). The K90A catchment has a trellis drainage pattern with six large tributaries and five minor tributaries flowing into the Krom River from the south side and seven large and numerous short tributaries flowing in from the northern side of the river. Alluvial fans occur at the end of a number of tributaries, curbing the extent of the palmiet wetlands (these fans can be considered to play a significant role in the structure of the wetlands). This is particularly evident at Kompanjiesdrif. Water tends to flow diffusely through the palmiet wetlands, with very small channels forming along the perimeter of the wetlands. Grundling *et al.* (2017) list the main sources of water for the palmiet wetlands in the upper Krom River as river water, groundwater, side seepage, and shallow sub-surface flow through alluvial fans.

Gully erosion is a major concern along the Krom River and has largely been attributed to land use change (in particular poor farming practices), the building of roads and railway lines and infestation by black wattle (Haigh et al., 2009; Rebelo, 2012). According to Rebelo (2012), channels caused by the head-cuts can drain groundwater from the alluvium and in the process may destroy the wetlands. Working for Wetlands has undertaken various rehabilitation interventions along the Krom River, including the placement of erosion-control structures (gabions) within the river. One of these structures is located at the end of the Kompanjiesdrif wetland (Figure 3.4).

Figure 3.4 Erosion-control structure at the bottom of the Kompanjiesdrif wetland.

According to Ellery *et al.* (2009), valley-bottom wetlands (such as those in the Krom River) are especially vulnerable to gully erosion. This is due to continuous accumulation of sediment in the wetlands which produces a steep longitudinal slope. Erosion may be caused by human activity (for example, by confining flow when pipe culverts are placed beneath a road) but it may also take place naturally when "the surface of a wetland is steepened longitudinally by prolonged sedimentation and ultimately exceeds a critical threshold of slope stability" (Ellery *et al*., 2009:52). Lagesse (2017), Schlegel (2017) and Pulley *et al.* (2018) examined gully erosion in the upper Krom River wetlands and have indicated that erosion and subsequent gully infilling may, in fact, play an important role in the formation of these palmiet wetlands and that gully erosion appears, in this case, to be a natural process. Pulley *et al*. (2018) identified gullies within the Kompanjiesdrif wetland by coring through the wetland with a steel gouge corer, Edelman auger, and/or Russian peat corer. Coring took place until the depth of refusal which was either when a layer of sand was reached (repeatedly collapsed) or a historical gully (normally on bedrock) was reached. Elevations were measured using a differential global positioning system (DGPS). In the Kompanjiesdrif wetland, four gullies are located in the centre of the wetland opposite alluvial fans and are between 5.0 and 8.2 m deep (Figure 3.5). Two gullies that are filled with sediment are also located on the alluvial fans. The age of the gullies is between 470 to 7060 YBP (pre-dating late 18th-century European farming) (Pulley *et al.,* 2018).

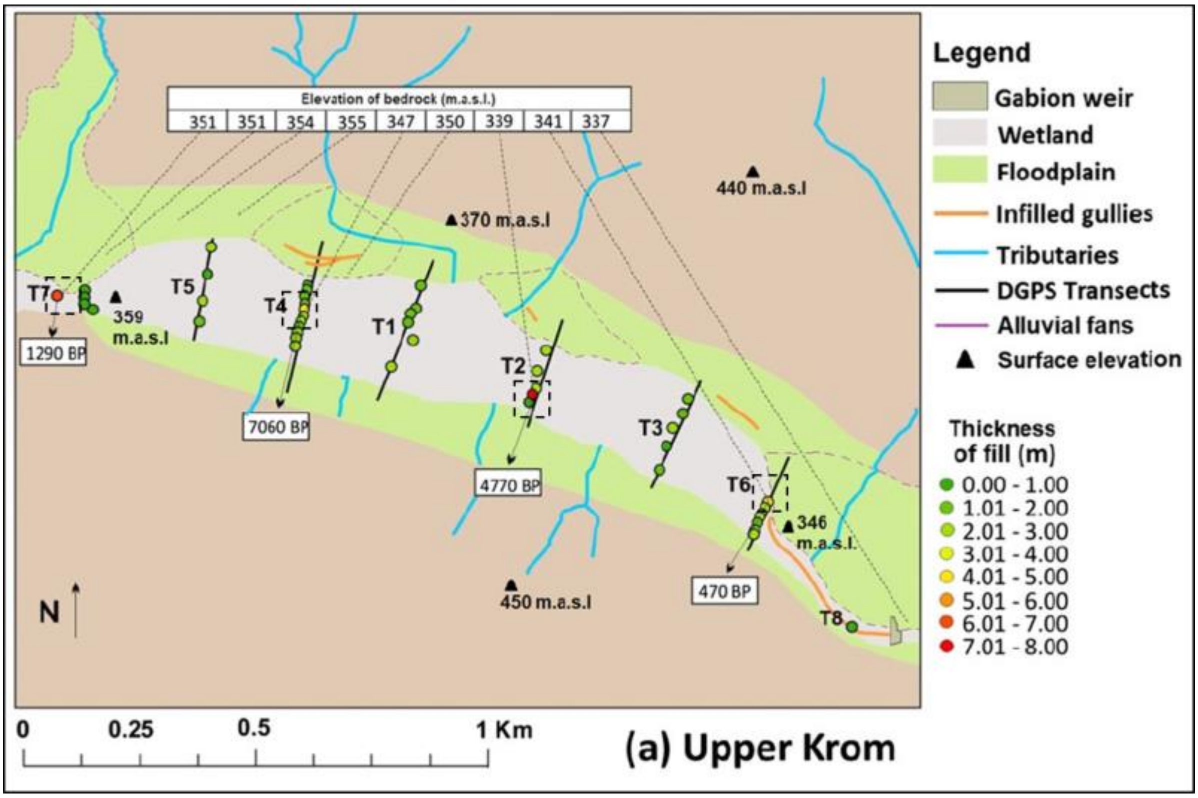


Figure 3.5 Age and thickness of infilled gullies in the Kompanjiesdrif wetland. Gullies in the wetland are smaller than gullies outside the wetland and are indicated by black stippled boxes. DGPS = differential global positioning system, BP = before present (adapted from Pulley *et al.,* 2018).

According to Pulley *et al.* (2018) when localised clastic sediment is deposited into the wetland it results in a steeper longitudinal slope. This factor combined with the fact that alluvial fans also narrow the valley, focussing flows, enhances the probability of exceeding the threshold of land surface stability and, in turn, allowing gully erosion to begin. The bed of the gullies usually has a smaller slope than the wetland surface. Sediment deposited as a result of this erosion shapes the land surface to a slope closer to the river's regional slope. This gentler slope provides ideal conditions for wetland formation. The regional slope along the Krom River is 0.35%, however, the longitudinal slope of the Kompanjiesdrif wetland is 1.02% (Figure 3.6a), illustrating the steepness of this erosional reach compared to the regional slope. The bedrock underneath the wetland has a slope of 0.85%. Gully incision causes the slope of the bedrock to decrease in comparison to the wetland's surface (base of the gully has a slope of 0.18%) (Figure 3.6b). The gradient of the downstream depositional reach is higher than the gradient of the gully bed, located immediately upstream, and is closer to the regional slope (Figure 3.6c) (Pulley *et al*., 2018). Figure 3.7 illustrates the locations along the Krom River where the longitudinal slope of the wetland, the depositional reach and erosional reach was measured by Pulley *et al*. (2018).

Human factors such as poor land management or the presence of alien invasive vegetation can increase natural gully formation along the Krom River, but Pulley *et al*. (2018) show that this gully erosion could also be caused by intrinsic factors.

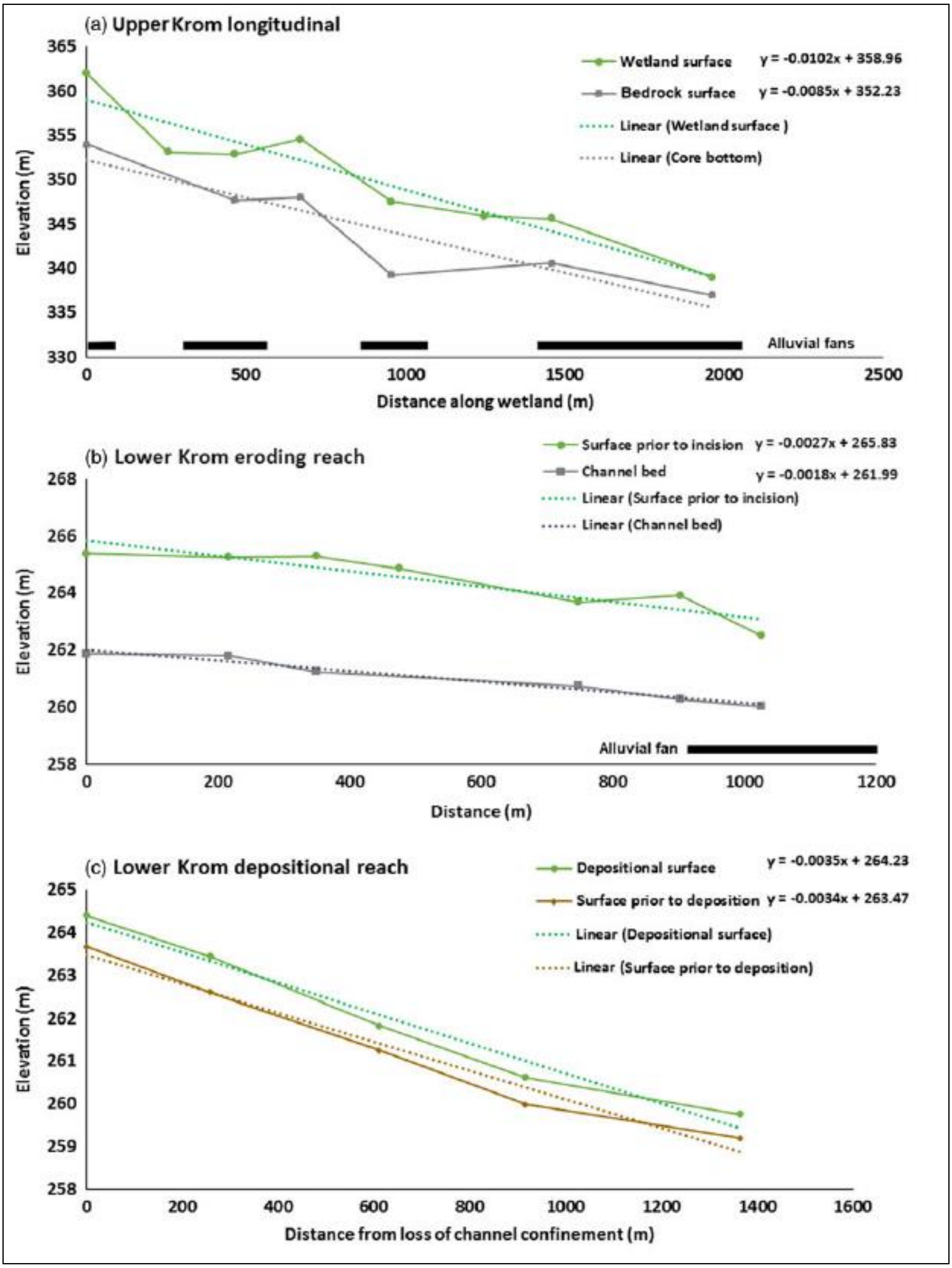


Figure 3.6 Change in slope along the Krom River with distance (Pulley *et al.,* 2018).

Figure 3.7 Locality map illustrating the locations of longitudinal slope measurements taken by Pulley *et al*. (2018).

3.5 Geology

The Krom River is located within quartzitic sandstones and shales of the Cape Supergroup, specifically the Bokkeveld Group (which tends to cover the valley-bottom) and the Table Mountain Group (TMG) which were deposited in a passive margin basin between 500 and 330 million years ago (Thamm and Johnson, 2006).

Approximately 330 million years ago compression of these sedimentary rocks (due to a subduction zone along the southern boundary of Gondwana) resulted in the formation of the folded and faulted Cape Fold Belt (McCarthy and Rubidge, 2005). The 1:250 000 geological map of the area (Toerien, 1986) illustrates the intensely folded nature of the Krom River catchment, with anticlines occurring in the south followed by synclines (along the Krom River valley) and anticlines again in the north. Figure 3.8 illustrates the geology of the study catchment.

The two wetlands that are the focus of this study are located in the centre (valley-bottom) of an overturned syncline of the Cape Fold Belt rocks. As is evident in the geological cross-section (Figure 3.9), the valley is comprised of less resistant shale material and the steeper valley sides tend to consist of more resistant quartzitic sandstone. Table 3.1 provides a more detailed lithological description of the rocks in the study catchment.

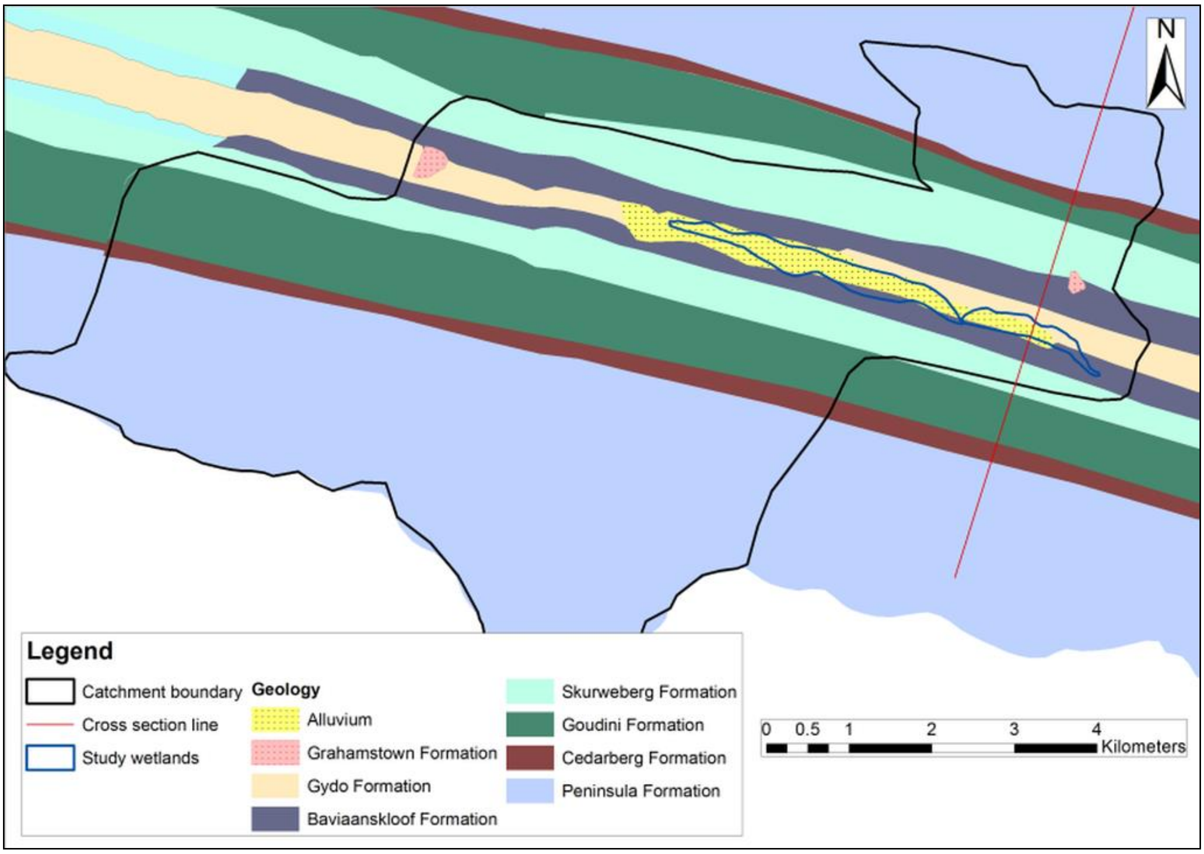


Figure 3.8 The geology of the study catchment based on the 1:250 000 geological map (Toerien, 1986) with the location of the cross-section (illustrated in Figure 3.8) indicated by the red line.

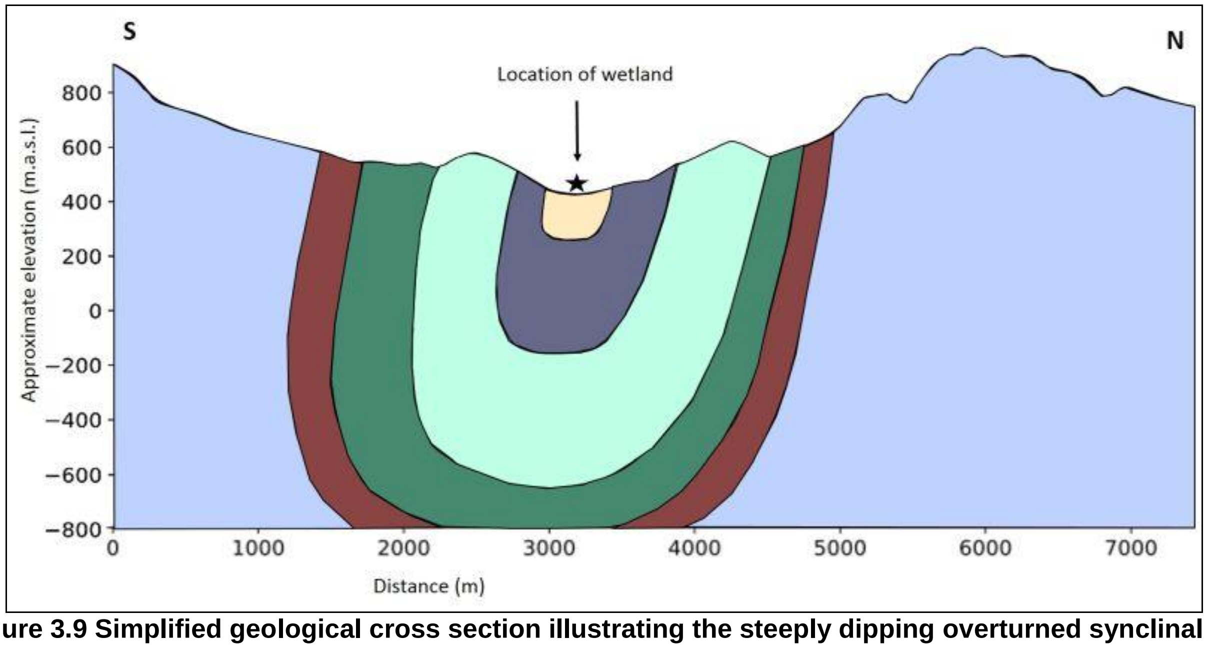


Figure 3.9 Simplified geological cross section illustrating the steeply dipping overturned synclinal rocks of the Cape Supergroup, with the wetland located in the centre of the valley-bottom (vertical exaggeration = 2).

Table 3.1. Stratigraphy of the study area (Toerien, 1971-1972; Toerien, 1972; Toerien, 1986; Thamm and Johnson, 2006 and Toerien, n.d.).

	Group	Sub-group	Formation	Lithology
				Alluvium.
			Grahamstown	Terrace gravel, silcrete, and ferricrete.
	Bokkeveld	Ceres	Gydo	Black shale with minor siltstone, fossiliferous.
	Table Mountain	Nardouw	Baviaanskloof	Impure feldspathic sandstone (fine to medium-grained), minor shale, fossiliferous.
			Skurweberg	White-weathering (medium to coarse-grained) quartzitic sandstone, feldspathic towards the top, cross-bedded.
			Goudini	Brownish-weathering quartzitic sandstone (fine to coarse-grained), minor siltstone and shale.
			Cedarberg	Black shale, arenaceous towards to the top and can be fossiliferous.
			Peninsula (main unit of the Cape Supergroup)	Whitish-weathering quartzitic sandstone (medium to coarse-grained).

The wetland basins appear to be located on the Post Africa II erosion surface (formed approximately 5 Ma), while the Post Africa I surface (formed approximately 20 Ma) is above the wetland surface located on a break in slope in the northern Suuranys Mountains (Figure 3.10). The African Erosion surface (formed before 60 Ma) is located on the crest of the northern Suuranys Mountains (McCarthy and Rubidge, 2005; Lagesse, 2017).

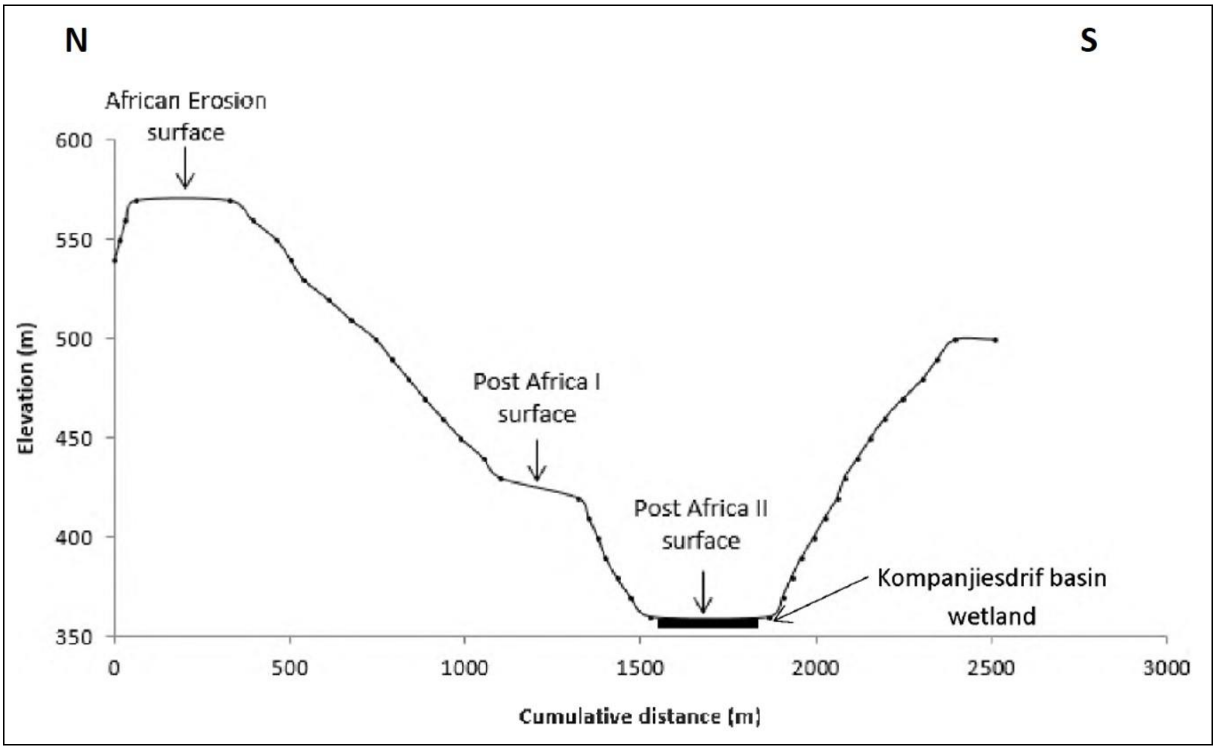


Figure 3.10 Position of the Kompanjiesdrif wetland basin in relation to the three erosion surfaces (Lagesse, 2017).

3.6 Geohydrology

The Cape Supergroup sandstones and quartzites can be a significant source of groundwater, but the volumes of water they yield are variable and are generally dependent on the occurrence of fractures, faults and folding to provide secondary porosity and flow paths (Xu *et al.,* 2009). Dennis and Pretorius (2006) estimated the groundwater contribution to baseflow in the K90A catchment to be 3.58 million m^3/a using a numerical flow model (MODFLOW). Dennis and Pretorius (2006) excluded protected areas in the catchment from their study as they were completing a groundwater reserve study and assumed that no groundwater abstraction is allowed in a protected area. Thus a smaller catchment area (178 km^2) was used in the model compared to the actual catchment area of 214 km^2. Xu *et al.* (2009) estimated baseflow (using baseflow separation) in the K90A catchment to be 7.5 million m^3/a (24.9% of the MAR). The GRA2 groundwater baseflow zones of South Africa map illustrates that the study area is located within a high groundwater baseflow zone (Figure 3.11) (DWAF, 2006).

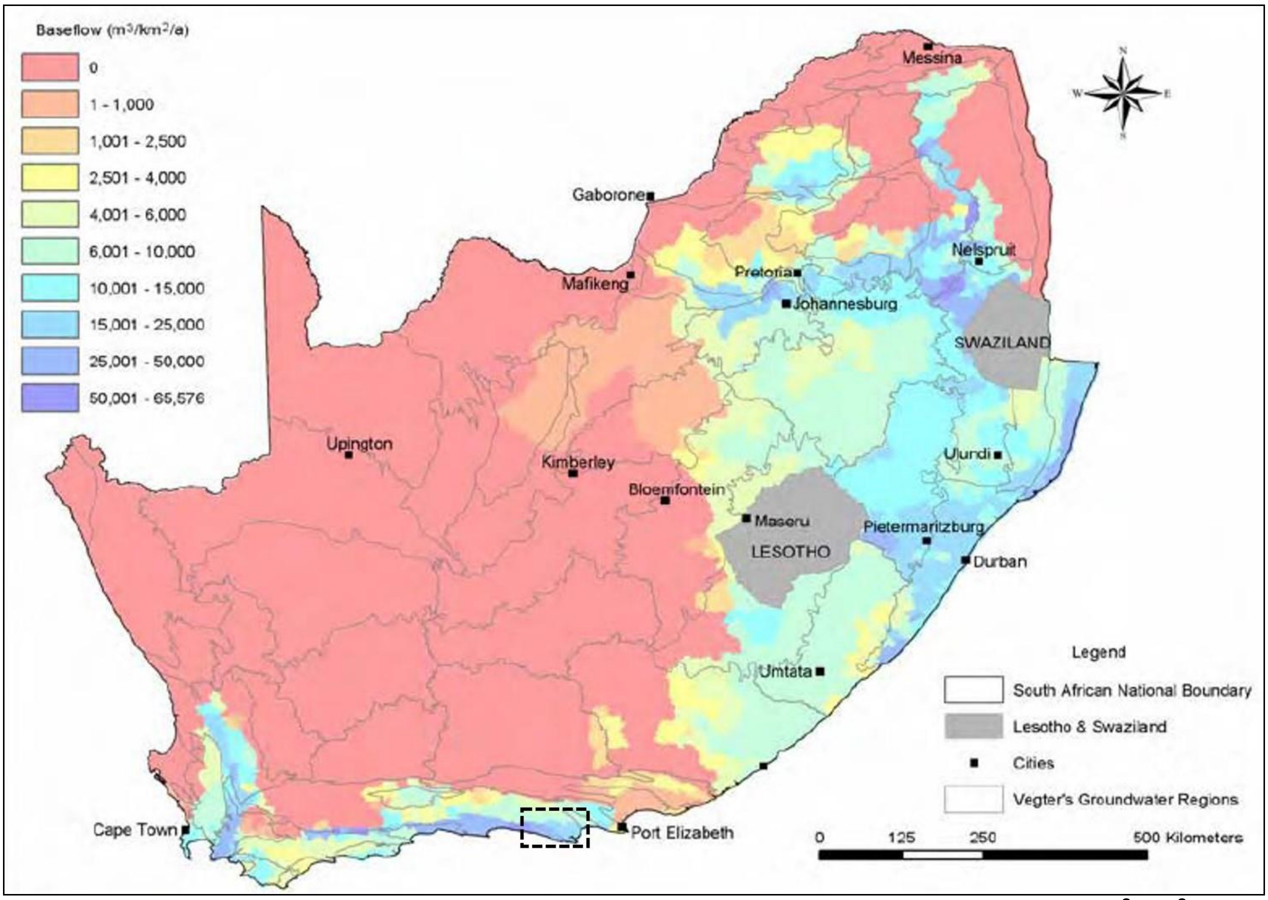


Figure 3.11 Mean annual groundwater contribution to baseflow map of South Africa in $m^3/km^2/a$ (DWAF, 2006). Study area highlighted by a black stippled box.

3.6.1 Impacts of erosion-control structures and gully erosion on groundwater dynamics along the Krom River

De Haan (2016) investigated the effect of erosion-control structures and gully erosion on the groundwater dynamics of the Krom River. The water table was mapped (by installing piezometers and measuring water elevation with a dip metre and DGPS) in the vicinity of erosion-control structures (at the end of the Kompanjiesdrif wetland) and at planned erosion-control sites along the Krom River in order to investigate the effect these structures, as well as gully erosion, has on groundwater dynamics along the Krom River. Water table elevations were measured at 3 sites along the Krom River using piezometers (Figure 3.12).

Figure 3.12 Sites of sub-surface water level measurement using piezometers installed adjacent to erosion control structures (at site A) and potential future structures (site B and C) (De Haan, 2016).

The erosion-control structures at site A (end of the Kompanjiesdrif wetland) have caused a 7.76 m difference in surface water elevation above and below the structures. The structures have raised the water table upstream of them; causing an increase in saturation of the wetland and encouraging diffuse flow across the wetland (the flow is not concentrated into a channel but is rather spread out across the wetland). According to De Haan (2016) the structures also ensure flood retention by increasing the amount of water held by the wetland during high flows; thereby reducing peak flows. The structures improve the water quality by reducing the downstream sediment load. This capturing of sediment upstream, however, (causing a reduced downstream bed load) has damaged the downstream stream bed. Since the implementation of the erosion-control structures in 2003 the main head-cut has remained at the same location (not migrated) but has widened significantly over a ten year period.

It was found that the water table is significantly deeper along eroded reaches compared to the non-eroded reaches of the river (Figure 3.13 and 3.14a and b). According to De Haan (2016), this is because gully erosion causes drainage of the inter-gully area causing a drop in the water table as the gullies deepen. The water table along the eroded reaches also tends to slope towards the channel ('recharging the channel'), while along the non-eroded section the water table tends to slope away from the channel.

The investigation at site A (Figure 3.13) (described by De Haan, 2016) took place under impacted conditions where the structure resulted in upstream saturation and prevented downstream sediment deposition. The 'eroded' section is just downstream of the structure and 'non-eroded' section is just upstream of the structure. Without the structure, the water table is anticipated to behave differently and the eroded section is not expected to drain the water table as significantly.

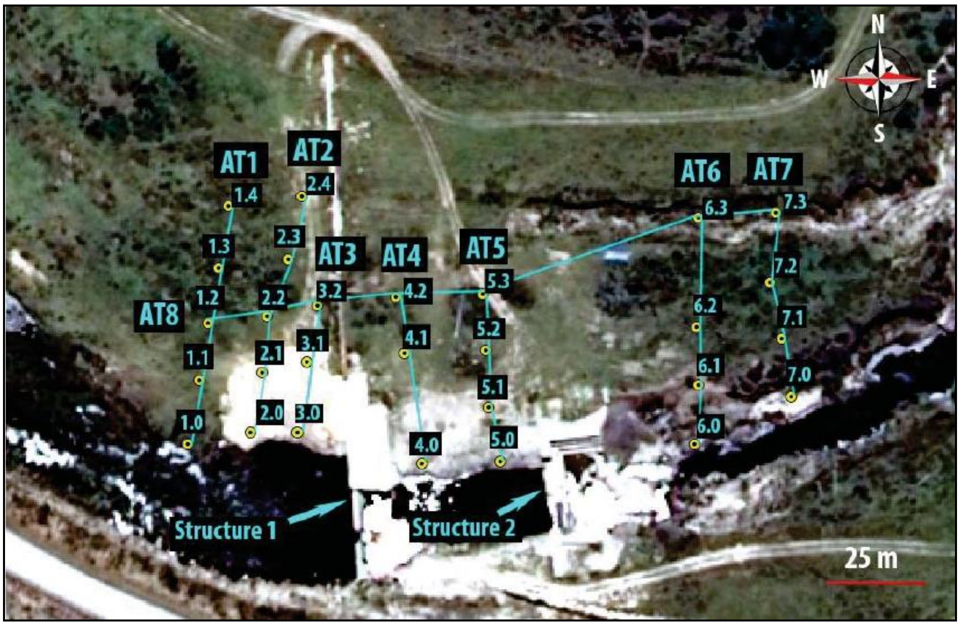


Figure 3.13 The locations of transects at site A (bottom of Kompanjiesdrif wetland). Transect AT1 is along the non-eroded reach and AT6 is along the eroded reach downstream of the erosion-control structures (De Haan, 2016).

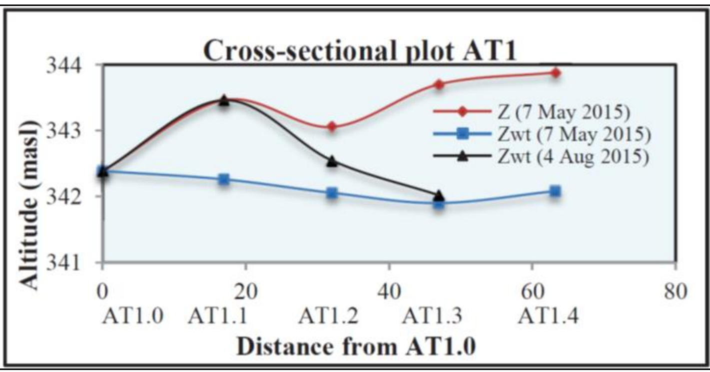


Figure 3.14a cross-sectional profile along a non-eroded reach of the river channel. Z = surface elevation, Zwt = elevation of the water table (De Haan, 2016).

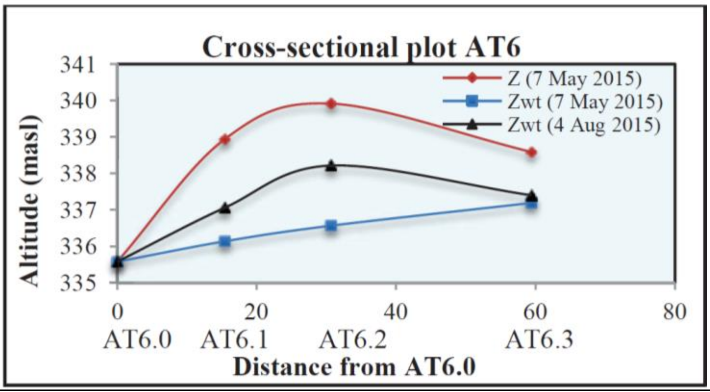


Figure 3.14b cross-sectional profile along the eroded reach of the river illustrating the drop in water table elevation compared to the surface elevation (De Haan, 2016).

De Haan (2016) also discovered old palmiet remnants at various locations and depths (up to 2.6 m below ground level) at site C which implies that palmiet has been present in the Krom River catchment (and has been re-establishing itself after erosion) for thousands of years. This also supports the theory of ‘cutting and filling’ in the catchment put forward by Pulley *et al.* (2018). De Haan (2016:35) states that “it could be argued that structures disrupt the natural long-term cycles to a certain extent. In this context, one could argue that the act of implementing structures implies trying to force a natural dynamic system to remain constant for as long as possible in order to benefit the needs of mankind".

4 METHODOLOGY

4.1 Data collection

The investigation focussed on the small-scale dynamics of the palmiet wetland system in order to increase general understanding of the surface water and groundwater processes of these palmiet wetland systems. The majority of the field work was thus focussed on the Kompanjiesdrif wetland system (and the associated alluvial fans), with some field work being undertaken at the upstream Krugersland wetland. A severe drought was experienced in the study area over most of the study period (end of 2016 and during 2017) and data collection was adversely affected.

4.1.1 Hydrocensus

The Department of Water and Sanitation (DWS) National Groundwater Archive (NGA), DWS Water Authorisation Management System (WARMS) database and a local borehole expert were consulted to determine the location of boreholes in the study area. A borehole (BH1) is located upstream of the Krugersland wetland, but no boreholes were found in the vicinity of the Kompanjiesdrif wetland (Figure 4.1 and 4.2). A number of other boreholes are located just outside the study catchment.

4.1.2 Installation of piezometers

Four alluvial fans encroach onto the northern bank of the Kompanjiesdrif wetland basin from tributaries of the Suuranys Mountain range. The intention was to install piezometers on the first alluvial fan (westernmost fan) to determine if there is preferential flow through the boulder material of this fan into the wetland. Holes were drilled using a hand-held Dutch auger. Holes that were drilled towards the top of the fan were unsuccessful as hard boulders, typically found at the head of an alluvial fan, were intersected. These holes did not reach the water table despite deep pits being dug (maximum 2 metres deep). A number of auger holes, located on the outer edges of the alluvial fan were, however, successfully drilled through to the water table and in some cases to bedrock. Holes were also drilled in the wetlands and piezometers were installed. Refer to Figures 4.1 and 4.2, and Table 4.1 for details of all installed piezometers.

Piezometer pipes were installed in the successful holes, along with data loggers in selected piezometers for measuring variations in water height. Data loggers were installed in June 2016 in Piezometer A, B, C, D and in BH1 and monitored water levels for a period of 8 months. These loggers were removed and reinstalled in different holes in February 2017, May 2017 and August 2018. A Geomax Zenith 10/20 differential global positioning system (DGPS) was used to measure the location and elevation of the piezometers as well as to measure cross-sectional transects through the river. During the drought experienced in 2017 some of the piezometers dried up, and the data loggers were therefore above the water level.

4.1.3 Electrical Resistivity Tomography Survey

An Electrical Resistivity Tomography (ERT) survey was undertaken in February 2017 at the Kompanjiesdrif wetland to investigate the sub-surface dynamics within the alluvial fans (Figure 4.1). An Abem SAS 1000 Terrameter and ES 10-64 switching unit were used in the field survey. Three ERT transects were undertaken using the Wenner measuring protocol, at an electrode spacing of 4 m. Maximum investigation depth with this electrode spacing and measuring protocol is 24 m.

4.1.4 Water quality and stable isotope sample collection and analysis

Water samples were collected from all piezometers, the borehole (BH1), the Krom River and a tributary of the Krom River (Figure 4.1 and 4.2). In May and August 2017 no surface water sample could be collected from the river under the R62 bridge (top of Kompanjiesdrif wetland), as well as from certain piezometers due to the drought (Figure 4.4). No tributary sample was collected in August 2017 as we were unable to access the tributary. Electrical conductivity (EC) and pH were measured in the field using a Hanna HI98129 ph EC tester, YSI Pro Plus multiparameter water quality meter, Hanna HI9829 multiparameter water quality meter and Hach SL1000 water quality meter. Chloride was measured using the Hach SL1000 chloride probe in May 2018.

Two additional boreholes (BH 2 and 3; Figure 4.2) located just outside of the study catchment (within the Peninsula Formation quartzitic sandstones – with one being located at or close to the contact of the Cedarberg Formation shale) were also sampled in May 2018. These boreholes are situated in the same geology as the groundwater that would flow from tributaries into the wetlands in the study catchment and are therefore considered to be representative of the groundwater in the catchment area. The boreholes were purged before sampling (a minimum of 3 times the volume of the water in the borehole was removed). The piezometers were emptied (using a bailer) before sampling (due to the slower recovery only 1 times the volume of water in the piezometers was removed).

All water samples were analysed for $^{2}H/^{1}H$ and $^{18}O/^{16}O$ ratios in the laboratory of the Environmental Isotope Group (EIG) of iThemba Laboratories, Johannesburg and the Mg, Ca, K, Al and Si content was tested using a Palintest Photometer 7100 at Rhodes University.

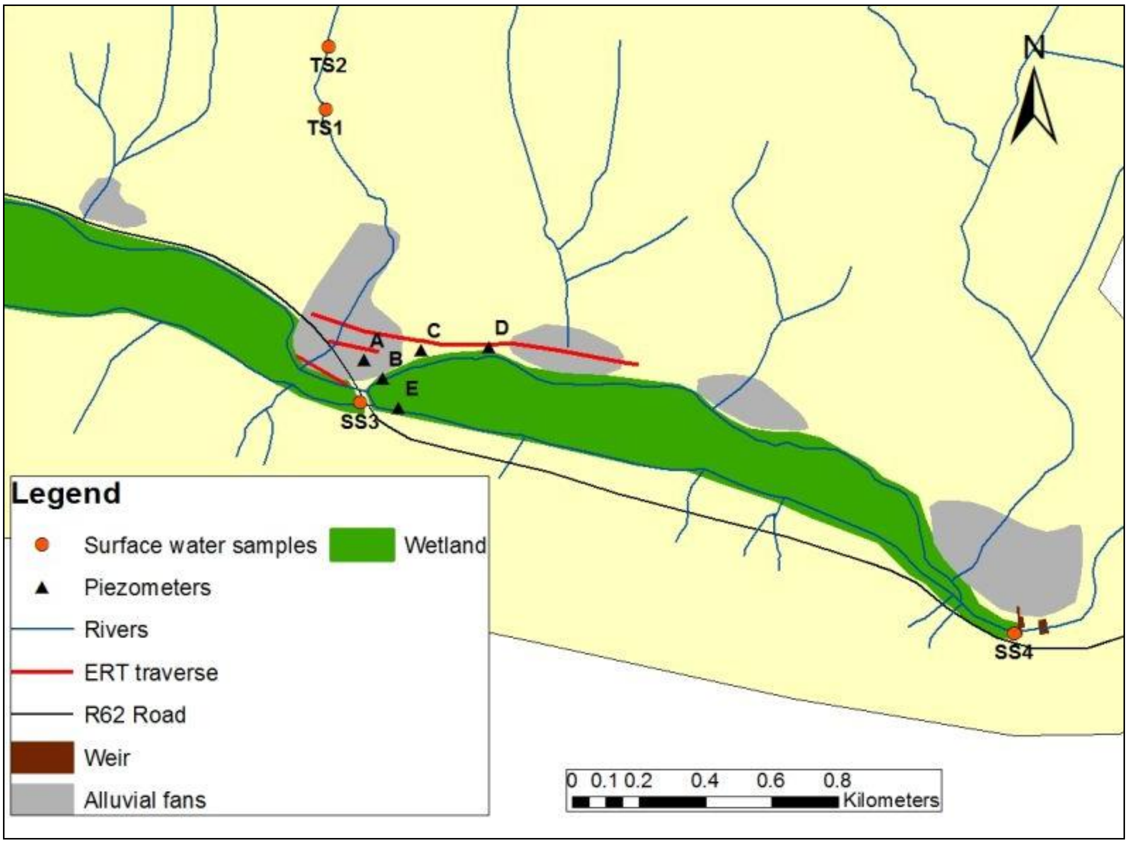


Figure 4.1 Location of piezometers, surface water sampling sites and ERT transects in the vicinity of the Kompanjiesdrif Wetland.

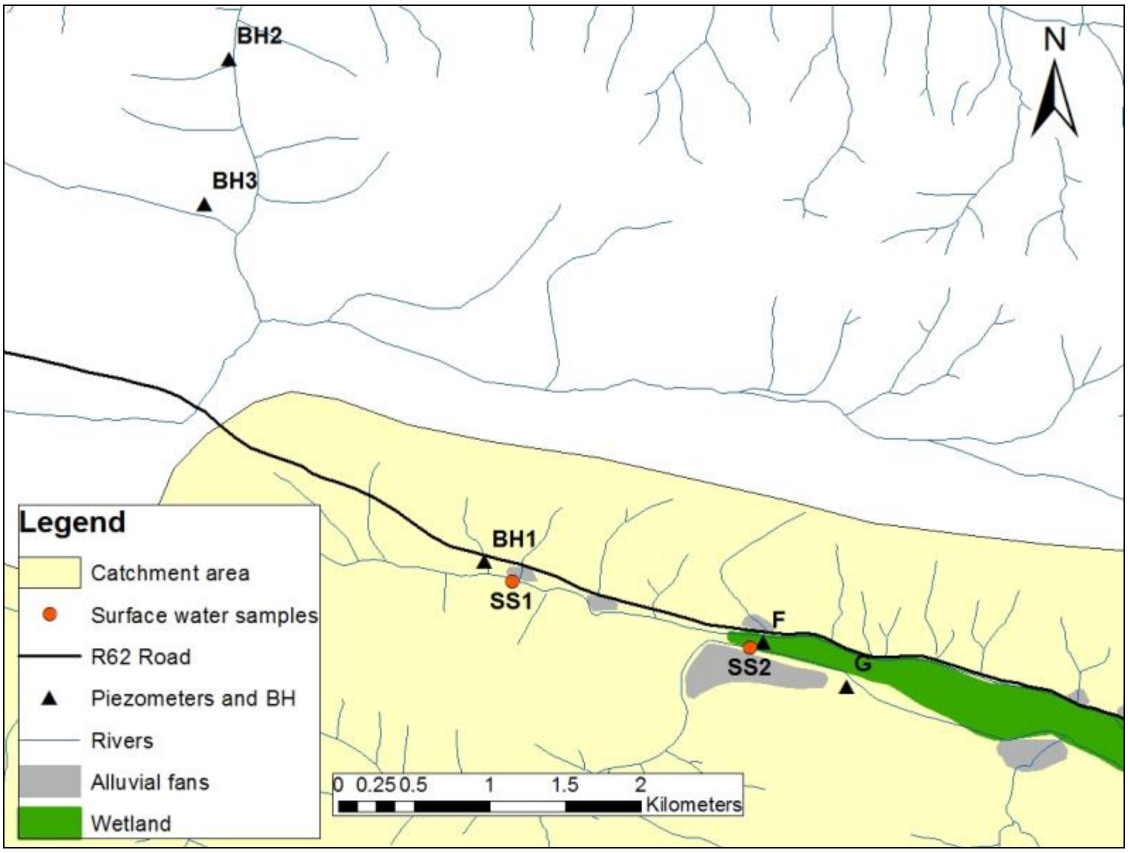


Figure 4.2 Location of piezometers and surface water sampling sites at the Krugersland wetland as well as the borehole upstream of the wetland. Two additional boreholes (BH2 and BH3) located outside the study catchment were also sampled and are illustrated here.

4.1.5 Data loggers in the river

Data loggers were installed in three positions (upstream and downstream of the wetlands) in the Krom River channel to measure changes in water height and assist with developing the rating curve (Figure 4.3). The nature of the river channel (affected by artificial weir and culvert structures) made it difficult to find good locations for installing data loggers. Unfortunately, the data loggers were also above water for large periods of time during the drought in 2017.

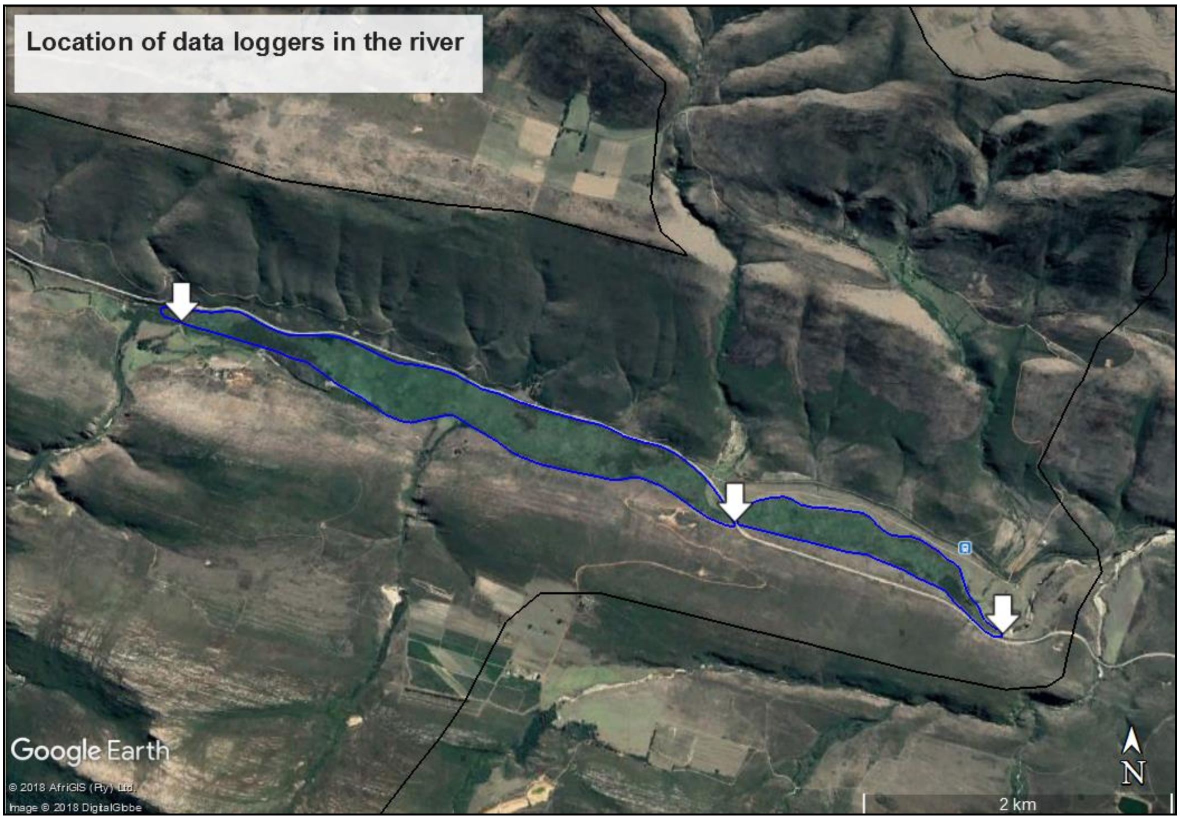


Figure 4.3 Location of data loggers in the river.

4.1.6 Measurement of flow

Flow velocity was measured using a Marsh-McBirney Flo-Mate 2000 in open water (along 'cells') at SS3 and just below SS4 (Figure 4.1). Discharge of each cell was calculated by multiplying the flow velocity by the area (depth x width) of each cell.

Table 4.1 Details of piezometers and boreholes

Piezometer/ borehole	Location (decimal degrees)	Elevation – top of pipe/casing (m.a.s.l.)	Depth of hole (below top of pipe/casing in m)	Comments
A	-33.877281° 24.053235°	359.39	4.25	
B	-33.877793°, 24.053720°	355.60	1.9	
C	-33.877018°, 24.054751°	355.77	4.45	
D	-33.876941° 24.056576°	354.63	4.27	
E - in Kompanjiesdrif wetland	-33.878577° 24.054145°	356.22	4.5	
F – in Krugersland wetland	-33.867201° 24.017502°	391.70	2.98	
G	-33.869800° 24.022436°	380.885	3	
BH1	-33.862396° 24.000902°	422.691	55.55	Appears to be located at the contact between the Baviaanskloof Formation sandstone and Bokkeveld Group shale. Data logger was removed from the borehole by the landowner at the end of January 2017 so that the borehole could be pumped to provide water during the drought.
BH2	-33.832670°, 23.985720°	498	-	Located outside the study catchment within the Peninsula Formation.
BH3	-33.841250°, 23.984270°	518	-	Located outside study catchment within the Peninsula Formation (close or at the Peninsula Formation – Cedarberg shale contact).

Table 4.2 Details of surface water sampling sites.

Surface water samples	Location (decimal degrees)	Comments
River sample 1 (Krom) – upstream of wetlands (SS1)	-33.863561°, 24.002574°	
River sample 2 (Krom) (SS2)	-33.867476° 24.016712°	
River sample 3 (Krom – under R62 bridge) (SS3)	-33.878393°, 24.053147°	No samples were taken during 2017 due to the drought experienced during field visits. Only 1 sample taken during May 2018.
River sample 4 (Krom: bottom of Kompanjiesdrif wetland) (SS4)	-33.884654° 24.070770°	
Tributary of Krom 1 (May 2017) (TS1)	-33.870520° 24.052180°	Both samples are from the same tributary but were collected on different dates. The second sample was also collected slightly higher up in the tributary than the first. Sampling point is located within the Nardouw Sub-group.
Tributary of Krom 2 (May 2018) (TS2)	-33.868820°, 24.052270°	

15th June 2016

2nd February 2017

31st May 2017

11th August 2017

22nd May 2018

Figure 4.4. Illustration of the variation in water levels at the top of the Kompanjiesdrif wetland (underneath the R62 bridge: -33.878420°, 24.053210°). A particularly dry period was experienced in the catchment between February and August 2017.

4.2 Models used

The ultimate purpose of the modelling was to test the hypothesis of palmiet system functioning. The data collection indicated a groundwater contribution to the palmiet wetlands and the models were used to test this hypothesis. The models that were set up for this investigation include the Pitman hydrological model, Groundwater Yield Model for the Reserve (GYMR) and the mixing cell model (MCM). The Pitman hydrological model was set up by Dr Jane Tanner and was used primarily to support the MCM. The GYMR is a groundwater model and was set up to provide an estimate of the groundwater contribution to baseflow and amount of groundwater storage in the entire catchment. Originally it was intended to focus more on hydrological modelling (Pitman), but due to the drought and resulting lack of flow information which meant the GYMR and Pitman models could not be validated, the focus shifted to a MCM which uses hydro-chemical information and traces the movement of water into the wetlands.

4.2.1 The Pitman model

The modified Pitman model was set up by Tanner (pers. comm.) to represent the water balance of the catchment. Although the lack of flow data hindered the calibration and validation of the model, available information (observed flow data from data loggers and Fruitlook wetland evapotranspiration data) was used to constrain the model outputs where possible.

The model is semi-distributed with each sub-catchment containing its own rainfall and evapotranspiration demand time series (potential ET) and its own parameter set used to signify the main hydrological processes. In this investigation, the model was applied in a semi-distributed manner by splitting the upper K90A catchment into linked sub-catchments based on the direction of surface water and groundwater flow. The full details of the model are available in recent publications (Hughes *et al.,* 2006; Hughes, 2013) and the structure of the model is illustrated in Figure 4.5. The full model also includes interception, infiltration, surface runoff and routing components. A wetland sub-model (Hughes *et al.,* 2013) was used to represent the wetlands.

The model was set up using local climate data from a weather station run by Dutoit Agri, located 13 km north of the study site. The weather station measured hourly rainfall, temperature, relative humidity, solar radiation and wind speed and the Penman-Monteith equation was used to produce a time series of potential evapotranspiration (PET).

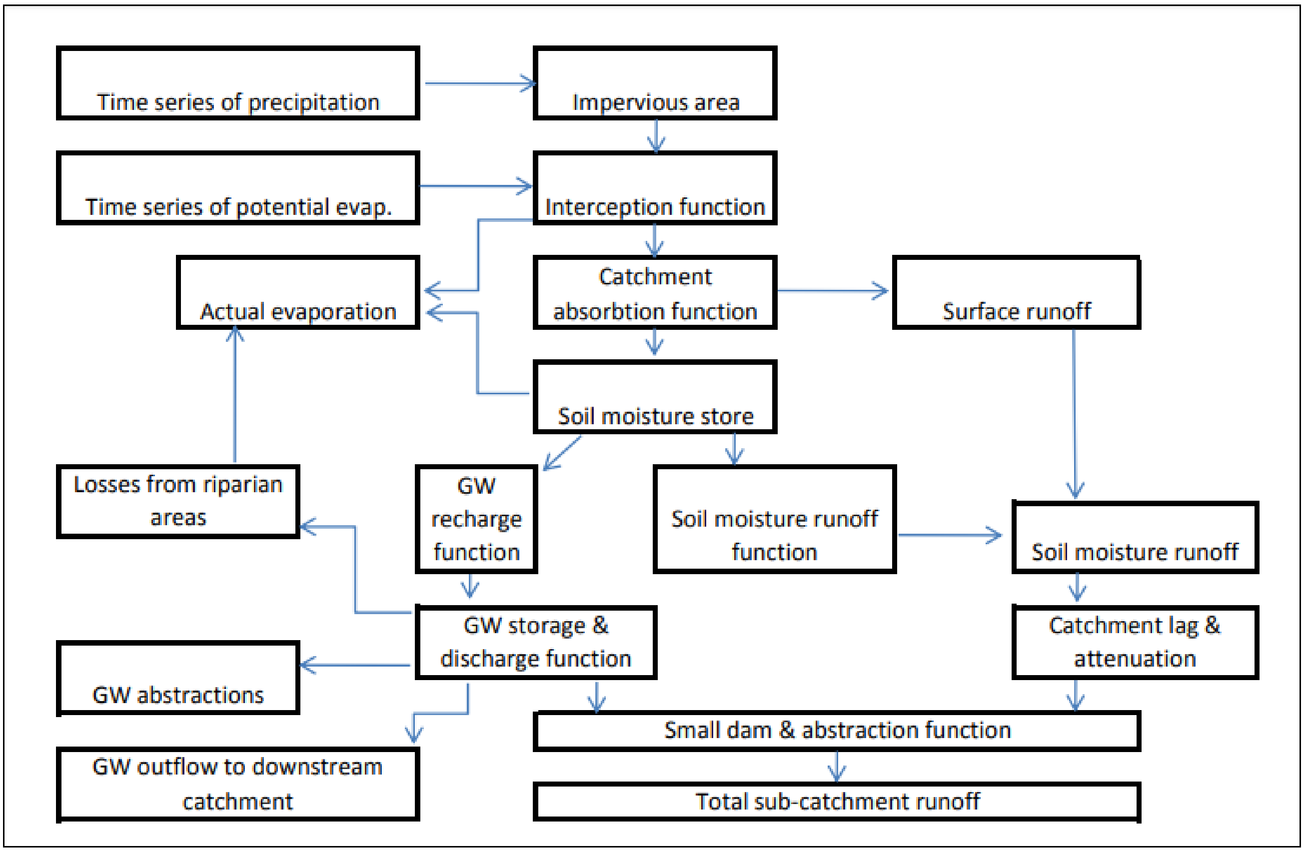


Figure 4.5 Conceptual Pitman model structure (Tanner, 2013).

4.2.2 Groundwater Yield Model for the Reserve (GYMR)

Vivier *et al.* (2007) and Vivier *et al.* (2009) developed an improved model (in Microsoft Excel) for assessing the groundwater component of the reserve. This model is known as the Groundwater Yield Model for the Reserve (GYMR). The GYMR evaluates groundwater potential in terms of yield and takes into account variations in rainfall-recharge and system losses (Vivier *et al*., 2009). This model is specifically developed for determining groundwater reserve determinations for groundwater management. It does not give you the *actual* current groundwater balance but is usually used to determine allocatable groundwater flow balances that aid in groundwater management. The GYMR does not take into account transmissivity of the aquifer, but it does provide an estimate of the groundwater volume in storage (Vivier *et al*., 2009; DWA, 2010). Figure 4.6 illustrates GYMR conceptual model.

The GYMR was used (and adapted) in this investigation to determine the approximate groundwater contribution to river baseflow and approximate groundwater storage volume of the aquifer in the study catchment. Certain parameters in the GYMR were not applicable to this investigation and were thus excluded.

The groundwater balance in the GYMR is defined by the following equation (Vivier *et al.,* 2007; Vivier *et al.,* 2009 and DWA, 2010):

$$\Delta GV_{ST} = Q_R + Q_{DS} - Q_{BH} - Q_{LSF} - Q_{BHN} - Q_{IR} + Q_{IRR} - Q_{MDW} - Q_F - Q_{AVEG} - Q_{WLD} - Q_{RVEG} - Q_{SF} - Q_{GETL} - Q_{GBF} - Q_{EWR}$$

$+GV_{ST}$ = Volume of groundwater in storage (L^3)

$+Q_R$ = Recharge from rainfall ($L.T^{-1}$)[1]

$+Q_{DS}$ = Inflow from dam seepage ($L^3.T^{-1}$)

$-Q_{BH}$ = Abstraction from boreholes for water supply ($L_3.T^-1$)

$-Q_{LSF}$ = Abstraction from boreholes for livestock farming ($L_3.T^-1$)

$-Q_{BHN}$ = Allocation for basic human needs and communities ($L_3.T^-1$)

$-Q_{IR}$ = Abstraction for irrigation ($L_3.T^-1$)

$+Q_{IRR}$ = Return recharge from irrigation ($L_3.T^-1$)

$-Q_{MDW}$ = Mine dewatering ($L_3.T^-1$)

$-Q_F$ = Forestry groundwater use ($L.T^{-1}$)

$-Q_{AVEG}$ = Alien vegetation ($L.T^{-1}$)

$-Q_{WLD}$ = Wetlands fed by groundwater ($L.T^{-1}$)

$-Q_{RVEG}$ = Riparian vegetation ($L.T^{-1}$)

$-Q_{SF}$ = Spring flow ($L_3.T^{-}1$)

$-Q_{GETL}$ = Groundwater flow (ET) losses ($L.T^{-1}$)

$-Q_{GBF}$ = Groundwater base flow ($L_3.T^{-}1$)

$-Q_{EWR}$ = Ecological Water Requirement (component of groundwater baseflow) ($L_3.T^{-}1$)

Where L = length and T= time

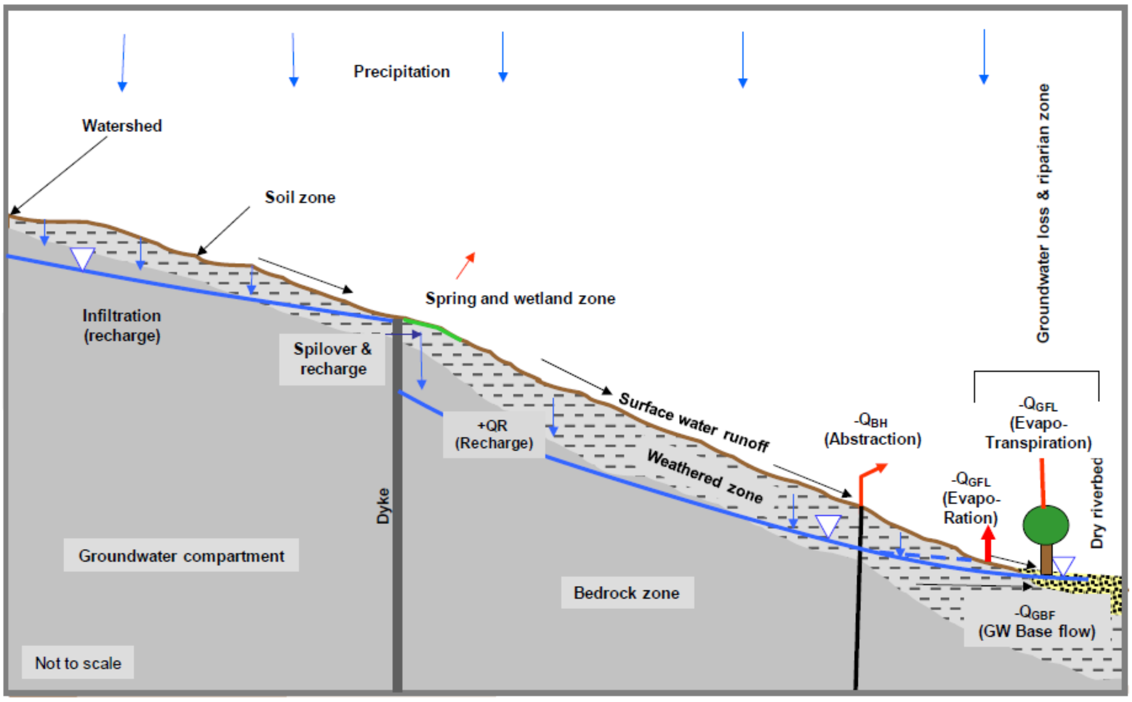


Figure 4.6 Illustration of the GYMR conceptual model that includes flow losses (DWA, 2010).

Set up of model

The components that were relevant in this investigation include GV_{ST}, Q_R, Q_{BH}, Q_{AVEG}, Q_{RVEG}, Q_{GETL} and Q_{GBF}. The main model input data and sources of data used in the Krom catchment investigation are described in Table 4.3.

Table 4.3 GYMR model data inputs and sources of data.

No	Model data input	Source and assumptions
1	Catchment area	The study catchment was manually delineated and the surface area was measured in ArcGIS.
2	Geology	Geological units were sourced from the 1:250 000 geological map and geological unit surface areas were measured in ArcGIS.
3	Recharge (% of rainfall) per geological unit	Source: DWS (2015). Conservative estimates were taken from this study which was located in the same geology (TMG and Bokkeveld). See table 4.4.
4	Specific yield (used in the estimation of the volume of groundwater in storage)	Source: Jia (2007), DWS (2015).
5	Storativity (used in the estimation of the volume of groundwater in storage)	Source: Jia (2007), DWS (2015).
6	Aquifer thickness of the weathered and fractured zone	Source: GRA2 GIS maps (WR2012).
7	Monthly precipitation	Data obtained from Dutoit Agri (Pty) Ltd at Twee Riviere – located approximately 13 km from the study area.
8	Monthly evaporation	Potential evapotranspiration data obtained from Dutoit Agri (Pty) Ltd – located approximately 13 km from the study area.
9	Monthly river flow	Modelled Pitman river flow data for the study catchment (Tanner, pers. comm.).
10	Abstraction volumes from boreholes and springs	DWS WARMS data (estimate).
11	Water loss due to riparian vegetation and alien vegetation	Surface areas of riparian vegetation and upland alien vegetation areas were measured in ArcGIS. ET rates for alien vegetation were estimated using rates in Dye *et al.* (2001) and Meijninger and Jarmain (2014).

Table 4.4 Recharge (% of rainfall) assigned per geological unit (DWS, 2015).

Recharge Geology 1- Alluvium (% of rainfall)	Recharge Geology 2- Grahamstown gravels (% of rainfall)	Recharge Geology 3- Bokkeveld shale (% of rainfall)	Recharge Geology 4- Nardouw Sub-group (% of rainfall)	Recharge Geology 5- Cedarberg shale (% of rainfall)	Recharge Geology 6- Peninsula Formation (% of rainfall)
5.00%	2.00%	2.00%	3.50%	2.00%	5.00%

The groundwater storage volume of the aquifer in the study catchment was estimated using the following calculation:

(Aquifer thickness of weathered zone x total surface area of the catchment x specific yield) + (Aquifer thickness of fractured zone x total surface area of the catchment x storativity).

4.2.3 Mixing cell model

Mixing cell models in hydrological modelling

Mixing models have been used to model hydrological systems successfully by various authors including Robson and Neal (1990), Harrington *et al*. (1999), Liu *et al.* (2004), Partington *et al.* (2011), and Wilson (2015) and can be used to estimate the groundwater component of baseflow in a river. This has been demonstrated by Matthews (2013) who made use of a mixing cell model (MCM) developed by Adar (1984) to quantify the groundwater component of baseflow at a test site along the Modder River in Bloemfontein as well as in quaternary catchments A42A, A42B and A42C in Limpopo and quaternary catchment D73F in the Northern Cape, South Africa.

The mixing cell concept

In a mixing cell model, the flow of mass in a system is modelled by separating the system into a number of mixing cells and then formulating a mathematical algorithm to describe flow into, out of and within the cells (Campana, 1975). The basic principle of the mixing cell model is that the volume of inflow into a system will equal the volume of outflow for the relevant time step (Figure 4.7). A water balance equation is applied to each cell and a tracer concentration (for example dissolved chemicals, stable isotope ratios, and electrical conductivity) is required for each inflow included in the water balance (as well as for the cell itself). Chemical mass balance equations are developed for each cell using the available tracer data and these mass balance equations aid in restricting the water balance equation to yield more accurate estimates of the unknown inflows into the system (in comparison to estimates developed using only a water balance equation) (Matthews, 2013).

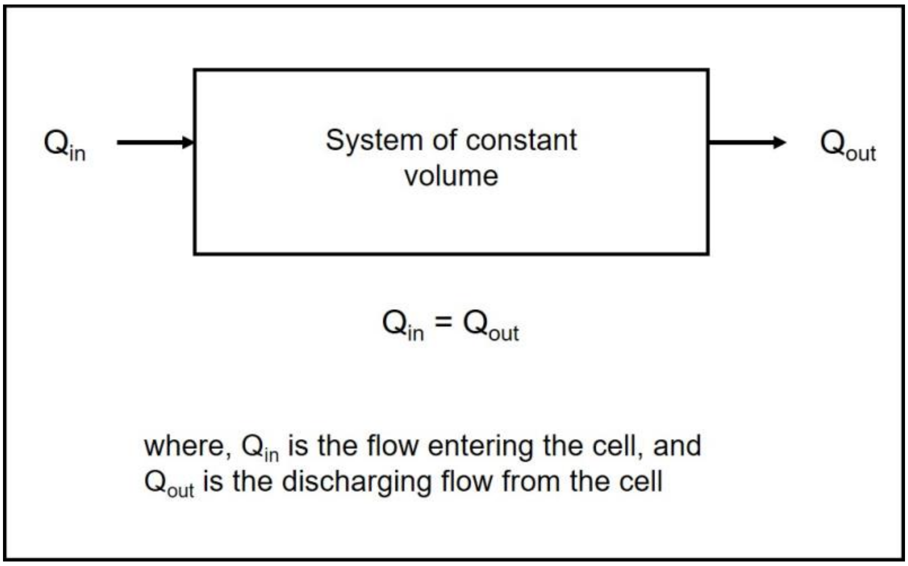


Figure 4.7 Illustration of the mixing cell model concept (adapted from Matthews, 2013).

The mixing cell model (MCM) developed by Adar (1984) and utilised by Matthews (2013) has been applied to this study area to quantify the quantity of groundwater (and other inflows) entering and sustaining the palmiet wetlands.

Methodology and brief mathematical description

Adar and Kuells (n.d.) developed software for running a mixing cell model in Excel for a steady flow system. The model makes use of a Mixing Input Generator (MIG) that runs within Excel. The software is downloadable for free from http://www.uhydro.de/hywa/en/models/compartmentmodels? Examples and a short manual are also provided on the website.

An updated MCM code and manual were provided by Prof. Eilon Adar (of Ben-Gurion University of the Negev) for the purposes of this study. The brief description of one of the typical mass balance equations used is provided below and is taken from this manual as well as from Adar (1996). For a more detailed description and further mass balance equations used in the model refer to the abovementioned manual.

A set of mass balance equations for the water and solute is written for each cell over a given time period. For a simple flow model of water (constant density) the mass balance equation for a cell n is written as:

$$Q_n - W_n + \sum_{i=1}^{I_n} q_{in} - \sum_{j=1}^{J_n} q_{nj} = S_n^{*} \frac{dh_n}{dt}$$

Where,

Q_n = Flow sources into cell *n*,

q_{in} = flow from the upstream i^{th} into the n^{th} cell,

q_{nj} = outflow from the n^{th} cell into the j^{th} cell,

W_n = abstraction from cell n,

S_n = storage capacity in cell n,

h_n = hydraulic head related to that compartment,

I_n and J_n = number of sources and cells from which flow enters and leaves the n^{th} cell

Figure 4.8 illustrates these flow parameters in a compartmental system.

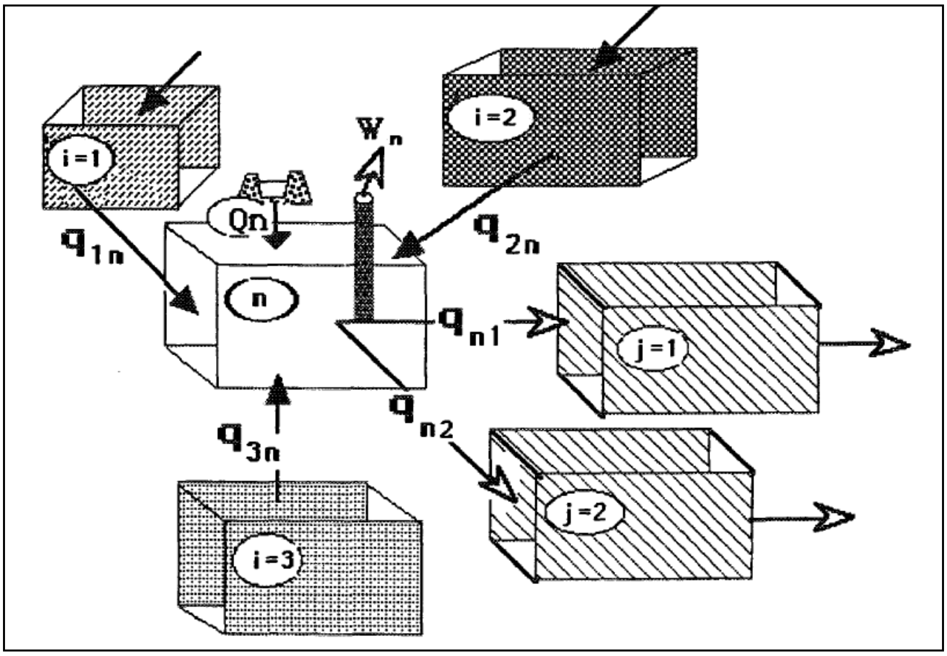


Figure 4.8 Illustration of the various flow parameters used in the MCM (Adar, 1996). (q=unknown flows, i and j = direction of flow, Q_n = known inflow into the cell and W= known outflow from the cell).

Set up of model

Unlike the GYMR (catchment scale), the MCM was set up at a smaller (wetland-specific) scale and only for one month (sufficient water quality data was only available for one month). The MCM created by Adar (1984) and originally designed for determining multiple inflow sources into an aquifer(s) (by dividing these aquifers into separate MCM cells) was adapted here in order to determine the quantity of groundwater inflows into the palmiet wetlands. The two palmiet wetlands were thus defined as 'wetland cells' with various unknown inflows (groundwater and surface water) contributing to them.

The MCM could not be set up for 2017 as water quality data was unavailable for certain key sampling points due to the drought. A 'single cell' and a 'two cell' MCM were set up for May 2018 (using tracer data collected on 22 May 2018). Although the catchment was generally wetter over this period, compared to previous field trips, no significant rainfall was experienced in the catchment immediately prior to and during the sampling period (Figure 4.9).

It was decided to first set up a single cell model for the Kompanjiesdrif wetland as this wetland had the most data and in the MCM manual it is recommended that a single cell model is used as a preliminary assessment before a more complex multi-cell model is set up (Adar and Kuells, n.d.).

The MCM requires an outflow volume and there is no flow gauge at the outflow point of the study catchment, but a data logger (that measures changes in water height) was installed in the river at the outflow of the catchment for a limited period of time.

The Pitman wetland sub-model was set up to represent the wetlands as sensibly as possible although, without adequate catchment outflow data, it was not possible to identify key hydrological information regarding wetland hydrological behaviour. It was not straightforward to determine the spill relationship (the release of water from the wetland) without observed data (Tanner, pers. comm.). The Pitman model appeared to underestimate the spill at the outflow point of the wetlands during May 2018 (based on field observations). The outflow volume used in the MCM for May 2018 was thus estimated by using the available rating curve data (created using limited data from the downstream data logger, at SS4, by Tanner, pers. comm.) over 2016 and 2017.

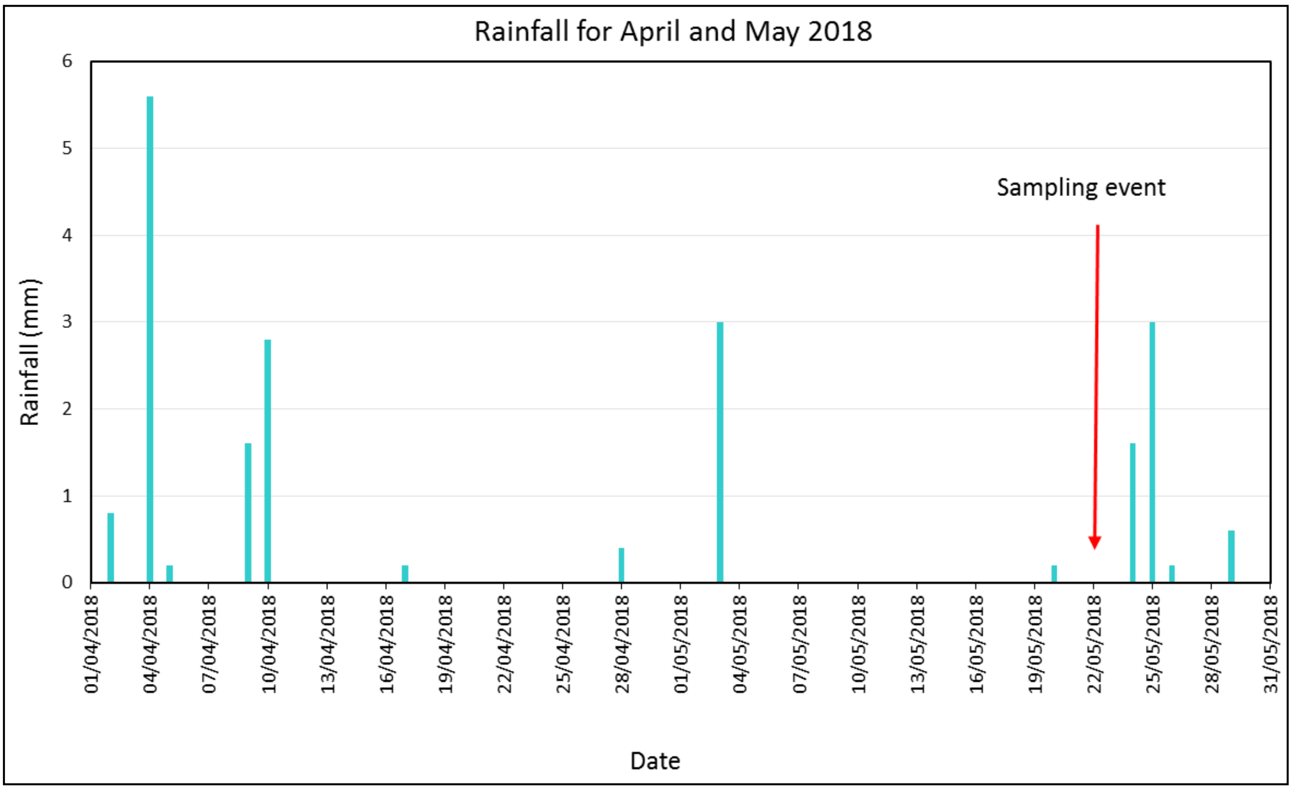


Figure 4.9 Rainfall in the study catchment over April and May 2018 (from a weather station located 13 km north of the study site).

Single cell

The downstream Kompanjiesdrif wetland was defined as the ‘wetland cell’ in the single cell model set up (Figure 4.10). The MCM software requires at least two mixing cells and so a fictitious wetland cell with exactly the same water quality data as the first cell was created (as per examples in the MCM manual). The chemistry of the wetland cell was defined using tracer concentrations obtained from the outflow point of the wetland. Inflow into the wetland was defined by tracer concentrations of the outflow point of the upstream wetland (Krugersland wetland). Tributary inflow into the wetland was defined by the tracer concentration of the main nearby large tributary that flows into the Kompanjiesdrif wetland. Groundwater inflow into the wetland was defined separately by the tracer concentrations of BH1, BH2, and BH3. Even though BH2 and BH3 are located outside the study catchment, they are considered to be representative of the groundwater chemistry in the study area due to their location in the same geology (Peninsula Formation). ‘Shallow sub-surface inflow’ into the wetland was defined by the tracer concentration of piezometer A. An evapotranspiration loss volume (modelled in Pitman) for the wetland was included as an ‘outflow’ volume from the wetland cell. All tracers were given an equal weighting for the model run.

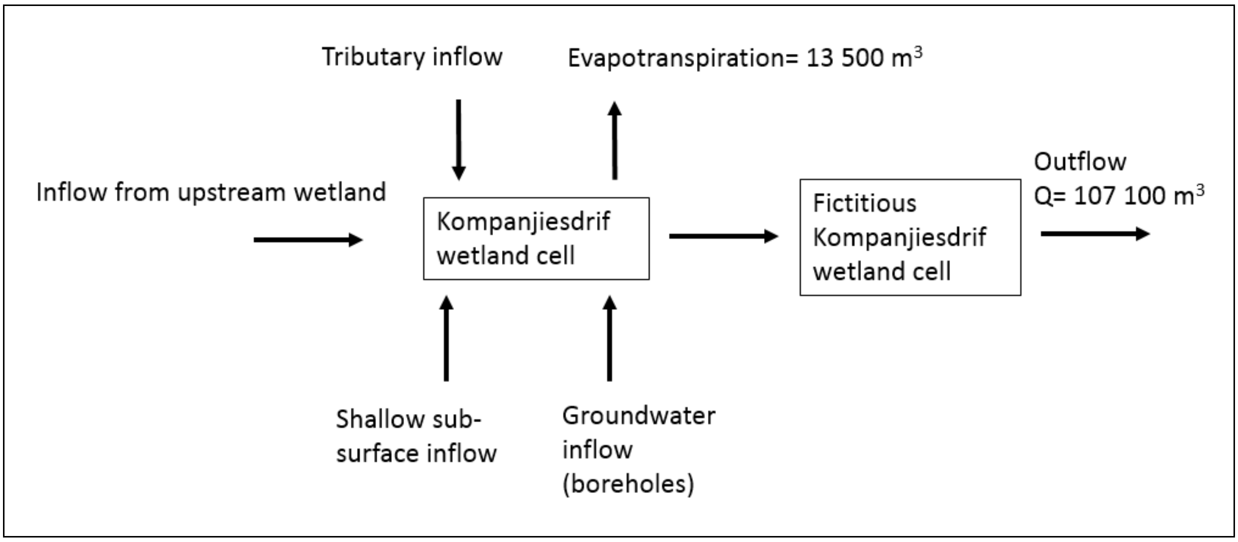


Figure 4.10 Single cell model set up for the Kompanjiesdrif wetland in May 2018.

Two cell

In the two cell model set up the Krugersland wetland was defined as the first wetland cell (upstream) and the Kompanjiesdrif wetland was defined as the second wetland cell (downstream wetland) (Figure 4.11). The chemistry of each of these wetland cells was defined using the tracer concentrations of their outflow points. Tributary inflow into the wetlands was defined using the tracer concentration of one of the main tributaries that enter the Kompanjiesdrif wetland (this tributary was also used as an inflow to the Krugersland wetland as it was considered to be generally representative of the chemistry of the tributaries in the catchment). Groundwater inflow into the wetlands was defined by the tracer concentrations of BH1, BH2, and BH3 separately.

‘Shallow sub-surface inflow’ (defined by piezometers) was excluded from the two cell model as in initial model set-ups and model runs no inflow volume was yielded from the piezometers. All tracers were given an equal weighting for the model run. An evapotranspiration loss volume was included as outflow volumes from each wetland.

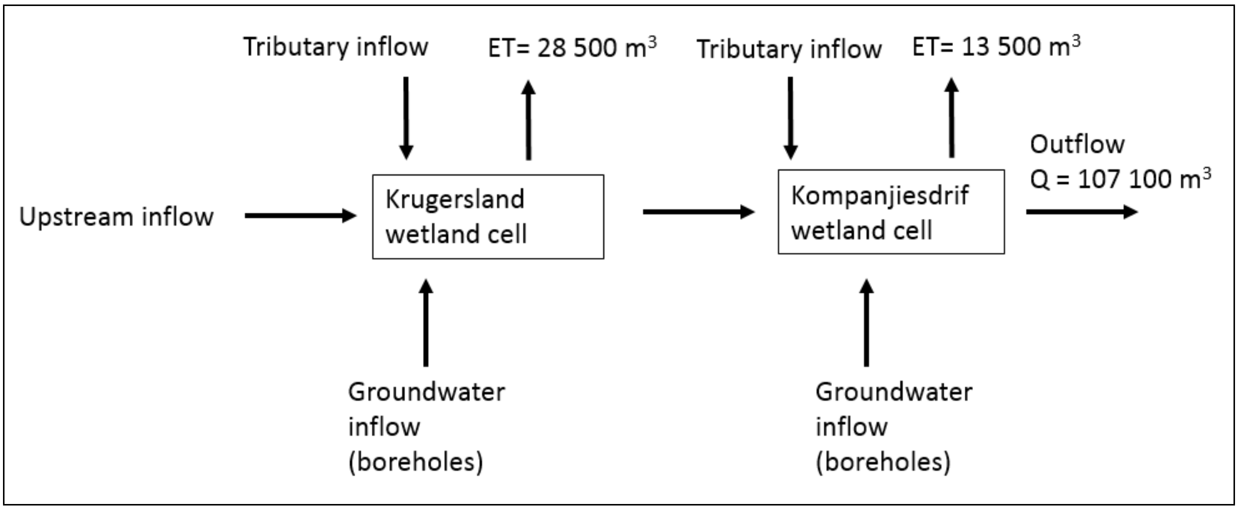


Figure 4.11 Two cell model set up for the Krugersland and Kompanjiesdrif wetlands in May 2018.

Abstraction/loss volumes other than ET were excluded from the set-up of the MCM (as other abstraction/loss volumes from the wetland cells are uncertain). Tracers used in the model (from water samples collected in May 2018) are illustrated in Table 4.5.

Table 4.5 Tracers used in the mixing cell model (units in pH units, µS/cm, mg/l and $^{0}/_{00}$).

Unknown inflow or cell	pH	EC	Mg	Ca	K	Cl	Si	Al	δD	δ^{18}O
Inflow into the Krugersland wetland	6.34	124.00	3.00	0.00	0.60	42.30	2.63	0.00	-23.09	-5.24
BH1 (groundwater)	6.21	1149.00	27.00	13.60	3.30	298.00	12.66	0.05	-33.74	-6.21
Tributary	6.37	419.00	10.00	6.00	1.80	140.00	4.03	0.38	-30.72	-6.21
Wetland 1 cell (Krugersland)	6.46	169.40	5.00	0.80	0.40	47.10	5.63	0.03	-19.90	-4.69
Wetland 2 cell (Kompanjiesdrif)	7.38	212.30	7.00	0.80	1.00	78.40	5.63	0.02	-21.25	-4.88
Wetland 2 cell (Fictitious cell)	7.38	212.30	7.00	0.80	1.00	78.40	5.63	0.02	-21.25	-4.88
PZA	6.05	955.00	47.00	23.60	6.90	315.00	15.95	1.10	-28.57	-5.76
BH2 (groundwater)	5.46	174.00	5.00	0.00	0.00	61.20	3.94	0.00	-33.95	-6.74
BH3 (groundwater)	5.92	258.00	9.00	1.20	2.80	76.20	9.38	0.00	-37.19	-6.89

4.3 Water use of palmiet

ET is a key component of a wetland's water budget. Many riparian landowners consider palmiet to be a high-water user (Rebelo, 2012), but there is limited data on the water use of palmiet. The water use of palmiet formed a minor component of this project and was investigated in order to quantify the role of ET in the hydrology of palmiet wetland systems, compare the results with available literature and contribute to the general scientific understanding of these wetland systems.

The water use of palmiet was investigated by obtaining ET estimates for palmiet at the Krom River study site and at other locations in the Western Cape (Figure 4.12). The following data sources were used:

- Fruitlook (www.fruitlook.co.za) – Fruitlook calculates ET using the 'ETLook' algorithm (Pelgrum *et al*., 2012) and has a pixel size range of <30 to 250m (Jarmain *et al*., 2014);
- Moderate Resolution Imaging Spectroradiometer - MODIS (MOD16A2: https://search.earthdata.nasa.gov/search) with a pixel size of 500m.

The Pitman hydrological model is a water balance model that uses a time series of potential ET and available water to estimate actual ET. Modelled Pitman ET data (Tanner, pers. comm.) was compared with Fruitlook and MODIS data.

Daily scintillometer data (unpublished) was provided by Dr Caren Jarmain for the Helderstroom palmiet wetland (along Riviersonderend River in the Western Cape) which was measured over a brief period in October 2008. This daily ET data was compared with MODIS ET data for this wetland over the same period.

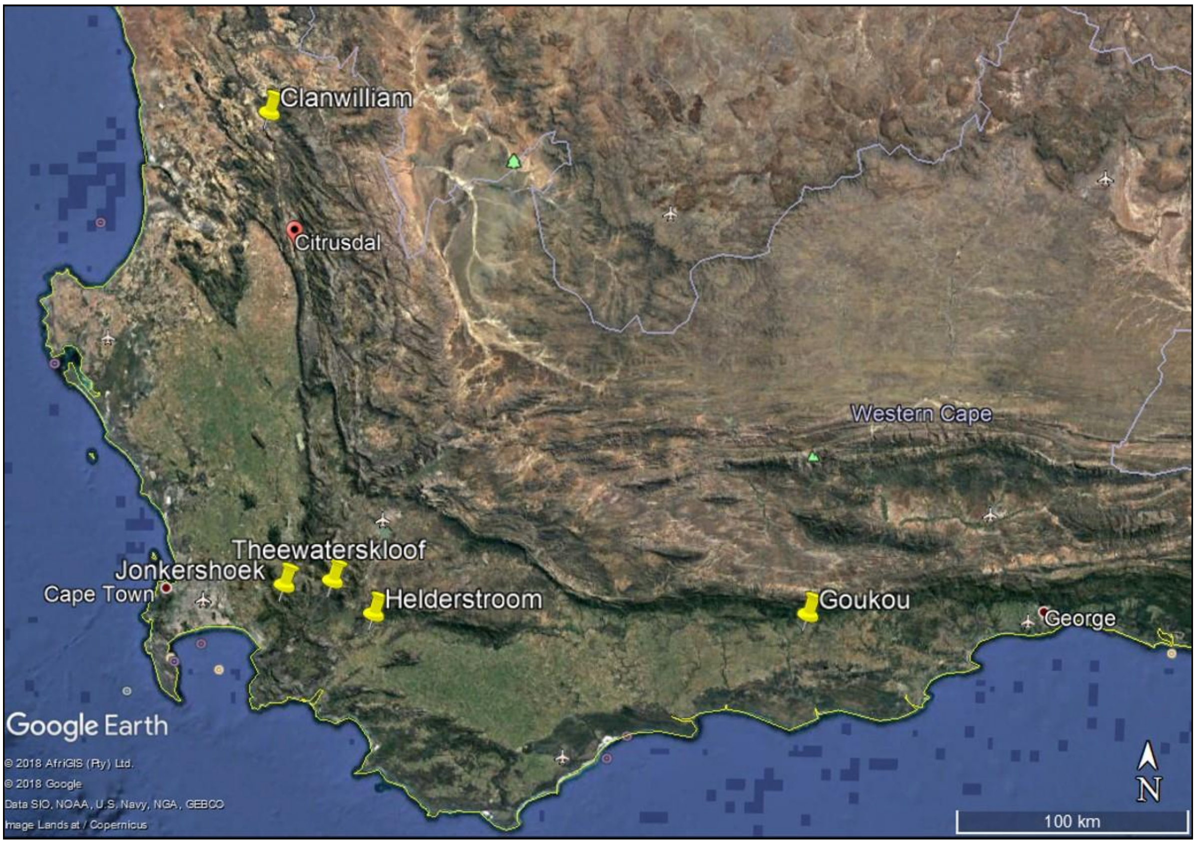


Figure 4.12 Location of palmiet wetlands in the Western Cape, South Africa. Goukou wetland is within the H90A and H90C catchment, Helderstroom wetland is within the H60D catchment, Theewaterskloof wetland is within the H60B catchment, Jonkershoek wetland is within the G22F catchment and the Clanwilliam wetland is within the E10J catchment.

5 RESULTS

5.1 Results of data collection

5.1.1 Surface and sub-surface water levels

The surface (where available and measured) and sub-surface water levels for the period between June 2016 and May 2018 are illustrated in Figures 5.1, 5.4 and 5.5. There has been a decline in rainfall in the study area since August 2016 and the area experienced a severe drought in 2017. This is also reflected in the decline in elevation of the surface and sub-surface water levels. Manual dip readings taken in piezometers A-D and the borehole (BH1), in June 2016 and at the end of January 2017, indicated an average drop in sub-surface water level of between 0.5 and 0.7 m. Dip readings of all holes (A-G and borehole) in May 2017 indicated a further drop in water levels since January 2017 of between 0.4 and 0.7 m. Water levels had dropped even further (average of 0.3 m) in August 2017. This equates to an average drop in water level in the piezometers of about 1.4 m over the period between June 2016 and August 2017. Piezometer B (edge of Kompanjiesdrif wetland) and F (in Krugersland wetland) were dry in May 2017 and August 2017.

Manual dip readings taken in May 2018 indicated that sub-surface water levels had increased by an average of about 0.8 m since August 2017. Most water levels measured in May 2018 were, however, still lower than initial readings taken when field work began in June 2016.

The water level of the borehole (BH1) was at 407.19 m.a.s.l. in May 2018 (compared to 409.67 m.a.s.l. in June 2016 when the study began). The borehole had not been pumped for 6 months prior to this water level measurement. The farmer indicated that he had ceased pumping from this borehole due to the salty water affecting his equipment (indicating that the groundwater is moving through or in contact with shale-rich rock).

A floodplain cross-section was surveyed using a DGPS running from BH1 (north) and across the river channel below it (south) in May 2017 (Figure 5.2 and 5.3). The cross-section illustrates the change in water level in the borehole over various months. The reading taken in May 2017 would have been affected by pumping of the borehole which took place during that month. It is evident that the borehole level is lower than the adjacent river channel in the months that it was monitored which indicates that it is unlikely that the river at this point is receiving much diffuse groundwater input from the aquifer. The borehole was monitored during a predominantly dry period though and its level in relation to the river channel could change during much wetter periods. Also illustrated in Figure 5.2 is the surveyed downstream water level in the river channel in May 2017.

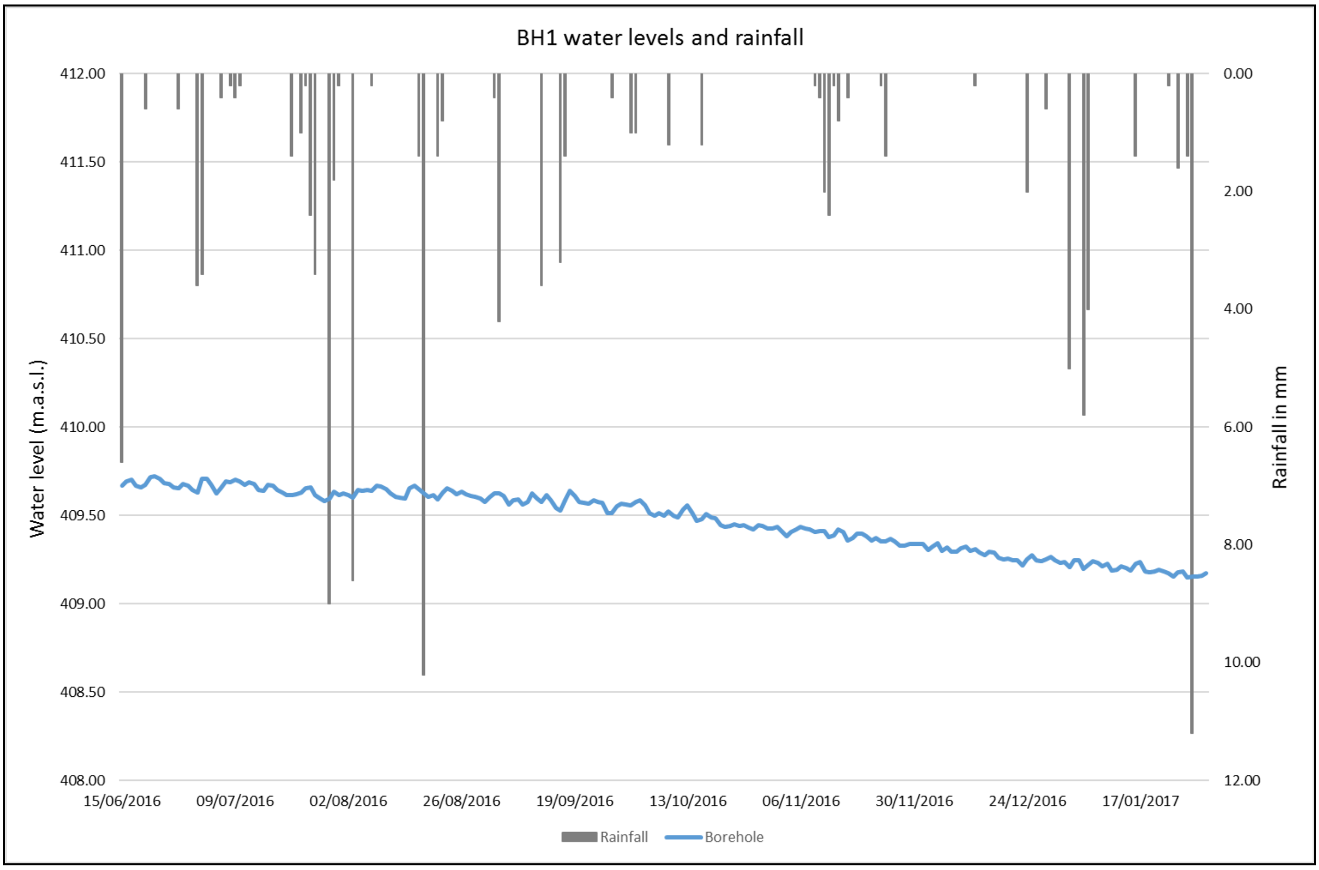


Figure 5.1 BH1 water levels between June 2016 and January 2017 (water levels ceased to be measured by a data logger in January 2017 due to the start of pumping of the borehole by the farmer).

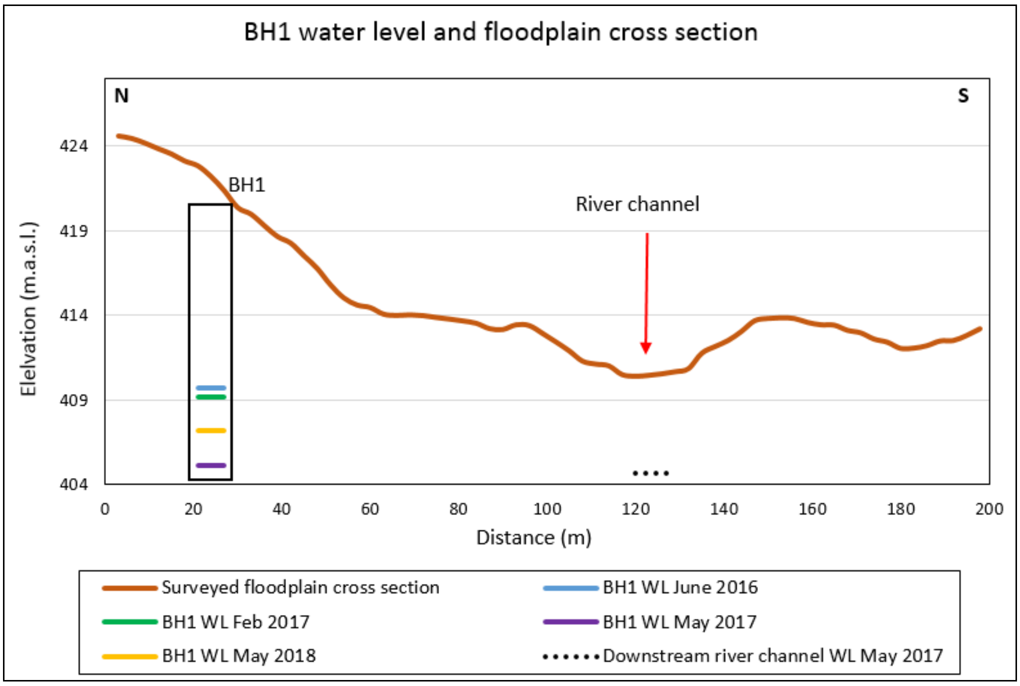


Figure 5.2 Illustration of the surveyed floodplain cross section completed in May 2017 with the location of BH1 and the river channel from north to south illustrated. BH1 water levels over various months are also illustrated. The May 2017 borehole level is probably slightly lower than it would be naturally due to borehole pumping by the farmer which took place that month. Also illustrated is the water level of the river channel in May 2017 (the dotted line) which is located 200 m downstream of the borehole (at SS1). The location of the surveyed cross section is illustrated in Figure 5.3.

Figure 5.3 Location of the surveyed cross section (illustrated by a white line) and downstream surveyed water level measurement (SS1) in May 2017.

Interestingly the surface water elevation at SS3 (Figure 5.4) is higher than the water elevation of PZA (in June 2016 and May 2018) and the water elevation of PZE (in the wetland), which is located about 80 m downstream of SS3 (Figure 4.1 and 4.4 in section 4.1). The higher water level at SS3 compared to PZE and PZA is understandable considering the steep longitudinal slope of the Kompanjiesdrif wetland (Figure 3.6 in section 3.4) and the fact that SS3 is situated between two large bridge pylons in a ‘pool’ type environment (raising the water level) where the water flows slowly into the wetland.

The surface water at SS2 has remained quite shallow and the water level has remained relatively constant throughout the study period (Figure 5.5).

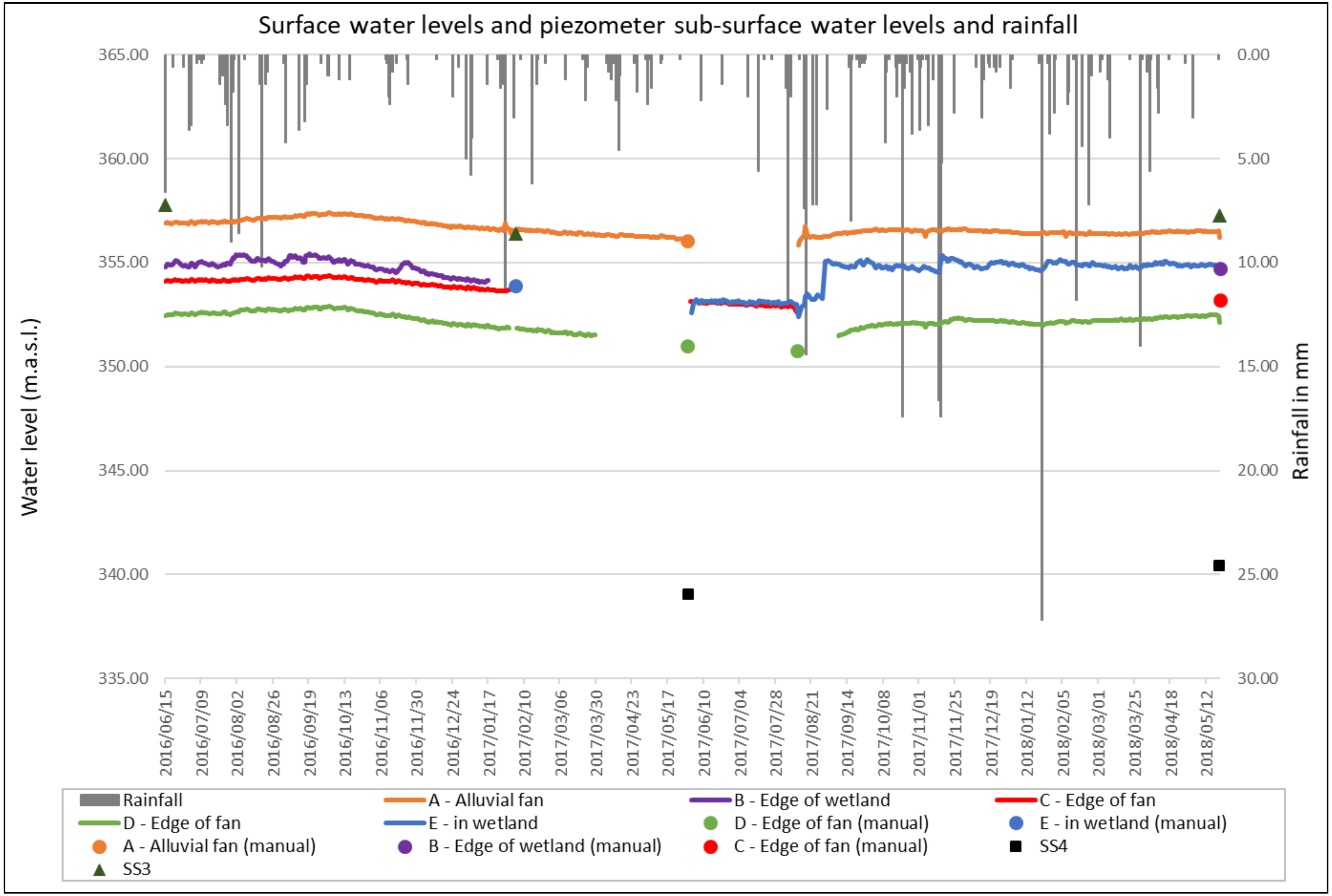


Figure 5.4 Surface and sub-surface water levels at Kompanjiesdrif. Piezometer water level measurements taken using a data logger. Manual piezometer readings taken with a dip metre are illustrated as dots.

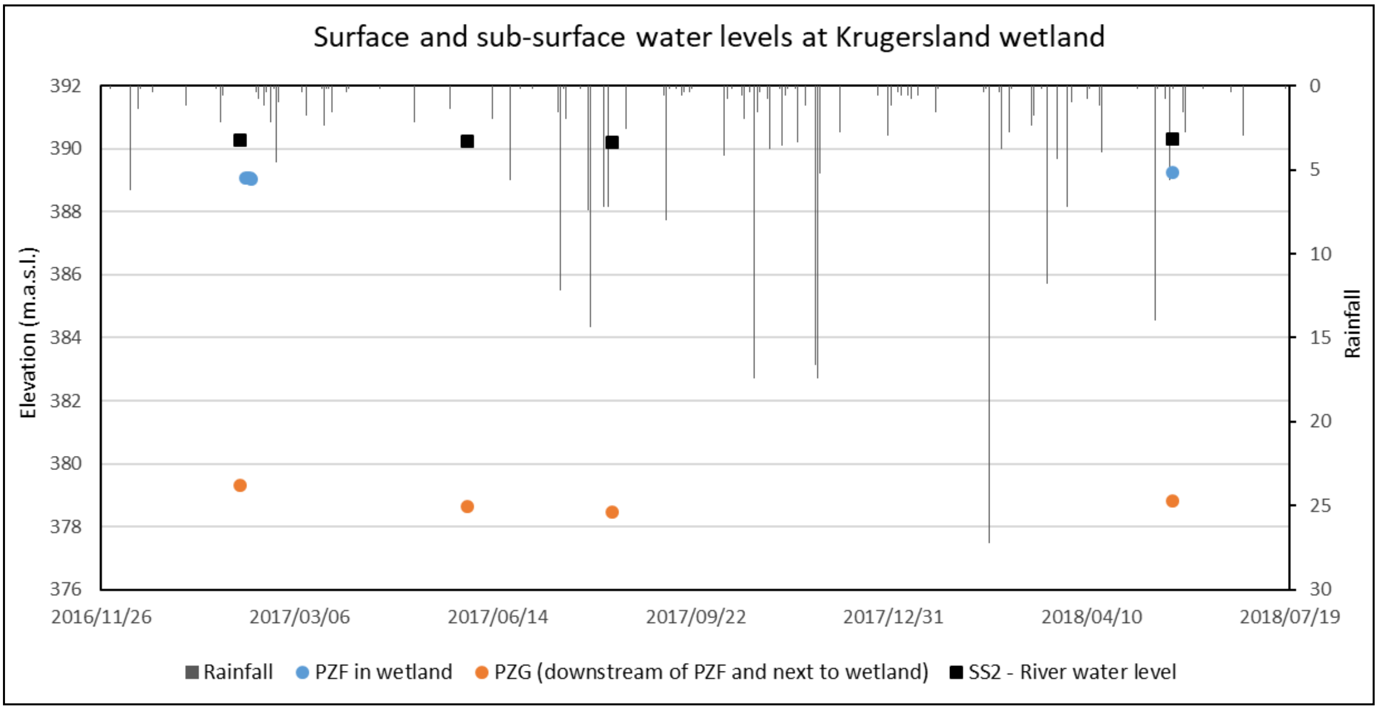


Figure 5.5 Surface and sub-surface manual water level measurements at the Krugersland wetland. PZF was dry when it was measured in May and August 2017.

5.1.2 Flow measurements

Flow velocity was measured under the Kompanjiesdrif bridge (between the Krugersland and Kompanjiesdrif wetlands) and converted to discharge (in m^3s^{-1}). The measurements for 21 May 2018 and 16 June 2016 are provided in Table 5.1 and Table 5.2. Despite the relatively deep water level, the flow velocities were either zero or very low. This illustrates the slow rate of movement of water between the wetlands and the attenuation of flow carried out by the wetlands.

The measurements taken in June 2016 were over a longer cross-section than in May 2018 due to higher water levels.

Table 5.1 Flow measurements at the top of the Kompanjiesdrif wetland in May 2018.

	Distance	*Cell width*	*Total depth*	*Flow velocity*	*Discharge*
	(m)	**(m)**	**(m)**	**(m/s)**	**(m^3s^{-1})**
1	0.5	0.5	0.33	0	0
2	1	0.5	0.79	0	0
3	1.5	0.5	0.76	0	0
4	2	0.5	0.81	0.02	0.008
5	2.5	0.5	0.89	0	0
6	3	0.5	0.91	0.01	0.005
7	2.5	0.5	0.98	0	0
8	4	0.5	1.02	0.01	0.005
9	4.5	0.5	1.12	0	0
10	5	0.5	1.04	0	0
11	5.5	0.5	0.98	0	0
Total					0.018

Table 5.2 Flow measurements at the top of the Kompanjiesdrif wetland in June 2016.

	Distance	*Cell width*	*Total depth*	*Flow velocity*	*Discharge*
	(m)	**(m)**	**(m)**	**(m/s)**	**(m^3s^{-1})**
1	1	0.5	0.32	0.01	0.002
2	1.5	0.5	0.45	0	0
3	2	0.5	0.56	0.01	0.003
4	2.5	0.5	0.58	0	0
5	3	0.5	0.665	0.01	0.003
6	3.5	0.5	0.67	0	0
7	4	0.5	0.91	0	0
8	4.5	0.5	0.9	0	0
9	5	0.5	0.63	0.01	0.003
10	5.5	0.5	0.69	0	0
11	6	0.5	0.67	0	0
12	6.5	0.5	0.83	0	0
13	7	0.5	0.96	0	0
14	7.5	0.5	1.07	0	0
15	8	0.5	1.16	0	0
16	8.5	0.5	1.23	0	0
17	9	0.5	1.19	0	0
18	9.5	0.5	1.17	0	0
19	10	0.5	1.2	0	0
20	10.5	0.5	1.17	0.01	0.006
21	11	0.5	1.08	0	0
22	11.5	0.5	1.01	0	0
23	12	0.5	0.91	0	0
24	12.5	0.5	0.78	0	0
25	13	0.5	0.85	0	0
26	13.5	0.5	0.74	0	0
27	14	0.5	0.21	0	0
28	14.5	0.5	0.19	0	0
29	15	0.5	0.32	0	0
Total					0.017

Table 5.3 illustrates very slightly higher flow rates that were measured in the river channel 130 m downstream of the Kompanjiesdrif wetland. These were measured on 14 June 2016 in shallower water than the upstream measurements.

Table 5.3 Flow measurements taken downstream of the Kompanjiesdrif wetland in June 2016 (GPS coordinates: -33.88406232, 24.07275052).

	Distance	***Cell width***	***Total depth***	***Flow***	***Discharge***
	(m)	**(m)**	**(m)**	**(m/s)**	**(m^3s^{-1})**
1	0.3	0.3	0.06	0.02	0.000
2	0.6	0.3	0.15	0.02	0.001
3	0.9	0.3	0.16	0.02	0.001
4	1.2	0.3	0.20	0.01	0.001
5	1.5	0.3	0.18	0.02	0.001
6	1.8	0.3	0.07	0.01	0.000
7	2.1	0.3	0.06	0.01	0.000
8	2.4	0.3	0.11	0.04	0.001
9	2.7	0.3	0.15	0.15	0.007
10	3	0.3	0.16	0.15	0.007
11	3.3	0.3	0.17	0.2	0.010
12	3.6	0.3	0.19	0.11	0.006
13	3.9	0.3	0.17	0.06	0.003
14	4.2	0.3	0.16	0.06	0.003
15	4.5	0.5	0.1	0.02	0.001
Total					0.042

5.1.3 Electrical Resistivity Tomography Survey

Amaya *et al.* (2016) highlight the effectiveness of using ERT surveys for mapping aquifer systems in alluvial fans. The ERT survey conducted at the Kompanjiesdrif wetland indicates a distinct increase in resistivity along the alluvial fans (red, purple, orange areas) with lower resistivities between the fans (Figure 5.6 and 5.7). This confirms the likelihood of the presence of distinct preferential sub-surface flow paths through the alluvial fan material to the wetland.

The material between the fans, with a lower resistivity, appears to be a combination of shale, silt, and clayey material. The resistivities shown are consistent with those described for these geological materials by Palacky (1988). The survey also indicates that Piezometer D is located within the lower resistivity material (shale, clay, silt). Only Piezometer D was located close to the ERT transect during the survey. Similar ERT profiles and resistivity values across alluvial fan environments are described by Giocoli *et al.* (2008) and Amaya *et al.* (2016).

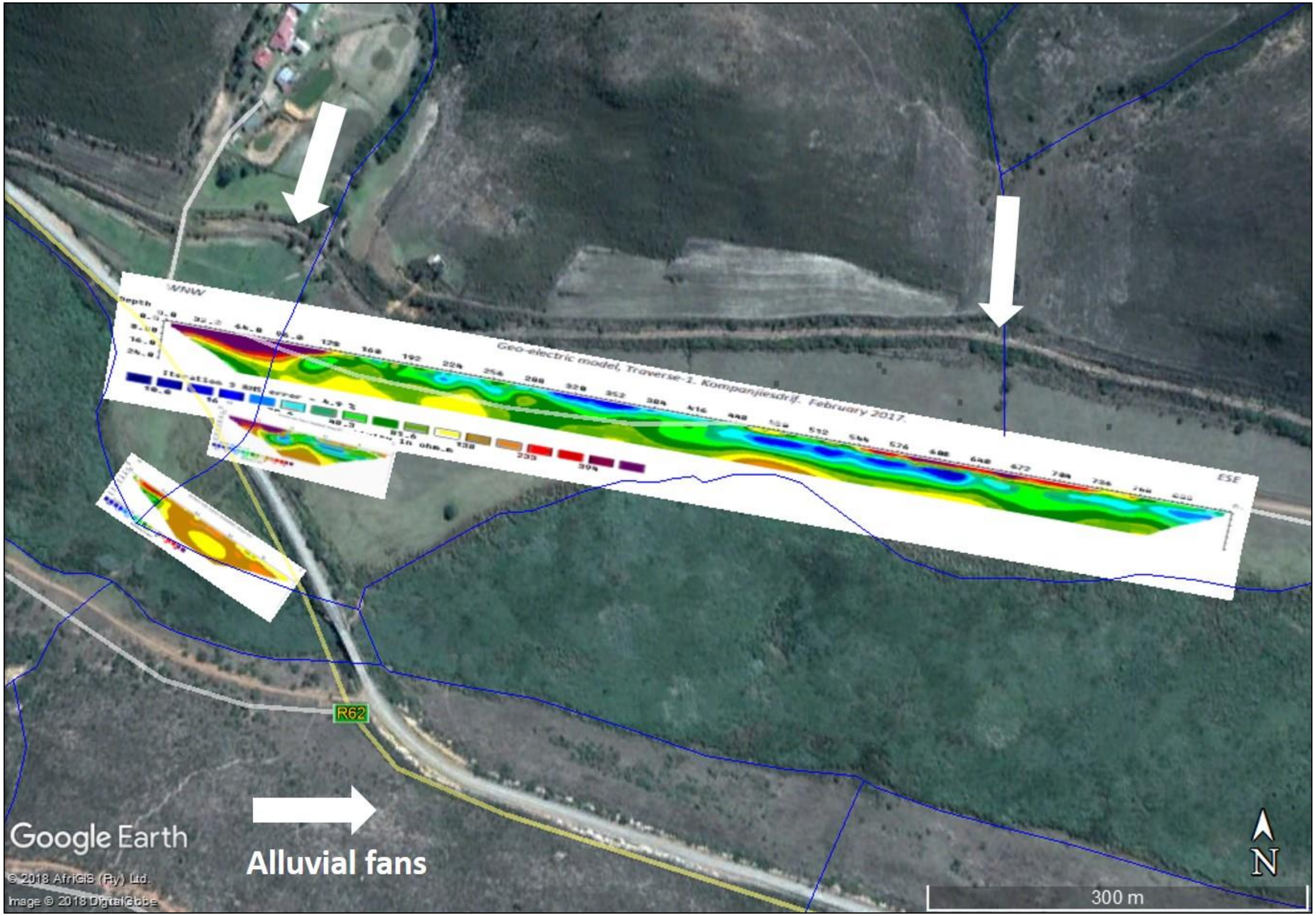


Figure 5.6 ERT survey results for transects at the Kompanjiesdrif wetland with alluvial fans entering the wetlands illustrated by white arrows. Alluvial fans are indicated by higher resistivity readings (red and purple).

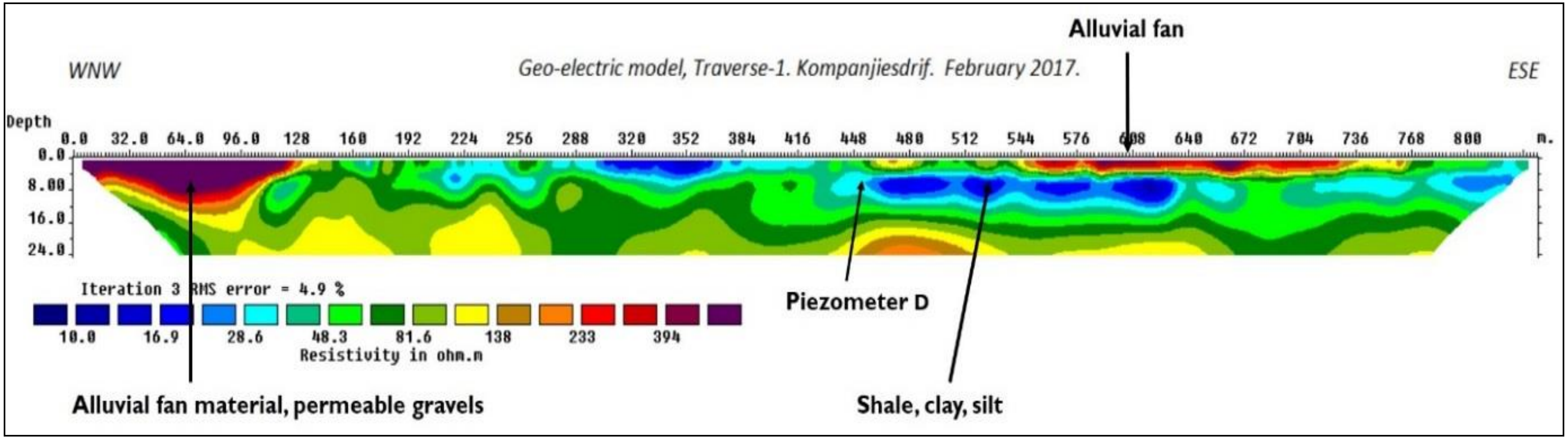


Figure 5.7 ERT survey results for the upper ERT transect at the Kompanjiesdrif wetland (across the alluvial fans and parallel to the wetland). The location of piezometer D along the ERT transect (in lower resistivity material) is also illustrated.

5.1.4 Water quality and stable isotopes

The nature of some of the surface water sampling points along the Krom River which are located in 'pool' type environments (due to artificial weir structures) needs to be taken into account when interpreting the water quality results. The SS1 and SS4 sampling sites would have experienced higher rates of evaporation and slower flow during the drought in 2017 due to the weir structures at these locations affecting flow. The sampling event in May 2018 was during a wetter period than in 2017, when there was a higher water level in the main Krom River channel and water was flowing faster over the weir structures (instead of 'pooling' behind the structures).

Stable isotopes

The stable isotope plots for the various surface water, piezometer, and borehole samples are illustrated in Figures 5.8, 5.9 and 5.10. A single rainwater sample was collected in August 2017 and is presented in the August 2017 graph. No tributary sample was collected in August 2017 (due to site access issues). No SS3 and piezometer F sample were collected in May 2017 and August 2017 due to the drought and no piezometer D sample was collected in August 2017 due to the drought. The global meteoric water line (GMWL) developed by Craig (1961) is plotted on the graphs, along with the local meteoric water line (LMWL). The LMWL is taken from Diamond (2014) and was determined using rainfall data collected at the Lentelus rainfall station in the Kouga Mountains (located approximately 50 km north-west of the study catchment). Two additional borehole samples (located just outside of the study catchment) were collected in May 2018 and the isotope results for these are shown in Figure 5.10.

The graphs illustrate an enrichment in lighter isotopes for the rainwater and borehole samples, compared to the surface water and piezometer samples. SS1 (upstream) is more enriched in heavier isotopes than SS2 and in May 2018 is the most enriched sample. This is possibly due to the fact that the sample was taken from a weir structure (and downstream of the weir structure) where water was at times standing still and not flowing (subjected to high evaporation). The SS1 sample is thus not a good 'upstream' representative sample. All samples plot relatively close to or on the LMWL. The August 2017 rainfall sample plots right next to the LMWL confirming that the LMWL gives a good indication of the isotopic signature of rainfall in the study area.

The fact that the tributary sample is more enriched in lighter isotopes than the other piezometer and surface water samples and plots relatively close to the borehole samples confirms the likelihood that this tributary receives a large groundwater input (especially since there were no significant rainfall events during or immediately prior to sampling of the tributary).

Interpreting stable isotopic signatures of wetlands and river samples in the TMG can be complex (as noted by Barrow, 2010) due to the fact that they are impacted by evaporation and may receive various quantities and have various sources of groundwater and surface water. There is no immediately obvious link between the groundwater isotopic signatures and the wetland isotopic signatures (PZE, PZF, SS3, and SS4) in Figure 5.8 to Figure 5.10. The stable isotopes of piezometers A, C, and D (parallel to the Kompanjiesdrif wetland) become progressively more enriched in a downstream direction.

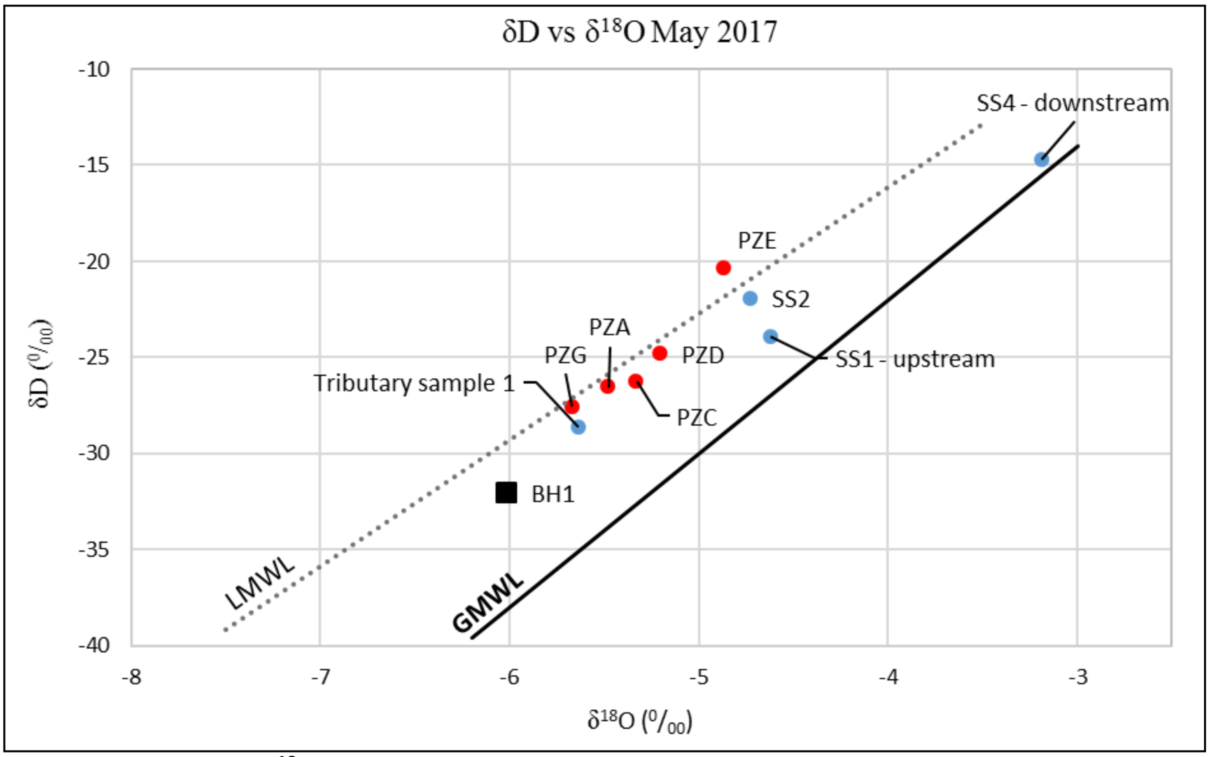


Figure 5.8 Plot of δD vs δ^{18}O for May 2017. LMWL = Local Meteoric Water Line (Diamond, 2014). GMWL = Global Meteoric Water Line (Craig, 1961).

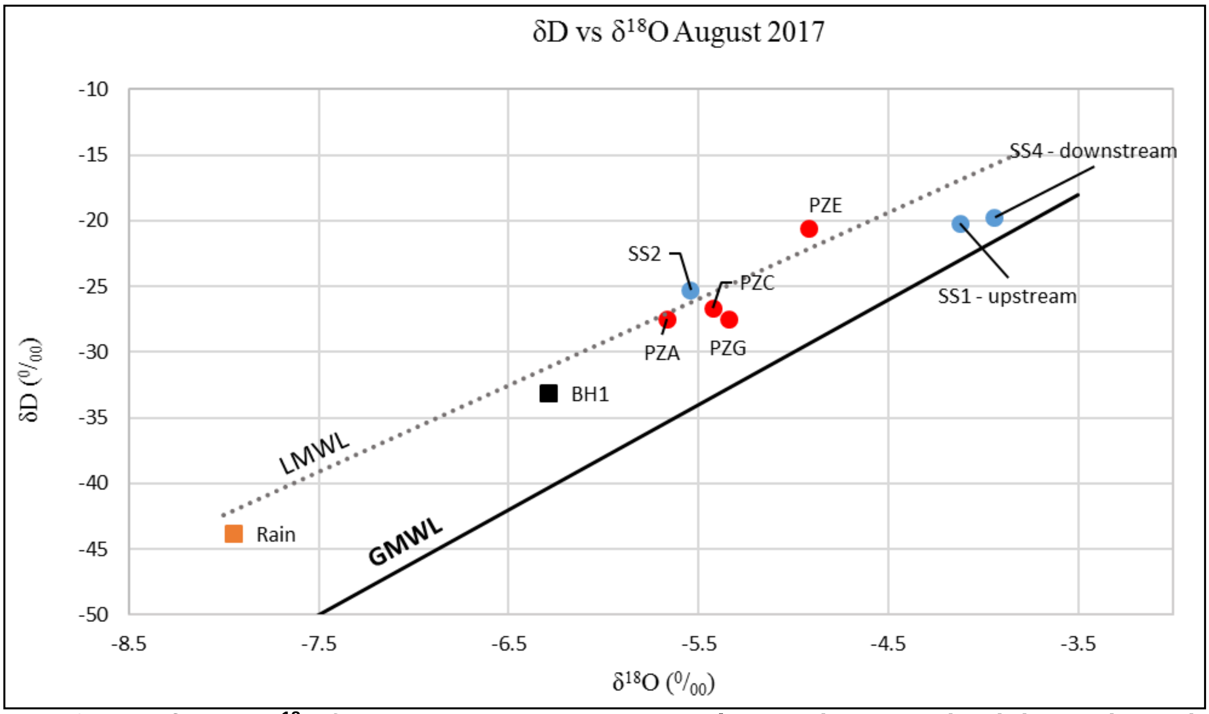


Figure 5.9 Plot of δD vs δ^{18}O for August 2017. LMWL = Local Meteoric Water Line (Diamond, 2014). GMWL = Global Meteoric Water Line (Craig, 1961).

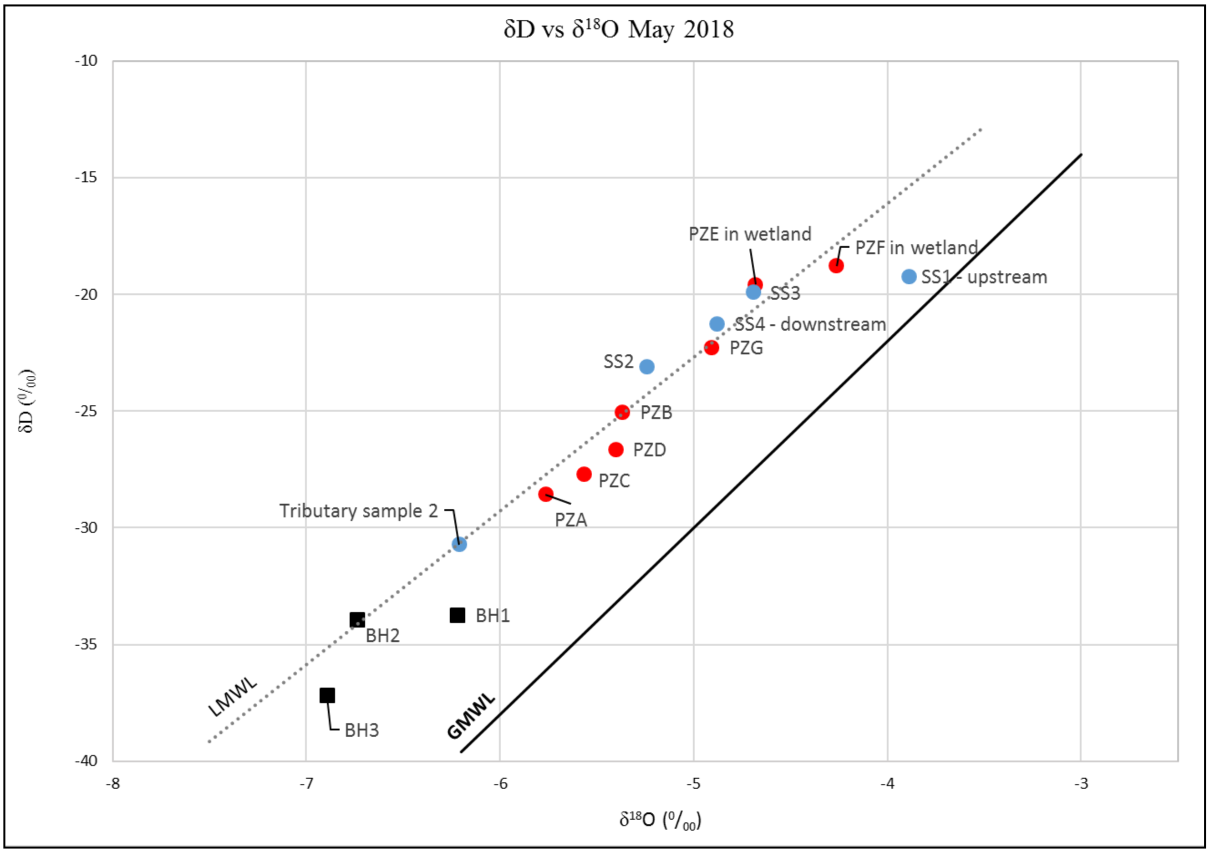


Figure 5.10 Plot of δD vs $\delta^{18}O$ for May 2018. LMWL = Local Meteoric Water Line (Diamond, 2014). GMWL = Global Meteoric Water Line (Craig, 1961).

Change in water quality and stable isotope signature with distance along the Krom River channel

Figures 5.11 to 5.13 illustrate the EC, chloride and $\delta^{18}O$ content of water at various sampling points moving from the top to the bottom of the catchment in May 2018. Sampling points that were located in the main Krom River channel are plotted on the red or purple lines and wetland piezometer or surrounding piezometer or borehole sampling points are represented as dots. The approximate location of large tributaries that enter the main river channel from the north and south are illustrated by the dark blue arrows.

There was no significant rainfall in the months preceding the sampling event in May 2018 and it is thus reasonable to assume that the tributaries flowing into the wetlands and main river channel consist predominantly of groundwater.

The chloride and EC graphs show high concentrations at BH1 (Figure 5.11, Figure 5.12). According to Smart and Tredoux (2002), TMG aquifers usually have an EC below 100 mS/m (1000 µS/cm) with an average range of 20 to 50 mS/m (200 to 500 µS/cm). Higher ECs are common in more shale-rich rocks. Smith *et al.* (2002) analysed the water quality of boreholes in the Nardouw Sub-group and Peninsula Formation (within the Dysselsdorp and Calitzdorp area) and found that the Nardouw Sub-group had a mean EC value of 30 mS/m (maximum of 155 mS/m) and Peninsula Formation had a mean EC of 10.4 mS/m (maximum of 26.3 mS/m). BH1's chloride content is higher than the mean value for the Nardouw aquifer reported by Smith *et al.* (2002) but is within the maximum range. Field observations and consultation of the 1:250 000 geological map of the area (Toerien, 1986) indicate that the borehole is either located within the Gydo Formation (Bokkeveld Group) or at the contact of the Gydo Formation (shale-rich) and the Baviaanskloof Formation (sandstone and minor shale). The EC and chloride content of BH1 confirm that the groundwater is coming into contact with the Bokkeveld shale. Unfortunately, no borehole logs are available for BH1.

The EC of BH2 and BH3 is within the range reported for the Peninsula Formation by Smith *et al.* (2002), but the chloride content is slightly higher. BH3 also has a slightly higher chloride and EC value than BH2, but this is expected based on its location at or close to the Cedarberg shale – Peninsula Formation contact.

The high chloride and EC content of the SS1 sample are likely due to high evaporation at the sampling point. It is also unlikely that the higher EC and chloride content at SS1 is caused by groundwater input from the Bokkeveld shale at this point as Figure 5.2 illustrates that the water table at BH1 is lower than the elevation of the nearby stream channel. Also, the isotope signature is enriched with heavier isotopes at SS1 which can be explained by the high evaporation at this sampling point. There is a spike in the chloride and EC content at PZF and PZE. This is probably due to evapotranspiration in the wetland (the wetland plants exclude certain salts e.g. chloride during transpiration) and the tributaries carrying in groundwater (which tend to have a slightly higher EC and chloride content than surface water) just before these points. The tributary sample has a slightly higher EC and chloride content in comparison to the river samples. The fact that the tributary has been subjected to evaporation and receives continuous groundwater input (with a slightly higher EC and chloride content than river samples – see BH2 and BH3) could explain this.

The gradual increase in EC and chloride in the surface water samples (SS2, SS3, and SS4) moving downstream can be attributed to evaporation and groundwater input from the tributaries. If the main river channel and wetlands were receiving large volumes of groundwater input from the Bokkeveld aquitard (via diffuse flow) then the EC and chloride content of SS2, SS3, SS4, PZF, and PZE would be expected to be much higher than it is (based on the water quality of BH1).

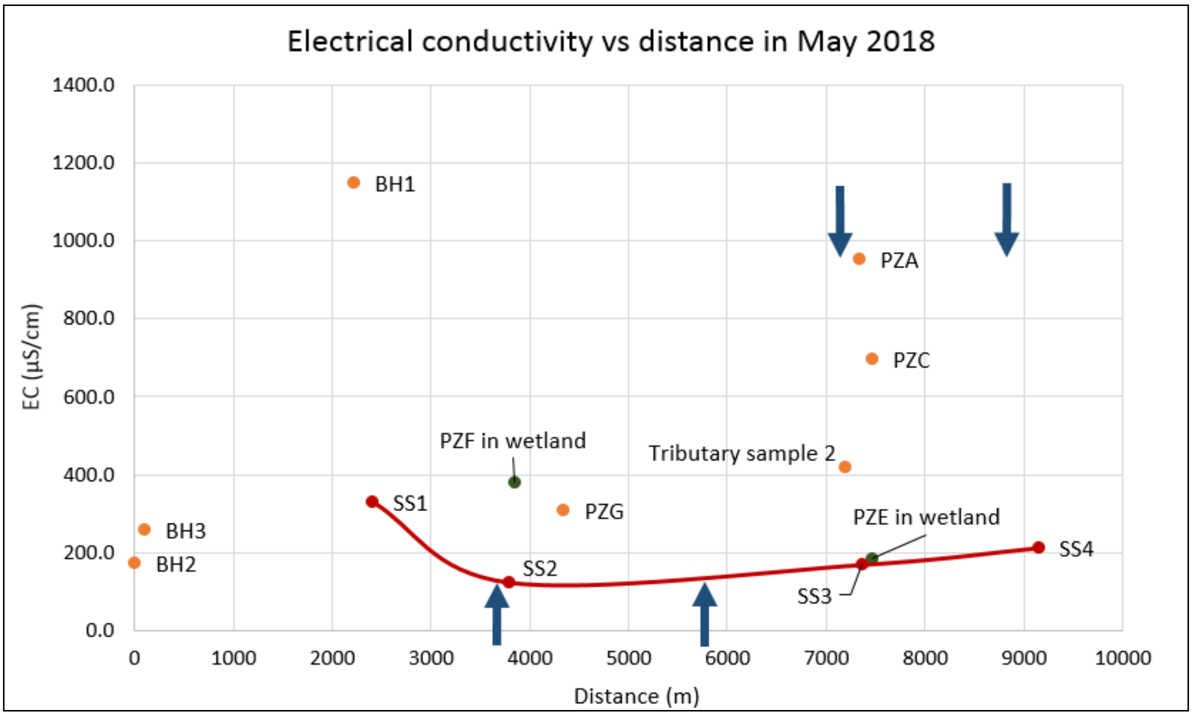


Figure 5.11 EC vs distance for May 2018. Dark blue arrows indicate the approximate location of large tributaries entering the main Krom River channel. PZD has a very EC which skews the graph and it was thus left off.

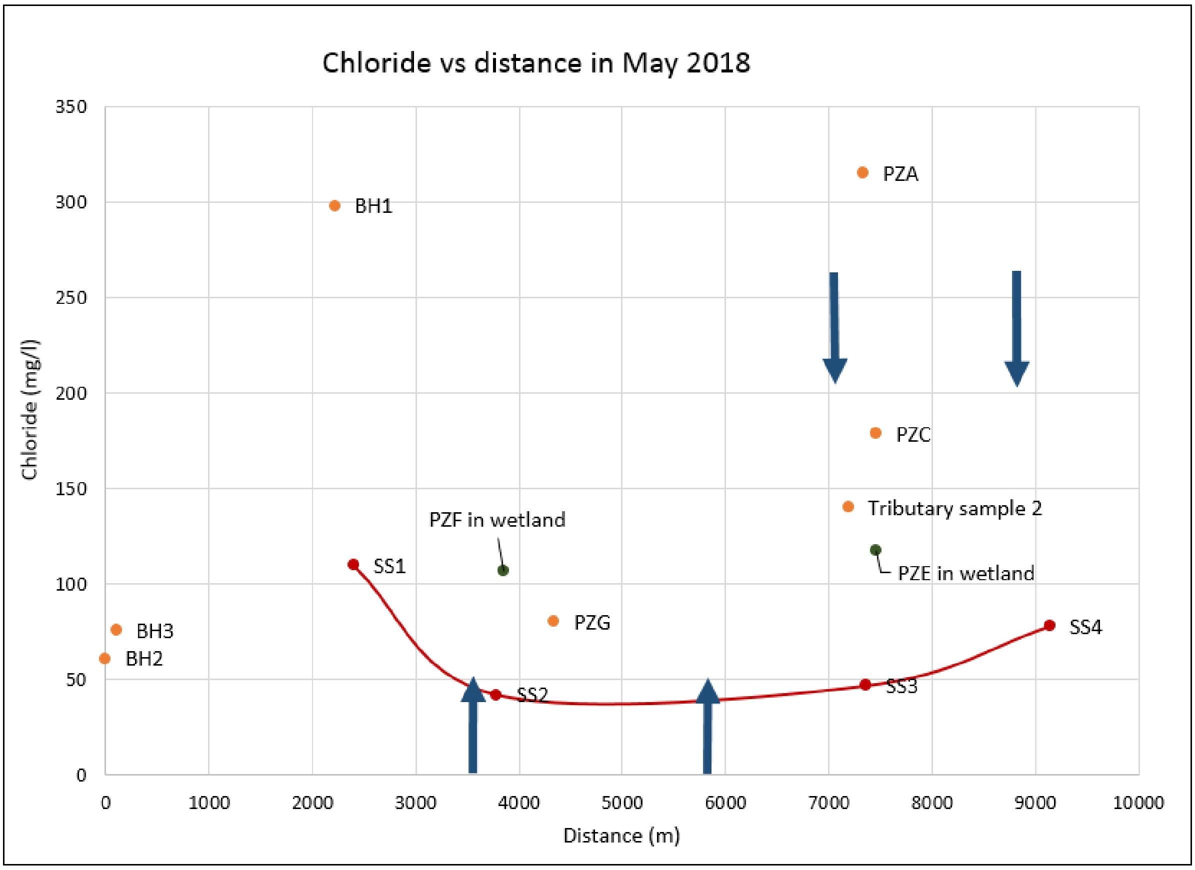


Figure 5.12 Chloride (red line) vs distance for May 2018. Dark blue arrows indicate the approximate location of large tributaries entering the main channel. PZD has a very high value which skews the graph and it was thus left off.

Ignoring SS1 (situated at a weir structure and impacted by evaporation), the $\delta^{18}O$ graph (Figure 5.13) illustrates that the river samples become lighter as one moves downstream (from SS2 onwards), even though one would expect the water to become more enriched in heavier isotopes due to evaporation in a downstream direction (in particular the SS4 sample). This indicates that the tributaries before these sampling points are probably carrying in fresh groundwater (lighter $\delta^{18}O$ concentration). The spike at SS2 (lighter $\delta^{18}O$ concentration) can be attributed to the large tributary flowing into the main river channel (carrying in lighter groundwater) before that sampling point.

The fact that in 2017 SS4 is more enriched in heavier isotopes than the other surface water samples (Figure 5.8 and 5.9 above) is likely due to the drought, lower inflow from the tributaries and higher evaporation at the sampling point over that period.

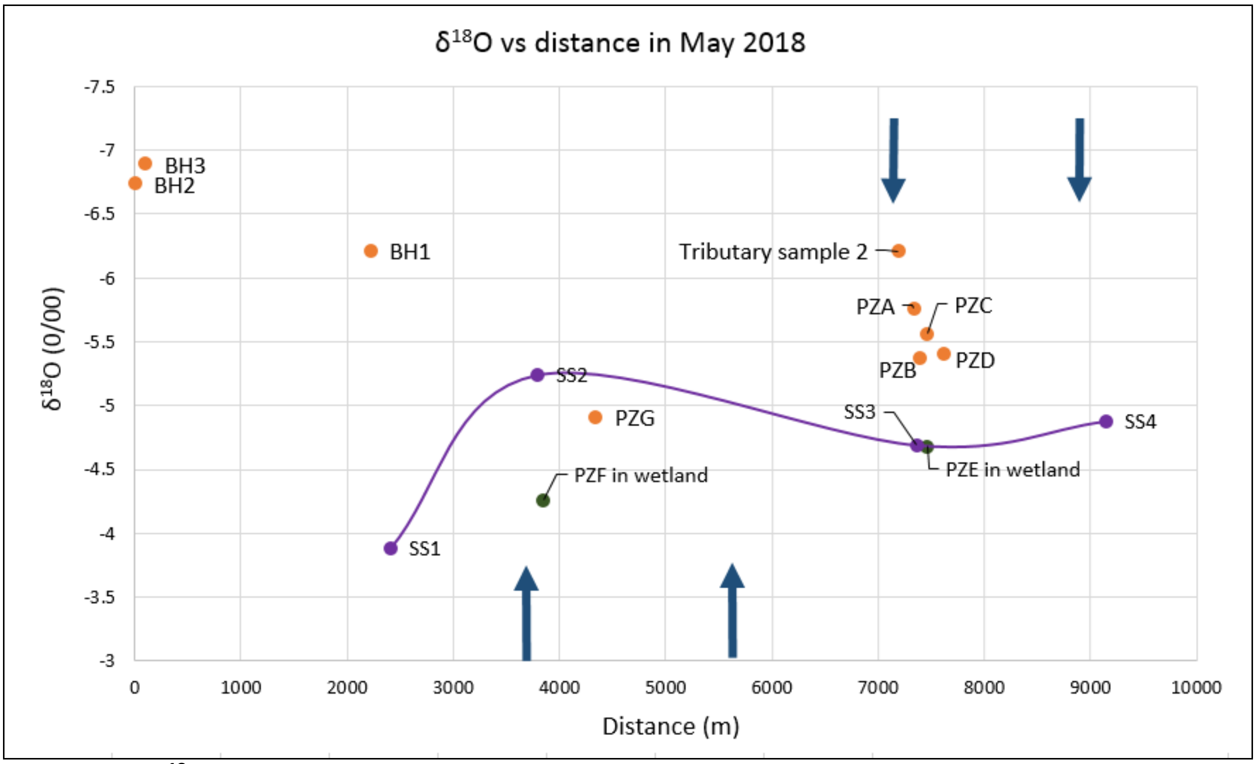


Figure 5.13 $\delta^{18}O$ (purple line) vs distance for May 2018. Dark blue arrows indicate the approximate location of large tributaries entering the main channel.

Physico-chemical water quality results

Table 5.4 to 5.6 provide the results of all physico-chemical parameters that were analysed for the water samples.

Table 5.4 Water quality results for May 2017 (units in µS/cm, pH units and mg/l).

Sample	*EC*	*pH*	*Cl*	*Ca*	*Si*	*Mg*	*Al*	*K*
SS1	519	7.38	-	2.8	5.6	5	0	2.1
SS2	200	7.4	-	0	3.3	5	0	1.4
SS3	*no sample*							
SS4	380	7	-	1.6	4.6	6	0	1.2
TS1	575	6.7	-	5.6	7	10	0	0.9
PZA	1248	5.84	-	37.6	3.6	30	0.08	4
PZC	848	6.23	-	8.4	9.15	16	0	3.7
PZD	6750	5.52	-	0	10.55	220	0.28	11.5
PZE	308	-	-	0	5.86	7	0.03	3.9
PZF	*no sample*							
PZG	425	5.96	-	3.6	6.8	9	0.06	5.6
BH1	1438	6.32	-	4.8	15.5	23	0.04	4

Table 5.5 Water quality results for August 2017 (units in µS/cm, pH units and mg/l).

Sample	*EC*	*pH*	*Cl*	*Ca*	*Si*	*Mg*	*Al*	*K*
SS1	463	5.86	-	1.6	4.3	9	0.06	0.5
SS2	156	5.31	-	3	2.7	6	0	1
SS3	*No sample*							
SS4	320	7.05	-	2	4.3	7	0	0.6
PZA	1014	6.22	-	24	13.1	28	0.19	22
PZC	874	6.24	-	6.4	7.97	18	0.17	2.3
PZD	7277	5.32	-	*Not enough sample*				
PZE	243	6.53	-	1.6	5.63	7	0	5.6
PZF	*No sample*							
PZG	353	6.9	-	*Not enough sample*				
BH1	1051	5.97	-	17.2	13.4	22	0	3.3

Table 5.6 Water quality results for May 2018 (units in µS/cm, pH units and mg/l).

Sample	*EC*	*pH*	*Cl*	*Ca*	*Si*	*Mg*	*Al*	*K*
SS1	332	6.94	110	1.6	5.2	1	0	0.9
SS2	124	6.34	42.3	0	2.6	3	0	0.6
SS3	169.4	6.46	47.1	0.8	5.6	5	0.03	0.4
SS4	212.3	7.38	78.4	0.8	5.6	7	0.02	1
TS2	419	6.37	140	6	4.03	10	0.38	1.8
PZA	955	6.05	315	23.6	15.9	47	1.1	6.9
PZC	699	6.04	179	8.4	10.08	15	0.06	2.7
PZD	6547	5.03	2540	0	15.01	310	1.2	3.4
PZE	183.9	5.81	118	0	5.16	11	0.18	4
PZF	381	5.76	107	0	5.86	13	0.01	2.4
PZG	308	5.84	80.6	0	7.5	13	0	6.5
BH1	1149	6.21	298	13.6	12.7	27	0.05	3.3
BH2	174	5.46	61.2	0	3.94	5	0	0
BH3	258	5.92	76.2	1.2	9.38	9	0	2.8

5.1.5 Conceptual model development

The conceptual models that were considered during the field investigation and modelling exercise included:

1. Groundwater/interflow is not a significant contributor to the system, therefore the system is sustained purely through surface water (surface runoff and direct precipitation).
2. Sub-surface water (groundwater, interflow or both) contributes to the system via preferential flow paths in the alluvium, fed by the surrounding quartzite TMG geology.
3. Sub-surface water (groundwater, interflow or both) contributes to the system via diffuse flow through the surrounding Bokkeveld shales and sandstones, which are recharged by the surrounding quartzite TMG formations.

During the first site visit in June 2016, the main Krom River was flowing and instrumentation of the catchment began. During subsequent site visits in February and May 2017, however, it was observed that a severe drought had resulted in many parts of the river drying out completely. It was evident that water was still continuously flowing in certain tributaries of the Krom River, despite the severe drought. This was particularly evident at the main Kompanjiesdrif tributary where water emerges at the top of a steeply dipping sandstone outcrop of the Nardouw Sub-group. Water flows through the tributary towards the valley, disappears into the sub-surface (alluvial material) and then presumably emerges again in the wetland. A local farmer below the tributary makes use of some of this water for household use and farming. The farmer indicated that his family has lived on the land for a number of years and the tributary has never run dry.

Based on the results of the data collection (water quality, stable isotopes and ERT survey) it is proposed that the palmiet wetlands are sustained by sub-surface water (both groundwater and interflow) moving through preferential flow paths in the alluvial fans, which are, in turn, sustained by groundwater discharge from the surrounding sandstone and quartzites of the Nardouw Sub-group and Peninsula Formation. The conceptual model provided in Figure 5.14 illustrates the various flow paths that are proposed here, as well as the probable Bokkeveld and Cedarberg Formation aquitards (as described by Rosewarne, 2002b) separating the individual aquifers.

A similar situation exists in the Hex River Valley, which has also formed along a syncline, and there are strong linkages between the alluvial fans within the valley and the TMG groundwater (Rosewarne, 2002b). The TMG alluvium is a prominent groundwater storage reservoir and an estimated 5 million m^3/a seeps into the TMG/Bokkeveld aquifer beneath it (Rosewarne, 1981 and 2002b). According to Colvin *et al.* (2003:26), who describe typical TMG groundwater discharge settings, the "colluvial and alluvial deposits formed from the quartzites result in many streams which appear and disappear as surface flows, particularly on the alluvial fans that are a prominent feature in many valleys".

Brown *et al.* (2003) describe similar scenarios for the interaction between the TMG aquifer and alluvium or rivers and indicate that the Skurweberg aquifer (Nardouw) generally provides water directly to river baseflow in the main river channel, while water from the Peninsula Aquifer mainly flows into tributary rivers contributing to the main river channel. Springs associated with the Nardouw aquifer are usually low volume and intermittent while Peninsula Formation springs are generally perennial. In the case of the study catchment, it is unlikely that the Nardouw aquifer provides water directly to river baseflow (via diffuse flow) as the Nardouw aquifer is not in direct contact with the wetlands and main river channel.

The folded and fractured nature of the TMG and Bokkeveld rocks mean that despite the proposed aquitards and boundaries between the individual aquifers (Figure 5.14) there is probably still some groundwater flow between the aquifers via fractures. Water level data (section 5.1.1) and water quality data (section 5.1.4) illustrate that it is unlikely that there is a significant groundwater discharge from the surrounding Bokkeveld shale into the palmiet wetlands.

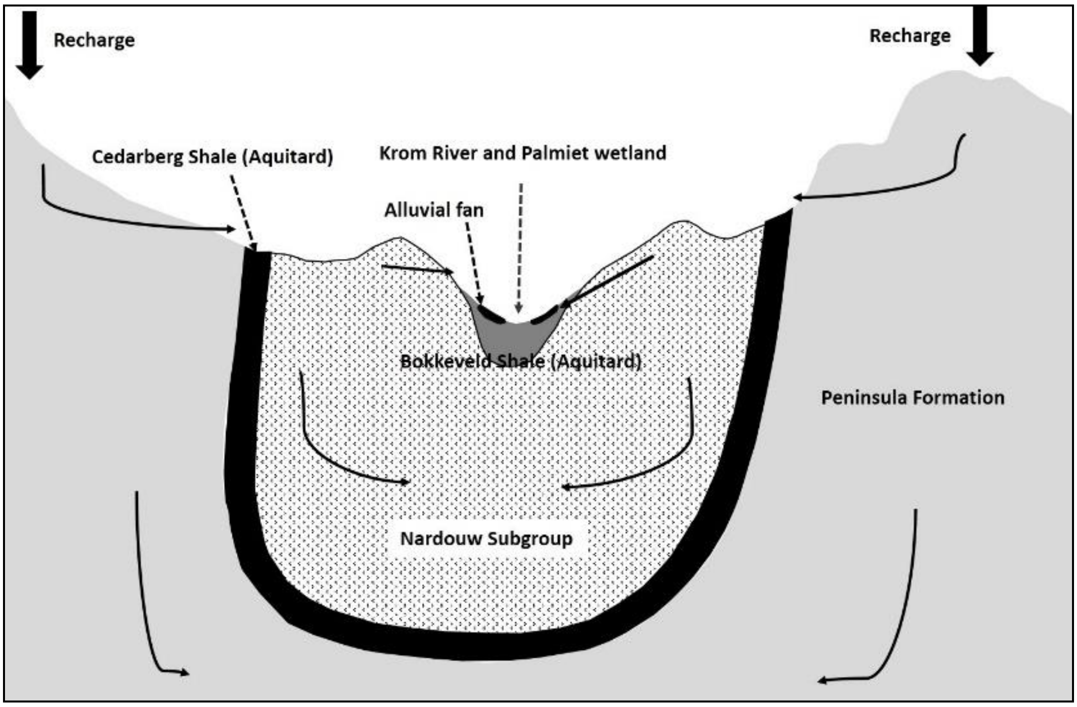


Figure 5.14 Conceptual model illustrating the flow of groundwater to the wetlands via alluvial fans and tributaries, which in turn derive this water from the Nardouw and Peninsula aquifer.

5.1.6 Small-scale alluvial fan dynamics

Recovery of piezometer water levels at the Kompanjiesdrif wetland

A simple recovery test was undertaken for piezometers A, B, C and D in February 2017 by emptying the piezometers (using a bailer) and taking regular manual dip readings of the water level (every half hour). Piezometer B and C took just over a day to recover fully, whereas A and D recovered relatively quickly (within 7.5 hours and 5 hours respectively). This provides an indication of the transmissivity of the alluvial fan material and the surrounding alluvium. It is surprising, considering the location of D (between the fans) and probable location in more shale-rich material (based on ERT survey) that it recovered faster than A in February 2017.

In May 2017 piezometers A, C, D, and E (in the wetland) were emptied again and dip readings were taken the next day. Piezometer B was already dry and was thus not measured. Piezometer A and C recovered within a day, but D and E took just over a day to recover. The slower recovery of D compared to February 2017 could be as a result of the lower water table (due to the drought) and a resulting change in the preferential flow paths at this site. In August 2017 after emptying all of them, piezometers A, D and E did not recover fully within 24 hours, but C did.

In May 2018 (sub-surface water levels had increased in the catchment) piezometers A, C, D, and E all recovered within 24 hours of being emptied. Piezometer E was filling up rapidly while being emptied. Piezometer B did not recover fully (Table 5.7 below).

Generally, the piezometers within the alluvial fan and in the surrounding alluvium appear to have an overall low hydraulic conductivity.

Table 5.7 Summary of the results of recovery tests of piezometers.

	Recovery time			
	Feb-17	***May-17***	***Aug-17***	***May-18***
Comments	Recovery measured every half hour	Recovery measured over 24 hrs		
PZA (on fan)	7.5 hrs	<24 hrs	>24hrs	<24hrs
PZB (edge of wetland)	>24 hrs	-	-	>24hrs
PZC (edge of fan)	>24 hrs	<24hrs	<24hrs	<24hrs
PZD	5 hrs	>24hrs	>24hrs	<24hrs
PZE (in wetland)	-	>24hrs	>24hrs	<24hrs (filling up rapidly while emptied)

Figure 5.15 Location of piezometers that simple recovery tests were undertaken on.

Sub-surface dynamics of piezometers at the Kompanjiesdrif wetland

The elevation of the water table at piezometer D (Figure 5.15) is consistently lower than the elevation of the water table in the wetland. Lagesse (2017) surveyed the water level of the Kompanjiesdrif wetland along a number of transects using a DGPS in May 2015 (Figure 5.16). At the time of the survey, the water level was sufficiently elevated throughout the wetland that it could be measured at the surface without the use of an auger or installation of piezometers. Lagesse (2017) illustrates that the direction of the slope of the water table changes along certain transects of the wetland. In transect 1 and 5 the water table slopes towards the northern edge of the wetland and in transects 2, 4 and 6 the water table slopes primarily towards the southern edge of the wetland. This is linked to the presence of alluvial fans which constrict the wetland and steepen the land surface on the northern side at transects 2, 4 and 6. Whereas, at transect 1 and 5 there are no alluvial fans present and the land surface on the northern side of the wetland has a gentler slope than the southern side (land surface is higher on this side). The water table at transect 3, however, does not follow the trend and appears to slope gently towards the southern side even though there are no alluvial fans present on the northern edge of the wetland at this transect.

Pulley *et al*. (2018) also noted slight irregularities (repeated mounding) along the length of the longitudinal slope of the Kompanjiesdrif wetland which they attributed to the impinging alluvial fan sediment.

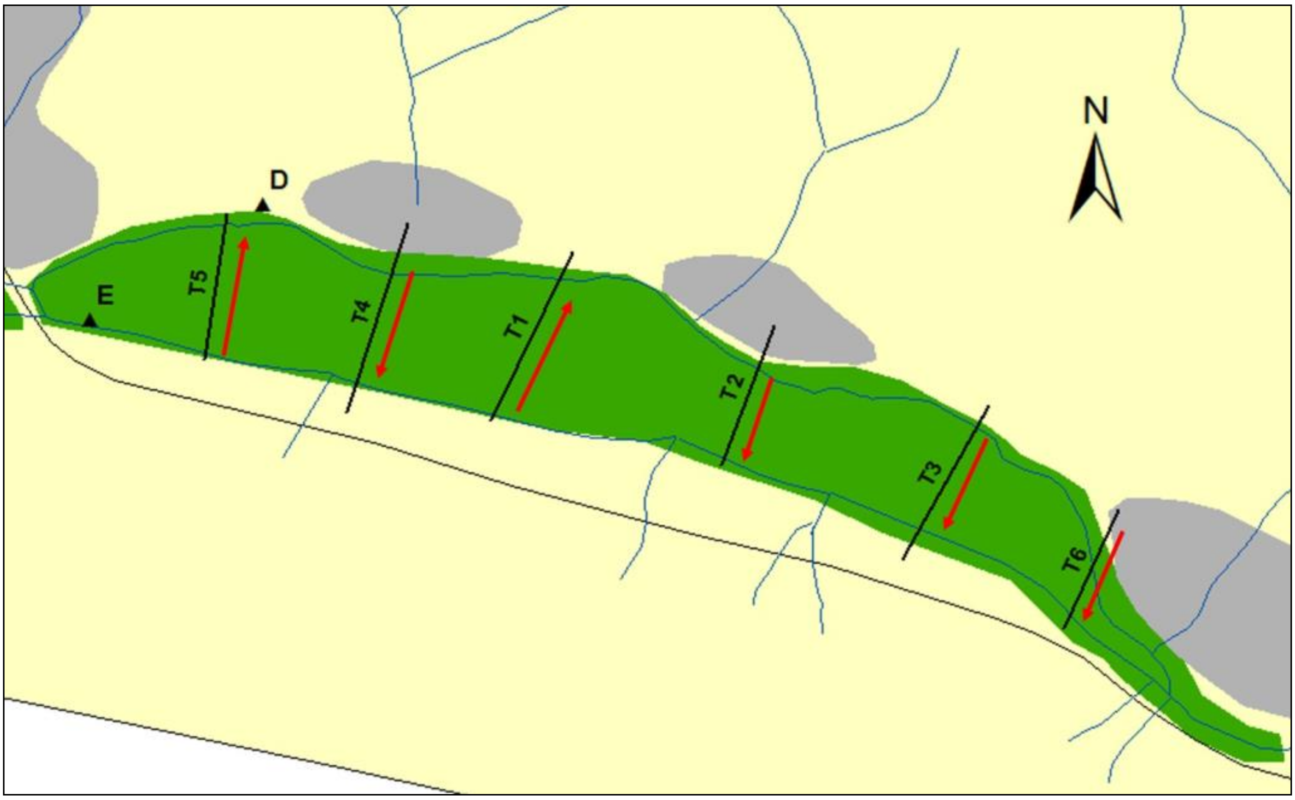


Figure 5.16 Direction of the slope of the water table along various transects in the Kompanjiesdrif wetland according to Lagesse (2017). The location of piezometer E and D and the alluvial fans (in grey) in relation to the wetland transects is also indicated. The direction of the slope of the water table is indicated by red arrows.

Sub-surface water levels measured in May 2018 for the piezometers at the Kompanjiesdrif wetland illustrate that piezometer D has a lower water level than that of the wetland (piezometer E) (Figure 5.17), confirming Lagesse's (2017) findings. The probable sub-surface flow directions (based on field observations and water level data) are illustrated in Figure 5.17. The observed water level data and the directions of the slope of the water table described by Lagesse (2017) indicate that, as sub-surface water enters the Kompanjiesdrif wetland, it appears to flow towards (and 'recharge') piezometer D and then flow downstream. According to these water levels, it appears as though the alluvial fans recharge the wetland and the wetland recharges the valley bottom alluvium between the fans.

Figure 5.17 Proposed sub-surface flow directions at the Kompanjiesdrif wetland with water levels measured in May 2018.

Water quality of piezometers at the Kompanjiesdrif wetland

The EC and chloride content of piezometers A, C and D are higher than that of the tributary, river samples and piezometer E in the wetland at Kompanjiesdrif. Piezometer D has a substantially higher EC and chloride content than the other piezometers and surface water samples (Figure 5.18). The very high EC value reported for piezometer D correlates with the ERT results described in section 5.1.3 (located off the alluvial fan in shale/clayey material with a low resistivity and high conductivity).

The very high EC and chloride content of piezometer D in comparison to the others can only be explained by its location in shale/clay-rich material (with a high salt content) and the fact that it is located off the alluvial fans in material that is recharged slower (probably from the wetland) and is subjected to higher evaporation.

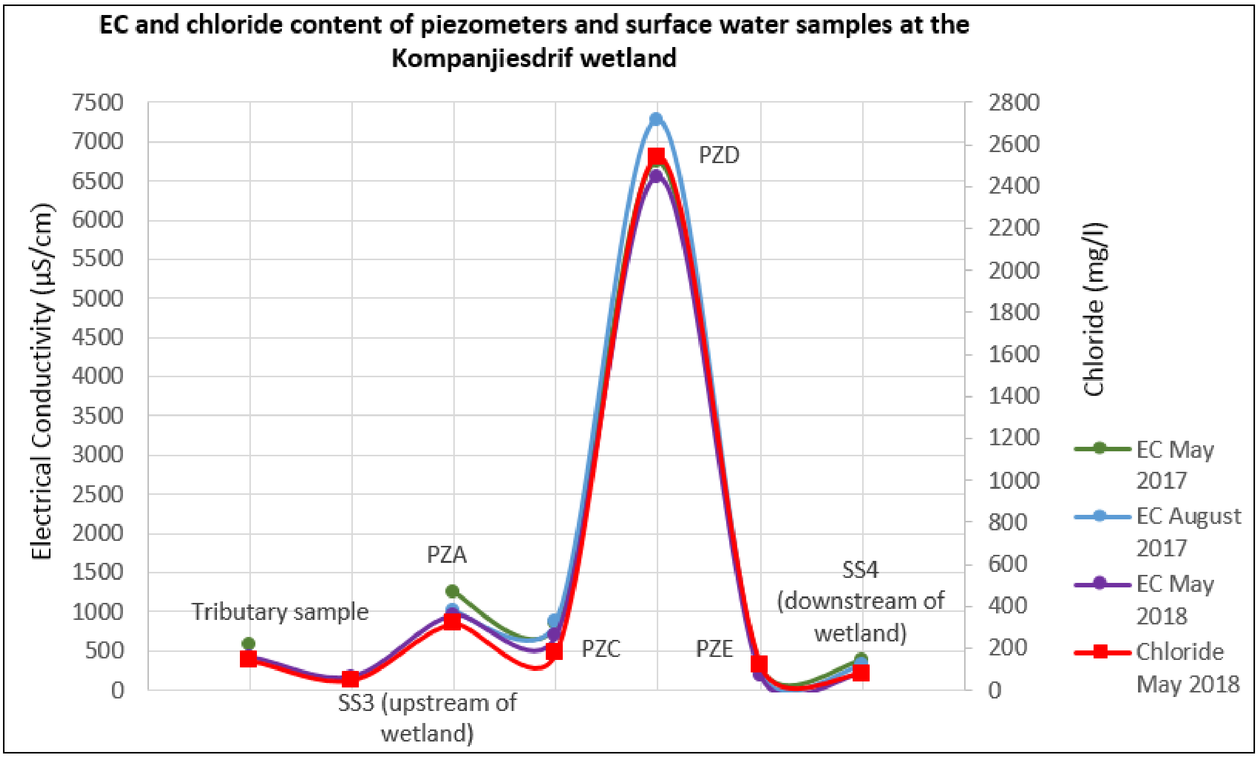


Figure 5.18 EC and chloride content of the piezometer and surface water samples at the Kompanjiesdrif wetland.

5.2 Modelling results

5.2.1 Pitman hydrological model

The model was set up with and without the wetlands to assess what impacts the wetlands have on the hydrological system. Without flow data to validate the model simulations, however, it is not possible to confirm the outputs. Figure 5.19 illustrates that the Pitman model simulated a fairly significant attenuation of flows with the wetland sub-model. For example, the peak flow in July 2012 (3.16 mcm), without the wetland sub-model, was reduced by about 1.14 mcm and was delayed by about two months with the wetland sub-model (Figure 5.19).

The average water balance components are shown in Tables 5.8 (wetland water balance) and 5.9 (low flows within the catchment) (Tanner, pers. comm.). Without further flow data, it is not possible to identify whether this is a realistic representation of wetland dynamics.

Table 5.8 Average monthly water balance components of the wetland over the simulation period (7 years) given in $m^3 \times 10^6$

Variable	Upper wetland (Krugersland)	Lower wetland (Kompanjiesdrif)
Wetland inflow	0.19	0.20
Wetland outflow (spill)	0.15	0.19
Wetland evaporation	0.06	0.03
Storage volume	0.90	0.57

Table 5.9 Average monthly contribution of groundwater and interflow to low flows in the tributaries and rivers supporting the wetland given in $m^3 \times 10^6$

Variable	Upper wetland (Krugersland)	Lower wetland (Kompanjiesdrif)
Groundwater contribution to baseflow	0.03	0.009
Interflow contribution to baseflow	3.85	3.57

5.2.2 GYMR

The GYMR monthly groundwater contribution to baseflow (in red) along with the Pitman groundwater contribution to baseflow (green stippled line), Pitman river flow (with and without the wetlands sub-model) and monthly rainfall are illustrated in Figure 5.19. The GYMR groundwater contribution to baseflow compares quite well with the Pitman groundwater contribution to baseflow.

The GYMR total monthly average groundwater contribution to baseflow is 0.09 mcm/month, while Pitman estimates a total monthly average groundwater contribution of 0.04 mcm/month. The GYMR groundwater contribution to baseflow in the catchment for May 2018 was calculated to be zero (even though the tributaries did not stop flowing with no rainfall). Interestingly both the GYMR and the Pitman model reported zero or very low groundwater contribution to the rivers in May 2018 reflecting the extreme dryness of the catchment. The models were unable to represent the sustained groundwater baseflow that was observed, given the dry conditions.

The total estimated groundwater volume in storage in the study catchment, determined using the GYMR, is 8 297 625 m^3.

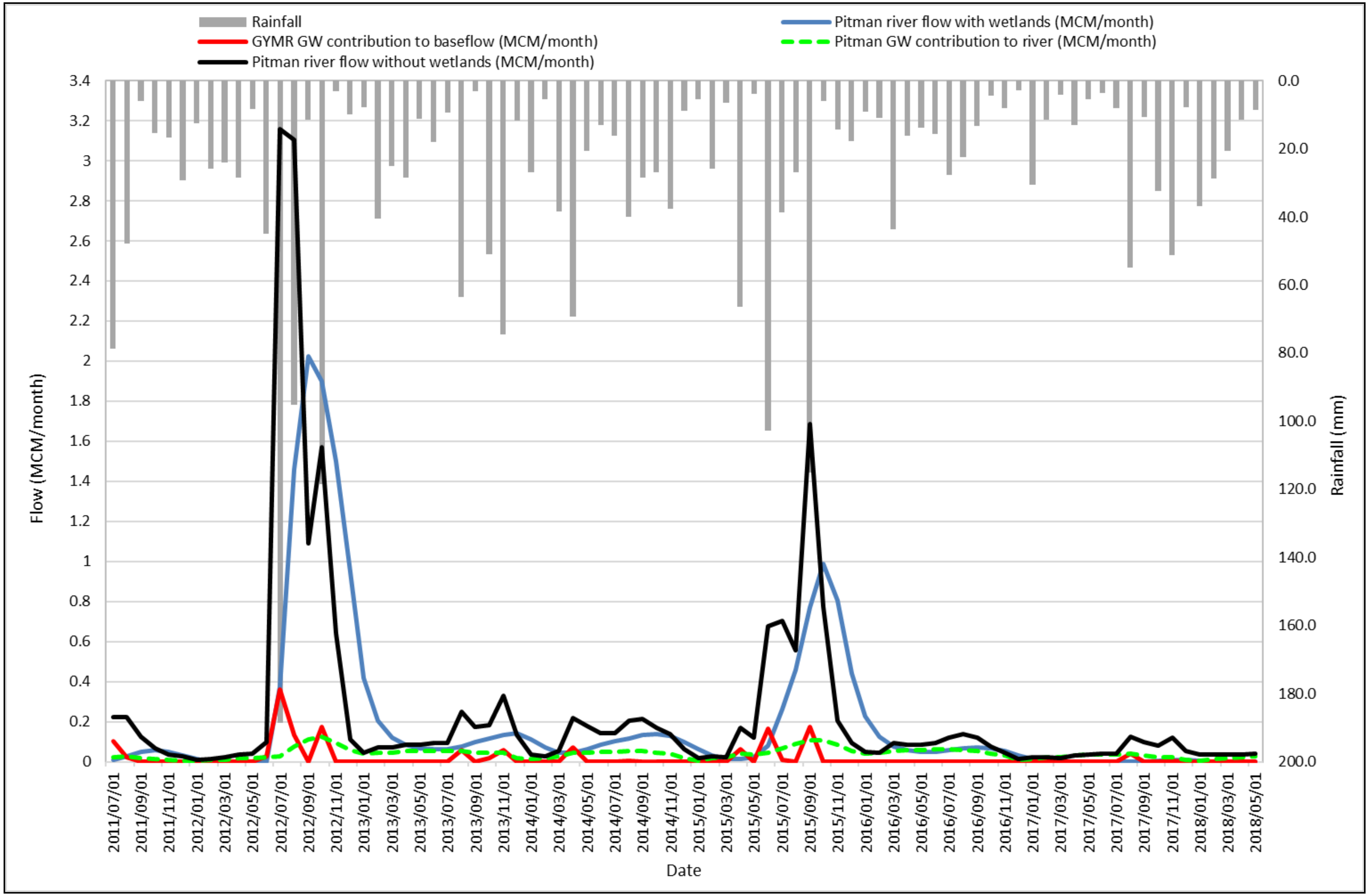


Figure 5.19 GYMR groundwater contribution to baseflow (red), Pitman river flow without wetlands (black line), Pitman river flow with wetlands (blue line), Pitman groundwater contribution to the river (green) (Tanner, pers. comm.) and rainfall (grey) between 2011 and 2018.

5.2.3 Mixing cell model

Single cell

The MCM flow results (unknown inflow volumes and percentages) for the single cell model are illustrated in Table 5.10 and Figure 5.20. The water balance error is 2.61% and average chemical mass balance error is -3.8%. These errors are within the acceptable range as described in the MCM manual (less than 15 to 20%). The 2.61% water balance error indicates that there is more water flowing out of the system than flowing in from known sources, indicating that there are thus additional unidentified water sources that are not accounted for.

Inflow from the upstream wetland contributes 67% of the total inflow into the Kompanjiesdrif wetland and groundwater contributes 33% of the total inflow (defined by BH1, BH2, and BH3). The upstream inflow is expected to consist of a mixture of surface water and groundwater. Shallow sub-surface inflow (defined by the tracer concentrations of PZA) is 0%. This is surprising as it is evident there is sub-surface flow moving through preferential flow paths in the alluvial fan material to the wetland. The fact that PZA is not situated on the main trunk stream entering the wetland through the alluvial fan, and therefore within alluvium with low transmissivity, could explain this.

Also surprisingly, the tributary inflow (considered to be mostly groundwater during May 2018), based on isotope data and the lack of rainfall in the catchment) is 0%. The contribution from this tributary is expected to be high as it flowed continuously during the drought and is one of the larger tributaries entering the wetland. The water quality of this tributary is thought to be a good representative sample for the 'general' water quality of all tributaries entering the wetland (as it is situated in the same geology as the other main tributaries). However, the MCM has indicated that it is not necessarily a good representative sample and only additional sampling of the other tributaries in the catchment would confirm this. Also, the tributary has been subjected to evaporation which would alter its chemistry and ideally the sampling point should be at the source of the tributary where it first emerges from the aquifer. In this case, it was not possible to access the headwaters of the tributary to access more suitable seepage points. The groundwater flow into the system is unusual since it becomes surface flow prior to reaching the wetlands. And it could be that the unusual way the groundwater system works is not able to be captured by the model, which instead recognises a groundwater contribution through BH2 and 3 (which according to the water chemistry is quite similar to the tributary).

It is more likely that the 32.6% groundwater contribution identified by the model actually reaches the wetland through the tributaries and not via diffuse flow. The 0.4% inflow indicated for BH1 (located within Bokkeveld shale/Nardouw-Bokkeveld shale contact) is probably contributed via diffuse groundwater discharge into the wetland.

The modified Pitman model estimates a groundwater contribution to the river (or wetland) of 5 200 m^3 for May 2018 which is approximately 7 times smaller than the total groundwater contribution estimated by the MCM of 38 797.01 m^3, although the Pitman model had no way to validate this figure while the MCM values are determined from the chemistry data. The groundwater quantity estimated here by the MCM includes all groundwater contribution into the wetland from upstream sources and tributaries.

Table 5.10 May 2018 single cell MCM results for unknown inflows.

Name of inflow	Inflow volume (m^3/month)
Upstream inflow	78 658.97
Tributary inflow	0
Shallow sub-surface inflow	0
BH1 (groundwater)	496.25
BH2 and BH3 (groundwater)	38 300.76

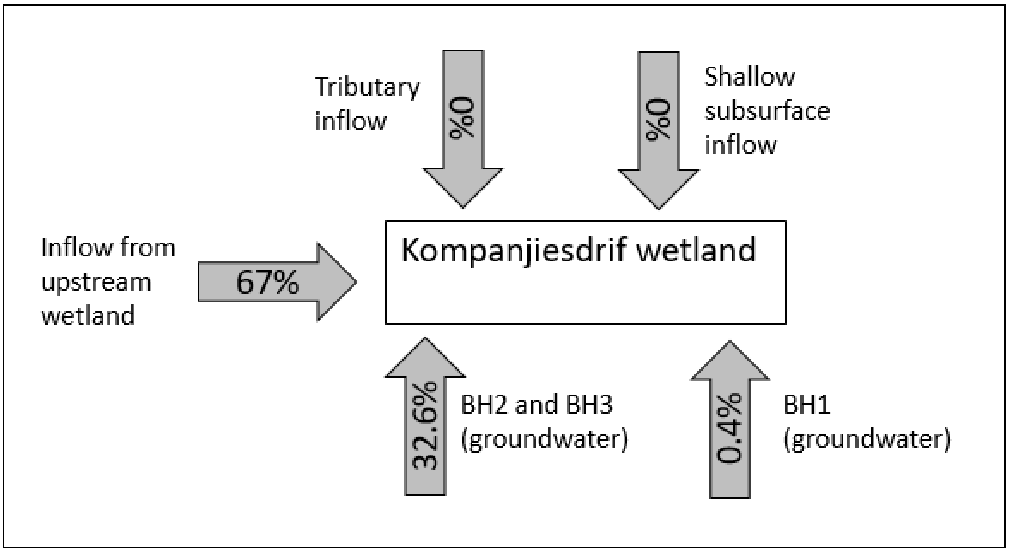


Figure 5.20 Inflow percentages determined by the MCM for the single cell model.

Two cell

The MCM flow results (unknown inflow volumes and percentages) for the two cell model are illustrated in Table 5.11 and Figure 5.21. The water balance error for the two cell model is higher than the single cell model at 13.89% and the average chemical mass balance error is -2.24%. These errors are still within the acceptable range as described in the MCM manual (less than 15 to 20%). The 13.89% water balance error once again indicates that there are potentially additional unknown inflow sources into the wetlands that are not accounted for.

Upstream inflow into the Krugersland wetland accounts for 19.1% of the total inflow. The two cell model does yield a contribution from the tributaries (of 3.6% and 2.8% respectively) although this contribution is smaller than expected (possibly for the same reasons described above), but the fact that the model picks up a contribution indicates the tributary is a source. As discussed above, there could be various reasons for the contribution being smaller than expected.

Groundwater inflow (calculated from boreholes) into the Krugersland wetland accounts for 18.1% of the total inflow and groundwater inflow into the Kompanjiesdrif wetland accounts for 56.4% of the total inflow. Inflow from BH1 would enter the wetlands as diffuse groundwater discharge, whereas the other groundwater inflow (BH2 and 3) would likely enter the wetlands via tributaries.

The flow between the wetland cells (from Krugersland to Kompanjiesdrif) is calculated to be 32 224.13 m^3. The groundwater contribution to the Kompanjiesdrif wetland is 72 394.67 m^3 (higher than what was estimated in the single cell model) and to the Krugersland wetland is 23 317.18 m^3. The groundwater contribution to the Krugersland wetland is similar to that estimated in Pitman (for May 2018) of 20 600 m^3 for that wetland. The smaller tributary inflows (4562.39 m^3 and 3582.78 m^3 respectively) would likely also be mostly comprised of groundwater and interflow.

Table 5.11 May 2018 two cell MCM results for unknown inflows.

Cell	Name of inflow	Inflow volume (m^3/month)
Cell 1 – Krugersland wetland	*Upstream inflow*	24 531
	Tributary inflow	4 562
	BH1 (groundwater)	1 399
	BH2 and BH3 (groundwater)	21 918
Cell 2 – Kompanjiesdrif wetland	*Tributary inflow*	3 583
	BH1 (groundwater)	1 239
	BH2 and BH3 (groundwater)	71 155

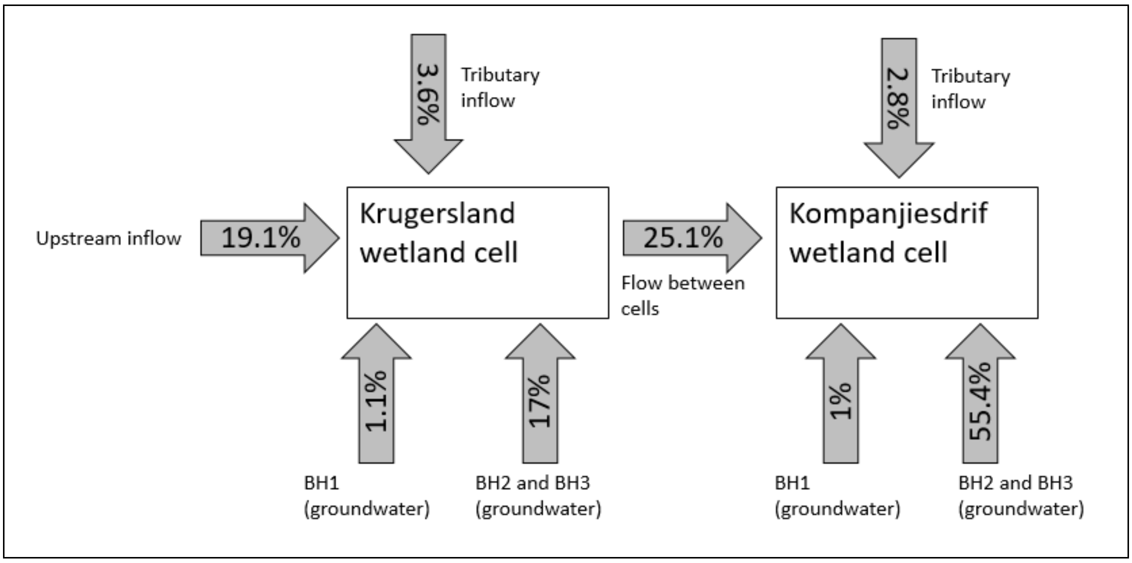


Figure 5.21 Inflow percentages determined by the MCM for the two cell model.

The MCM calculated a significant groundwater contribution to the wetlands in May 2018, whereas the GYMR estimated zero groundwater contribution for May 2018, indicating that the water quality data allows the MCM to pick up a groundwater contribution where other models may not.

5.3 Water use of palmiet

5.3.1 Evapotranspiration estimates of palmiet wetlands

ET estimates for the palmiet wetlands along the Krom River and elsewhere in the Western Cape are illustrated in Figure 5.22 below. The MODIS and Fruitlook ET estimates for the Krom River wetlands are significantly lower than the modelled Pitman ET estimates for these wetlands. Fruitlook ET data for the Krom River wetlands were only available over a short time period and it thus cannot be compared well to the other data. The Pitman ET data, however, compares well with the Fruitlook ET estimates for the Theewaterskoof and Helderstroom wetlands (these wetland sites both receive similar rainfall as the Krom River study site). The Fruitlook ET for the Helderstroom and Theewaterskloof wetland both decreased markedly between August 2017 and March 2018. This is likely due to the severe drought experienced in the Western Cape, although the ET of the Jonkershoek (higher rainfall area than the other Western Cape wetlands) and Clanwilliam (lower rainfall) wetlands did not decrease as significantly over this period. The Pitman ET for the Krom wetlands was only slightly lower over this period (even though a drought was also experienced in the Krom River catchment in 2017).

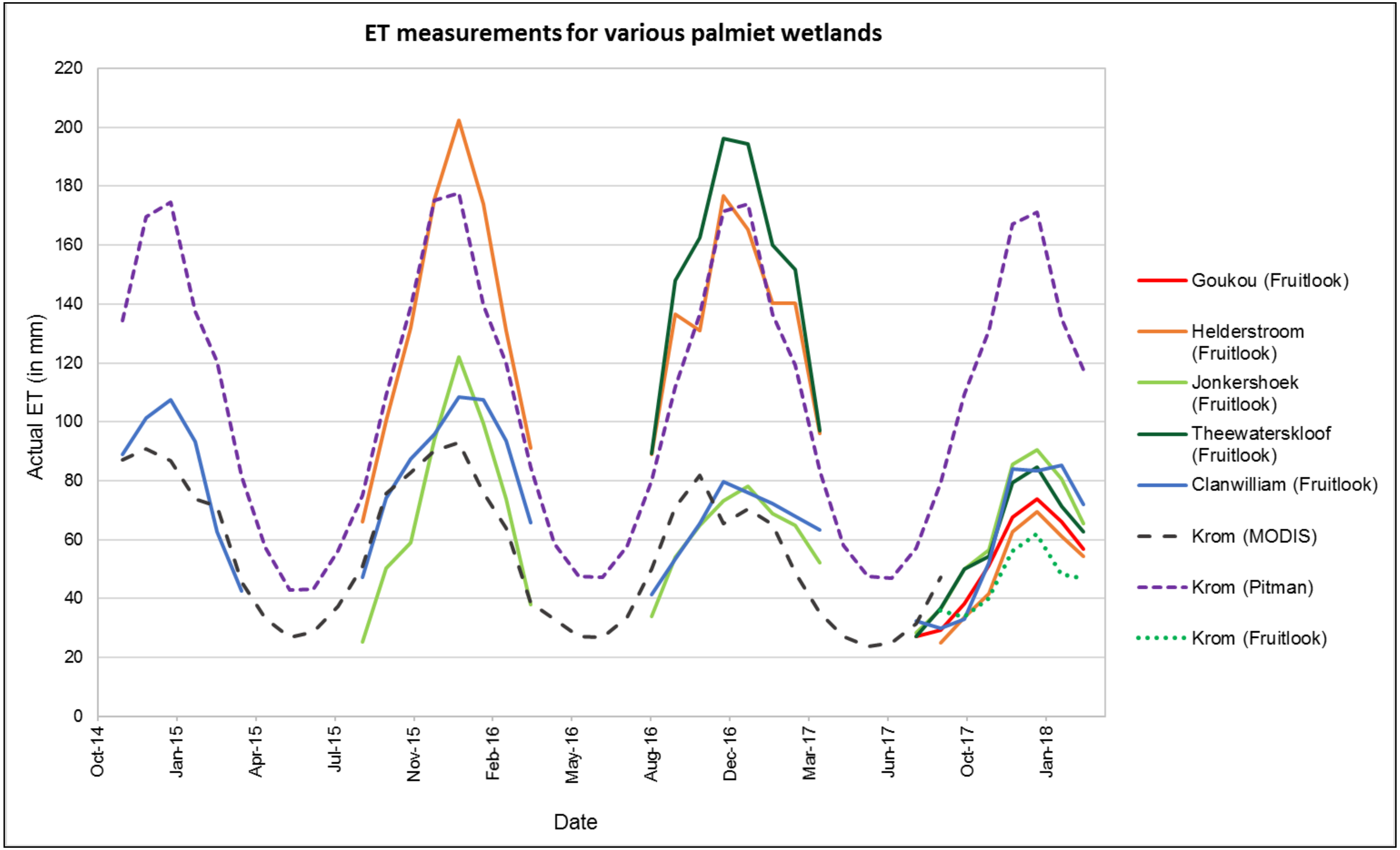


Figure 5.22 Monthly evapotranspiration rates of palmiet wetlands in the Eastern and Western Cape

Table 5.12 illustrates annual ET estimates for palmiet and other vegetation types (*Phragmites communis*, *Acacia mearnsii* and Fynbos) for various areas in South Africa and from various sources. The annual ET estimate reported by Rebelo *et al*. (2015) for palmiet along the Krom River is significantly lower than that estimated using the Pitman model. These estimates were, however, modelled over different time periods and the ACRU model was run over many more years (50) than Pitman. The ACRU model is also known to underestimate the ET of wetland plants. The annual MODIS ET for palmiet along the Krom River is lower than the Pitman ET estimate as well as that reported by Rebelo *et al.* (2015). The annual MODIS ET estimate reported by Rebelo (2012) for Jonkershoek is closer to the Pitman ET for the Krom River wetlands, but this could be because Jonkershoek receives significantly higher rainfall than the Krom River catchment and the MODIS ET is thus higher there. The various palmiet ET estimates illustrated here indicate that palmiet uses a similar amount of water (or less) as *Phragmites communis* (a common wetland plant).

Based on the available estimates in Table 5.12 palmiet generally appears to use less water than alien invasive *Acacia mearnsii* (black wattle) and possibly also less than Fynbos (depending on the area and climate). Rebelo (2012) and Rebelo *et al.* (2015) also illustrate that palmiet uses less water than *Acacia mearnsii*.

Table 5.12 Annual ET estimates for *Prionium serratum*, *Phragmites communis* (common wetland reed), *Acacia mearnsii* and Fynbos derived using various methods including the Agricultural Catchments Research Unit (ACRU) model, Pitman model, MODIS, Bowen ratio energy balance (BREB) and eddy covariance technique (Dye *et al*., 2001; Dye *et al*., 2008; Rebelo, 2012; Rebelo *et al*., 2015 and Tanner, pers. comm.).

Source	Location	ET of *Prionium serratum* (annual estimate in mm)	ET of *Phragmites communis* (annual estimate in mm)	ET of *Acacia mearnsii* (annual estimate in mm)	ET of Fynbos (annual estimate in mm)
Tanner (pers. comm.) (Pitman model – average based on 7 years of data)	Krom River (EC)	1221	-	-	-
MODIS (this study – average based on 7 years of data)	Krom River (EC)	679	-	-	-
Rebelo *et al.* (2015) - ACRU model	Krom River (EC)	694.6 ± 21.46	-	899.4 ± 44.6	430.39
Rebelo (2012) - MODIS	Jonkershoek (WC)	1043	-	-	-
Dye *et al.* (2001) – BREB technique	Jonkershoek (WC)	-	-	1503	1332
Dye *et al.* (2001) – BREB technique	Gilboa (KZN)	-	-	1260	-
Dye *et al.* (2008) – Eddy covariance and BREB	Orkney (NW)	-	1174	-	-

Table 5.13 illustrates MODIS ET data for the Helderstroom palmiet wetland (along the Riviersonderend River) versus scintillometer ET data for this wetland provided by Dr Caren Jarmain. The total ET measured by the scintillometer over a 9 day period was 35.7 mm compared to 16.7 mm for MODIS. This data and the data provided in Figure 5.22 and Table 5.12 indicate that MODIS appears to underestimate the ET of palmiet for the Krom study area. This is probably due to the MODIS pixel size and the comparatively small size of the palmiet wetlands. MODIS is therefore probably not picking up the full wetland ET signal.

Table 5.13 Scintillometer and MODIS ET data for the Helderstroom palmiet wetland over a 9 day period.

Date	Scintillometer (mm/day)	MODIS (mm/day)
14/10/2008	2.9	1.9
15/10/2008	3	1.9
16/10/2008	2.8	1.9
17/10/2008	5.9	1.9
18/10/2008	6.1	1.9
19/10/2008	6.3	1.8
20/10/2008	3.8	1.8
21/10/2008	2.9	1.8
22/10/2008	2	1.8
Total over 9 days	***35.7***	***16.7***

6 DISCUSSION

This chapter is a discussion of the project results and has been structured according to the following sections, which are listed and briefly described, below:

- *Water quality and stable isotopes*

  The water quality and stable isotope results have been discussed in detail in Section 5.1.4. Also discussed in Section 5.1.4 is the impact of large tributaries, consisting predominantly of groundwater, on the water chemistry and stable isotope signature of the main Krom River channel.

  Although the aim of the project was not to investigate the water quality and stable isotopic composition in the catchment area in great detail (or to provide insights into the possible use of this water for domestic purposes), there were some interesting water quality and stable isotope results which are discussed in Section 6.1. The catchment is located within an important water source area and it seemed pertinent to briefly discuss the quality of the water (based on the limited measured parameters) and compare it with available national water quality standards (Section 6.1.1).

- *Hydrological and groundwater modelling*

  The results of the modified Pitman hydrological model and Groundwater Yield Model for the Reserve (GYMR) are discussed in Section 6.2. The results of the mixing cell model, which was used to simulate source contributions to the wetlands, are discussed in Section 6.2.1.

- *Water use of palmiet*

  The results of evapotranspiration estimates for palmiet using Fruitlook, MODIS, scintillometer data and the Pitman model are discussed in Section 6.3.

- *Conceptual model*

  The proposed conceptual model indicating the various water sources and flow paths to the palmiet wetlands is discussed in Section 6.4.

- *Characteristics of palmiet*

  Section 6.5 discusses the characteristics of palmiet and the hydrological functioning of palmiet wetlands (Section 6.5.1).

6.1 Water quality and stable isotopes

The various physico-chemical parameters analysed for BH1 groundwater samples (in May 2017, August 2017 and May 2018) were compared with the average values reported by Smith *et al.* (2002) for the Nardouw aquifer to illustrate the Bokkeveld shale influence on the groundwater of this borehole (as discussed in Section 5.1.4). The results tend to be consistently higher than the average values reported by Smith *et al*. (2002), but are within the maximum range. The stable isotope composition tends to be more enriched in heavier isotopes than the average range reported by Smith *et al*. (2002). The $\delta^{18}O$ concentration is more enriched than the maximum reported range by Smith *et al*. (2002). Table 6.1 provides the physico-chemical and isotope results for BH1, BH2 and BH3 in May 2018 as well as the mean and maximum range for these parameters in the Nardouw and Peninsula aquifer reported by Smith *et al*. (2002).

The physico-chemical parameters of the groundwater sample from BH2 (in the Peninsula Formation) compare well with the ranges for the Peninsula aquifer reported by Smith *et al.* (2002). Chloride and magnesium are, however, higher than the maximum range reported by Smith *et al*. (2002). The stable isotope signatures are slightly more enriched in heavier isotopes than the reported range (maximum of -35.5 δD and -7.06 $\delta^{18}O$).

The physico-chemical parameters of the groundwater sample from BH3 are generally higher than the average values reported by Smith *et al.* (2002) for the Peninsula aquifer. The parameters are, however, within the maximum reported range, except for chloride and magnesium (which are also higher than BH2). This is probably due to BH3's location at or close to the Cedarberg Shale – Peninsula Formation contact (Figure 6.1). The $\delta^{18}O$ concentration is slightly more enriched than the reported range, but δD falls within the reported range. The stable isotope composition of these boreholes is, however, expected to differ slightly from the range reported by Smith *et al*. (2002) as the boreholes analysed by them were located in the Western Cape and the isotopic composition of groundwater can differ from area to area as it is affected by factors such as temperature, evaporation, altitude, amount of rainfall, etc. (Diamond, 2014).

Some comparisons have been made here between the water chemistry of the boreholes in the study catchment and results of a chemical analysis completed for various boreholes in the Nardouw and Peninsula aquifer by Smith *et al.* (2002). Parsons (2009), however, cautions against comparing the water chemistry of boreholes in the TMG with the ranges described by Smith *et al.* (2002) as the chemical ranges are not necessarily unique to TMG aquifers and the chemical composition of TMG aquifers can vary quite significantly.

The chemistry of tributary sample 2 (TS2- sampling point located within the Nardouw Sub-group, but based on the geology map is likely receiving groundwater input from the Peninsula aquifer too) is similar to BH2 and BH3 (Section 5.1.4), although the EC and chloride content is higher as a result of evaporation. TS2's stable isotope composition is also lighter (enriched in lighter isotopes) than all other surface water and piezometer samples indicating the large groundwater contribution to this tributary.

Table 6.1 Water quality parameters and stable isotopes for BH1, BH2 and BH3 in May 2018. Also illustrated are the mean and maximum values reported by Smith *et al*. (2002) for these parameters for the Nardouw and Peninsula Aquifer. EC units in mS/m for ease of comparison. Other units = pH units and mg/l. Values that are higher than the maximum value reported by Smith *et al*. (2002) are highlighted and underlined.

		EC	pH	Mg	Ca	Cl	Si	K	δD	$δO^{18}$
Nardouw Aquifer (Smith *et al*., 2002)	*Mean*	30	6	5.8	10.2	56.2	6.4	5.1	-45.2	-7.3
	Maximum	155	8.3	43.1	73.4	395.2	18.1	16.2	-27.7	-6.3
	BH1	114.9	6.21	27	13.6	298	12.7	3.3	-33.7	**-6.22**
Peninsula Aquifer (Smith *et al*., 2002)	*Mean*	10.4	6.2	1.8	3.3	18	3.8	0.8	-42.8	-7.3
	Maximum	26.3	7.6	3.2	30.4	34.1	9.4	2.3	-35.5	-7.06
	BH2	17.4	5.46	**5**	0	**61.2**	3.94	0	**-33.9**	**-6.74**
	BH3	25.8	5.92	**9**	1.2	**76.2**	9.38	**2.8**	-37.2	**-6.89**

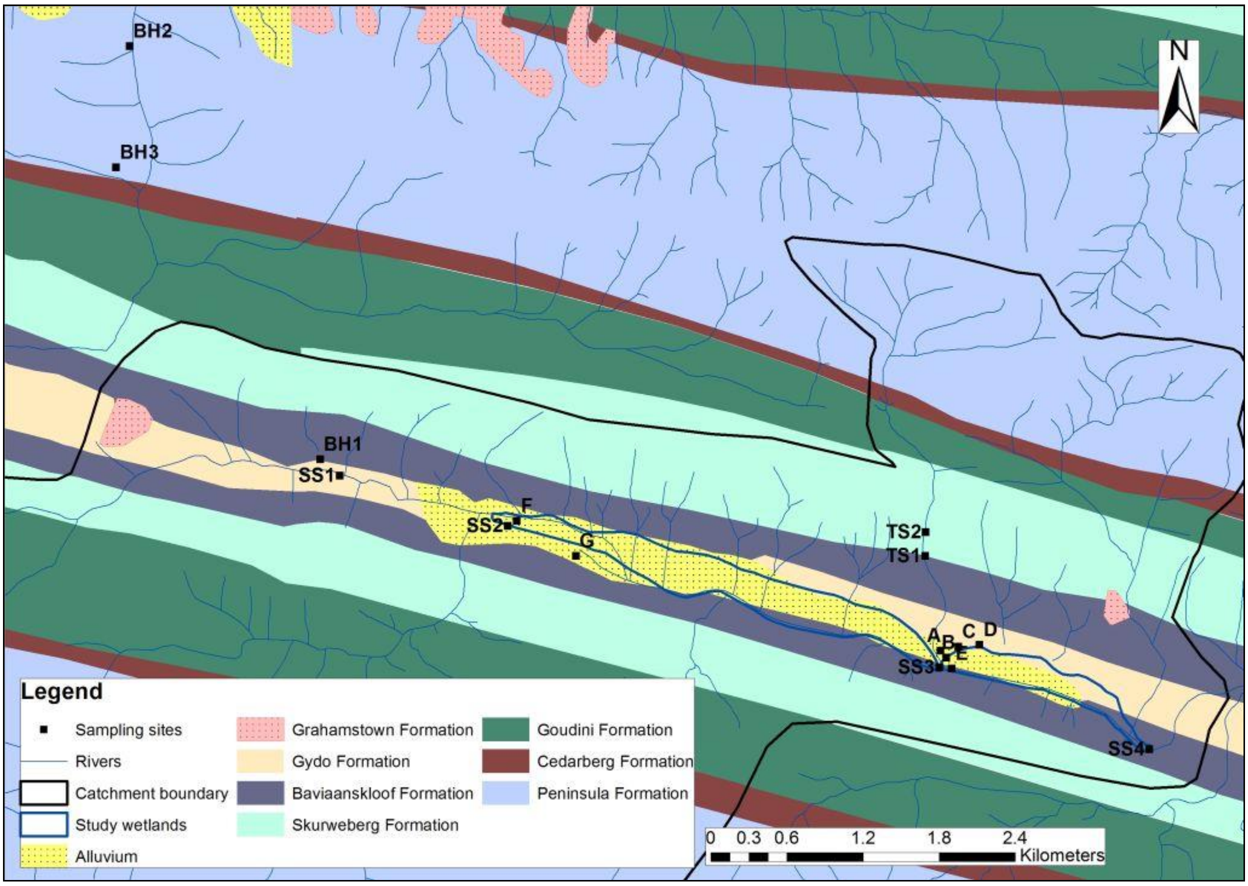


Figure 6.1 Location of the water sampling points on the 1:250 000 geological map (Toerien, 1986).

Rebelo *et al.* (2018) conducted a study of the water purification ability of the palmiet wetlands along the Krom River. The data collection for their study took place in September 2014 and three of their surface water sampling sites (K13, K14, and K15) along the Krom River coincide with SS2 (just upstream of palmiet wetlands), SS3 and SS4 (just downstream of palmiet wetlands) from this investigation.

The limited water quality parameters measured in May 2018 for these three sampling sites compare well with the results described by Rebelo *et al.* (2018), with a similar trend shown in that the majority of these parameters increase in concentration downstream (except for potassium and pH which, according to Rebelo *et al*.'s (2018) results, decrease). Figure 6.2 illustrates the pH and EC measurements taken in May 2018 for the 3 surface water sampling sites versus those obtained by Rebelo *et al.* (2018) for the same sites in September 2014. A similar increase in EC is shown, but a contradictory increase in pH is shown.

This same increase in pH downstream between sample sites SS2 and SS4 (no SS3 sample taken due to drought) is observed in the August 2017 results, but in May 2017 there is a slight decrease in pH downstream (Table 5.4 and 5.5 in Section 5.1.4). It is surprising that the pH generally increases downstream considering the typical acidic nature of peatlands (Bourbonniere, 2009; Grundling *et al*., 2017) and the constant TMG groundwater inputs (lower pH) into the wetlands. Also, the pH of PZE (in the Kompanjiesdrif wetland) tends to be lower than the downstream surface water (pH of 5.81 in May 2018), although this sample might not be directly comparable to the surface water as it extends into the peat and sub-surface.

The differences in pH (compared to Rebelo *et al.'s* (2018) data and between the May 2018, August 2017 and May 2017 samples) is possibly due to seasonal changes in the wetland hydrology or variations in agricultural inputs into the wetlands over the different time periods. Only more detailed and regular water quality sampling could shed light on the mechanisms causing these pH differences.

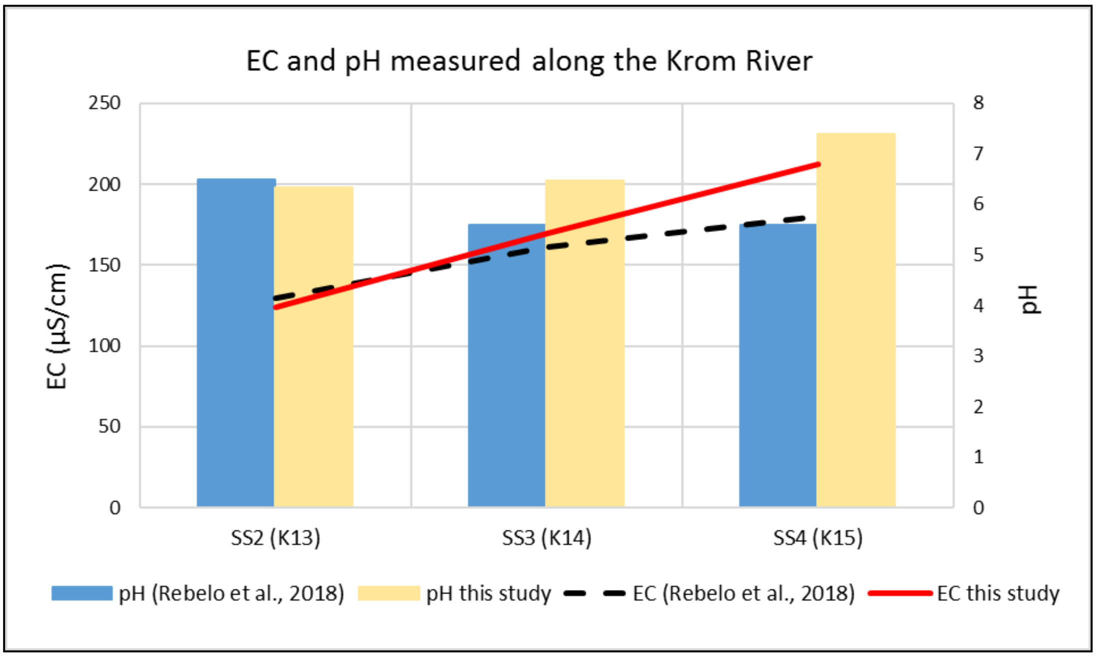


Figure 6.2 Electrical conductivity and pH measurements of selected surface water sampling sites in May 2018 along with measurements taken by Rebelo *et al.* (2018) at the same sites in September 2014.

6.1.1 Water quality and fitness for use

Smart and Tredoux (2002) describe TMG groundwater as having a high quality, low salinity, high iron concentration and as being slightly acidic (with a pH range of 5.5 to 7). The borehole water samples collected in the study area do fall within this pH range (Section 5.1.4 and Table 6.2) and also have a relatively low salinity (except BH1 which is influenced by the Bokkeveld shales).

Table 6.2 provides the water quality results of selected sample sites in May 2018 for the limited water quality parameters that were tested as well as the DWAF target water quality guidelines (1996). Water quality values that are higher than the DWAF target range are in bold and underlined, but it does not necessarily mean that water with values higher than the target range is unsuitable for human consumption. Slightly higher results can simply mean the water could affect plumbing, could taste bitter or cause corrosion of appliances. Only significantly higher values than the target range could affect human health (causing diarrhoea, nausea, vomiting, etc.).

Based on these parameters the water quality in the study area can generally be described as good. The chloride content of TS2 and BH1, and EC content of BH1 are slightly high, but the DWAF guidelines state that a chloride content between 100 - 600 mg/l is still safe to drink. The water would just taste salty and possibly cause corrosion of appliances. According to the DWAF guidelines an EC range of 70 – 150 mS/m (BH1) is still safe to drink but would taste salty. The landowner of BH1 stated that the borehole water had corroded his equipment and the borehole pump had to be removed. This borehole water is thus undesirable to use for domestic purposes. This is common for groundwater extracted from Bokkeveld shale aquifers.

The aluminium content of the tributary sample is higher than the target range, but an aluminium range of between 0.15 – 0.5 mg/l is still safe to drink. The pH of BH2 and BH3 is slightly lower than the target range and could possibly have adverse health effects. The DWAF guidelines (2016:118) state that "pH does not exert direct health effects, but may exert indirect health effects via metal solubility". Further water quality parameters such as iron, sodium, total alkalinity, sulphate, nitrate, and phosphate would need to be tested to get a clearer idea of the suitability of the water in the study area for domestic use.

BH1 (located in the Bokkeveld shale / Bokkeveld - Nardouw contact) has a higher pH than BH2 (Peninsula) and BH3 (Peninsula / Peninsula - Cedarberg shale contact) which is expected for groundwater from shale-rich aquifers. According to Dennis and Pretorius (2006:43), the "shale and mudstones have a buffering effect on the groundwater". A higher chloride concentration, possibly due to the presence of clay-rich rocks, appears to cause an increase in pH (Smith, 2006). The more crystalline Peninsula aquifers are not buffered (they have a lower chloride, calcium and bicarbonate content) and thus have a more acidic pH (Smart and Tredoux, 2002; Smith, 2006). The slightly higher pH of BH3 compared to BH2 is probably due to the buffering effect of the nearby Cedarberg shale formation on this groundwater.

The conceptual model indicates that the majority of river water is sourced from surface runoff and groundwater from the Nardouw and Peninsula aquifer and 'salty' water from the shales does not contribute significantly to the system.

Table 6.2 Water quality results of selected sample sites for May 2018 along with the DWAF Domestic Water Use Target Water Quality Range (1996). EC units converted to mS/m for ease of comparison. Other units used are pH units and mg/l. Values higher than the target range are indicated in bold and underlined.

	SS2 (upstream of wetlands)	SS4 (downstream of wetlands)	TS2	BH1	BH2	BH3	DWAF domestic water use target water quality range (1996)
EC	12.40	21.23	41.9	**<u>114.9</u>**	17.4	25.8	0 - 70
pH	6.34	7.38	6.37	6.21	**<u>5.46</u>**	**<u>5.92</u>**	6 – 9
Cl	42.3	78.4	**<u>140</u>**	**<u>298</u>**	61.2	76.2	0 - 100
Ca	0	0.8	6	13.6	0	1.2	0 - 32
Si	2.6	5.6	4.03	12.7	3.94	9.38	-
Mg	3	7	10	27	5	9	0 - 30
Al	0	0.02	**<u>0.38</u>**	0.05	0	0	0 - 0.15
K	0.6	1	1.8	3.3	0	2.8	0 - 50

6.2 Hydrological and groundwater modelling of the Krom River catchment and palmiet wetlands

The **modified Pitman hydrological model** (set up by Tanner, pers. comm.) illustrates that the palmiet wetlands play an important role in attenuating flows (Section 5.2) and retain a large volume of water in storage. This storage volume was observed to be slowly released during dry periods, maintaining downstream river flow. It was not straightforward to determine the spill relationship (the release of water from the wetland) without observed data so the model was set up to represent spill as it was conceptualised from time spent working in the catchment. The wetland spill relationship was set up to represent a system that released water slowly under lower flow conditions but released water faster as the flow increased. Above a certain flow, all water moves directly over the wetland with reduced attenuation from the wetland. The wetland sub-model was calibrated against wetland size, depth and amount of evaporation expected from the wetland. This was based on evapotranspiration from other palmiet wetlands as determined using Fruitlook (Section 4.3). The monthly average total groundwater contribution to baseflow in the catchment is 0.04 mcm/month while the monthly average total interflow contribution to baseflow in the catchment is 7.43 mcm/month. The simulated interflow component is higher but also more variable than the groundwater component, as expected.

The **Groundwater Yield Model for the Reserve (GYMR)** (Vivier *et al.,* 2009) was set up and adapted to provide a rapid estimation of the groundwater contribution to baseflow in the study catchment (Section 5.2.2). The GYMR total monthly average groundwater contribution to baseflow is estimated to be 0.09 mcm/month and a significant volume of groundwater was estimated to be in storage in the study catchment (8 297 625 m^3). The total monthly average baseflow volume compares relatively well with that modelled in Pitman (Figure 5.19 in Section 5.2). The GYMR model is not expected to give detailed groundwater baseflow estimates (it is a simple excel based model) and it was designed for groundwater reserve determination studies at a coarse (quaternary catchment) scale using mostly available desktop and literature information (in catchments where there is often sparse data available). It was set up in this study to compare with the Pitman model and MCM estimates. The recharge percentages used in the model were conservative and based on available literature. A recharge rate of 3.5% of rainfall was used for the Nardouw Sub-group and 5% for the Peninsula Formation. In a groundwater reserve determination study of the Krom River catchment Dennis and Pretorius (2006) obtained recharge estimates of 3% (of MAP) for the K90A and K90B catchments using the chloride method, 3% for a borehole in the Kareedouw area using the Earth method and 5% for the K90A catchment using a numerical model (MODFLOW).

No comprehensive studies have been undertaken on the recharge rate of TMG aquifers and recent investigations illustrate that these rates might be higher than previously thought. Recharge rates can range from around 5% MAP in drier areas to greater than 20% MAP in higher lying areas that have an annual rainfall of more than 600 mm/a. Recharge rates of 35% MAP are possible in areas receiving greater than 1000 mm/a of rainfall (Parsons, 2002).

Groundwater level and rainfall data in the study catchment could be used for estimating recharge (using, for example, the Rainfall Infiltration Breakthrough method or Water-Table Fluctuation method). These measured recharge rates (used in the GYMR) would yield a more accurate estimate of groundwater baseflow, in comparison to running the model using recharge rates from the literature. An investigation into recharge rates of the aquifers in the Krom catchment is a useful topic to be considered for future research.

6.2.1 Simulating source contributions to the wetlands using a mixing cell model

A mixing cell model (MCM), developed by Adar (1984) was set up to determine the unknown inflow volumes into the palmiet wetlands using available tracer data and an estimated outflow volume (out of the downstream wetland). Due to limited available chemical data over the study period in 2017, the MCM was only set up for May 2018. The MCM estimated a significant groundwater contribution to the wetlands, but this was during a dry period. This groundwater contribution relative to surface water would be lower during wetter periods.

The MCM groundwater contribution results are generally significantly higher than the Pitman groundwater contribution volumes into the wetlands for May 2018. The MCM cannot, however, be accurately compared with Pitman as Pitman simulates the groundwater contribution differently. The Pitman model deals with the system as an integrated system; where groundwater becomes surface water (as groundwater baseflow) and then groundwater again (transmission loss into the alluvium). Therefore the groundwater transitions repeatedly. In contrast, the MCM separates out the different water sources more explicitly (based on hydro-chemical information). The volume of groundwater contribution simulated by the Pitman model is a result of the way the model has been set up, and with no validation information for both total flow and groundwater flow, the volumes simulated by the model remain uncertain. The GYMR estimated no groundwater contribution to the wetlands in May 2018 (even though groundwater flow was observed in the wetland's tributaries), unlike the MCM.

The MCM can, therefore, be seen as giving a more accurate estimate of groundwater contribution than Pitman and the GYMR. Matthews (2013) used the MCM to determine unknown inflows into a small section of the Modder River below the Krugersdrift Dam in Bloemfontein. The MCM (and another method using water quality data – the Tracer method) found a groundwater contribution to the river whereas traditional baseflow separation methods found no groundwater contribution to the river. According to Matthews (2013), Gomo (2011) confirmed that there was in fact groundwater contributing to this river via an alluvial aquifer and reported on farmers in the area who confirmed groundwater seepage into the river. Matthews (2013:154) states that "the fact that both the MCM and the Tracer method indicated groundwater to be contributing to streamflow, while traditional methods did not, suggests that methods making use of water quality data could identify groundwater contributing to streamflow by unconventional pathways, where traditional methods could not. However, additional empirical studies and direct measurements are required to confirm this hypothesis".

It is surprising that the two cell model estimates a larger groundwater contribution to the Kompanjiesdrif wetland than the single cell model. This highlights the uncertainty associated with the MCM. The single cell model does, however, have a lower water balance error and thus, in theory, could be considered to be more accurate. Despite these uncertainties, the results from the MCM are showing that the groundwater contribution to the palmiet wetlands is significant and forms a large component of the wetland water balance.

Limitations to the accuracy of the results of the MCM include the following:

- Lack of accurate known outflow volumes from the wetlands in the catchment;
- Water samples were collected from limited sampling points. More water samples from all available large tributaries (at the source of these tributaries) entering the wetlands would probably yield a more accurate estimate of the various unknown wetland inflows;
- Only ten tracers (water quality parameters) were used in the MCM – the more tracers used the more accurate the model results;
- The model was only run using water quality data collected for one month due to the presence of the drought for most of the study period. More regular water sampling over a number of consecutive months would give a better idea of how the relative contributions change seasonally.

Although the various models (Pitman, GYMR, and MCM) used in this investigation differ somewhat in their volumes of groundwater contribution, all models pick up a significant contribution of groundwater. The MCM has demonstrated that there is little groundwater discharge into the wetlands from the surrounding Bokkeveld shale and that most of the contribution seems to come from the Peninsula and Nardouw aquifers. Since the wetlands are not in direct contact with these aquifers, the main entry point would be through the tributaries.

6.3 Water use of palmiet

Riparian and wetland plants are considered to be high water users (Birkhead *et al.,* 1997; Everson *et al.,* 2001) although this is not always the case. Some woodlands in Zambia, for example, have a higher ET than nearby wetlands (Bullock and Acreman, 2003). Rebelo (2012:135) states that palmiet “is perceived by many riparian landowners as a high water-user causing blockages in rivers, and is therefore often removed so that the floodplain sediments can be cultivated or converted into pasture”. There is limited data on the water use of palmiet wetlands, with investigations only having been undertaken by Jarmain (unpublished, 2008); Rebelo (2012) and Rebelo *et al.* (2015). In a stomatal conductance study, Rebelo (2012) determined that palmiet is a fairly low water user for a wetland plant.

Actual ET data were sourced for palmiet wetlands along the Krom River and elsewhere in the Western Cape using Fruitlook and MODIS. Modelled Pitman actual ET data was provided by Tanner (pers. comm.) for the Krom River (Section 5.3.1). The annual modelled Pitman ET estimates for the Krom River wetlands were higher than those estimated by Rebelo *et al.* (2015) using the ACRU model but compare well with the ET of the Helderstroom and Theewaterskloof palmiet wetlands (Fruitlook). The ACRU model is, however, known to underestimate ET in wetlands due to model structure issues with water availability for wetland plants (Le Maitre, pers. comm.). The annual Pitman ET estimate of approximately 1221 mm for palmiet in the Krom is not significantly higher than an annual ET for *Phragmites communis* of 1174 mm (Dye *et al.,* 2008) or the annual ET estimate for the large Mfabeni Mire of 1053 mm (dominated by reed/sedge vegetation with minor *Sphagnum* and also swamp forest) (Grundling, 2014). The Pitman ET was higher than the MODIS ET for the Krom wetlands but again, MODIS was found to underestimate wetland ET (due to lack of correspondence between pixel size and wetland size). Scintillometer ET measured by Jarmain (2008) for the Helderstroom palmiet wetland (35.7 mm) over a 9 day period confirmed this, as measured ET values were significantly higher than the corresponding MODIS ET (16.7 mm).

The modelled Pitman estimates for the Krom wetlands illustrate that ET forms a relatively small component of the wetland water balance (section 5.2.1). Rebelo (2012) states that the water use of palmiet is a cost to consider when evaluating the costs and benefits of a wetland in comparison to that of cropland, but that when the goods and services that wetlands provide are considered, it is apparent that the benefits are significantly greater than those of cropland. In the case of the Krom River palmiet wetlands, it is evident that these wetlands provide various important ecosystem services, in particular, carbon storage (Grundling *et al.,* 2017), sediment trapping and flood attenuation.

6.4 Conceptual model

The conceptual model described in Section 5.1.5 (and illustrated in Figure 6.3) describes a typical TMG synclinal aquifer setting with alluvial fans playing an important groundwater-surface water interaction role; as sub-surface water discharges through these fans into the valley bottom. TMG scenarios such as this have been described by Rosewarne (2002b), Colvin *et al.* (2003), DWAF (2008a) and DWAF (2008b). The modelling and water quality data confirm that there is little groundwater contribution from the surrounding Bokkeveld rocks, but since most of the contribution from groundwater comes from aquifers not in direct contact with the wetland, it has to be from the tributaries.

Various authors have also suggested that groundwater discharge from surrounding quartzitic sandstones of the TMG plays an important role in sustaining palmiet wetlands (Job; 2014; Bekker, 2016; Lagesse, 2017). None of these authors have, however, confirmed this groundwater discharge from the TMG aquifer into palmiet wetlands, nor the mechanisms of this discharge into the wetlands. However, this study has confirmed that there is a significant groundwater contribution to palmiet wetlands along the Krom River and has illustrated the mechanisms of groundwater contribution to the wetlands.

The proposed model is that the palmiet wetlands are sustained by sub-surface water (both groundwater and interflow) moving through tributaries and preferential flow paths in the alluvial fans which are in turn sustained by groundwater discharge from the surrounding sandstone and quartzites of the Nardouw Sub-group and Peninsula Formation. The model is supported by field observations, water quality data, stable isotope data, an ERT survey, and hydrological and mixing cell modelling. Although the MCM could not represent the tributary pathway contribution of groundwater to the wetlands well, it did confirm that there is a very little contribution from the Bokkeveld aquifer into the wetlands. This indirectly confirms the groundwater contribution via tributaries to the wetlands. If the Peninsula/Nardouw aquifer groundwater contribution was via diffuse flow, travelling through the Bokkeveld aquifer, this would be evident by a large chemical impact on the wetlands as a result of the saline Bokkeveld water (which is not observed).

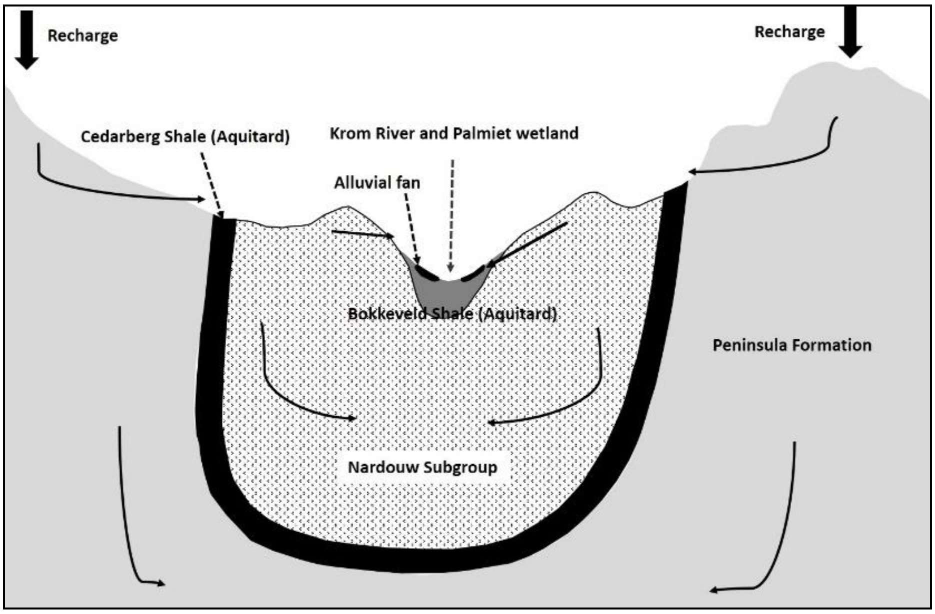


Figure 6.3 Conceptual model illustrating the sustained flow of groundwater to the wetlands via alluvial fans and tributaries, which in turn derive this water from the Nardouw and Peninsula aquifer.

6.5 Characteristics of palmiet

Similar to *Phragmites australis* (Saltonstall and Meyerson, 2016) and *Cyperus papyrus* (Ellery, 1988), palmiet behaves as an ecosystem engineer (Sieben, 2012; Barclay, 2016) because it has the ability to alter its environment and, in the case of the Krom catchment, create large unchannelled valley-bottom wetlands. Its deep rooting system and clonal growth form are thought to be key traits allowing it to play this role (Sieben, 2012).

Palmiet grows relatively quickly (Munro and Linder, 1997) and plays an important role in trapping sediment and in peat formation (Job, 2014; Barclay, 2016). It is evident that the Krom River palmiet wetlands have survived various cycles of erosion and fires over thousands of years (De Haan, 2016; Pulley *et al*. 2017 and 2018). Barclay indicates that palmiet restores eroded gullies along the Krom River and according to Lagesse (2017), Schlegel (2017) and Pulley *et al.* (2018) this gully erosion may be a natural part of palmiet wetland functioning and formation.

Palmiet most commonly occurs in the TMG sandstones (mostly in the Western Cape and parts of the Eastern Cape), but can also be found in the Natal Group sandstones (southern KwaZulu-Natal) and it is thought to only grow in acid, nutrient-poor material (typical of TMG sandstones) (Boucher and Withers, 2004; Sieben, 2016).

Munyai (2013), however, investigated the soil nutritional levels of various sites across South Africa where palmiet is known to grow, as well as sites (in the same geographic region) where it does not grow. It was found that soil nutritional values of the palmiet sites and non-palmiet sites were similar, indicating that the distribution of palmiet is not necessarily linked to edaphic factors but that other parameters (for example, hydrological regime) may, in fact, be responsible for its occurrence.

6.5.1 Hydrological functioning of the palmiet wetlands

Job (2014) postulates that the folded and fractured quartzites of the Langeberg Mountains are an important source of water to the Goukou palmiet wetland (Western Cape) and that this sustained water source appears to be sufficient enough to generate hydrological conditions that support peat formation. Job (2014) suggests that without this sustained groundwater discharge from the Cape Supergroup quartzites the wetland would probably not exist in its current form.

The project has identified that a consistent water supply in the form of low flows in rivers is important for palmiet's establishment and survival. It is thus proposed that palmiet is possibly more reliant on a consistent water supply for its existence and survival than it is on soil and water quality (acidic nutrient-poor water and soils) as stated by other authors.

The palmiet wetlands clearly retain a significant amount of water, leading to the maintenance of prolonged flows, and a larger baseflow. However, it is hypothesised that the occurrence of palmiet as the dominant species in this wetland is due to the sustained low flows related to catchment geology and high hydrological connectivity between the catchment and the wetland that is enabled by flow paths that allow the free flow of water from the catchment to the wetland.

7 CONCLUSION

The Krom River is an important water source for the city of Port Elizabeth. Palmiet wetlands along the Krom River provide important ecosystem services such as carbon sequestration, flood attenuation, water purification, and sediment trapping. These endemic wetlands are, however, particularly threatened and palmiet wetlands within the K90A and K90B catchments have decreased in size by 84% over the last century. This decline has largely been attributed to invasion by alien trees such as *Acacia mearnsii* (black wattle) and agricultural activity (Rebelo *et al*., 2015). Working for Wetlands and Working for Water have been clearing black wattle and installing rehabilitation structures in the Krom catchment for a number of years. There are, however, serious knowledge gaps in the understanding of palmiet wetland structure and function, particularly in respect of the hydrological functioning of these wetland systems.

This project was aimed at determining the hydrological functioning (with a focus on groundwater-surface water interactions) of the palmiet wetlands along the Krom River. Improved understanding of the hydrological functioning will contribute to the ongoing rehabilitation work on the wetlands as we now have a better understanding of why palmiet wetlands are found in the TMG and what conditions result in their formation. The investigation focussed on small-scale dynamics of the palmiet wetland system in order to increase general understanding of the surface water and groundwater processes of these wetland systems. Field work was concentrated on the Kompanjiesdrif and Krugersland palmiet wetlands in the upper K90A catchment. The investigation involved the installation of piezometers, water quality and stable isotope sampling and analysis, an Electrical Resistivity Tomography survey, and hydrological and mixing cell modelling. Data collection and modelling was, however, impacted by a severe drought experienced in the catchment over the study period (2016 and 2017). This drought resulted in there being a lack of flow data for the catchment.

The results of the investigation indicate that the hydrological functioning of palmiet wetlands is closely linked with high sub-surface discharges typically associated with TMG aquifers. It is proposed that the palmiet wetlands are sustained by significant amounts of sub-surface water (both groundwater and interflow) moving through preferential flow paths in the alluvial fans and tributaries, which are in turn sustained by groundwater discharge from the surrounding sandstones and quartzites of the Nardouw Sub-group and Peninsula Formation.

The palmiet wetlands clearly retain a significant amount of water, leading to the maintenance of prolonged flows, and a larger baseflow. However, it is hypothesised that the occurrence of palmiet as the dominant species in these wetlands is due to the sustained low flows related to catchment geology and high hydrological connectivity between the catchment and the wetland that is enabled by flow paths that allow the free flow of water from the catchment to the wetland. It is further proposed that palmiet is possibly more reliant on a consistent water supply for its existence and survival than it is on soil and water quality (acidic nutrient-poor water and soils) as stated by other authors.

Geomorphology is another key driver of these palmiet wetland systems and palmiet plays an important role in trapping sediment. Various authors have indicated that palmiet wetlands in the Eastern and Western Cape have survived numerous episodes of erosion over thousands of years (Job, 2014; De Haan, 2016; Bekker, 2017; Lagesse, 2017; Pulley *et al.,* 2017; Schlegel, 2017 and Pulley *et al*., 2018). It is suggested by Pulley *et al.* (2018) that gully erosion, in fact, plays a long-term role in palmiet wetland formation along the Krom River.

Palmiet forms in environments with a consistent water supply, and a regular supply of sediment. It dominates in high flood conditions due to its deep root structure and clonal growth (dependent on significant sediment supply) allowing it to withstand high floods where other wetland plants would be washed away. Due to the high sediment load, localised increases in slope lead to the formation of erosion gullies but the deposited sediment just downstream creates environments suitable for new wetland formation. The fast growth of palmiet plants allows it to quickly establish and stabilise before the next flood event. This cycle of erosion and re-establishment results in little net hydrological loss from the catchment. The local lowering of the water table in response to erosion gullies would not result in excessive 'drainage' of water from the system in the longer term due to wetland re-establishment just downstream of the eroded site.

The aims of this study were the following:

1. **Determine the surface and groundwater dynamics of the Krom River upper catchment (K90A).**

Field observations, water quality results, stable isotope results, and results of the mixing cell model indicate that the palmiet wetlands are fed by both surface runoff and groundwater from the Nardouw and Peninsula aquifers. Sub-surface water from these aquifers (both groundwater and interflow) moves through preferential flow paths in the alluvial fans and tributaries to the wetlands. Large catchment tributaries flowed continuously, even in severe drought conditions. Water quality results and results of the mixing cell model indicate that there is only minor diffuse groundwater inflow into the wetlands from the Bokkeveld shale aquitard.

2. **Identify the relationship between the palmiet wetlands and hydrological functioning of the catchment.**

Aim 2 of the study was impacted by the drought and a lack of flow data. Field observations indicate that water moves diffusely through the palmiet wetlands, with small channels forming along the perimeter of the wetlands. Zero or very low flow rates were measured in open surface water between the wetlands. Continuous outflow from the wetlands was evident, even in the severe drought confirming that the palmiet wetlands are being continuously supplied with water and that they play a role in the maintenance of these prolonged flows. The hydrological model indicates that the palmiet wetlands play an important role in flood attenuation.

Conclusions linked to the specific project aims and evidence for these conclusions are described in more detail in Table 7.1 below.

Table 7.1 Project aims and the conclusions linked to them.

Aim	Conclusion	Evidence
1. Determine the surface and groundwater dynamics of the Krom River upper catchment (K90A)	*Groundwater and interflow contribution from the TMG Peninsula and Nardouw aquifers to the Krom River tributaries recharge the wetlands via preferential flow paths within the tributary alluvial fans.* • Larger catchment tributaries flowed continuously, even in severe drought conditions. • Water quality within the tributaries is similar to that of groundwater from the Peninsula aquifer (although with evapotranspiration water losses). • The wetland was largely un-impacted by the severe drought, and remained green throughout, despite no visible inflow from the upstream river. • The water quality analysis and mixing cell model indicate a large groundwater baseflow contribution to the system. • Water level gradients within the wetland indicate that water is moving from the alluvial fans onto the wetlands	**Section 5.1.1, 5.1.3, 5.1.4, 5.2.3**
	The wetlands are located within a shale aquitard (Bokkeveld shale) with little diffuse recharge into the wetland from the surrounding shale geology. • Water quality within the wetlands and river indicates little influence from the saline groundwater within the Bokkeveld shale (demonstrated by water quality of BH1). • The results of the mixing cell model indicate only a very minor contribution to the wetlands from the Bokkeveld shale aquifer (BH1).	**Section 5.1.1, 5.1.4 , 5.2.3**
	The wetlands recharge the valley-bottom aquifers (Bokkeveld shale and alluvial deposits) outside of the recharge areas within the alluvial fans. • Water level gradients within the wetland indicate that water is moving from the wetlands onto the surrounding valley-bottom between the alluvial fans. • Sub-surface water levels on the valley-bottom (between the fans) are lower than that of the	**Section 5.1.1, 5.1.6**

Aim	Conclusion	Evidence
	wetland.	
2. Identify the relationship between the palmiet wetlands and hydrological functioning of the catchment.	*The wetlands attenuate river flows and maintain low flows.* • Water moves diffusely through the palmiet wetlands, with very small channels forming along the perimeter of the wetlands. • Zero or very low flow rates measured between the wetlands (downstream of Krugersland wetland and upstream of Kompanjiesdrif wetland) even at significant water level depths of over 1 metre. • Continuous outflow from the wetland throughout the severe drought, even with no visible upstream inflow. • According to the hydrological and wetland sub-model (non-validated), the wetlands do play an important role in flood attenuation and the maintenance of low flows.	**Section 2.7.3, 5.1.2, 5.2.1.**

8 RECOMMENDATIONS

Lack of flow data inhibited calibration of the hydrological model and the use of accurate outflow volumes in the mixing cell model. It is recommended that flow in the catchment be continuously monitored (particularly during wetter periods) to contribute to a better understanding of palmiet wetland response to moderate and high flows.

The water quality data and mixing cell model show good potential for tracing sources of water supplying the wetlands. It is recommended that more detailed water quality (including additional parameters to the ones measured in this investigation as well as additional sampling points) and isotope sampling under different catchment conditions (wet and dry) be carried out to improve the understanding of the various water inputs into the system under different conditions.

Working for Wetlands have completed various rehabilitation interventions in the Krom catchment, which (in the short term) appear to have improved the catchment for the better. De Haan (2016) (Section 3.6.1) illustrates the benefits and some drawbacks of the erosion-control structures that have been implemented below the Kompanjiesdrif wetland. This along with the work carried out by Pulley *et al.* (2018) indicates that Working for Wetlands should perhaps (in consultation with wetland specialists) look at alternative wetland protection methods (preferably less invasive methods) in the Krom catchment.

A more detailed investigation (additional to De Haan's (2016) work) into the impact of gully erosion (within the palmiet wetlands and downstream of the palmiet wetlands) on the groundwater dynamics of the catchment is a possible area for future research.

It is recommended that the palmiet wetlands in the Krom catchment be protected from any further degradation due to agricultural activities and encroachment.

Any future planned large-scale groundwater abstraction in the catchment must consider the ecological water requirements of the wetlands.

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