

Hydrological Modelling of the Rietvlei Wetland, Western Cape, South Africa: Identifying possible Environmental Impacts

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Dissertation accepted in fulfilment of the requirements for the
degree *Master of Science in Environmental Sciences with
Hydrology and Geohydrology* at the North-West University

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Graduation May 2020

24160040

ACKNOWLEDGEMENTS

*A smooth sea never made a skilled sailor.
Franklin D. Roosevelt*

Firstly, I would like to acknowledge the contribution of the Africa Earth Observation Network (AEON) Iphakade Earth Stewardship Science Initiative in funding this study – as well as Dr Gaathier Mahed's role in securing the funding and making this journey a reality.

I would also like to thank my supervisor, Prof Ingrid Dennis, for her patience and her role in ensuring that the path toward the completion of this dissertation remained possible.

A special thank you and acknowledgement to Mr Koos Retief, Biodiversity Area Manager: Milnerton (City of Cape Town Environmental Management Department) for his willingness to assist and avail the data that made this study possible. I would also like to acknowledge the researchers who undertook the initial study of the Diep Estuary, specifically Mr Hanief Ally and Mr. Ross Campbell, for their professionalism and contribution to the understanding of this dynamic area. I would also like to thank Mr Elmer Jansen for his collection of soil samples within the Rietvlei Wetland that contributed to meeting the objectives of this study.

Then - to those closest to me, none of this would have been possible without your fierce love, unwavering support and belief that this journey would indeed be worth it.

The journey has been mine – but the result is yours:

- Moeder, Susan van Staden – thank you for being the pillar that supported me. The strength and resilience you've shown and instilled in me has served as my motivation, every day.
- Sus, Chanel van Staden – thank you for being the light that encouraged me. The kindness you've shown has served as a reminder that this journey represents more than a collection of words, just as our lives represent more than a collection of days.
- Ouma, Hanna Fourie – thank you for being the breeze that guided me. The safe haven you've been reminded me that I was valued, always.

Family – the grace you've shown reminded me that a journey without purpose leads to a result without merit. Without your support, encouragement and guidance – I would not be a man deserving of this moment. Thank you most for believing in me, and providing purpose to my journey.

ABSTRACT

Conceptualizing the hydrological processes governing wetland environments is only possible when the defining attributes of the wetland are considered and understood. In this case, the groundwater level fluctuations, wetland hydroperiod (or periods of saturation), wetland residence time, groundwater-surface water connectivity and soil texture distribution of a complex coastal wetland are conceptualized to enhance the understanding of the hydrodynamics of the system.

The Rietvlei Wetland has been significantly impacted by alterations to its geomorphology and hydrodynamics due to anthropogenic stressors. Thus, by considering and quantifying these aspects in the wetland's current environment, the environmental impacts and the significance of these impacts to enact change upon the wetland may be identified.

Soil texture provides insight into the runoff/infiltration relationship and potential sub-surface preferential flow pathways within the wetland. This in return governs the groundwater movement and distribution within the wetland, as the characteristics of the porous media would determine the magnitude and direction of groundwater and surface water flow, as well as control the groundwater-surface water interactions based on the ability to conduct water horizontally and vertically. As the nature of wetland environments is defined by a shallow water-table, it makes the identification of extended periods of saturation in the current environmental setting all the more important. Identifying these events would contribute to the conceptualization of the historic impacts from and on the surrounding environment, and provide a reasonable indication of hydropatterns within the wetland. Once identified, the wetland residence time was considered, as the flow through the wetland determines the extent of its capacity to filter and flush water within the wetland environment, especially within the central Marsh/Vlei region.

Geostatistical and conceptual modelling techniques were utilized to quantify and conceptualize these aspects within the Rietvlei Wetland. Through the use of these methods - which include spatial modelling, interpolation and numerical integration - the wetland attributes were successfully conceptualized and where relevant quantified; and through the incorporation of historic data and existing literature, the significance of the impact of the identified aspects was determined by way of a qualitative environmental impact assessment.

Wetland hydrology, Groundwater, Hydroperiod, Residence time, Hydrodynamics, Soil texture, Interpolation, Environmental impact

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CHAPTER 1 INTRODUCTION

1.1 Preamble

Wetlands cover 6% of the earth's land surface and play a key role in maintaining regional ecosystem function and integrity (Erwin, 2009). Wetlands capture, store and transport water; thus, these environments play a key role in hydrological and biogeochemical cycles, and form a critical part of the water cycle (Junk *et al.* 2013). Acknowledging the significance of wetlands in water resource management, invites the need to assess wetland hydrology. Assessing the hydrological processes within wetlands is only possible when the defining factors of a wetland are considered and understood. In this case, the nature of the soils and key wetland attributes of a complex coastal wetland are assessed by considering the soil texture, wetland hydroperiod, wetland residence time, water level fluctuations and the spatial variability of groundwater salinity. These include surface and groundwater fluctuations, as well as potential tidal influences. This region and others like it have experienced adverse alterations to its natural hydrodynamics, and these have led to wetland degradation and habitat loss as a result of intensified anthropogenic activity (Hutchings and Clark, 2010; Kazezyilmaz-Alhan *et al.* 2007; Da Cruz, 2014).

The Rietvlei Wetland, located within the Western Cape Province of the Republic of South Africa, will be the primary focus of this study. The Rietvlei Wetland is a 900-hectare (ha) wetland reserve and is designated as one of the wetlands of international importance by the Ramsar Convention, which recognizes its important role in maintaining the ecosystem balance within the Diep Estuary (Coastal and Environmental Consulting, 2011).

Wetlands, such as the Rietvlei, are subject to water-dependent ecosystems where the surface water and groundwater interactions are closely linked and controlled by the hydrogeological properties, tidal fluctuations and the nature of the porous media within the bounds of the wetland. Thus, the need to view the system holistically arises. This ensures a comprehensive understanding of:

- the natural environment in its current state,
- the effects of anthropogenic pressures on the environment and the possible contribution to the decline in present ecosystems services, and
- the associated impacts on the hydrological cycle.

Once a true understanding of the system has been defined, and it creates the astute possibility of identifying pertinent environmental aspects and modelling the complexities of the associated impacts on the system in its current state.

Thus, this study presents a framework for the conceptualization of the hydrodynamics within the wetland, and its natural response to identify the key environmental aspects – with the intent to gain insight into the hydrogeological complexities of the wetland in its current state to assist future restoration and management efforts.

1.2 Problem statement

The Rietvlei Wetland is unique as it has experienced great changes over time that have altered the hydrodynamics of the wetland system. These changes have been driven by anthropogenically induced stressors, specifically via:

- (i) the dredging of the northern portion of the wetland and subsequent formation of a large central lake,
- (ii) reduced natural inflow due to upstream groundwater and surface water abstraction,
- (iii) changes in the natural salinity regime brought forth by the discharge of large quantities of freshwater effluent from an adjacent Potsdam waste water treatment works (WWTW) (Ally *et al.* 2017a; Campbell *et al.* 2017).

The Rietvlei is also home to a series of shallow pans, which are internationally recognized for their ecological importance to birdlife (Viskich *et al.* 2016). The soil characteristics and hydroperiods of these pans are of particular importance as they drive these ecological processes and provide an indication of the natural system's response to the afore mentioned stressors (Hutchings *et al.* 2016). Thus, analysing and defining key wetland attributes will aid in conceptualizing the impacts from and on the surrounding environment. These include the identification of periods of saturation that occur as a result of water fluctuations, which are governed by the porous media's ability to conduct water horizontally and vertically across the wetland, and governs the wetland's ability to store and transport water, the impacts of which are reflected by the wetland residence time

To date the Rietvlei Wetland has only been studied as a part of the Diep Estuary's hydrodynamic functioning. However, the Rietvlei itself experiences unique environmental impacts associated with the contributions from the upper catchment, historic alterations to its hydrological functioning, bidirectional flow from the estuarine environment and severe anthropogenic stressors that has impacted on the Rietvlei's ability to function as a wetland. It is thus pertinent to assess the Rietvlei Wetland in-depth to comprehend its current state and the manner in which it is impacted by the surrounding environment and vice versa.

1.3 Purpose and objectives

This study aims to define the key wetland attributes of the Rietvlei wetland, which include water level fluctuations, residence time, hydroperiod and the soil texture distribution across the wetland; which is necessary to establish a sense of the hydrodynamics of the wetland in its current state, and provide insight into how these aspects and the larger wetland are hydrogeologically connected and impacted by the surrounding environment.

To realize this scope, the following objectives were set:

1. To utilize historic groundwater (and available surface water) data to establish possible trends in pan inundation and / or identify hydroperiods associated with the wetland,
2. To reasonably define the key wetland attributes of the wetland, which include wetland residence time, hydroperiod and groundwater-surface water connectivity,
3. To utilize Soil Particle Size Distribution data to define soil types and texture distribution across the wetland,
4. To use the soil characteristics of the shallow unconfined aquifer in conjunction with the associated groundwater trends and wetland attributes to establish potential environmental impacts on the local natural environment and vice versa, and
5. To conceptualize the hydrological processes and environmental impacts associated with the Rietvlei Wetland.

Through realizing these objectives - the hydrogeological system and its natural response will be conceptualized, and a coalition of tangible hydrological data will be presented. This in turn will identify key environmental aspects and potential impacts, and in doing so highlight the interactions within the wetland environment and the significance of these interactions to cause change.

CHAPTER 2 STUDY AREA

2.1 Locality

The Rietvlei Wetland is situated within the larger Diep Estuary, which in turn forms part of the lower drainage region of Diep River Catchment, located within the City of Cape Town Municipality, Western Cape Province, South Africa (Figure 1).

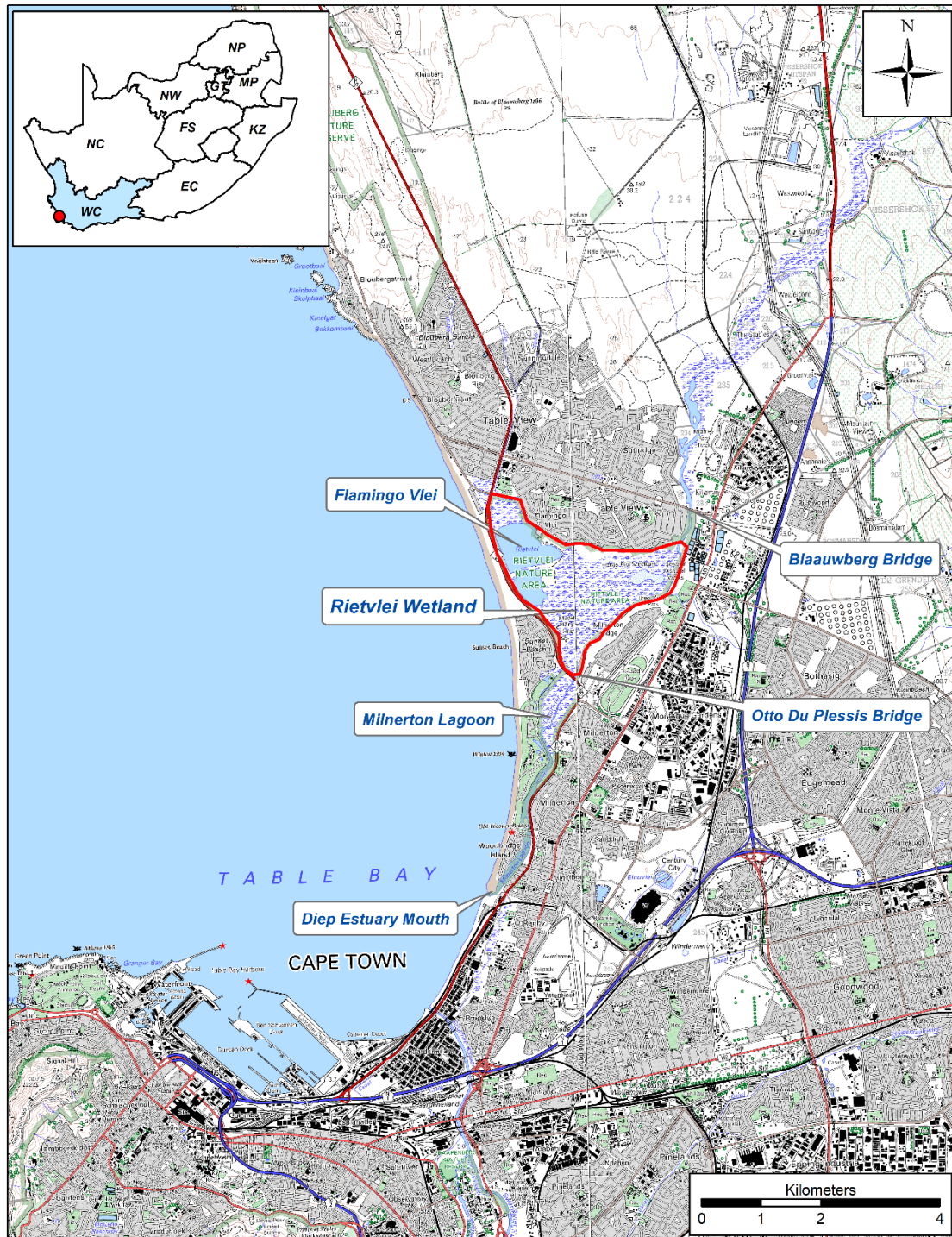


Figure 1. Locality of the Rietvlei Wetland, Western Cape Province, South Africa

For mapping purposes, the following topographical (a) and geological (b) maps were used:

- a. 1:50 000 topographical map: 3318 CD Cape Town and 3318 DC Bellville,
- b. 1:250 000 geological map: 3318 Cape Town.

The estuarine region within the catchment comprises of the Rietvlei Wetland (including the Flamingo Vlei) and the Milnerton Lagoon (including the Zoarvlei outlet), which together cover an approximate area of 9 square kilometres (km²) or 900 ha. The Diep River originates in the Riebeeek Kasteel Mountains north-east of Malmesbury and flows approximately 65 km south-west toward Cape Town before entering the Atlantic Ocean via the Milnerton Lagoon, approximately 5 km north of the Cape Town Central Business District. The total size of the Diep Catchment is 1522 km², with its main tributary being the Mosselbank River, accompanied by minor tributaries Swart, Groen, Klein and Riebeeek which merge with the Diep River prior to entering the estuarine region at the Blaauwberg Road Bridge (DWS, 2017).

2.1.1 Diep Estuary

Most recently the Diep Estuary has been described by the Department of Water and Sanitation (DWS) (2017) as a temporarily open estuary, which the Department based on the classification of Whitfield (1992). Within this report, the Estuary Functional Zone is defined as 834 ha and the canal area as 229 ha.

Historically, the Diep Estuary had been connected to the Salt River estuary via the Zoarvlei. This system drained into the Atlantic Ocean by way of two mouths, one near the present-day Salt River Canal and the other just north of the current Diep Estuary (Viskich *et al.*, 2016).

The Diep Estuary has experienced significant environmental and ecological change over time due to continuous development and anthropogenic stressors (Table 1). The most significant results of these changes have been:

- (1) changes to the natural salinity regime,
 - a. The salinity within the Milnerton Lagoon has been significantly lowered due to the addition of freshwater effluent from the Potsdam Waste Water Treatment Works (WWTW);
 - b. Higher observed salinity due to the ingress of sea water whilst the estuarine mouth is open, contradicting the upstream alkaline flows associated with the Malmesbury Shales;
 - c. A reverse salinity gradient occurs when the mouth is closed due to high evaporation rates, which may result in hypersaline conditions;

(2) sedimentation which has led to the estuary becoming shallower, altering the hydrodynamics of the system (Ally *et al.* 2017a; Campbell *et al.* 2017).

Table 1. Historic hydrological changes within the Diep Estuary (Viskich *et al.*, 2016; Jackson *et al.*, 2011)

Early 1900s	<i>The Diep Estuary is permanently open to the sea, and the Milnerton Lagoon is cut off from the sea by way of a sandbar due to large scale siltation.</i>
1950 - 1970	<i>Changes in the salinity regime of Diep Estuary are reported, as a direct result of the estuarine system transitioning to a temporarily open/closed system.</i>
1960	<i>The Potsdam Waste Water Treatment Works (WWTW) is constructed.</i>
1974 - 1976	<i>Dredging of the north-western section of the Rietvlei Wetland (and subsequent formation of the Flamingo Vlei Lake) results in the local shallow pans being pumped full of seawater, i.e. highly saline water.</i>
1991	<i>Freshwater input from the Potsdam WWTW is discharged into a canal which bypasses the Rietvlei Wetland and directs flow to top of Milnerton Lagoon. This has resulted in the Estuary becoming permanently open.</i>

2.1.1.1 Potsdam Wastewater Treatment Works

The Potsdam Waste Water Treatment Works (WWTW) is located immediately east of the Rietvlei Wetland, near the Blaauwberg Bridge where the Diep River enters the Estuarine Region (Hutchings *et al.*, 2016). It is reported as of 2016 that the Potsdam WWTW has the capacity to operate at 47ML/day, and currently operates at 43.9ML/day (City of Cape Town, 2016). The impact of the WWTW is the addition of high volumes of freshwater to the estuarine system, which is discharged into a canal (constructed in 1991) that bypasses the Rietvlei Wetland area and directs the effluent and river flow to the top of the Milnerton Lagoon. The result of the construction of this bypass canal and additional freshwater effluent has resulted in the estuary mouth remaining permanently open, which has in turn lowered the salinity of the Milnerton Lagoon, most prominently noted during summer months (Viskich *et al.*, 2016).

2.1.2 Rietvlei Wetland

The Rietvlei Wetland is defined as the area between the Otto du Plessis Drive Bridge and the Blaauwberg Road Bridge (Figure 1). The Rietvlei is a large freshwater wetland, under natural conditions (Viskich *et al.* 2016), covering an approximate area of 560 ha on the floodplains of the Diep River, which flows into the Milnerton Lagoon and, subsequently Table Bay (Figure 1). The Rietvlei Wetland is the largest temporary vlei in the south-western Cape and forms part of the Table Bay Nature Reserve (Jackson *et al.*, 2008).

The Rietvlei is home to various habitats, which include a freshwater lake (Flamingo Vlei), a series of shallow pans (prone to winter flooding), reed beds, a tidal lagoon, coastal dunes and a true riverine habitat.

Bordering the wetland are (Chapter 2.4.2, Figure 6):

- (1) intensive road networks (R27 West Coast Roads) leading to and from Cape Town and its suburbs to the west,
- (2) an industrial hub to the east that houses a petroleum refinery (Chevron), a fertilizer factory, the Potsdam WWTW and low-cost housing,
- (3) urban residential developments to the north and south of the Rietvlei, and
- (4) the Milnerton Lagoon outlet to the south at the Otto du Plessis Bridge.

Although situated in an active residential and industrial hub, the Rietvlei is home to over 180 different bird species and approximately 220 different plant species, specifically rich in Cape Fynbos. The wetland is considered a highly valuable ecosystem; thus, its importance has been recognized as such:

- (1) Identified as an important Bird Area by Birdlife International;
- (2) Importance of Biodiversity recognized by the South African Government in 1984 by establishing a Nature Reserve;
- (3) Declared as a Protected Natural Environment in 1989, and established as the Rietvlei Wetland reserve in 1993 (Hutchings *et al.*, 2016; DWS, 2017).

2.1.3 Milnerton Lagoon and Diep Estuary Mouth

The Milnerton Lagoon forms part of the lower part of the Diep Estuary, prior to the river draining into the Atlantic Ocean via the Diep River. The lagoon is an extensive water body and stretches alongside a golf course, flows toward the historic Woodbridge and drains into the Atlantic Ocean.

The Zoarvlei area (located in Paarden Eiland, south of Milnerton Lagoon) enters the ocean at the same location as the Diep River, and is considered as part of the Diep estuary (Hutchings *et al.*, 2016). Historically, the Zoarvlei connected the Diep River and Salt River.

2.2 Climate and meteorological overview

The Diep River Catchment lies within a semi-arid zone and experiences a Mean Annual Precipitation (MAP) that ranges between 400-600 mm/a, and a Mean Annual Evaporation (MAE) of 1490 mm/a (Jackson *et al.*, 2011). The natural Mean Annual Runoff (MAR) of the Diep Catchment is reported as 42 million m³/a (DWS, 2017).

Compared to the larger catchment, the Rietvlei Wetland experiences a MAP ranging between 150-300 mm/a, and a MAE of 1200-1300 mm/a (data obtained from weather station: Milnerton CW390 for the years 2016 – 2018). The Rietvlei Wetland (and larger Diep Estuary) is prone to winter flooding due to the seasonal nature of its rainfall, as the region experiences most of its rain during winter months, i.e. May through August (Figure 2).

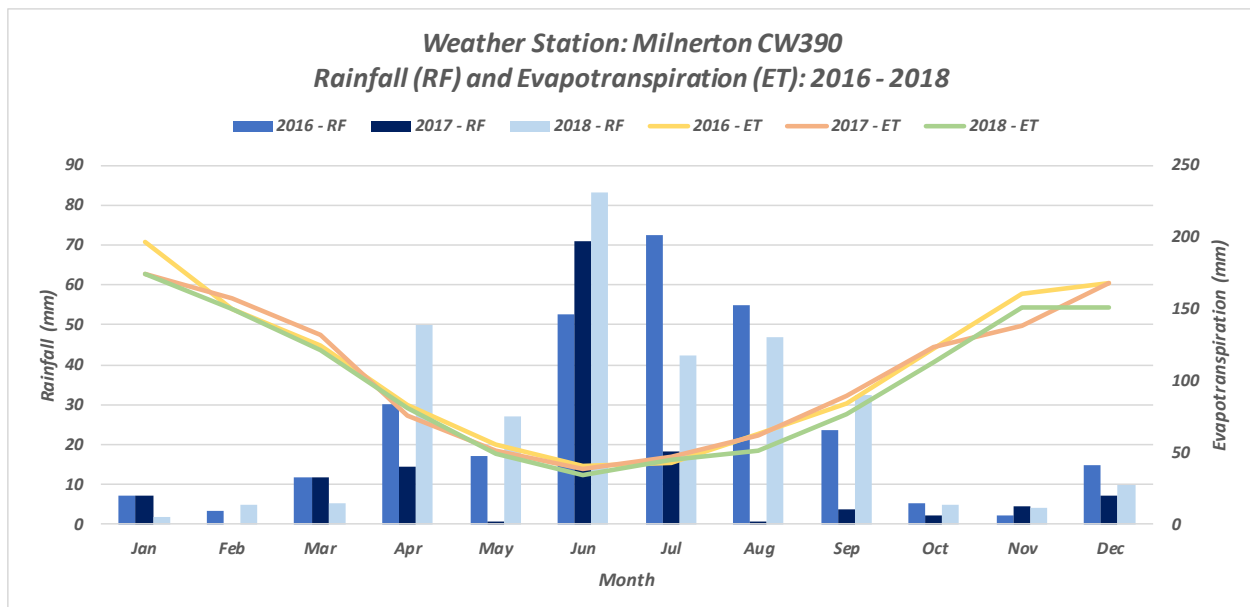


Figure 2. Rainfall and evapotranspiration within the vicinity of the Rietvlei Wetland: Weather Station Milnerton CW390

2.3 Geology

The geology of a catchment determines the contribution of groundwater to the hydrology of the system (Hutchings *et al.*, 2016). The Diep Catchment, which includes the Diep Estuary, consists mainly of formations characterized by the Malmesbury group and Cape Granite Suite (Figure 3). The weathering of the Malmesbury group shales in the catchment has led to high clay fraction within the estuary sediments (Hutchings *et al.*, 2016).

The lithological classification of the Rietvlei Wetland region can be divided into three distinct geological zones (Figure 4). The upper layer covers the entire wetland and is described as Calcareous Soil (Qb).

This layer is underlain by unconsolidated white sand (Qw) to the west, and light grey - pale-red sandy soil (Qs) to the east. These alluvial deposits overlay the bedrock of the Malmesbury Group.



Figure 3. Geological description of the Rietvlei Wetland, Western Cape Province, South Africa (1:250 000 Geological Map 3318 Cape Town)

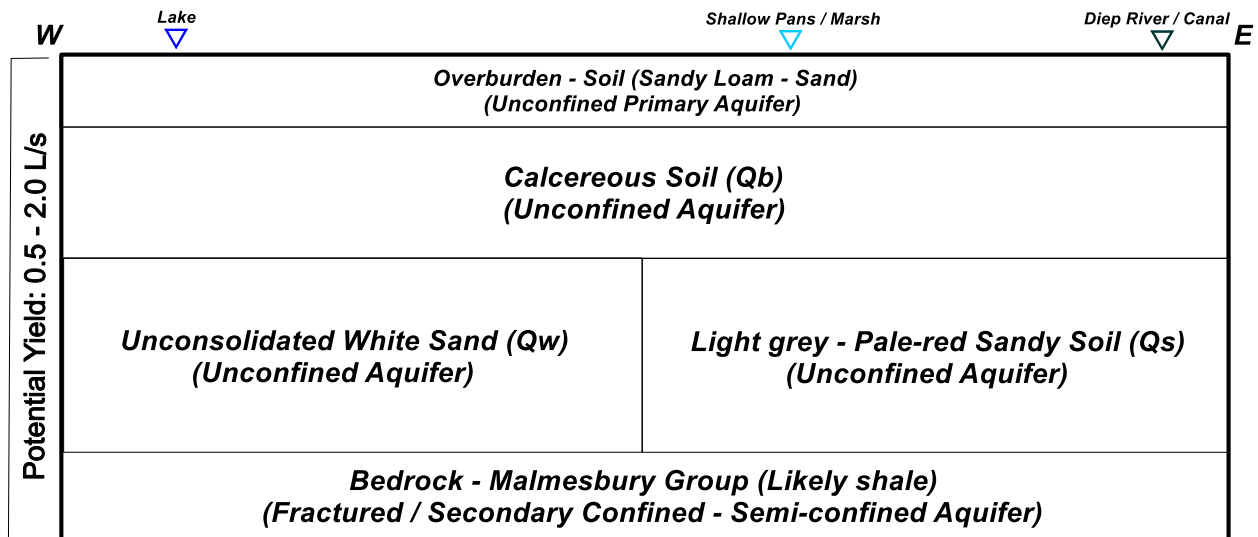


Figure 4. Simplified geological cross-section of the Rietvlei Wetland

2.4 Soils and land cover

2.4.1 Hydrological soils

According to the U.S. Department of Agriculture (USDA) (2007) SCS Hydrological Soil Groups, the soils within the wetland are classified as a dual hydrological soil group, which consists of B/C soils (Figure 5). This implies that under undrained conditions of the soils in the area would share characteristics with the Group B soils, whilst under drained conditions of the soil will retain characteristics from the Group C soils (Table 2).

Table 2. Hydrological Soil Groups within the Rietvlei Wetland (USDA, 2007)

Characteristic	Hydrological Soil Group B (undrained conditions)	Hydrological Soil Group C (drained conditions)
Runoff potential when wetted	Moderately low	Moderately high
Transmissivity and Hydraulic conductivity	Water transmission is unimpeded. Hydraulic conductivity: (1) Top 50cm: 10 - 40 micrometres per second, (2) soil deeper than 100cm: 0.4 – 4.0 micrometres per second	Transmissivity is somewhat restricted. Hydraulic conductivity: (1) top 50cm: 1.0 – 10.0 micrometres per second, (2) soils deeper than 100cm: 0.4 – 4.0 micrometres per second
Soil texture	Clay: 20 – 40% Sand: 50 – 90%	Clay: 20 – 40% Sand: <50%
Water table	Depth to water table is greater than 60cm	Depth to water table is greater than 60cm.

According to the USDA (2007), for the purpose of hydrologic soil groups, “adequately drained” means that the seasonal high-water table is kept at least 60 centimetres below the surface in a soil where it would be higher in a natural state.

The soil forms within the Rietvlei Wetland have been documented as Fernwood, Clovelly and Hutton Soil Forms (Moorcroft, 2019). These soil types are characterized by an Orthic A top horizon underlain by an E-horizon, Yellow-Brown Apedal B-horizon or Red Apedal B-horizon, respectively. These top soils (Orthic A-horizons) are characterized as a mineral horizon formed at surface, consisting predominantly of mineral particles mixed with organic matter, and would occur widespread across the wetland (Soil Classification Working Group, 1991). The E-horizon, associated with the Fernwood soil form, presents pale in colour and with a weak structure characterized by a lower content of colloidal matter (e.g. clay) than the overlying horizon (Soil Classification Working Group, 1991); and would likely be associated with the unconsolidated white sands (Qs) covering the western side of the wetland. The Yellow-Brown and Red-Brown Apedal B-horizons, associated with the Clovelly and Hutton soil forms, are mineral horizons characterized by concentrations of silicate clay, sesquioxides, organic matter, lime and the disappearance of depositional stratification by weathering of rock and soil structure (Soil Classification Group, 1991); and would likely be associated with the pale-red sandy soils covering the eastern side of the wetland.

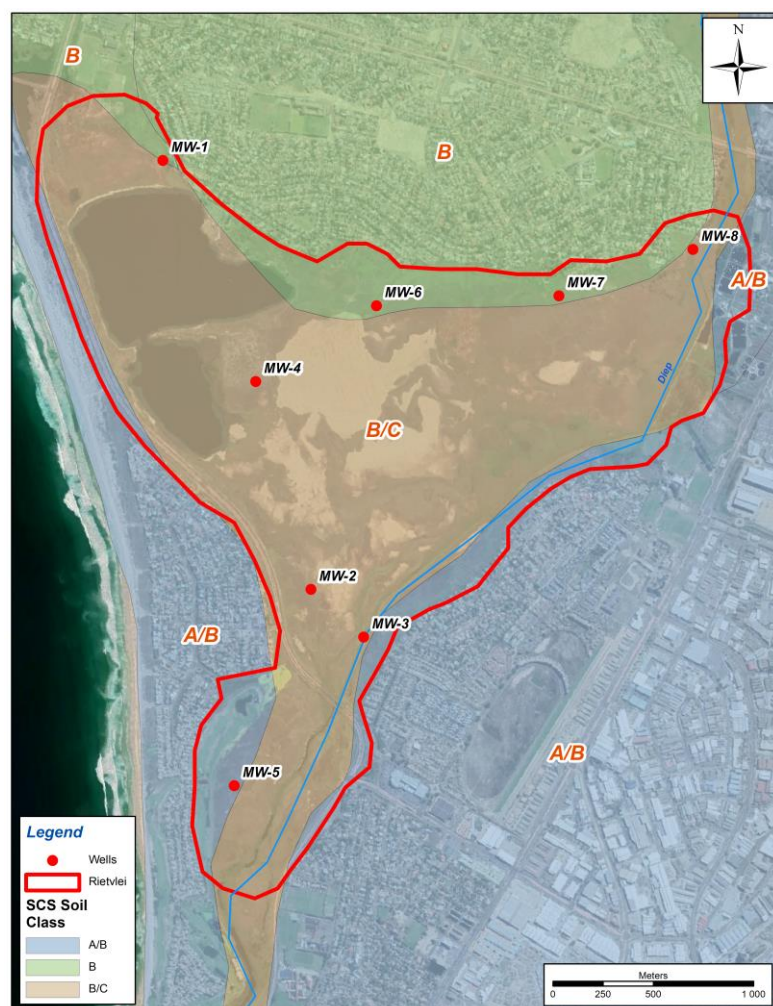


Figure 5. SCS Soil Classes: Rietvlei Wetland (USDA, 2007)

2.4.2 Land cover

The predominant land use within the larger Diep River catchment is agriculture (cultivated land); however, the area immediately surrounding the estuary is mainly urban residential, industrial and conservation (Figure 6).

Development has continued to encroach upon the estuary and has as a result altered the hydrodynamics of the system, deteriorated water quality and enhanced the invasion of alien and other indigenous species (Viskich *et al.*, 2016). Considering the environmental and ecological impacts and extent of the development the estuary has faced, it is difficult to say with certainty what its natural flow regime would look like today (Campbell *et al.*, 2017).

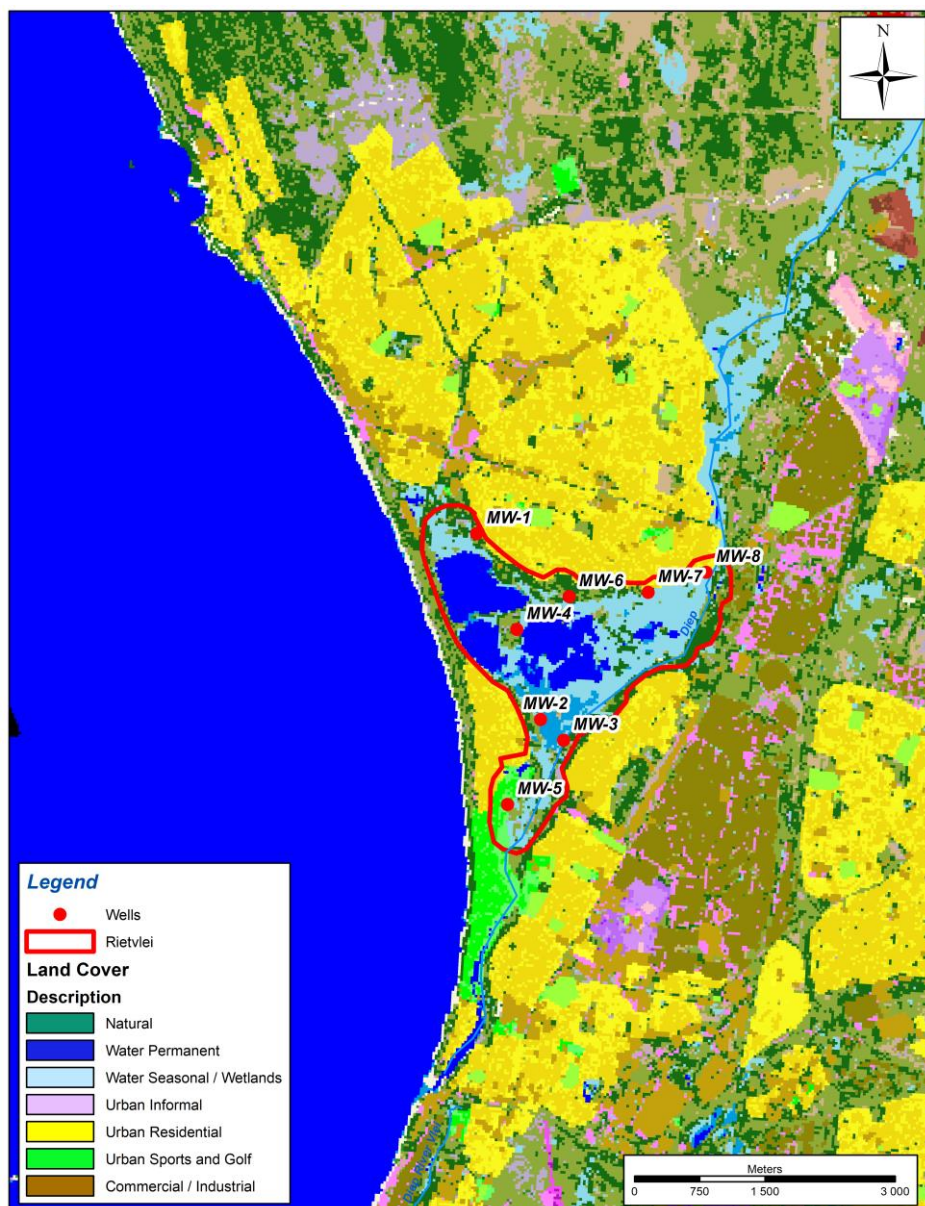


Figure 6. Land cover within and surrounding the Rietvlei Wetland (Geoterraimage, 2015)

2.5 Topography

The Rietvlei Wetland is situated within the plain, or level lands of the floodplain of the Diep River. The wetland consists of inland salt pans within the central marsh/vlei, with a freshwater lake to the north-west and the Milnerton Lagoon to the south (Figure 7). A constructed canal drains to the eastern border of the wetland, and discharges at the outlet of the wetland into the Milnerton Lagoon, prior to draining into the Atlantic Ocean via the estuarine mouth.

The surface elevation is the highest toward the northern border of the wetland, where runoff drains toward the marsh/vlei. The lowest elevation is within the central marsh/vlei, which results in a pressure gradient inducing groundwater flow toward this area.

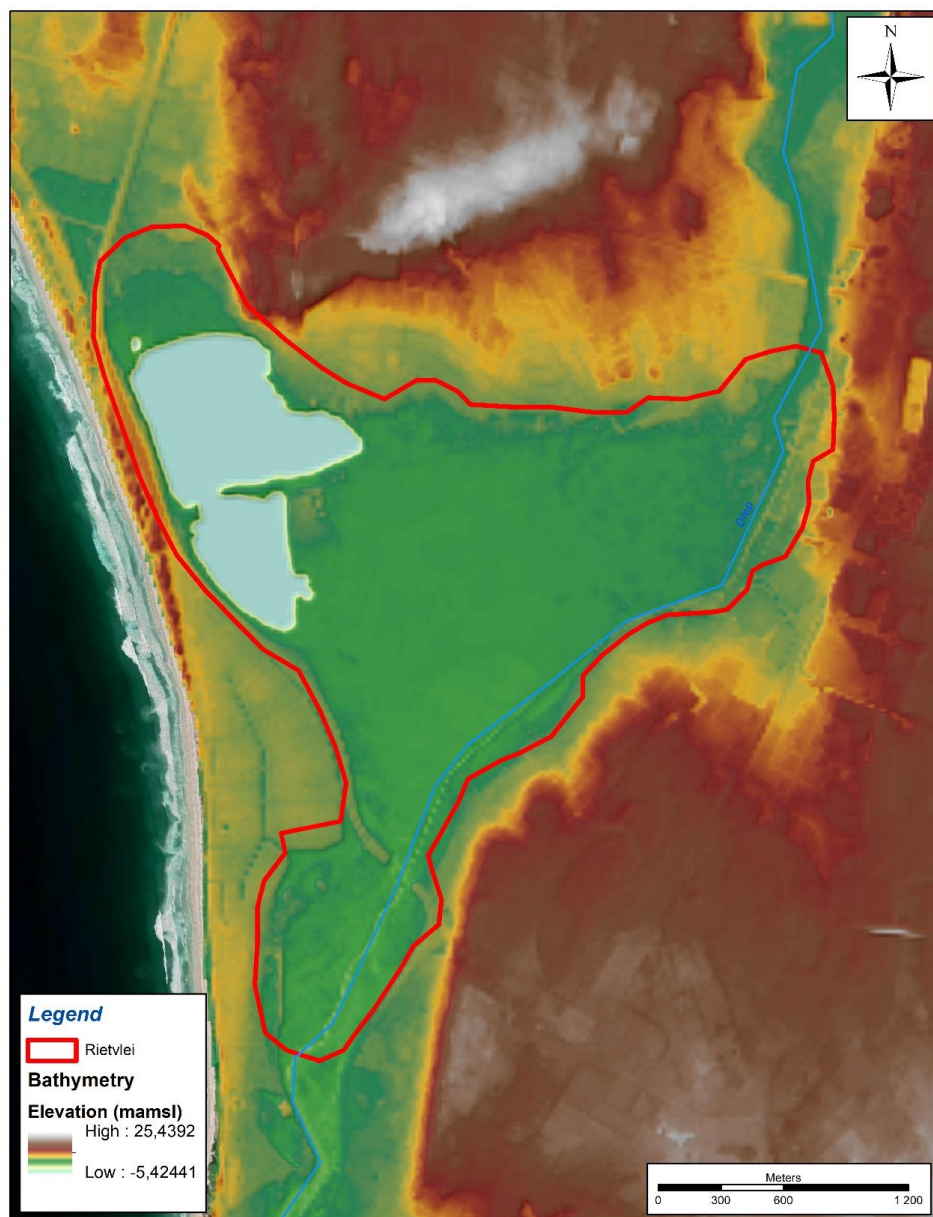


Figure 7. Bathymetry of the Rietvlei Wetland (LiDAR data UTM34S obtained from Ally et al., 2017)

2.6 Surface water

The Diep River Catchment (Quaternary Catchment G21F) forms part of the larger Berg/Olifantsdoring Water Management Area (DWS, 2017). Quaternary catchment G21F would serve as the area of interest with regards to the catchment-to-coast response, which is required to interpret the upstream impacts on the Diep Estuary, and subsequently the Rietvlei Wetland. Ally *et al.* (2017a) provides a hydrodynamic model for the Diep Estuary that considers this approach.

The Diep River is naturally perennial and dries up toward the end of summer/autumn months due to low rainfall and upstream agricultural abstractions. This dry period is associated with low runoff from the surrounding region, during which discharge from the Potsdam WWTW and urban storm-water runoff supplements flow to the river in the lower estuarine region.

Surface water features within the Rietvlei Wetland include the Flamingo Vlei, a deep-water lake (approximately 9m deep), the Bayside Canal (draining into the lake), the Diep River (and the constructed canal) and numerous permanent and seasonal pans.

The Department of Water Affairs and Forestry (DWAF) (now the Department of Water and Sanitation, DWS) operates three flow-gauging stations along the length of the Diep River and its main tributary, the Mosselbank River. Only one station has been operational post-1980 (Ally *et al.*, 2017).

According to Hutchings *et al.* (2016), the Mean Annual Runoff (MAR) within the catchment has decreased since the 1970s. The DWS (2017) states that the natural MAR of the Diep River catchment is 70 million m³/a, whilst the present-day MAR is closer to 42 million m³/a. The Natural Flow of the Diep River mouth is reported as 88 million m³/a; whilst the catchment's water demand as reported by the DWS (2017) is 75 million m³/a, of which 67 million m³/a are used for irrigation and 1 million m³/a by afforestation and alien plants.

2.6.1 Surface water quality

Hutchings and Clark (2010), Jackson *et al.* (2011) and Paulse *et al.* (2009) have reviewed the water chemistry of the Diep River. From these reviews, the authors have identified sources of contamination within the catchment, which may affect the Diep Estuary and subsequently the Rietvlei Wetland. These include:

- Run-off containing fertilizers, organic waste and pesticides from agricultural areas in the upper catchment drains toward the estuary via the Diep River;

- Storm water discharges from residential areas, which may contain contaminants, such as pathogens, nutrients and waste. Low-cost housing areas on the eastern bank is mentioned as a notable concern;
- Industrial facilities adjacent to the Rietvlei wetland, which include a petroleum refinery and a fertiliser factory – the latter having now closed, although it may still contribute to the nutrient load via storm water runoff. The primary effluent from the refinery is not discharged into the estuary, but the storm water runoff is;
- Montagu Gardens industrial area which discharges storm water via an open canal that discharges into the wetland near the Theo Marais sports fields;
- Effluent from the Potsdam WWTW, discharged into a constructed canal that diverts flow from the wetland, and discharges into the Milnerton Lagoon.

Subsequent studies in the lower reaches of the Diep River have been conducted on the storm water quality and runoff draining into the main river canal (ICE, 2011). The conclusions drawn from these studies describe the general water chemistry and noted:

- A high variability in Total Suspended Solids (TSS) content in the river, not attributed to seasonal changes,
- Strong seasonal patterns of Total Phosphorous and Orthophosphate content,
- An increase in phosphorous concentrations as a result of evapo-concentration, which is attributed to low upstream inflows during summer months,
- Strong seasonal variations in Electrical Conductivity (EC) values, with notable elevated values in the dry season and lower values in the wet season.

Other possible sources of contamination that could impact the environment and ecology of the wetland include:

- An advancing saltwater freshwater interface due to excessive groundwater pumping for small scale irrigation of household gardens, and
- Leaching of excess fertilizers, pesticides and nutrients from the golf course as well as residential areas.

Not only are these aspects of importance to groundwater and surface water quality, it could provide insight into the source for the anomalous EC values. These sources could also translate into environmental and ecological impacts on surface water bodies as a result of surface water run-off and the long residence time associated with wetlands.

Hutchings *et al.* (2016) indicate that the water quality in the Diep River and the canals draining the catchment is poor. This entails a level of environmental, ecological and hydrological

degradation, and invites the need to further assess the possible impacts on water quality. It is also noted that the bacterial water quality in the Rietvlei area is excellent compared to that of the Milnerton Lagoon and Zoarvlei area (Paulse *et al.*, 2009). The Milnerton Lagoon has in the past been declared as unsafe for recreational purposes due to microbiological contamination (Jackson *et al.*, 2011). This might be attributed to the addition of effluent from the Potsdam WWTW and subsequent runoff from the surrounding land-use.

The water quality in the lower reaches of the Diep River has not only been subject to detrimental anthropogenic stress; it has also been impacted upon by natural aspects such as the transport and deposition of weathered upstream Malmesbury Shales which has resulted in siltation and potential decreased infiltration due to a higher clay content. Thus, it is important to assess both natural and anthropogenic aspects within this region.

2.7 Groundwater

There are two prominent aquifer systems that describe the hydrogeology of the Diep River catchment (Campbell *et al.*, 2017). These are:

- (1) Intergranular aquifers consisting of unconsolidated sediments along the coastal plain, and
- (2) Fractured and weathered secondary aquifers of the Malmesbury and Cape Granite bedrock underlying the Swartland region and areas of the coastal aquifer.

The first type of aquifer predominates in the immediate vicinity of the Rietvlei due to its proximity to the ocean, as well as the unconsolidated nature of the floodplains, temporary pans and surrounding areas. Campbell *et al.* (2017) concluded that the intergranular aquifer is connected directly to the river and vlei system, and the second is present at greater depths. In this report it was also mentioned that the groundwater abstracted by the surrounding communities are likely from this aquifer. Both these aquifer systems have potential groundwater yield of 0.5 – 2.0 L/s (DWS, 2017; Pitman & Bailey, 2015).

The upper primary unconfined aquifer in the upper catchment maintains poor water storing and/or transport properties and is thought to contribute a negligible amount to the base flow of the Diep River under current conditions (Hutchings *et al.*, 2016). The negligible contribution of base flow is supported by the fact that the flow of the Diep River completely dries up during summer months due to the upstream abstraction of groundwater and surface water for agricultural use. However, under natural conditions, there would be base flow from the aquifer to the Diep River. Due to the lack of recent surface water flow data in close proximity or upstream of the wetland the current contribution of base flow could not be determined. In order to determine the actual contribution of

base flow or the lack thereof, discharge (or flow) data must be obtained by installing a flow meter at the inlet and outlet of the wetland.

Campbell *et al.* (1992) compiled a database, comprising multiple reports and interviews related to the coastal aquifers of South Africa. The Cape Flats Aquifer as well as Atlantis Aquifer, which could be seen as the most relevant to the area of interest, were also extensively reviewed and included in the aforementioned database. Table 3 provides an overview of the hydrogeological characteristics associated with these coastal aquifers. Moorcroft (2019) determined through the use of stable isotope data analyses that the main source of groundwater recharge within the region is rainfall, and indicated an average recharge of 13.42 mm/year.

Table 3. Aquifers present within the Diep River catchment (Campbell *et al.*, 2017)

Aquifer	Porosity (%)	Transmissivity (m²/day)	Permeability (m/day)	Recharge (m³ *10⁶/year)
Atlantis	23	50-1300	0-15	11-16
Cape Flats	10-12	50-650	20	60

The groundwater vulnerability within the Rietvlei Wetland and larger Diep Estuary is classified as very high according to the DRASTIC-methodology (Musekiwa & Majola, 2011). This methodology is widely applied within South Africa, and states that the inherent vulnerability of an aquifer relies on its hydrological, geological and hydrogeological properties. Thus, considering these properties within the area, a very high risk of groundwater contamination exists, supporting the importance of conserving and managing groundwater as a resource to sustain the healthy functioning of the hydrological and ecological dynamics within the area.

2.8 Biodiversity and current ecological state

This section is based on the summary of the Diep Estuary's biodiversity assessment by Hutchings *et al.* (2016). The vegetation of the Diep Estuary is subdivided into six categories, which include: open pans, sedge pans, sedge marsh, reed marsh, and perennial wetland and Strandveld species. Alien species (such as Vlei Grass, Australian Acacias and Kikuyu Grass) have invaded the estuary (Hutchings *et al.*, 2016).

A comparison of data from recent decades has shown a notable decline in invertebrate species within the Milnerton Lagoon, as well as a change in species composition. An increase in insect (and alien invertebrate) species characteristic of freshwater dominated systems was observed during the assessment conducted by Hutchings *et al.* (2016), whilst a light is shone on the decline in sand prawns in the Milnerton Lagoon in Viskich *et al.*, (2016). Fish diversity in the Diep estuary

has declined from 12 species in the 1950s to 5 species in 2014 (Viskich *et al.*, 2016). This may be indicative of ecological degradation when compared to the natural baseline state of the estuary.

According to the National Biodiversity Assessment (van Niekerk & Turpie, 2012), the Diep Estuary is rated as having a “Poor” mean Estuary Health State and was classified as an Ecological Category E (which refers to the system as highly degraded, due to extensive loss of natural habitat, biota and basic ecosystem functions). This may be attributed in part to the presence of microalgae associated with the agricultural runoff within the upper reaches and the discharge of treated waste water effluent in the lower reaches of the catchment.

Van Niekerk and Turpie (2012) identified various indicators of estuary health, highlighting that the pressures on the estuarine system are mainly related to water pollution and loss of habitat (Table 4). The estuary health condition of the system, with the exception of hydrology, are also rated as poor, due to high levels of disturbance and degradation of the natural system. Hutchings *et al.* (2016) suggests that in order for the estuary to better fulfil its ecological function, it has to be restored to an Ecological Category C by addressing the identified pressures (which refers to the system as moderately modified, where the basic ecosystem functions are predominantly unchanged; however, a loss and change of natural habitat and biota have occurred). This in turn shows that the wetland and larger area can be restored and maintained. The identified management concerns may aid in the determination of significant environmental and ecological aspects associated with the estuary.

Table 4. Indicators of Estuary Health, adapted from the Results of National Biodiversity Assessment for the Diep Estuary (van Niekerk and Turpie, 2012)

Indicator		Rating
Pressures	Change in Flow	Medium
	Pollution	High
	Habitat Loss	High
Health Condition	Hydrology	Fair
	Hydrodynamics	Poor
	Water Quality	Poor
	Habitat	Poor
	Biological State	Poor

CHAPTER 3 LITERATURE REVIEW

3.1 Introduction

Within this chapter an overview of the important terminology and definitions pertaining to the objectives set in Chapter 1, and study area described in Chapter 2 are presented.

An overview of hydrological modelling in the natural and ever-changing environment is provided within the context of the study, and sets out to discuss relevant techniques used to conceptualize groundwater levels, interpolate soil characteristics and analyse hydrological processes present within wetland environments (3.2).

Although these techniques are pertinent to meeting the objectives of this study, defining the wetland environment, its hydrological functions as an environmental resource and key wetland attributes were also considered (3.3). The wetland hydroperiod and residence time is highlighted as important attributes. Soil texture is also discussed in detail as an important attribute that controls wetland functioning (3.5). Following the overview of techniques used to understand and define wetland environments, the setting of the Rietvlei Wetland is considered by reviewing the unique hydrodynamics associated with estuaries and coastal wetlands (3.4).

Through this review, potential environmental aspects and impacts are defined and discussed within the context of the current environmental setting, and a preliminary framework for a qualitative environmental impact assessment presented (3.6).

3.2 Modelling the natural and ever-changing environment

Pitman (2011) describes the current state and future challenges of water resource assessment in South Africa, in which the decline in local hydrological monitoring is highlighted. The effective management of South African water resources relies on recognizing and understanding the limitations of these resources, both in the quantity and resilience to degrading quality. As a continuously developing country, South Africa is experiencing the present and past strains of an increasing water demand associated with social and economic growth. The appropriation of hydrological data and the advancements in technology in recent decades have provided the means of analysing and managing these challenges.

Pitman (2011) declares that the assessment of South African water resources has become even more complex in recent times due to the rapid and diverse expansion in land-use, deterioration of water quality and the need to examine the interaction between surface water and groundwater. The concerns raised with regards to the decline in the hydrological data monitoring network have

to be addressed to ensure that current and future water resource challenges are effectively managed. Inadequate hydrological data has proven to be the crux of the limitations of many local studies and pursuits to better understand the challenges South Africa faces with regards to the management of water resources.

A proper conceptualization of these challenges is essential in providing the tools needed to provide a reasonable framework that ensures the sustainability of local water resources. This is achieved by integrating soil characteristics and groundwater and surface water processes to gain a holistic understanding of the past, current and future state of rivers, dams and wetland areas. This is where hydrological modelling comes into play.

Hydrology is an elaborate science, as it aims to represent highly variable and non-stationary water-related processes (Beven, 2012). A model is defined as a simplified version of reality which helps deal with complexity by conceptualizing reality (James, 2005; Havenga *et al.*, 2007). This is clear in a hydrological model's aim to represent various components of the hydrological cycle (rainfall, evaporation, infiltration, surface runoff, groundwater recharge and base flow) and the links between them (Savadamuthu, 2007).

Whilst assessing hydrological systems, models enable hydrologists to extrapolate and interpolate hydrological variables in space and in time (Pretorius, 2011). These models are divided into physical, statistical and conceptual models (Pretorius, 2011), shown in Table 5.

Table 5. Model Types (Pretorius, 2011)

Model Type	Physical Models	Statistical Models	Conceptual Models
Description	Attempts to represent the physical processes present within a catchment	Uses mathematical algorithms to establish relationships between rainfall and runoff	Uses mathematical techniques to reduce the complexity of physical processes
Examples	MIKE SHE, SWAT, SWMM, MODFLOW, FEFLOW	Probability models; Time-series analysis	Watershed Model (Inputs and Outputs), Systems Modelling

Applied hydrological modelling techniques have proven to be accurate in representing the distribution of water within drainage regions (Beven, 2012). This is achieved by considering regional climatic conditions and physical catchment characteristics (Savadamuthu, 2007). Whilst attempting to model actual processes, uncertainty is always a concern. Thus, these models should be considered as an aid to understanding the hydrological complexities associated with areas such as the Rietvlei Wetland.

3.2.1 Modelling techniques used in present Case Study

Hydrological modelling provides a means to comprehend complex wetland hydrological processes in natural and altered environments. A model can thus be used to represent the essential characteristics of a system, comprising of a group of components or processes that interact with one another. Hydrological models can predict these interactions by addressing aspects by considering model inputs and outputs. In this case, hydrological analyses may provide a useful tool in projecting the nature of the hydroperiod in natural or altered systems, establishing an estimation of the wetland residence time, or provide insight into the soil texture distribution and how it varies spatially to potentially link this with variability in salinity or the occurrence of certain types of vegetation (U.S. EPA, 2008; Kazezyilmaz-Alhan *et al.*, 2007).

The search for simplification and generalization is restricted by the fact that the natural functions of wetlands, and specifically their determination of downstream river flow by extended residence times, are complex. Thus, a process-based approach is proposed as wetlands are non-homogenous, even at minute scales variations in the natural environment may be significant. This approach is considered within the development of conceptual models.

3.2.1.1 Water levels

Groundwater levels vary in time and space in ways too complex to represent with simple deterministic functions. Groundwater levels are used as an indicator of the stress the area is under; these levels also define the groundwater-surface water interactions and provides an indication of the groundwater gradient and flow (Münch, 2004).

SURFER, developed by Golden Software, is a powerful contouring, gridding and 3D surface mapping software. SURFER is used to analyse, map and interpolate multi-variate datasets, and may be applied in:

- Plotting groundwater elevation data to display gradients and flow direction,
- Contouring the extent of groundwater and soil contamination,
- Developing vector maps to describe the direction and magnitude of data points, and
- Creating surface maps/contours for use in groundwater flow models (Subramani *et al.*, 2012; Abu-Alnaeem *et al.*, 2018).

TRIPOL, developed by the Institute for Groundwater Studies (van Tonder *et al.*, 1996), is a software package that includes three interpolation methods: (i) classical Distance Weighting Method, (ii) Kriging, and (iii) Bayesian Estimation. Münch (2004) shows how these spatial interpolation techniques may be used in groundwater assessments to evaluate water levels.

Spatial datasets represent key components in the hydrological response of catchments to rainfall and the consequent recharge, runoff or evapotranspiration. Geographic Information Systems (GIS) may not possess the hydrological simulation capabilities of complex hydrological models, but is still useful in determining various catchment parameters and defining relationships among spatial variables, which include using Digital Elevation Models (DEMs) and spatial layers to determine the:

- (1) Flow direction and river canal characteristics (e.g. length and average slope of main watercourses),
- (2) Catchment area and physical properties (e.g. average catchment slope); and,
- (3) Distribution of geology, soil, land-use and vegetation (Gericke & Du Plessis, 2012).

ArcGIS, developed by the Environmental Systems Research Institute (ESRI), is a GIS-platform widely used for assessing, manipulating and managing spatial data – specifically ArcMap 10.2.2, which has been developed to allow users to visualize, analyse and manage spatial data to gain insight into real-world processes.

3.2.1.2 Interpolation of soil characteristics

The spatial variability of soil properties is not always reflected in conventional soil survey approaches as the soil units are limited by boundaries; thus, for the accurate estimation of soil properties continuous variability must be considered (Shit *et al.*, 2016).

Geostatistical methods, such as interpolation, are used to convert data from point observations to continuous fields. This allows the spatial variability and distribution to be quantified on the basis of the spatial scale of the study area, the distance between sampling points and the spatial patterns of by determining semi-variograms (Shit *et al.*, 2016). Thus, spatial patterns may be used to analyse the spatial variability of soil properties, such as soil texture.

Addis *et al.* (2016) assessed the performance of these interpolation methods used to predict the spatial distribution of soil properties and found that for soil textural classes, Ordinary Kriging (OK) is an acceptable, and in the case of silt and sand, preferred method of interpolating soil characteristics. Kriging interpolation can directly reveal the spatial distribution of soil properties at local scales (Shit *et al.*, 2016). Kriging is an advanced, computationally intensive, geostatistical gridding/estimation method that generates an estimated continuous surface from an irregularly spaced set of data points with z-values. Addis *et al.* (2016) and Shit *et al.* (2016) provide the equations for both Kriging and the associated semivariogram expression. Addis *et al.* (2016) also state that “Kriging utilizes the spatial variance structure available in a semivariogram and provides

a best linear unbiased estimate of an unmeasured value calculated from weighted values measured in a local neighbourhood”.

3.2.1.3 Conceptual modelling of hydrological processes

Conceptual hydrological models are used as the framework for understanding a system and the interactions between the surface and the sub-surface movement of water (Pretorius, 2011). These models lay at the heart of any quantitative analysis of hydrological components and the relationship (flows or fluxes) among features such as topography, hydraulic head differences and hydrostratigraphy (Liu *et al.*, 2017). These components are either represented graphically (e.g. geological cross-sections) or in tabular (e.g. process-flows) format.

Enemark *et al.* (2019) state that “hydrogeological conceptual models are collections of hypotheses describing the understanding of groundwater systems, and they are considered one of the major sources of uncertainty in groundwater flow and transport modelling”. This statement is important as it displays a systematic or process-based approach in conceptualizing complex systems. This involves the consideration of hypotheses which identify system boundaries, properties and processes relevant to the study at hand, and is the primary source used to assess the uncertainty associated with numerical groundwater modelling (Enemark *et al.*, 2019). These models are coupled with scenarios describing specific events, and allow the initial review of geological and hydrological concepts and data. The outputs in turn are used as a best practise to conceptualize the inputs and outputs of the system, and importantly whether or not data exists for these components (Maherry *et al.*, 2016).

Thus, the primary objective of a conceptual model is to convey the fundamental principles and basic functionality of the system it represents (Pyzoha *et al.*, 2008). This will in turn guide the determination of hydrological processes (the source, magnitude and direction) and the factors that impact them, and how these will be represented in a hydrological model (Maherry *et al.*, 2016). Conceptual models also identify the limitations of a model, by identifying the presence and adequacy of data for the various components intended to be represented by the model. This highlights the importance of conceptualizing a system before attempting to model.

Maherry *et al.* (2016) state that conceptual models are a simplification of reality but are only useful as long as the aspects considered are being monitored. In this study, the authors highlight that there is an insufficient representation of the underlying hydrological processes of wetlands in previous and current water resources assessments in South Africa, and that conceptual models are a useful tool in developing accurate and valuable hydrological models of these environments.

A simulation model cannot exist without there being a conceptual model (Liu *et al.*, 2017). Conceptual models provide a platform that considers the importance of recognizing the complex hydrological processes within wetlands, and their interaction with the environment. Thus, with an adequate conceptualization of a set of objectives, a framework is constructed that enhances the understanding of the system.

3.3 Wetlands

3.3.1 Wetland Hydrology

There is a great need to quantify the hydrology of urban wetlands as globally wetland habitat has been lost to encroachment (Kazezyilmaz-Alhan *et al.*, 2007; Viskich *et al.*, 2016). Eaton and Yi (2009) state that hydrology is considered as the most important control of wetland ecosystems, as wetlands create the hypoxic conditions necessary for hydric soil development, and the stressed conditions to which specialized vegetation adapt.

Hydrological processes in wetlands are dominated by the interaction between groundwater and surface water. The provision of this essential link results in wetlands being considered a 'water resource', which includes both their hydrodynamic functions and aquatic ecosystem support (Hunt *et al.*, 1999; Erwin, 2009; Collins, 2005).

In a South African context, these water resources are under the custodianship of the Department of Water Affairs (DWA), now the Department of Water and Sanitation (DWS). Aspects relating to the water resources of South Africa are defined, protected and regulated according to the National Water Act (Act 36 of 1998).

According to the National Water Act (NWA), wetlands are defined 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.

This definition, although adequate and widely applied, alludes to the physical characteristics of wetlands, notably wetland hydrology, vegetation and soil (Da Cruz, 2014). Another widely applied definition of wetlands, as used under the *Convention on Wetlands of International Importance*, is described below:

... 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.

Although both definitions are applicable and describe the Rietvlei Wetland, it is important to consider and distinguish between wetland and riparian areas; the reason being that key distinguishing features between wetland and riparian regions exist (Table 6), the most prominent being the extent and duration of saturation.

Both these environments are present within the study area. Riparian areas perform important ecological and hydrological functions, some of which are similar to those of wetlands. Thus, it is important to consider both wetland and riparian habitats in the process of making management decisions concerning water resources and biodiversity (Da Cruz, 2014), especially in a sensitive environment such as the Rietvlei Wetland.

Table 6. Distinguishing between Wetland and Riparian Areas, adapted from, DWAF (2005) and Da Cruz (2014)

Feature	Wetland	Riparian Area
Flow	Diffuse flow and low energy environment	Fast flowing, high-energy conditions
Saturation	Presence of water at or near the surface, either seasonally, periodically or permanently, i.e. extended periods of saturation	Not saturated long enough to develop wetland characteristics in the semi-arid climate of South Africa
	High water table resulting in saturation at or near the surface, leading to anaerobic conditions developing in the top 50cm of soil	
Soil	Hydric Soils (redoxymorphic features)	Alluvial Soils
Vegetation	Vegetation is adapted or tolerant to saturated soils, i.e. Hydrophytes	Vegetation is adapted to physical disturbances due to frequent overbank flooding from river or stream
Topography	Attributed to specific topographical settings within landscape (specific soils types or forms)	Alongside stream and rivers flowing in strongly defined canals

3.3.2 Wetlands as hydrological resources

Wetlands are unique hydrological resources and represent the transitional zone between aquatic and terrestrial ecosystems; thus, wetlands share attributes of both these wet and dry systems, as noted above. Shallow saturated conditions within these wetland environments, where perennial water lies at or near the land surface, create unique biogeochemical conditions and low energy environments, which are associated with flat landscapes (U.S. EPA, 2008).

The dynamic nature of wetland hydrology dictates that wetlands cannot be investigated separately from their regional environment (U.S. EPA, 2008). Thus, the Diep Estuary and the immediate surrounding environment is also considered during the course of the study.

The hydrology of wetlands is defined by its water budget, whereby inputs and outputs of water are identified (Brinson, 1993). Herein the authors reduce the components of a water budget to the following (Equation (Eq.) 1):

$$dS = PR + S_i + GW_i + NC_i - ET - S_o - GW_o - NC_o \quad \text{Eq. 1}$$

where **dS** represents the change in storage in the wetland; **PR** the net precipitation reaching the soil surface; **S_i** the stream inflows such as overbank / surface flooding; **GW_i** the groundwater inflow; **NC_i** the unchanneled surface water inflow; **ET** the evapotranspiration; **S_o** the stream outflows; **GW_o** the groundwater outflows or discharge to another hydrologic unit; and **NC_o** unchanneled water outflow (Brinson, 1993). Defining these sources may reveal the chemical make-up, flow paths and the energy required to transport the water to and from the wetland surface.

Water movement in wetlands are controlled by the spatial and temporal variability of energy, thus a change in energy with distance generates a force that causes water to move from zones of high energy to lower energy. These forces can be described as gravitational (moving from higher to lower elevations) or pressure (moving from high to low pressure zones), where the former dominates movement of surface water and the latter groundwater movement (U.S. EPA, 2008).

Due to the intimate linkage between surface water and groundwater in wetland hydrology, it is important to account for the influence of this interaction in wetland modelling. Kazezyilmaz-Alhan *et al.* (2007) describes the role of wetlands as a best management practise to decrease surface run-off peaks and improve surface water run-off quality. This is particularly applicable to this study, as wetland hydrology will serve as the key factor in conceptualizing and quantifying the distribution of water within the Rietvlei Wetland.

U.S. EPA (2008) defines three key hydrological variables that characterize wetland behaviour:

- (1) **Wetland water levels relative to soil surface:** Serves as an indicator of vegetation types and the wetland hydroperiod or periods of saturation,
- (2) **Wetland hydropattern:** Relates to the duration and frequency of water perturbations, and also describes the variations between inflows and outflows from the atmosphere, groundwater and surface water; and

(3) **Residence of water storage and movement through a wetland:** Relates to the ratio of the volume of water within the wetland to the rate of flow through the wetland.

Wetlands also serve as moderators of hydrological variability, storing flood flows and reducing flow velocities, thereby trapping nutrients and sediments. Thus, the hydrological nature of wetlands is unique - as the high residence time of water and periods of saturation create a dynamic hydrological system fit to sustain diverse environmental conditions.

3.3.3 Wetland hydroperiod

Groundwater level fluctuations are measured to quantify wetland hydrology - and the length of time that a wetland or part thereof is submerged to varying depths is referred to as the hydroperiod. Depth of inundation is an important component of wetland hydrology as it controls the survival of different vegetation species and the differentiation of habitat for wetland fauna.

A wetland hydroperiod considers water level fluctuations in the quantification of the wetland hydrology, and the duration of time the surface of the wetland is saturated. Mitsch and Gosselink (2007) provide an extensive definition for the term Hydroperiod:

The hydroperiod is the seasonal pattern of the water level of a wetland and is like a hydrologic signature of each wetland type. It defines the rise and fall of a wetland's surface and subsurface water. It characterizes each type of wetland, and the constancy of its pattern from year to year ensures a reasonable stability for that wetland. The hydroperiod is an integration of all inflows and outflows of water, but it is also influenced by physical features of the terrain and by proximity to other bodies of water.

Collins (2005) highlights that a hydroperiod is the result of the wetland's water balance, and therefore describes the variations in hydrological inputs and outputs that characterizes its ecology. Plots of water level vs. time have often been used to distinguish between different classes of natural wetlands (Mitsch & Gosselink, 2007).

Eaton and Yi (2009) also note that the hydroperiod concept includes sub-surface water, which relates to the time during which the soil is saturated to the land surface as the result of groundwater inundation. This is applicable to the Rietvlei wetland, as it is noted in previous reports (Campbell *et al.*, 2017) that surface flooding is a contributor to the hydroperiods noted within the seasonal pans. Hydroperiods are also pertinent to the successful development of vegetation, in particular the depth of the inundation within these zones of saturation. The importance of defining the hydroperiod of the wetland is that the treatment effectiveness of the wetland is directly related to the length of time that water is present in wetlands (i.e. hydroperiod) and hydraulic loading (inflow rate per wetland area) (Eaton & Yi, 2009; Kadlec & Knight, 1996).

Constant water depths and wetted areas are not typical of the dynamic hydrology found in tidal wetlands (Eaton and Yi, 2009). This is not solely due to tidal influence, but as a result of the geology (hydraulic conductivities of soil and rock layers) and climate (precipitation and evaporation) associated with these regions which control the hydrological response to recharge and discharge events (Boswell and Olyphant, 2006).

The different configurations of wetlands create various hydrological regimes with both unidirectional (treatment wetlands and flow through natural wetlands) and bidirectional flows (coastal and riverine wetlands). Considering wetlands experiencing bidirectional flows, the concept of a hydroperiod is not commonly quantified.

Eaton and Yi (2009) propose a method of quantifying a hydroperiod based on the analysis of the variation in water levels over time. Here they define the hydroperiod to include the proportion of time over which inundation occurs as well as the depth of inundation, so that it can be characterized for any point in the wetland where water level measurements are made. Although the authors developed the method for a coastal setting, where tidal forces control the hydroperiod, the method proposed by Eaton and Yi (2009) is also applicable to settings in which the hydroperiod is not as regular, or where fluctuations occur over longer periods in time. The proposed method applies a set of calculations for the water level fluctuation to a 24-hour period.

Water depth (h) is directly related to elevation, i.e. surface elevation (mamsl) - groundwater level (mamsl). Thus, there is a unique hydroperiod (Ω) for any elevation along the wetland profile because the water depth and wetted area changes continuously in time and space ($h=f(x, t)$).

Eaton and Yi (2009) present a scenario for tidal fluctuations over a tidal terrace using geometric methods, analytical solutions and numerical approximation. The method that would be applicable to this study is numerical approximation, which is achieved by calculating the area underneath the curve of the hydrograph representing water level fluctuation (inundation) over time.

Quantitative hydrologic analyses commonly use a hydrograph of total discharge (L^3/t) vs. time to represent stream flow, and in such cases (with the appropriate time units), the area under the curve given by the integral of the hydrograph function is understood to represent the total volume of flow (L^3) over a given time period at a specific location (Dingman, 2002 *in* Eaton & Yi, 2009). The method employed by Eaton and Yi (2009) proposes that the essential components (depth in units length, duration in units time) of the hydroperiod (Ω) of a location at any point (x) in a wetland is appropriately quantified by the integral of the water level (h) fluctuation over time, i.e. the area under the hydrograph curve.

Eaton and Yi (2009) quantify the hydroperiod of a wetland (Ω) at any point (x) as the integral of the water level (h) fluctuation over time (t) – Equation 2:

$$h = f(x, t) \quad \text{so hydroperiod } \Omega(x) = \int f(x, t) dt \quad \text{Eq. 2}$$

Difficulties associated with expressing the definition of a hydroperiod is that the function describing the water level fluctuation in most wetlands is not known, even though the water levels can be measured over time. However, Eaton and Yi (2009) state that if the function of time, $f(t)$, can be given by the observed data at a particular location, numerical integration of the water level data over time may be carried out. The resultant hydroperiod is expressed as the product of the meters inundation that occurs at a specific point per hour. The unit of time (hours, days or weeks) may be changed according to the wetland system.

Hydroperiods may be one of the most sensitive wetland characteristics when considering anthropogenic impacts, as they affect the ecosystem response to hydrological change (Collins, 2005). Thus, the importance of defining and maintaining the hydrodynamics of wetland systems cannot be understated

3.3.4 Wetland Residence Time

The hydrologic residence time is used to evaluate the time required for a hydrologic input to pass through the wetland. Quantifying the residence time within a wetland provides an indication of the circulation of water within the hydrological system, i.e. calculating the time it takes a water molecule to pass through an area.

The residence time (T_R) for a system with a constant volume and flow rate is simply the ratio between the volume of water within the wetland (V) and the flow rate (Q) – Equation 3:

$$T_R = V / Q \quad \text{Eq. 3}$$

U.S EPA (2008) states that the actual residence time is only appropriate under conditions where water within the wetland does not mix, no multiple inflows and/or exchanges occur at different points within the wetland, or flow into the wetland is not constant over time. Should these conditions not be met, the equation is still valid as an estimate of the average residence time.

Within the Rietvlei Wetland, it is assumed that the water within the wetland does not mix, and the inflow to the system is seen as the input from the runoff from the upper catchment entering the system at the Blaauwberg Bridge via the Diep River. The numerous storm water canals draining into the wetland are not continuously monitored, however Ally *et al.* (2017b) state that in the absence of more accurate data, the storm water flow may be approximated as the runoff water

entering the system. No data with regards to the outflow (at the Otto du Plessis Bridge) of the wetland has been quantified, thus the inflow is considered as the input (Q) of the system.

Different parts of a wetland may exhibit different hydrological residence times, i.e. water in active, flow through sections (streams) of a wetland may have shorter residence times than stagnant areas (ponds). However, U.S EPA (2008) states that the same equation may be applied regardless, granted each section is characterized using the volume of water present in the section, and the flow rate of the flow into the section of interest. In this case, the central pan (or Marsh/Vlei) area within the Rietvlei Wetland is considered.

3.4 The hydrodynamics of estuaries and coastal wetlands

The hydrology of coastal wetlands is characterized by strong, dynamic interactions between surface water and groundwater, which support the important functions of these environments (Yuan *et al.*, 2011).

Hydrodynamics refer to the movement of water and the capacity of water to enact change, i.e. transport sediments, flush hypersaline water from sediments and transporting nutrients to root surfaces (Brinson, 1993). The author also highlights three categories of hydrodynamics, which are considered in this study:

- a. Vertical fluctuations of the water table that result from evapotranspiration and subsequent replacement of precipitation (recharge) or groundwater discharge into the wetland,
 - a. Variables affecting vertical fluctuation, in this case groundwater rise and fall, are the rate of evapotranspiration and the frequency at which water deficits are replaced by groundwater transport and surface flow, as the direct result of precipitation inputs, i.e. groundwater recharge.
- b. Unidirectional horizontal flows that range from strong canal contained currents to sluggish sheet flow across a floodplain,
 - a. Ranges from barely perceptible surface or near surface movement to strong canal-contained erosive currents. In this case the Diep River, Potsdam WWTW canal and northern trenches account for the wetlands unidirectional horizontal flow.
- c. Bidirectional flows at the surface or near surface flows resulting from tides (Brinson, 1993),
 - a. Accounts for tidal influence, which on the wetland surface tend to be low.

The movement of water corresponds to the topographical setting of the wetland; thus, an estuarine setting is considered.

Groundwater in these environments may be defined as the water that is in the saturated zone, where it occupies the empty spaces (pores or fractures) in geological formations. Due to the fairly slow water movement through the sub-surface, once pollution enters an aquifer (or groundwater body), it could stay within this zone for lengthy periods of time (Yuan *et al.*, 2011). The infiltration of surface water may result in groundwater recharge, granted the water moves through the unsaturated (or vadose) zone. Due to the hydrogeology of the region, i.e. primary unconfined aquifer, the movement of groundwater and surface water is governed by topography and soil characteristics, which is indicative of movement of water from high (recharge) to low (discharge) elevations due to a gradient-difference.

An estuary refers to a body of water that forms the interface between a river and the ocean it flows into (Yuan *et al.*, 2011). Thus, estuarine regions link terrestrial and coastal ecosystems, which include dynamic estuary and coastal wetland ecosystems. Estuarine regions around the world are continuously under pressure. These pressures mostly relate to human activities (e.g. urbanization, agriculture and fisheries) which compromise the integrity of these systems by deteriorating local and upstream water quality.

Estuaries may be permanently or periodically open to the sea via an estuarine mouth, i.e. where the river drains into the sea (DWAF, 2005). When open to the sea, estuaries are characterized by water level fluctuations governed by ocean tides, and experience higher salinities due to saltwater intrusion (U.S. EPA, 2008).

These regions are reliant on the processes present within the entire river-basin, as estuaries are situated at the lowest point of a drainage basin. Therefore, it is important to factor in the potential impacts of the variability of spatial and temporal processes from upstream catchments.

3.4.1 Conserving and managing wetlands

Wetlands change over time through natural and anthropogenic impacts, and these changes affect the wetland's hydrology (U.S. EPA, 2008). Development has continued to encroach upon the Diep Estuary and as a result have altered the hydrodynamics of the system, deteriorated local water quality and led to an invasion of alien and indigenous species.

In the case of the Rietvlei, the Diep River forms a floodplain that provides a landscape position that allows wetland development. Natural forces of change may include materials such as sediments from upstream erosion. Human alteration is, however, a substantial force of change. The effects of human change to the environment are noted within the Rietvlei, as increased nutrient loads are present due to the discharge of waste water via trenches alongside the northern

boundary, increased sedimentation due to increased inflow from the discharge of water from the Potsdam WWTW and a host of other impacts discussed in Chapters 2 and 5.

Estuaries are highly productive ecosystems and provide an array of ecosystem services ranging from nurseries for fish and bird habitats, to recreation for local communities. These areas are highly vulnerable to urban development and as such, estuaries in close proximity to developed areas have been degraded. Locally this is the result of poor governance, as estuaries were not classified within the mandate of a specific government Department until 2008, when the implementation of Estuary Management Plans had been included within the National Environmental Management: Integrated Coastal Management (Act 24 of 2008). The C.A.P.E. (Cape Action for People and the Environment) Estuaries Programme has provided funding for these Estuary Management Plans, enabling a sustainable period of studying these environments, specifically the Diep Estuary, Western Cape Province, South Africa (Coastal and Environmental Consulting, 2011).

Recognizing the importance of these environments has led to an interest in understanding the nature of change within and surrounding wetlands, such as the Rietvlei, as these are highly valuable natural systems providing necessary ecosystem services. Thus, providing insight into the environmental aspects, such as the soil and groundwater characteristics within the wetland, would aid in the conservation and management of the wetland, as unknown attributes would be defined and aid future decision making.

3.5 Soil texture

Soil texture is one of the most important properties displayed by soil maps and may be defined as the relative proportions of clay, sand and silt content of a particular soil. Soil texture has a significant influence on the physical and mechanical behaviour of the soil and on the properties related to water content and, pertinent in this case, the movement of water. Soil texture directly affects the porosity of soil, which in turn, determines its water-retention, flow characteristics, rate of water intake, nutrient-holding capacity and long-term soil fertility (USDA, 2007).

In this case, the United States Department of Agriculture (USDA) textural soil classification is utilized as it considers Particle Size Distribution (PSD) as a determinant of infiltration rates of soil, and is commonly used around the world in water resources engineering (Garcia-Gaines & Frankenstein, 2015). The USDA classification system is based on the following primary classifications (Garcia-Gaines and Frankenstein, 2015):

- Sand: particle sizes ranging from 2.0 to 0.05 mm in diameter
- Silt: particle sizes ranging from 0.05 to 0.002 mm in diameter

- Clay: particles smaller than 0.002 mm in diameter.

These classifications are further refined in 12 classes described within the USDA triangle, soil texture classes (Figure 8). For the purposes of this study, the percentage of each grain size detected in the laboratory analysis was grouped according to the “Udden-Wentworth” size scale (Figure 9), and grouped within the USDA soil textural triangle (Figure 8) used to describe the distribution of the grain sizes and subsequent soil types at various depths across the wetland.

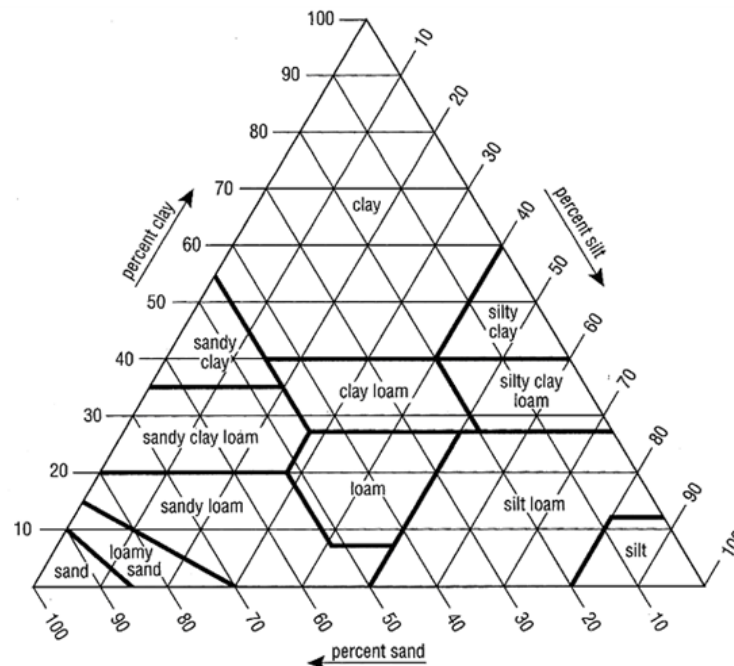


Figure 8. USDA soil textural triangle (Soil Survey Division Staff, 1993)

Millimeters (mm)	Micrometers (μm)	Phi (φ)	Wentworth size class
4096		-12.0	Boulder
256		-8.0	Cobble
64		-6.0	Pebble
4		-2.0	Granule
2.00		-1.0	Very coarse sand
1.00		0.0	Coarse sand
1/2	500	1.0	Medium sand
1/4	250	2.0	Fine sand
1/8	125	3.0	Very fine sand
1/16	63	4.0	Coarse silt
1/32	31	5.0	Medium silt
1/64	15.6	6.0	Fine silt
1/128	7.8	7.0	Very fine silt
1/256	3.9	8.0	
0.00006	0.06	14.0	Clay

Figure 9. Udden-Wentworth sedimentary grain-size scale (Wentworth, 1922)

This is pertinent as it would provide an indication of the infiltration characteristics of the wetland, which is linked directly to the system's hydrological response to recharge (groundwater) and runoff or surface flooding (surface water).

The primary classes described by the USDA were considered during the investigation, however the "Udden-Wentworth" size scale was selected to group the PSD in the various grain classes, as this classification is applicable to sediment and sedimentary rock (Figure 9).

In order to gain insight into the shallow unconfined to semi-confined aquifer that influences the groundwater fluctuations within the wetland, the distribution of the soil types must be defined, and in doing so provide an indication of the associated soil properties within the wetland. This can be achieved by way of interpolating soil characteristics, as discussed in section 3.1.1.2 (Deshmukh & Aher, 2014).

3.6 Environmental aspects and impacts

The natural environment is subject to continuous change associated with the increase in human population and encroaching developments. Nowhere are these changes of more significance than in water-dependent systems. These systems are sensitive to change, whether of natural or anthropogenic origin. Thus, it is important to identify these factors of change and the potential impact they might have on the functioning of these water-dependant systems, such as the Rietvlei Wetland.

A method of achieving the aforementioned, is by distinguishing between environmental aspects and impacts (Lappalainen *in* Jinseng, 2009). The potential of change within or to the natural environment is described as Aspects. The potential adverse effects of these aspects, or drivers of environmental change, on the natural environment are described as Impacts. Environmental impacts are the by-product of human activities that involve the reduction of environmental quality. This link between environmental management and the natural environment can thus be used to identify potential environmental aspects and their associated impacts to aid the management and conceptualization of natural and altered environments.

Environmental aspects can either result in positive or negative feedback from the natural system. These impacts can cause a change in the surface water flow regime, impact groundwater quality, cause ecological degradation and adverse health effects to surrounding communities.

In order to fully understand the application of the above-mentioned concept, an assessment by Lappalainen (*in* Jinsheng, 2009) wherein the environmental and ecological impacts of peat cutting and removal will be used as an example of the use of this methodology (Table 7).

Table 7. Aspects, impacts and potential degradation associated with harvesting peat (Lappalainen, 2009)

Aspect	Impact	Potential Environmental/Ecological Degradation
(a) Runoff	(1) Change in regional hydrology (2) Quality of surface waters	i. Siltation of downstream receiving bodies ii. Eutrophication

3.6.1 Potential environmental impacts associated with the Rietvlei Wetland

In essence, any change to the environment or resulting ecological degradation may be the direct or indirect result of the interaction between humans and the environment, or natural processes of change over time.

These aspects relate to changes in soil, vegetation, surface water and groundwater hydrology, land cover, ecology and socio-economic development. Table 8 presents a list of potential environmental aspects and potential impacts as reference for the objectives of the study (Block, 1999; Rhoades *et al.*, 1992).

Table 8. Potential environmental aspects and impacts associated with wetland environments (Block, 1999; Rhoades *et al.*, 1992)

Aspect	Impact
Irrigation	Soil degradation due to salinization and water logging.
Dissipation of stream energy	Reduces soil erosion and lessens turbidity. Long term impacts may include siltation which alter the characteristics of the wetland, e.g. reducing infiltration.
Biodiversity	Increase or decrease due to environmental or ecological impacts, e.g. pollution
Seasonal or perennial flow of water	Native landscape irrigation. Inputs from WWTW. Upstream abstraction of groundwater.
Land cover	Increase or decrease surface water run-off or infiltration.
Vegetation	Affects the efficacy of transferring nutrients to the food web, mitigating water temperature changes by producing shade and maintaining the geomorphology of riparian and wetland habitats.
Soils (hydric soils)	Possible anaerobic soil conditions due to permanent or seasonal soil saturation.
Erosion buffer	Absorbs the impacts of factors such as climate change, runoff and boat-wake.
Ecological succession	Soil and carbon cycles are stabilized, and surface is protected against drying.
Flow inhibitors	May cause distortion of natural hydrographs, via the inclusion of dams (or dam walls), artificial wetlands, canal diversions etc.
Agriculture and industrial pollutants	Reduces water quality and increases nutrient loads which may lead to eutrophication.
Social aspects	Encroachment as a result of increased property values associated with natural features may lead to pollution and a loss of habitat.

CHAPTER 4 METHODOLOGY

4.1 Introduction

This chapter provides an overview of the methods and techniques used to conceptualize and define the aspects discussed in the previous chapters.

These include:

- An analysis of the key wetland attributes and groundwater flow within the wetland, specifically a quantitative hydrological analysis of the wetland hydroperiod and wetland residence time (4.2),
- The interpolation methodology imposed to classify the soil texture within the wetland (4.3), and
- The framework for a qualitative environmental impact assessment that considers the outputs from all the aforementioned analyses (4.4).

4.2 Analysis of the Key Wetland Attributes of the Rietvlei Wetland

Eight shallow groundwater monitoring wells (Well 1 – Well 8) were sunk during the course of April 2015 by a team of scientists commissioned by the City of Cape Town to gain insight into the groundwater and surface water interactions and hydrodynamics within the greater Diep Estuary (Ally *et al.*, 2017a; Ally *et al.* 2017b), see Figure 11 (Chapter 5, p. 55). The data from this study was made available by the City of Cape Town for the purposes of this study.

The groundwater levels of each well were plotted over a period of time, and compared against the surface elevation, both in metres above mean sea level (mamsl) in order to establish an exceedance of this interface. An exceedance of the groundwater-surface interface would indicate the occurrence of a hydroperiod or period of saturation brought forth by surface flooding or pan inundation. Data availability varied for each well, and the monitoring period stretched from April 2015 to April 2018, with notable data gaps in all wells from 17 May 2015 to 27 June 2015 due to the memory of the data loggers being at capacity.

Thus, the period spanning the months of July to December was identified as the most complete sets of data across all wells, and are compared at each well for the years 2015 and 2016. This period falls within the annual wet season in the Western Cape region, which usually occurs during the winter months. The complete data sets for 2016 are used as reference to establish seasonal hydroperiod trends across the wetland (Annexure A).

4.2.1 Groundwater flow

Groundwater elevations (mamsl) were calculated by subtracting the measured groundwater level (mbgl) from the observed surface elevation (mamsl). Upon review of the available data, two distinct trends in the groundwater elevations were observed: (1) January to June is generally associated with deeper groundwater levels, whilst (2) July to December presents shallower groundwater levels and the potential for the occurrence of hydroperiods.

Thus, average groundwater levels for these two trends were calculated during 2016 (prior to the data gap from 01/01/2016 to 22/05/2016, and following the data gap 28/06/2016 to 31/12/2016) for each well, and used to generate groundwater contours and conceptualize the groundwater movement within the wetland. These periods are the only time-frames for which data is available at all wells for an entire year (Annexure A).

The first step in undertaking the conceptualization of the groundwater regime within the Rietvlei wetland, is visualizing its extent, distribution, composition and interaction with the surface environment. To accomplish this, mapping software capable of gridding and interpolating data is required. For the purposes of this study, SURFER (Version 13) was identified as the ideal package. Additionally, TRIPOL software was used to generate values for unknown groundwater levels within the wetland and adjacent estuary.

The TRIPOL input datasets consisted of data inputs from the eight known wells, which included their location (x- and y-coordinates), the measured groundwater levels (for the periods mentioned above) and the elevation values extracted from a continuous surface elevation raster generated from the LiDAR data for UTM 34S (Ally *et al.*, 2017a).

Groundwater level data spanning January to June 2016 was used to establish a statistical correlation, as it was observed that hydroperiods or recharge events negatively influence the correlation between groundwater and surface water elevations, which are more apparent during the second part of the year. Upon examination, it was found that in the study area for the aforementioned period, groundwater elevation and topography are correlated ($r=0.918$; $p=0.0036$; $R^2=0.842$). The relationship between groundwater elevation and topography is shown in Figure 10. The Bayes Estimation (Kriging) interpolation method has thus been selected as the preferred tool, as there was a strong correlation between groundwater and topography. Thus, the groundwater level estimates will be valid as the aquifer is unconfined to semi-confined (Münch, 2004).

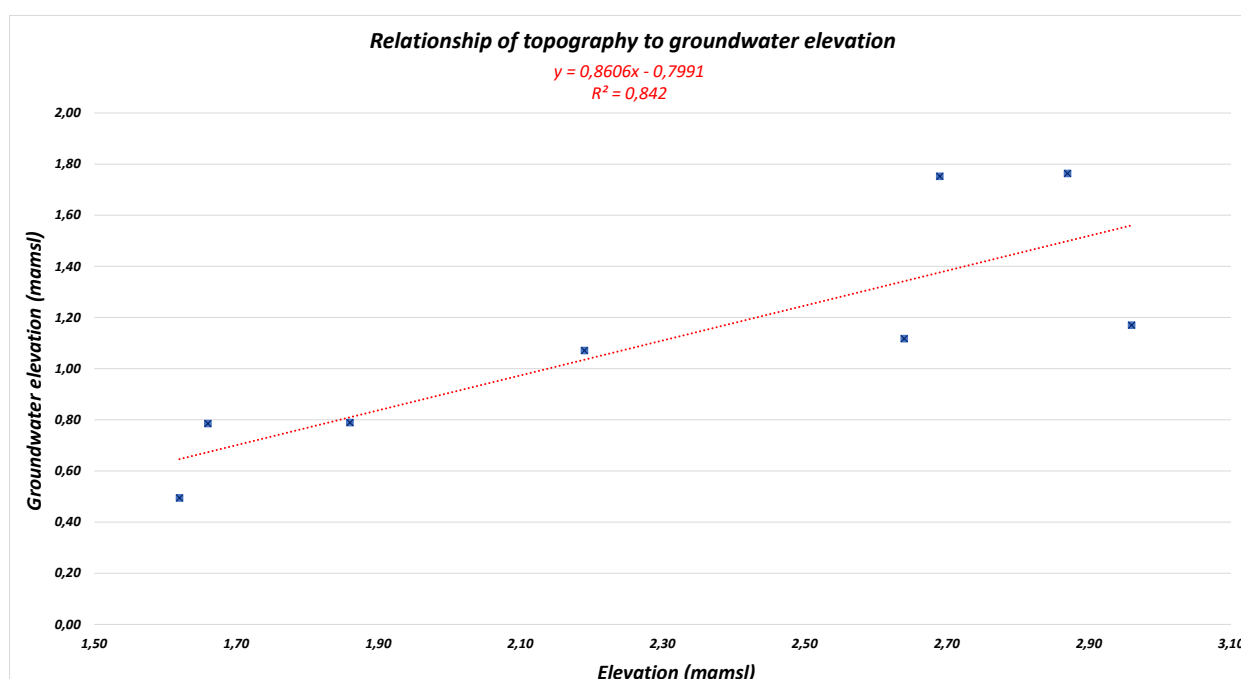


Figure 10. The relationship between groundwater elevation and topography

From the same surface elevation raster derived from the LiDAR data, a total of 100 random points was generated using the Data Management toolbox in ArcMap 10.2.2.

These points covered the wetland and the immediate surrounding environment. The elevations of these points were extracted and imported into a text file, along with the measured groundwater levels and surface elevations from the appropriate raster surfaces, as per TRIPOL input format requirements. After launching TRIPOL, the blank file is saved with the same file name as the text file which generates a reference map of the relevant wells and random elevation points in TRIPOL. The Bayesian interpolation function is then used to generate groundwater levels, which produces an output file (.wl) from which the interpolated groundwater elevations may be extracted and imported into an excel or text file for use in gridding software, such as SURFER.

Once in SURFER, the generated data must be put into a grid which includes x (latitude), y (longitude) and z (surface elevation or water level) values. Kriging (Ordinary Kriging) had been selected as the preferred Gridding Method for the irregularly spaced data points. Once a successful grid has been generated for a specific dataset, maps may be generated from this output grid. A statistics report is generated for every grid.

The analysis of variance (ANOVA) comparing the input groundwater elevation data is shown in Table 9. The results indicate that the outputs are significant, i.e. p -value is less than 0.05 for the data spanning January to June 2016, and comparable for the data spanning July to December 2016 (Fairbanks and Madsen, 1982). Thus, the groundwater grids interpolated using Ordinary

Kriging (in SURFER) are statistically significant when compared to the measured average groundwater elevations calculated for the same period.

Table 9. Comparison of analysis of variance of the Kriging technique used to derive groundwater elevations for the period: January – June 2016 and July to December 2016

Input data sets	ANOVA					
	Source of variation	df	SS	MS	F	p-value
Groundwater elevation (January to June 2016) vs. Bayesian (Kriging) Interpolation	Regression	1	1,262	1,262	18,584	0,005
	Residual	6	0,408	0,068		
	Total	7	1,670			
Groundwater elevation (July to December 2016) vs. Bayesian (Kriging) Interpolation	Regression	1	0,673	0,673	4,582	0,085
	Residual	6	0,734	0,147		
	Total	7	1,407			

From the monthly averages calculated for the periods spanning January to June 2016 and July to December 2016, groundwater flow contour maps depicting the groundwater levels and distribution within the region were generated. These contours were imported into ArcMap and projected over a satellite image (Projected Coordinate System: WGS1984, UTM Zone 34S). These maps provide a conceptualization of groundwater levels and distribution within the wetland.

4.2.2 Quantitative hydrologic analysis of hydroperiod

The methodology employed here is similar to the calculation of the volume of flow from a hydrograph, where the area under the curve of a hydrograph is calculated by assembling a series of rectangles in discrete time steps, as proposed by Eaton and Yi (2009). The width of the rectangles is equal to the duration between 2-time instants on the x-axis, and the height equal to the average of the y-values at the bounding time instants. The sum of these rectangles represents the area under the curve, and thus represents the total volume of flow past an outlet in the case of a flow hydrograph or in this case, the meters inundated over the surface at a specific point. This is referred to as numerical integration, and solves Eq. 2.

For the purposes of this study, time (t) is represented on the x-axis, and is divided in intervals of 0.5 hours for the period that the water level exceeds the elevation of the surface. The water level fluctuation (h) is represented on the y-axis in meters. A time (t) and water level (h) is assigned in the time series, thus an equation for the above-mentioned scenario may be written as:

$$\Omega(x) = (t_2 - t_1)\left(\frac{h_2 - h_1}{2}\right) + (t_3 - t_2)\left(\frac{h_3 - h_2}{2}\right) + \dots + (t_n - t_{n-1})\left(\frac{h_n - h_{n-1}}{2}\right) \quad \text{Eq. 3}$$

Where n is the last observation in the series. This approach provides the same solution as the process of solving the integral through differentiating and integrating the data. Here comparable results are obtained through a simplified approach, and addresses the concern raised by Eaton and Yi (2009) that the function describing the water level fluctuation in a wetland is unknown.

The integral (or sum of the area under the curve) was determined for the wells within the Rietvlei that experienced a hydroperiod, these include Well 1, Well 2, Well 3 and Well 8. The hydroperiod that occurred during 2016 could not be determined for well 3 as the hydroperiod extends into 2017 for which the data is not available. The observed water level for this period at well 3 is much higher than the surrounding environment; this rise could be the result of overbank flooding.

4.2.3 Quantitative hydrologic analysis of residence time

As discussed, the residence time is a measure of the average time a molecule of water spends in a reservoir. Assuming a steady state, the residence time (T_R) is the ratio of the volume (V), or storage capacity, of the wetland and the flow rate, the average between the inflow and outflow of the system, (Q) – see Equation 3.

The reservoir volume (or storage capacity) is determined by calculating the product of the area (A) and the average depth (D) within the wetland, ($V = A \times D$) both of which were determined in accordance with the methodology proposed by Anderson and Pollak (2016):

- *Area:*

The area of concern was identified as the central pan (Marsh/Vlei) region within the Rietvlei Wetland. The area of the delineated Marsh/Vlei area was calculated using the Calculate Geometry tool in ArcMap as m^2 (Table 10).

- *Depth:*

The depth of water within the wetland was analysed using ArcMap by utilizing the LiDAR data obtained through the study conducted by Ally *et al.* (2017a). The elevation of the delineated area was extracted from the LiDAR surface generated using interpolation, which is assumed to be equal to the ground elevation. Random points were generated across this surface, from which a

Triangular Irregular Network (TIN) was created within the bounds of the central pan area. The TIN surface was converted to a raster or grid surface. The original LiDAR surface, representing the ground elevation, was subtracted from the wetland water surface raster (derived from the TIN). The difference between the LiDAR surface and wetland water surface represents the average water depth within the central pan area (Table 10). Harrison (2010) states that the Marsh/Vlei depth is generally not more than 2 meters when it is at capacity (Table 10).

Ally *et al.* (2017b) quantified the inflow of the catchment to the system by way of the Simple method, which calculates the annual runoff of the catchment as a product of annual rainfall volume and a runoff coefficient. The authors determined that the annual flow for the catchment (of 16 km²) is approximately 2 488 000 m³, or 0,08 m³/s (Table 10). The DWS (2017) states that the natural MAR of the Diep River catchment is 70 million m³/a, whilst the present-day MAR is closer to 42 million m³/a. In this case, the most present-day MAR is considered, and expressed as 1,33 m³/s.

No data with regards to the outflow (Otto du Plessis Bridge) of the wetland has been quantified, thus the inflow is considered as the input (Q) to the Marsh/Vlei. Should data become available, Q would equal the average between the inflow and outflow of the Marsh/Vlei.

Following the calculation of the Volume (or storage capacity) and Inflow (Q) of the central pan area, the values were used to solve Equation 3. The output was converted from seconds (s) to months.

Table 10. Hydrological Inputs used to calculate Residence Time within the Central Pan area, Rietvlei Wetland

<i>Hydrological Scenario</i>	<i>A – Area (m²)</i>	<i>D – Depth (m)</i>	<i>V – Storage Capacity (m³)</i>	<i>I – Inflow (m³/s)</i>
Steady-state under current flow conditions	2 286 594,95	0,766	1 798 540,69	0,08
Steady-state at maximum storage capacity – current flow conditions	2 286 594,95	2.0	4 573 189,90	0,08
Steady-state under natural flow conditions	2 286 594,95	0,766	1 798 540,69	1,33
Steady-state at maximum capacity – natural flow conditions	2 286 594,95	2,0	4 573 189,90	1,33

4.3 Soil classification

In order to gain insight into the shallow unconfined aquifer that influences the groundwater fluctuations within the wetland, the distribution of the soil types must be defined, and in doing so provide an indication of the associated soil properties within the wetland. This can be achieved by way of interpolating soil characteristics (Deshmukh & Aher, 2014).

During the course of 2017 soil samples were collected at discrete intervals within the immediate vicinity of the previously installed groundwater monitoring wells using a hand-auger. These samples were submitted for analysis during the course of August and September 2017 and analysed by a competent soil scientist by way of a Malvern Mastersizer 2000.

The results were reported as Volume in % of various particle sizes ranging from 0.010 to 10 000 μm . These results were received and thereafter classified in accordance with the United States Department of Agriculture (USDA) Textural Soil Classification to define the soil type. The percentage (%) clay, silt, sand and gravel were determined by considering the Udden-Wentworth grain size scale to evaluate the Particle Size Distribution (PSD) of sediments (Wentworth, 1922).

Following the identification of each samples' textural soil class and grain size based on the PSD analyses, soil distribution maps were created by way of interpolation to establish possible trends in spatial variability in depth and across the wetland.

4.3.1 Soil texture distribution analysis

The soil texture distribution analysis of the soils within the wetland could only be obtained at limited sample points (Well 1 – Well 8), and would thus require some form of interpolation or spatial prediction. To meet these requirements Kriging was used to interpolate the datasets, as kriging is a geostatistical gridding/estimation method that generates an estimated continuous surface from an irregularly spaced set of data points using z-values.

Thus, interpolation is used to convert data from point observations to continuous fields, to allow the spatial patterns sampled by these measurements to be compared through spatial patterns. In the present study, soil samples from the 8 sampling locations (wells 1 – 8), collected at discrete depths (0.5-meter intervals) ranging from 0.5 to 3.0 meter below ground level (mbgl) within the study area were interpolated, and soil texture class and PSD maps prepared. Thus, a soil textural classification map was generated for every 0.5mbgl where sufficient data was present from most or all sampling locations.

4.4 Identifying environmental impacts

The identification of environmental impacts was based on the quantification of aspects related to the hydrology and soil texture within the environmental setting of the wetland. Thus, a qualitative assessment was launched based on the observations made during the course of the study.

The above-mentioned were categorized as Themes:

- Groundwater
- Soil
- Environmental setting.

Significant aspects pertaining to each theme were identified during the course of the study by reviewing previous studies and considering the quantitative analyses provided within this study.

The criteria to review these aspects and their associated impacts were outlined as follows:



Here the evaluation considers the

I. **Scale** as either:

- **Local:** Considers the impacts restricted to the Rietvlei wetland,
- **Regional:** Considers the impact of the surrounding environment on the Rietvlei wetland and vice versa,

II. **Frequency** / occurrence:

- **Permanent:** Considers the impact as naturally present, or present as a result of irreversible change,
- **Seasonal:** Considers the occurrence of the impact as either occurring during a specific season as a result of associated seasonal characteristics, e.g. increased rainfall experienced during winter results in the occurrence of hydroperiods,
- **Event-based:** Considers the occurrence as a result of a specific event, e.g. rainfall occurrence results in groundwater recharge or increased runoff,
- **Depth-dependent:** Considers the occurrence to occur at a certain depth beneath the surface, or that the impact is restricted to a certain layer e.g. geological successions, gradient variations or the change in the vertical salinity gradient (i.e. halocline).

The **Significance** is considered during the evaluation as the ability of the impact to cause change to the natural system or the resultant magnitude of the impact that has led to the alteration of the system, and are categorized as:

- **Low:**

The impact results in minimal change, or results in alteration to the system that may be reversed or alleviated through management only,

- **Medium:**

The impact has the ability to change the environment in its current state or has resulted in change or environmental degradation over time; the effects of which may be reversed or managed through restoration efforts,

- **High:**

The impact has resulted in irreversible change to the system, and caused environmental degradation – or has influenced the dynamics of the environment permanently. As such, these impacts are sensitive to change; to such an extent that the resultant alteration may be detrimental to the functioning or health of the system over the long term.

CHAPTER 5 RESULTS AND DISCUSSION

5.1 Introduction

This chapter presents the outputs generated from the previously discussed methods and techniques.

A brief overview of the monitoring network present within the wetland is provided, as well as the data sources used during the course of the analyses (5.2). The outputs are discussed in separate categories. The first of which is groundwater. In this section (5.3) the groundwater level fluctuations of the wells present within the wetland are discussed (5.3.1), as well as the results from the quantitative hydrological analyses of the wetland hydroperiod (5.3.2) and wetland residence time (5.3.3). The groundwater flow direction and magnitude are also presented herein (5.3.4). The second section discusses the classification of the soils within the wetland (5.4). This includes an analysis of the Particle Size Distribution data (5.4.1), and the outputs generated from the interpolation of the associated soil characteristics (5.4.2).

These analyses and results, in conjunction with a review of previous reports (5.5.1), are utilized to establish potential environmental impacts in accordance with the proposed qualitative environmental impact assessment methodology proposed in Chapter 4 (5.5.2).

Lastly, the quantitative and qualitative analyses are collated to conceptualize the hydrodynamics within the Rietvlei Wetland, which includes a geological cross section providing insight into the geohydrological components associated with the wetland, and an in-depth conceptual model that illustrates the hydrological processes within the wetland and the environmental impacts identified in the previous section. This conceptual model provides a digestible summary of all pertinent aspects pertaining to the study.

5.2 Rietvlei Wetland: Monitoring network and data sources

As previously mentioned, eight groundwater monitoring wells were sunk within the bounds of the Rietvlei Wetland (Figure 11). The table below presents the spatial data for each well (Table 11).

In addition to these wells, four surface water monitoring points were set up during the same period - the first at the Blaauwberg Bridge, the second at the Otto du Plessis Bridge, the third at Woodbridge and the fourth centrally positioned within the Flamingo Vlei lake. These loggers record the water level fluctuations within the canal, as well as the Temperature and Electrical Conductivity (EC) of the surface water.

Table 11. Details of the wells installed during 2015

Well	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Elevation (mamsl)	Average groundwater level (mamsl)
MW-1	18,49075	-33,83307	2,87	2.23
MW-2	18,49815	-33,85250	1,66	1.20
MW-3	18,50093	-33,85247	1,62	0.92
MW-4	18,49545	-33,84310	2,96	1.38
MW-5	18,49377	-33,86123	1,86	1.04
MW-6	18,50205	-33,83983	2,19	1.46
MW-7	18,51188	-33,83958	2,64	1.47
MW-8	18,51915	-33,83765	2,69	2.02

Meteorological data, rainfall and evaporation were obtained from the weather station installed by the team commissioned by the City of Cape Town: *Milnerton CW390*. This weather station is still active.

Tidal data for Cape Town harbour is obtainable through an open-source software called WXTide32, which simulates tidal data for international harbours. Tidal data may also be obtained from the South African Navy Hydrographic Office (SANHO) upon request. For the purpose of this study the simulated data from WXTide32 will be sufficient to establish a possible link between tidal and groundwater fluctuations.

Ally *et al.* (2017b) developed a hydrodynamic model for the Diep Estuary, specifically the Milnerton Lagoon, to establish a sense of the extent of saltwater intrusion from the estuary mouth and its effect on the ecology. In building this model, Lidar/Bathymetry data was made available from which a digital elevation model (DEM) or Bathymetric surface could be interpolated.

A desktop hydrocensus was undertaken to identify potential groundwater users, and groundwater losses, associated with the wetland (Annexure B). Data was obtained from the National Groundwater Archive (NGA). The NGA is an online or web-enabled database that allows access to groundwater related data for South Africa and is maintained and managed by the Department of Water and Sanitation (DWS). Upon review of this data, four well points (shallow, small diameter boreholes developed by way of jetting) were identified in the immediate vicinity of the wetland. A further four boreholes were identified upstream of the wetland. In addition to the well points and boreholes within the vicinity of the vlei; six well points and three boreholes were identified within the immediate vicinity of the Milnerton Lagoon. Whether or not these water points were still active did not form part of the scope of this study, but their presence opens up the pathway for water losses via abstraction in the wetland's water balance should they be quantified (Section 3.2.2).

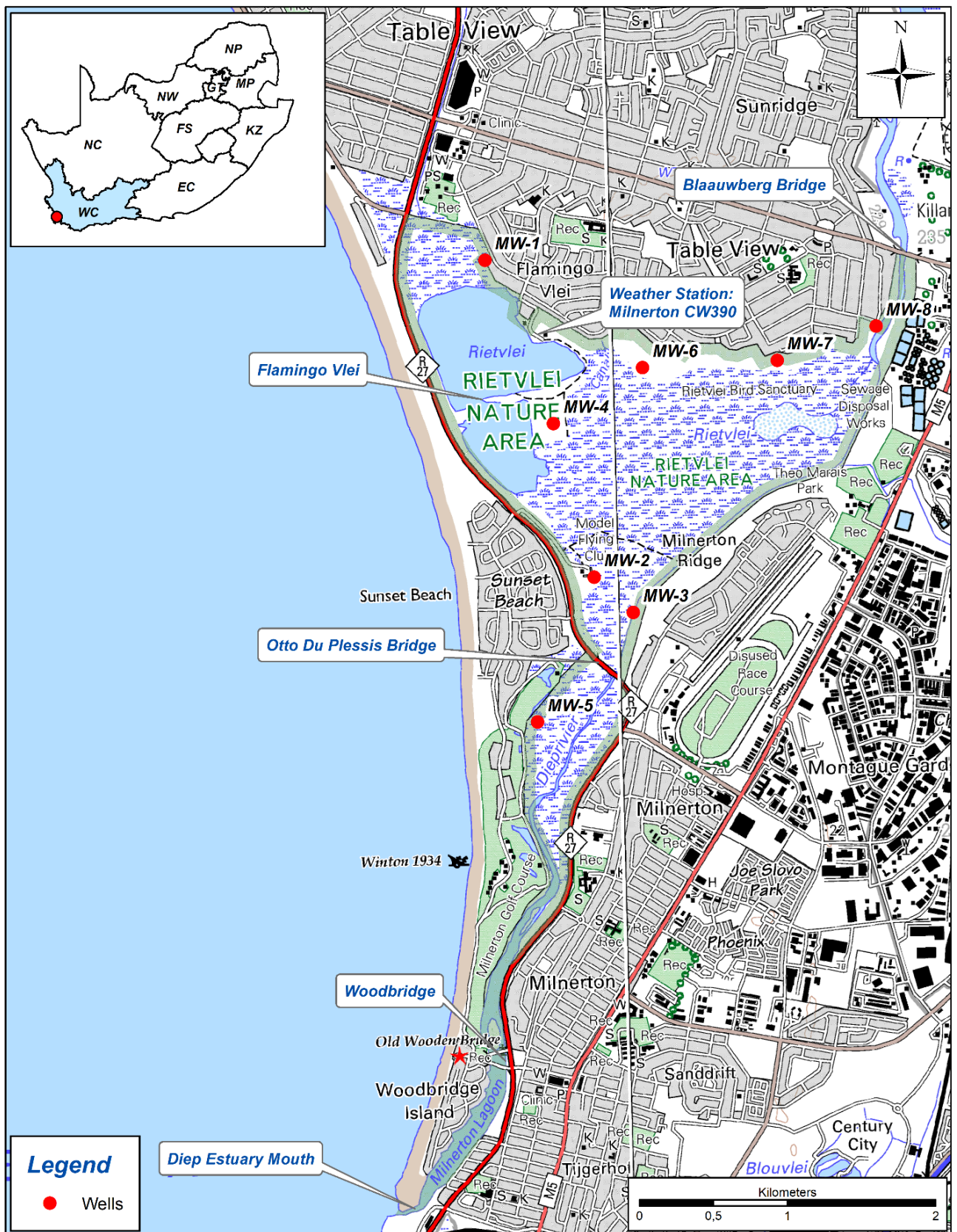


Figure 11. Rietvlei Wetland: Monitoring Network and Data Sources

5.3 Groundwater

5.3.1 Groundwater level fluctuations

As previously mentioned, the groundwater levels recorded from the data loggers installed in the eight groundwater wells within the Rietvlei Wetland (Campbell *et al.*, 2017), were graphed and compared to the professionally surveyed surface elevations of each well. An exceedance of this interface would indicate a hydroperiod, or period of saturation, as a result of pan inundation or surface flooding as a result of rainfall run-off, i.e. the addition of water to the system initiates a hydrodynamic response that may result in a saturated or flooded surficial environment. The rainfall and evaporation for the relevant period are presented in Figure 12 and Figure 13. The reason for this is to link rainfall events with potential recharge events at the various wells, and evaporation as a main contributor to water loss (groundwater discharge).

What follows are a comparison and discussion of the groundwater fluctuation associated with each well for a similar period during 2015 and 2016, which stretches from July to December. This is the only period where data is present in all wells for 6 months. The identified period coincides with the natural wet season of the region. This analysis also provides a rudimentary form of data validation, as observable trends provide confidence in the adequacy of the data.

Additional data is presented in Annexure A, which include the annual groundwater level variations during 2016. From this data it is evident that the region experiences deeper groundwater levels during summer or the dry season, and shallower groundwater levels during winter or the wet season. This is indicative of seasonally fluctuating groundwater levels and is observed in the data of all wells.

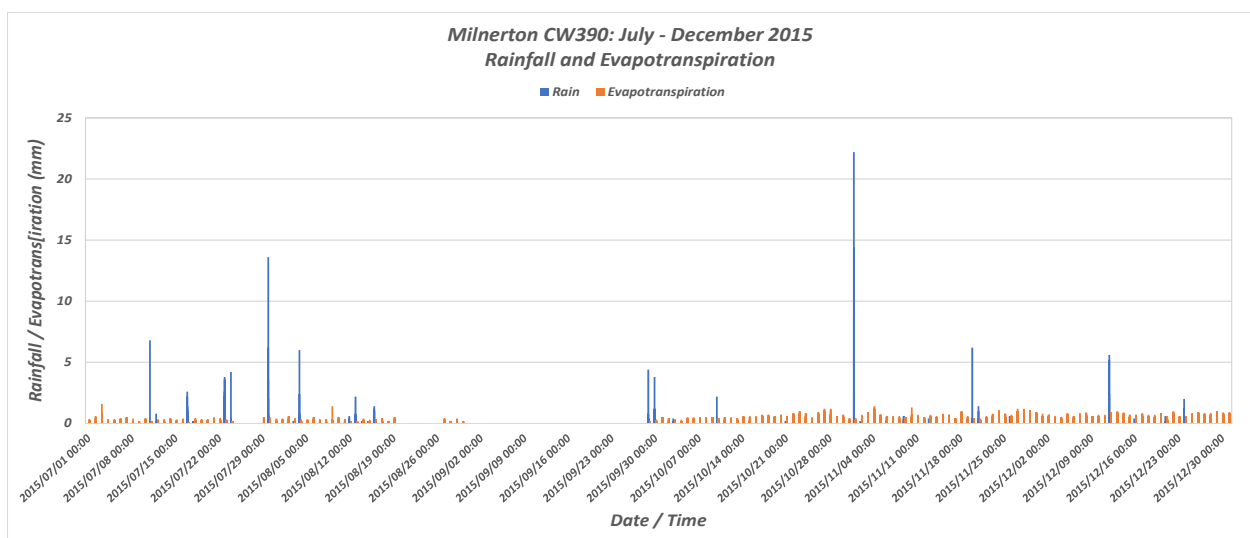


Figure 12. Weather station Milnerton CW390: Rainfall and evapotranspiration (hourly) for the period July to December 2015

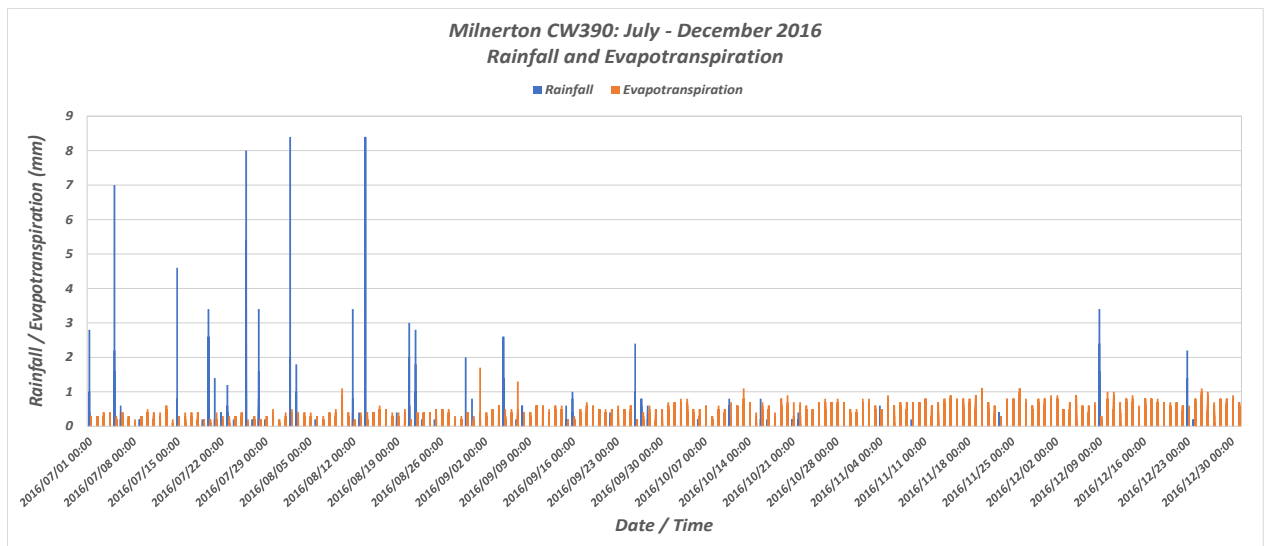


Figure 13. Weather station Milnerton CW390: Rainfall and Evapotranspiration (hourly) for the period July to December 2016

- **Well 1**

Well 1 was sunk in the north-eastern lobe of the wetland, upgradient of the Flamingo Vlei lake near the Seabird Rehabilitation Centre on Pentz Road. Upon review of satellite imagery, the immediate area presents evidence of shallow pans, thus a hydroperiod is expected at this well. The well is situated approximately 200m north of the lake and 850m east of the ocean

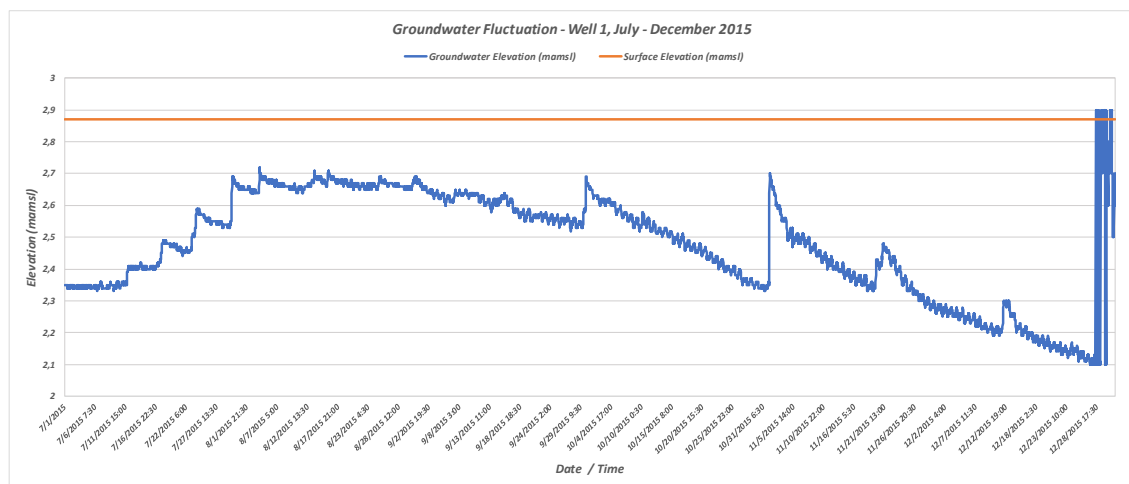


Figure 14. Groundwater Fluctuation at Well 1 for the period July to December 2015

During 2015 no hydroperiod occurred for the period July to December (Figure 14). The rainfall events that occurred during the period correspond with each of the recharge events which is indicative of a natural response to groundwater recharge as a result of precipitation (Figure 12). The anomaly toward the end of December does not correspond with a rainfall/recharge event and may be attributed to the logger being tampered with or removed from the well.

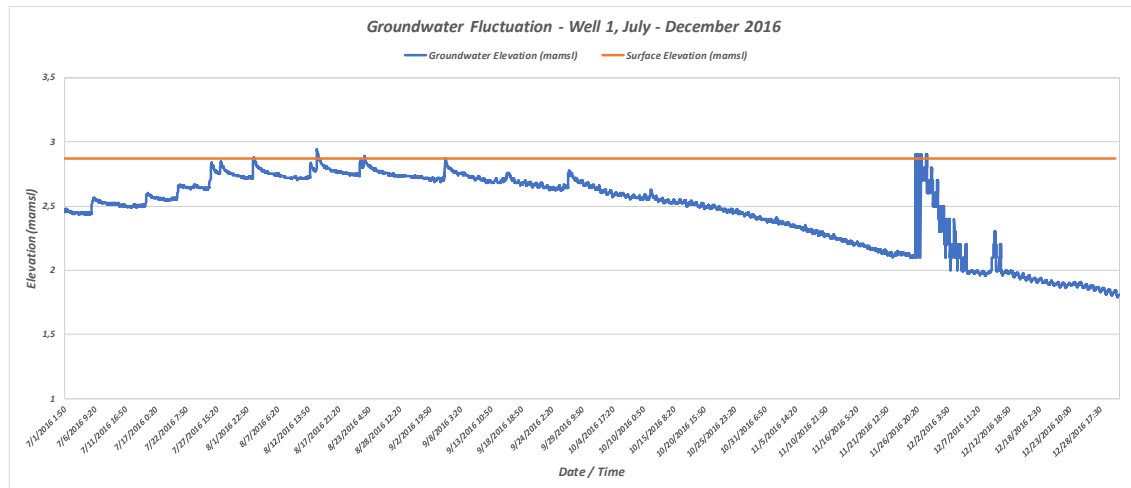


Figure 15. Groundwater Fluctuation at Well 1 for the period July to December 2016

During 2016 four (4) hydroperiods occurred during the 2nd of August to the 5th of September. Each event corresponds with observed rainfall/recharge events, the duration of each are presented below:

1. 2nd August – hydroperiod lasted 5 hours and experienced a rise of 0.01m above surface,
2. 14th August – hydroperiod lasted 13 hours and experienced a rise of 0.07m above surface,
3. 22nd August – hydroperiod lasted 4 hours and experienced a rise of 0.01m above surface,
4. 5th September – hydroperiod lasted 3.5 hours and experienced a rise to the surface.

The last exceedance of the surface does not correspond with a recharge event and occurs as a result of a 0.7-meter groundwater level rise in 30 minutes which might be indicative of surface water flooding rather than groundwater inundation. Campbell *et al.* (2017) state that the rapid increase in water level prior to these hydroperiods, or periods of saturation, suggest that the well is inundated by flow over the surface rather than the groundwater level rising from below the surface, as groundwater permeation is relatively slow. The logger could also have been removed.

Upon comparison of the data presented for 2015 and 2016 a clear trend in the rise and fall of the groundwater levels is observed, regardless of the difference in rainfall. During the second week of July both periods experience a steady increase in groundwater level (as a result of rainfall events), and indicate a decrease during the second week in September (as a result of increasing evaporation/evapotranspiration and decline in the occurrence of rainfall/recharge events). Thus, a natural response to the surrounding environment may be discerned from the data.

- **Well 2**

Well 2 was sunk within the Model Airfield immediately east of West Coast Road. Upon review of satellite imagery, it is evident that water is present at the surface and the potential for pan inundation exists. The well is approximately 900m east of the ocean.

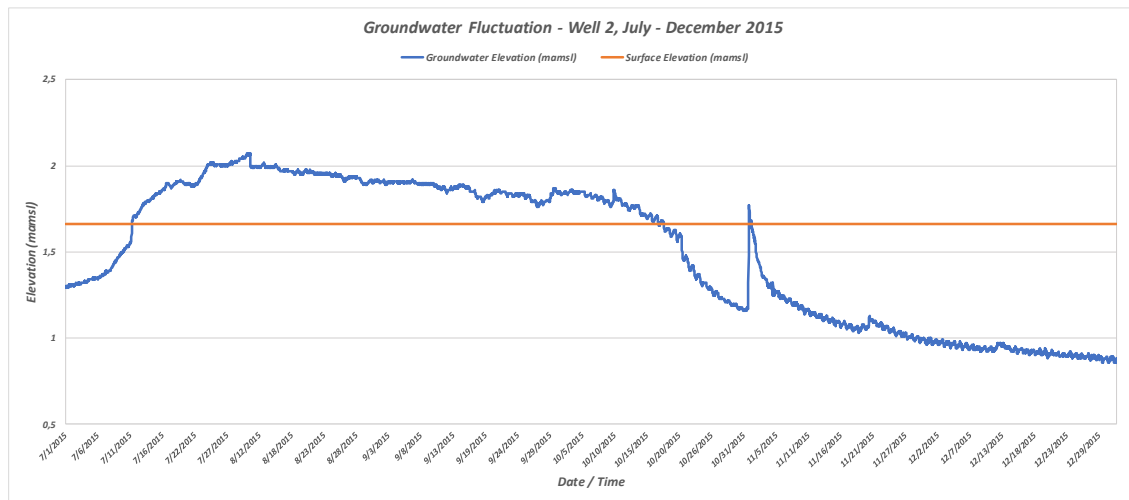


Figure 16. Groundwater Fluctuation at Well 2 for the period July to December 2015

During the course of July to December 2015 a clear hydroperiod as a result of groundwater inundation is present. There is no abrupt transition that would indicate an immediate response to a rainfall/recharge event. The hydroperiod occurs for approximately three months spanning from the 11th of July to 18th of October and experienced a rise of 0.501m above surface. A second hydroperiod occurred on the 1st of November in response to a rainfall/recharge event, and indicated an abrupt change that may be attributed to overbank flooding.

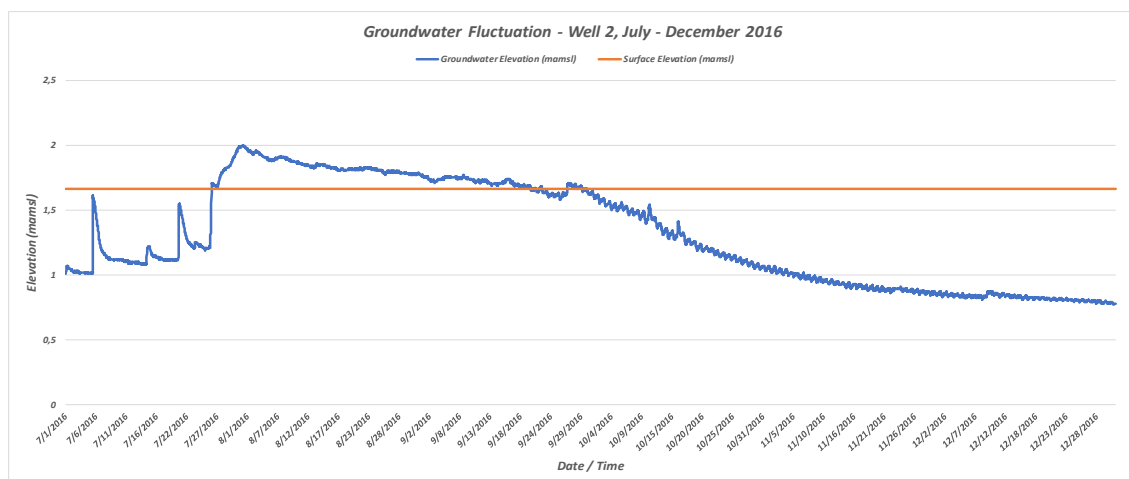


Figure 17. Groundwater Fluctuation at Well 2 for the period July to December 2016

During the course of July to December 2016, the natural system responds to two rainfall/recharge events prior to transitioning to an abrupt hydroperiod following a third rainfall/recharge event on the 26th of July which lasted until the 22nd of September, i.e. the hydroperiod lasted approximately 2 months during 2016 and experienced a rise of 0.44m above the surface.

Upon comparison of the data presented for well 2 during 2015 and 2016, a similar seasonal trend is observed during which the groundwater exceeds the surface interface prior to the end of July and drops below the surface by the end of September toward the first week in October.

- **Well 3**

Well 3 was installed immediately west of the Diep River draining the stretch between Blaauwberg Bridge and Otto Du Plessis Bridge alongside Milnerton Ridge. Well 2 is situated just east of Well 3 within the central pan area where the occurrence of hydroperiods and pan inundation are expected. The elevation of the well is the lowest of all wells; thus, surface water flooding may be expected toward the riverine environment of the Diep River. The well is 40m west of the riverine environment and approximately 1.1km east of the ocean.

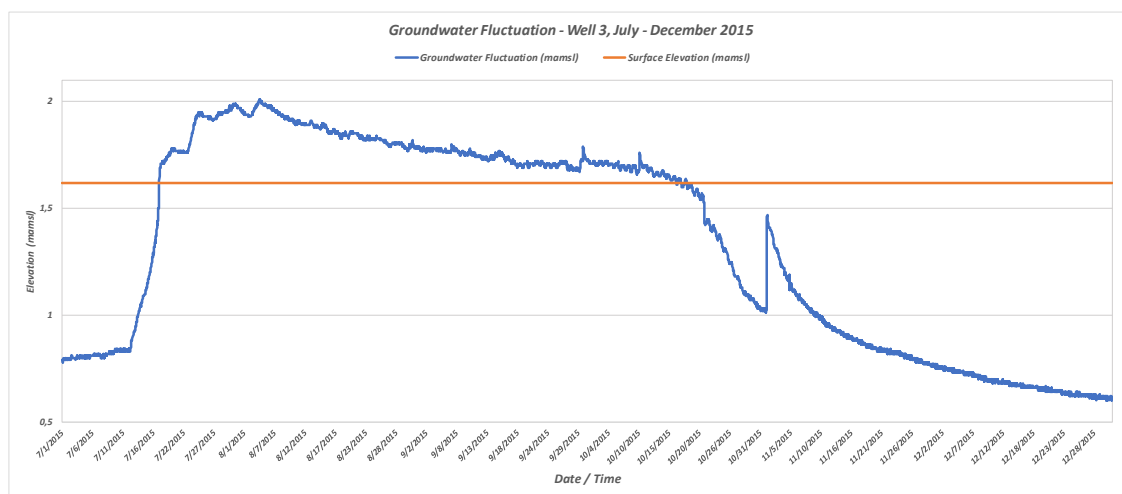


Figure 18. Groundwater Fluctuation at Well 3 for the period July to December 2015

During the course of July to December 2015, the hydrological system responds to a rainfall/runoff event, and possibly overbank flooding from the nearby canals which caused an abrupt increase in groundwater level. This event occurred on the 18th of July, where after the hydroperiod lasted 3 months and ended on the 18th of October. A rise of 0.38m above surface was observed.

Following this hydroperiod, a second abrupt increase in the water level is observed at the start of November following a rainfall/runoff event. This event did not result in a hydroperiod.

A similar trend in data is observed at Well 2 for the same period as a hydroperiod lasting 3 months, and the hydrological response that occurred at the start of November are observed at both wells. This may be indicative of a seasonal hydropattern within the area covered by wells 2 and 3.

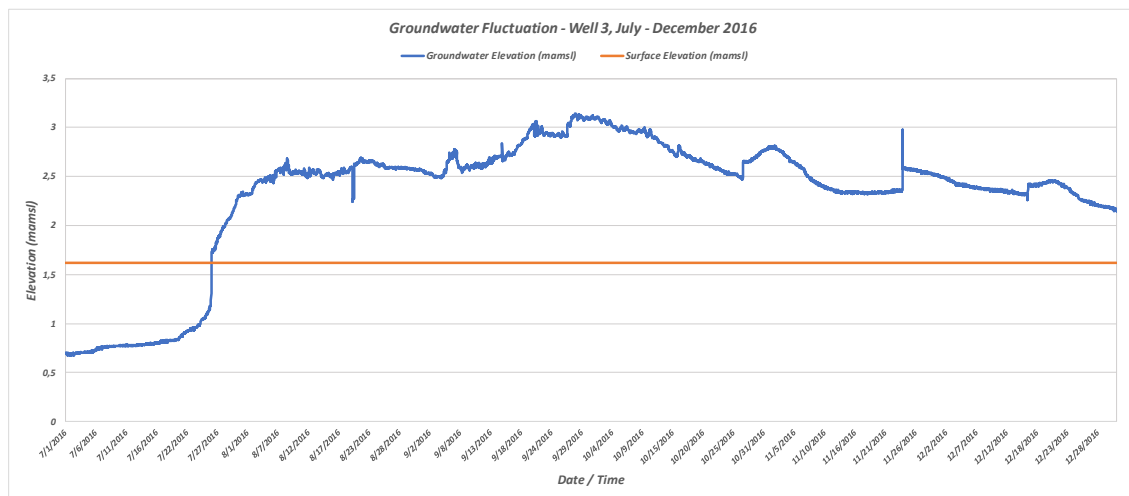


Figure 19. Groundwater Fluctuation at Well 3 for the period July to December 2016

During the course of July to December 2016, the hydrological system responds to a rainfall/runoff event, followed by possible surface water flooding from the nearby canal or Diep River which caused an abrupt increase in the groundwater level. This event occurred on the 26th of July and continued into the following year, and experienced a rise of 1.50m above surface. Data for 2017 is only available until the end of January due the logger failing; thus, the end of the hydroperiod is unknown, although the duration is in excess of six months. The data does however appear sporadic and does not correspond with the rainfall data during the hydroperiod as observed at previous wells.

There is no clear trend between the 2015 and 2016 data for Well 3, although the increase in water level is observed toward the end of July during both years which substantiates the seasonal trends observed in the previous wells.

- **Well 4**

Well 4 was installed in the central area of the wetland immediately east of the lower part of the Flamingo Vlei freshwater lake, and is situated approximately 900m east of the ocean. The elevation of the well is the highest observed at any well, and upon review of satellite imagery, no hydroperiod is expected to occur at this well or its immediate vicinity. This well may be constructed on top of material previously used to create an embankment to separate the lake from the pans. No hydroperiod occurred at this well during July 2015 to April 2018 (Annexure A). A similar

seasonal trend in groundwater fluctuation is observed, whereby an increase is observed toward the end of July and a decrease toward October.

- **Well 5**

Well 5 was sunk south of the Otto du Plessis Bridge within the floodplains of the Diep River, north of the Milnerton Lagoon. The well is situated approximately 450m east of the ocean.

Well 5 shows a strong correlation with the rainfall data, each increase in the groundwater level is associated with a rainfall/runoff event. This is indicative of a natural hydrological response to the rainfall/runoff events and well drained soils.

No hydroperiod occurred at this well during July 2015 to April 2018 (Annexure A). A similar seasonal trend in groundwater fluctuation is observed, whereby an increase is observed toward the end of July and a decrease toward October.

- **Well 6**

Well 6 was sunk 400m east of the main water body of the Flamingo Vlei lake, and is situated immediately south of residential properties and storm water canals. The well is situated upstream of the central pan area where permanent and seasonal pans occur approximately 1.7km east of the ocean.

There is a domestic well point (3318DC00259) approximately 200m north of the well with a recorded groundwater level of 0.5mbgl. If still active, it might influence the observed water levels. No hydroperiod occurred at this well during July 2015 to October 2016, whereafter a data gap occurs and resumes during September to November 2017 during which the logger was stolen (Annexure A). A similar seasonal trend in groundwater fluctuation is observed, whereby an increase is observed toward the end of July and a decrease toward the end of August.

- **Well 7**

Well 7 was sunk on the northern border of the wetland immediately south of residential properties and is situated approximately 700m west of the Diep River and the constructed bypass canal stemming from the Potsdam WWTW.

There are 2 domestic well points north east of the well. The geology was recorded at the first well point, 3318DC00713, as sand (0 – 4 mbgl), peat (4 – 6 mbgl) and alluvium (6 – 10 mbgl) underlain by siltstone and shale (>10 mbgl). The recorded groundwater level at the second well point,

3318DC00247, during 1997 was 2.47 mbgl. No hydroperiod occurred at this well during July 2015 to April 2018 (Annexure A).

A similar seasonal trend in groundwater fluctuation is observed, whereby an increase is observed toward the end of July and a decrease toward the end of August. Well 7 shows a strong correlation with the rainfall data; each increase in the groundwater level is associated with a rainfall/runoff event. This is indicative of a natural hydrological response to the rainfall/runoff events and well drained soils.

- **Well 8**

Well 8 was sunk on the western river bank of the Diep River immediately south of the Blaauwberg Bridge. The Potsdam WWTW is located 200m west of the well, as well as the freshwater discharge point where the effluent from the plant is canalized on the eastern border of the wetland.

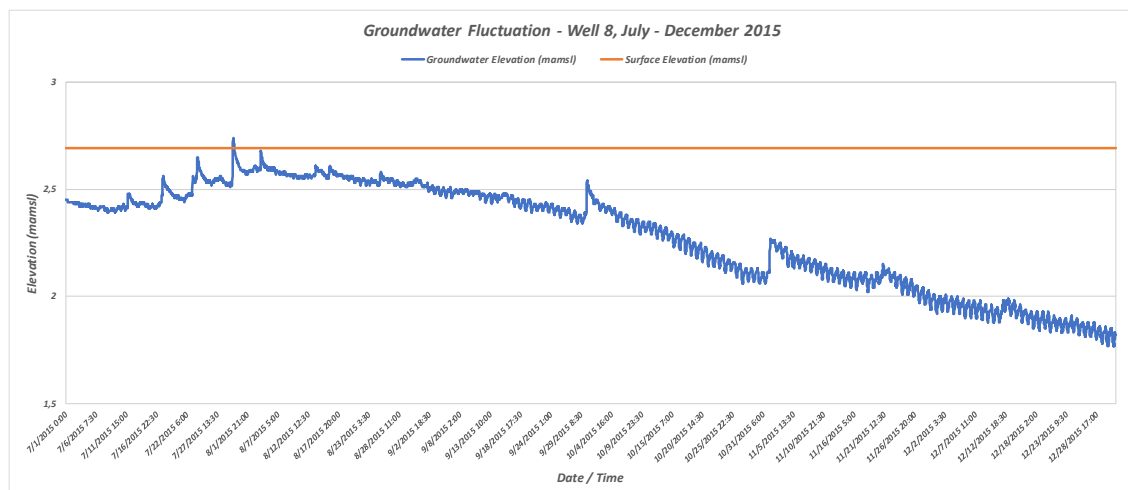


Figure 20. Groundwater Fluctuation at Well 8 for the period July to December 2015

During the course of July to December 2015, the hydrological system responds to several rainfall/runoff event, and possibly surface water flooding from the nearby river canal which caused an abrupt increase in groundwater level. One of these events resulted in a hydroperiod, which occurred on the 30th of July 2015 and lasted 6 hours.

Similar to 2015, well 8 experiences a single hydroperiod during the 3rd of August 2016 which lasted approximately six hours. There is also a good correlation between the increase in groundwater levels and rainfall/runoff events indicative of a natural hydrologic response and well-drained soils. A similar response is observed during both 2015 and 2016, where the groundwater level rises and peaks toward the end of July and subsides toward the end of August.

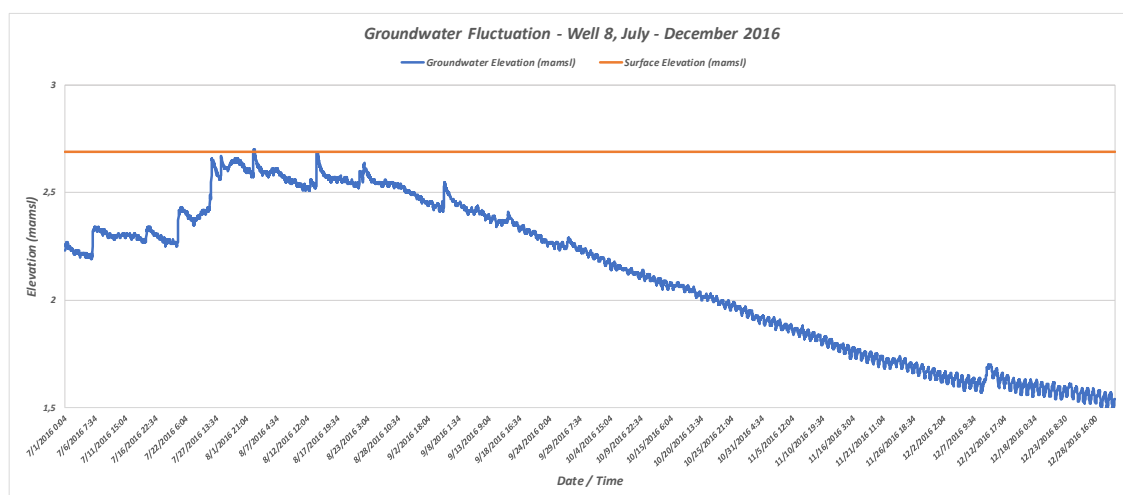


Figure 21. Groundwater Fluctuation at Well 8 for the period July to December 2016

- **Analysis of the hydroperiods observed at Well 1 - 8**

The groundwater fluctuations observed in all wells correspond with the observed rainfall/runoff events. Hydroperiods occurred at wells 1, 2, 3 and 8 during 2015 – 2016. A general trend of the groundwater levels increasing and peaking toward the end of July, and subsequently decreasing toward the end of September and the first week in October, was observed. Thus, where not permanently saturated, extended periods of saturation at the surface or the formation of shallow pans are expected between the end of July to the first week in October within the central wetland region, north of the lake and near the riverine environment situated near the inflow of the Diep River to the wetland.

Figures 22 and 23 provide an overview of the natural response of the system to the period highlighted above, i.e. the beginning of July to the end of September. From Figure 22, a clear rise in groundwater level (recharge) is observed and a subsequent decrease due to groundwater discharges (seepage or evaporation/evapotranspiration). Figure 23 presents the response of the surface water loggers during the same period. Blaauwberg Bridge presents a similar response to the groundwater observed at well 8, and indicates a delayed response to the rainfall event indicating that surface water runoff drains toward the river. The water levels within the Flamingo Vlei lake rise more gradually due to the size of the water body, i.e. a large volume of water would have to enter the system to initiate a response. The loggers installed at Otto Du Plessis Bridge and Woodbridge indicate a clear response to tidal fluctuation. The water level at the Otto du Plessis Bridge is higher than that of Woodbridge, which is to be expected as water drains south-west toward the estuary mouth. A clear response to rainfall/recharge events is however observed, as the general water level rises following these events, indicating that rainfall runoff does enter the system via runoff, and supports the possibility of the canals flooding during these events causing abrupt changes in groundwater levels (or readings) within the nearby wells.

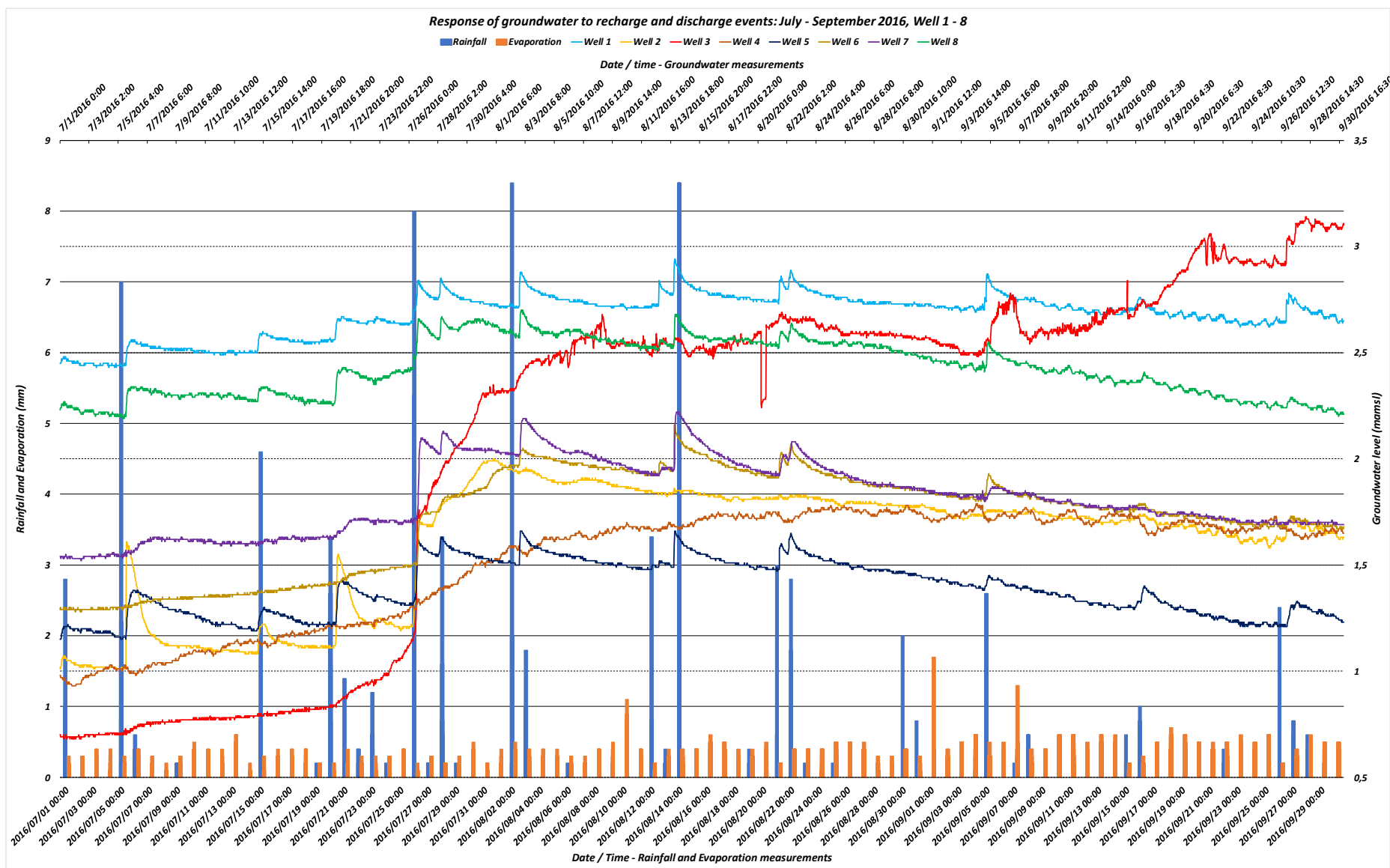


Figure 22. Hydrological response of groundwater to recharge and discharge events: July - September 2016, Wells 1 - 8

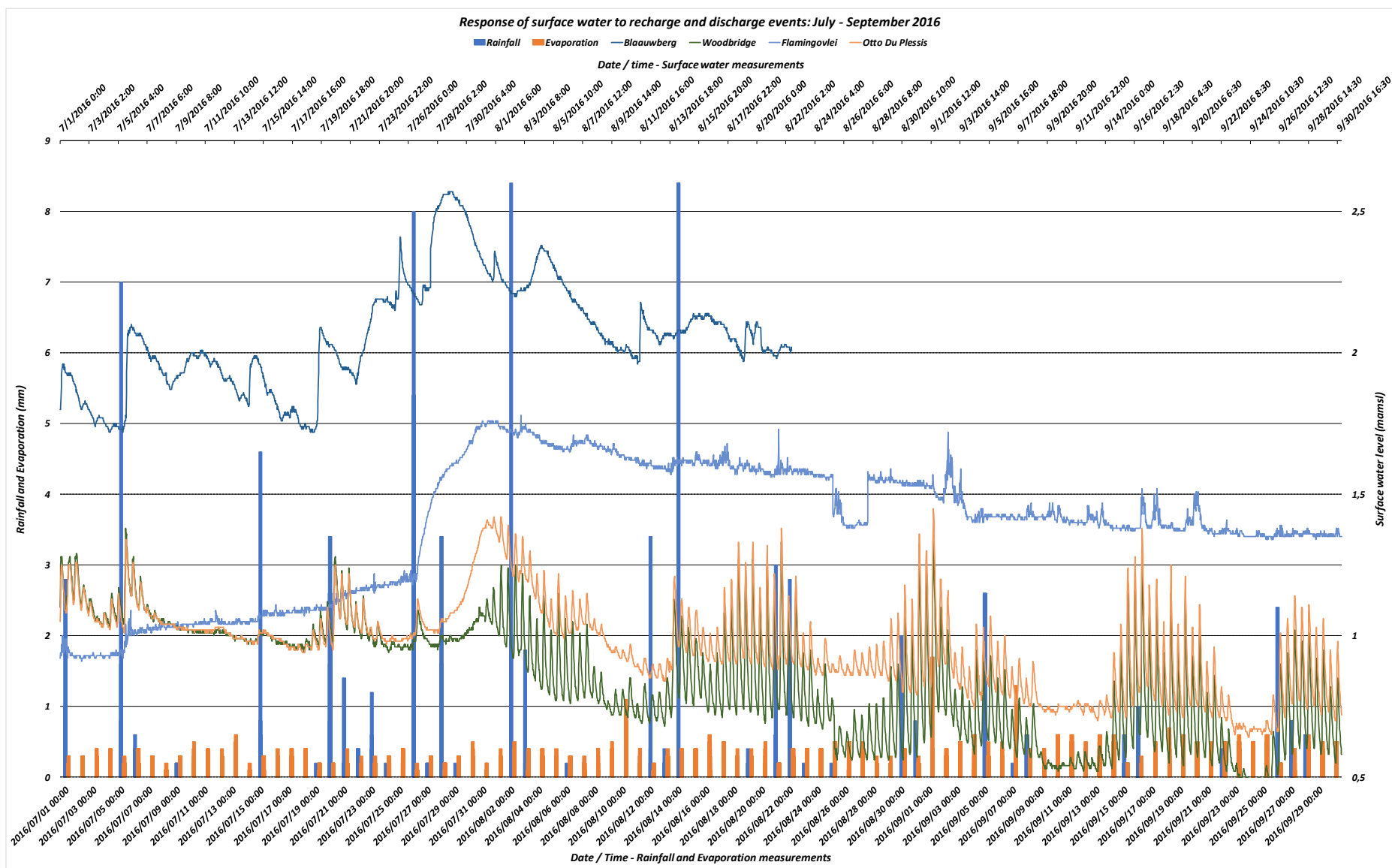


Figure 23. Hydrological response of surface water to recharge and discharge events: July to September 2016

5.3.2 Quantitative hydrologic analysis of wetland hydroperiod

The hydroperiod determined by the approach presented in section 4.1.2 (and proposed by Eaton and Yi, 2009), represents the meters inundated over the surface at a specific point for the period that the inundation occurred. In order to determine the hydroperiod (Ω) in terms of the unit (m.h) proposed by Eaton and Yi (2009), the integral is divided by the daily flood time – i.e. this converts the integral of the meters inundation that occurred for the duration of the flood time per day to the meters inundated over the surface per hour (m.h). Table 12 presents these results.

Table 12. Values of hydroperiod Ω (m.h) = $\int hdt$ calculated using Numerical Integration of field data for the hydroperiod occurrences during 2015 and 2016

Well	Date of Hydroperiod occurrence	Maximum depth (m)	Daily flood time (h)	Hydroperiod ($\Omega(x) = \int hdt$)	Hydroperiod Ω (m.h)
1	02/08/2016	0.01	3.5	0.01	0.003
	14/08/2016	0.07	12	0.4	0.033
	22/08/2016	0.01	4	0.35	0.009
2	11/07/2015 – 18/10/2015	0.501	24	5.29	0.22
	26/07/2016 – 22/09/2016	0.44	24	3.29	0.14
3	18/07/2015 – 18/10/2015	0.38	24	4.14	0.17
	26/07/2016 – unknown	1.5	24	-	-
8	30/07/2015	0.05	7	0.165	0.024
	03/08/2016	0.01	6	0.035	0.006

These results represent the meters inundated at a specific point within the wetland during the hydroperiod. Interestingly, there is a notable correlation with the hydroperiod results obtained through numerical integration and the average water level that occurred during the hydroperiod. Thus, the average water level of the inundation may be used as an indicator of the meters inundated with water during the hydroperiod.

5.3.3 Quantitative hydrologic analysis of Wetland residence time

The calculated residence time is presented in Table 13. Given the annual flow conditions presented by Ally *et al.* (2017a) and the calculated storage capacity (or volume) of the wetland, the residence time is estimated as 8,5 months under current conditions. This value provides a reasonable indication of the time it would take for water to drain from the inlet through the central pan area and out by way of the outlet at the Otto du Plessis Bridge.

Flow conditions and unknown parameters (i.e. the contribution of the storm water canals to inflow, and the actual outflow at the Otto Du Plessis Bridge) will also influence the residence time, as higher inflows would lead to a decrease in residence time.

Table 13. Estimated Hydraulic Characteristics and Residence Time of the Central Pan (Marsh/Vlei) area of the Rietvlei Wetland

Hydrological Scenario	A – Area (m²)	D – Depth (m)	V – Storage Capacity (m³)	I – Inflow (m³/s)	T_R – Residence Time (months)
Steady-state under current (estimated) flow conditions	2 286 594,95	0,766	1 798 540,69	0,08	8,5
Steady-state at maximum storage capacity – current flow	2 286 594,95	2,0	4 573 189,90	0,08	22
Steady-state under natural flow conditions	2 286 594,95	0,766	1 798 540,69	1,33	0,5
Steady-state at maximum capacity – natural flow	2 286 594,95	2,0	4 573 189,90	1,33	1,5

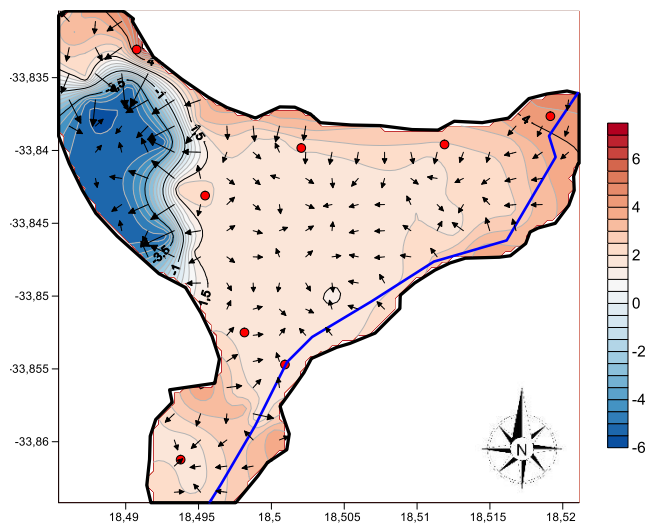
5.3.4 Groundwater flow

Table 14 provides an overview of the average groundwater levels associated with the identified period of study. The surface elevation and subsequent runoff trend are presented in Figure 24. The groundwater flow contours were generated for the periods January to June 2016 (Figure 25 and Figure 27) and July to December 2016 (Figure 26 and Figure 27).

Table 14. Average groundwater levels for the period Jul 2015 - Dec 2016

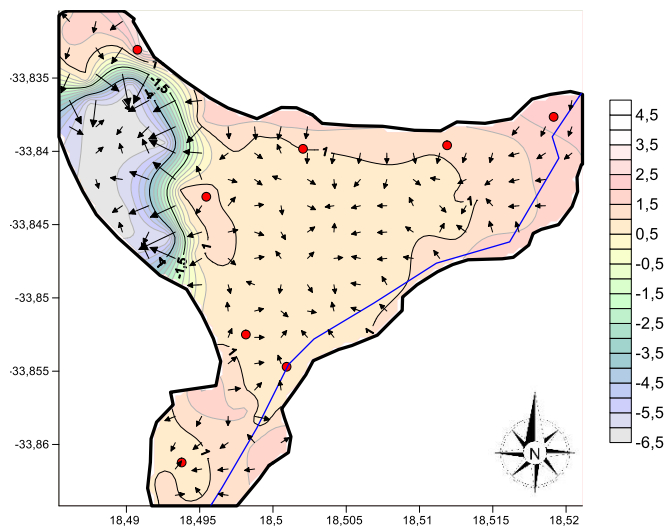
Well	Average groundwater level – Jul to Dec 2015	Average groundwater level – Jan to Jun 2016	Average groundwater level – Jul to Dec 2016	Elevation (mamsl)
MW-1	2.477	1.763	2.471	2,87
MW-2	1.314	0.785	1.509	1,66
MW-3	1.348	0.494	2.325	1,62
MW-4	1.595	1.012	1.490	2,96
MW-5	1.129	0.789	1.188	1,86
MW-6	1.623	1.071	1.695	2,19
MW-7	1.670	1.117	1.599	2,64
MW-8	2.291	1.752	2.119	2,69

Upon comparison of the groundwater movement during the first (January to June) and second (July to December) semesters of 2016, the general flow of groundwater is similar although the groundwater is on average closer to the surface during the second semester which leads to the contours near the lake being at a higher gradient and the groundwater mounding within the central wetland.



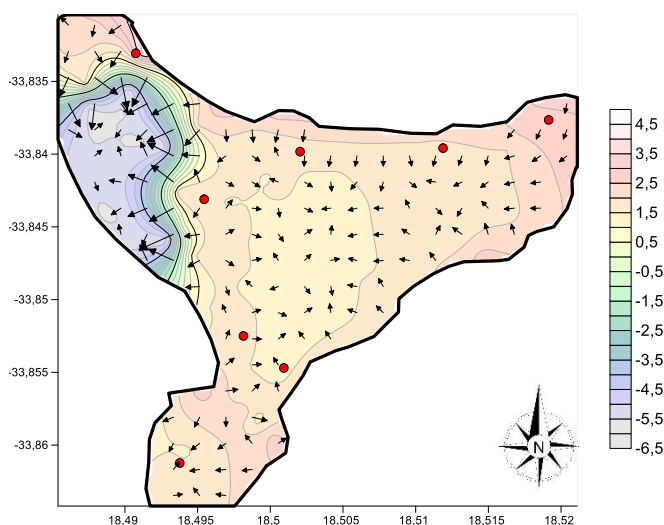
The surface elevation of the wetland ranges from a maximum of 6.96 mamsl in the north eastern corner of the wetland to sea level and below (-6 mamsl) within the Flamingo Vlei lake (Figure 24). Surface water runoff drains toward the lake and central region of the wetland as a result of the wetland being on the floodplains of the Diep River.

Figure 24. Surface Elevation Contours and Flow (mamsl)



The groundwater level for the period January to June 2016 ranged from a maximum of 3.57 mamsl in the north-eastern corner of the wetland to a minimum of -6.11 mamsl surrounding the Flamingo Vlei (Figure 25). The groundwater movement is generally toward the central pan area, with groundwater movement in the north western corner being diverted toward the lake.

Figure 25. Groundwater Contours and Flow: January to June 2016 (mamsl)



The same trend in groundwater movement is observed during the period July to December 2016 (Figure 26). During this period the groundwater is shallower or closer to surface with a maximum of 4.24 mamsl and a minimum of -5.40 mamsl near the lake. The groundwater is closer to surface within the central wetland region where hydroperiods are expected.

Figure 26. Groundwater Contours and Flow: July to December 2016 (mamsl)

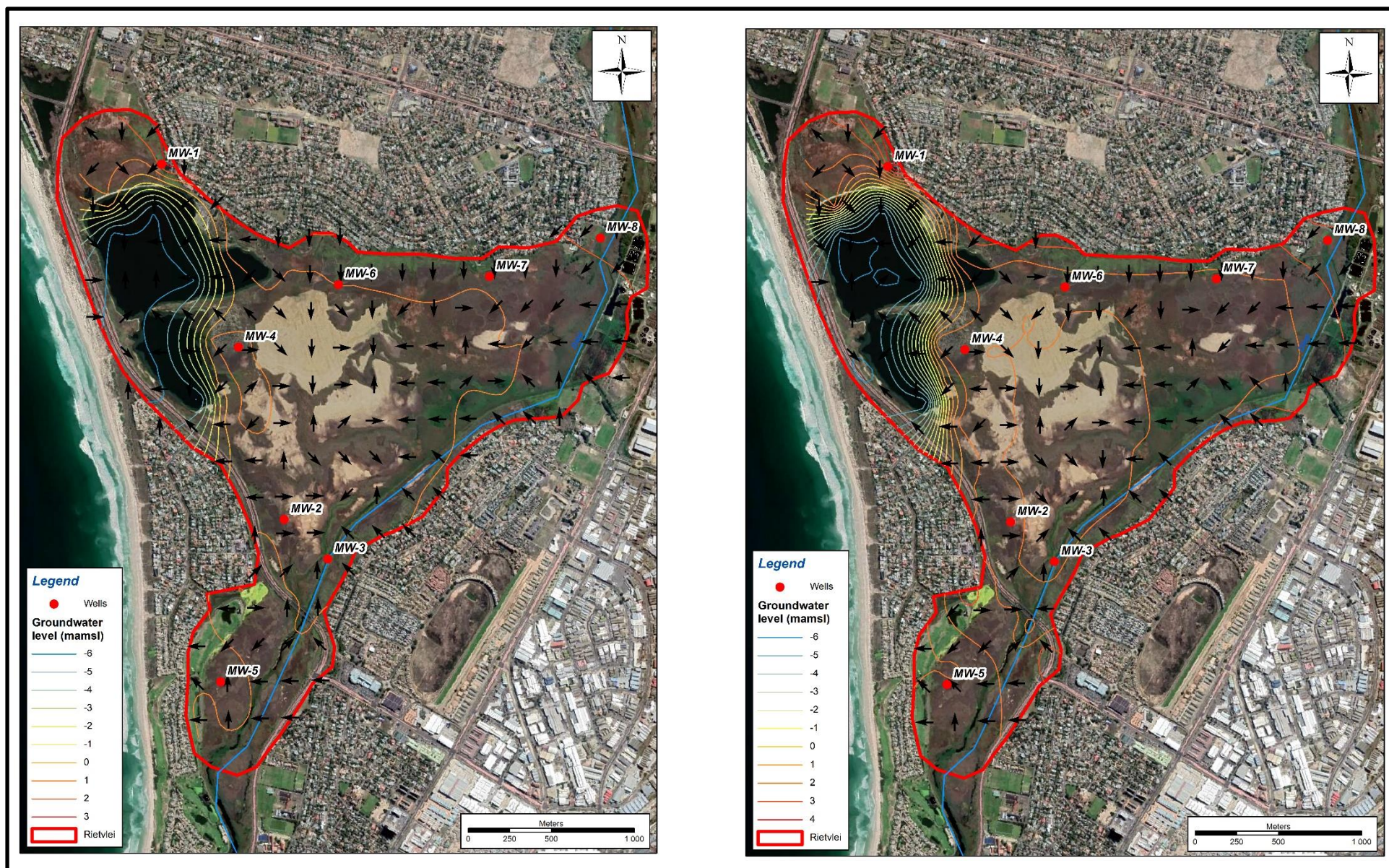


Figure 27. Groundwater Flow Contours: January to June 2016 (left) and July to December 2016 (right)

5.4 Soil

5.4.1 Soil texture distribution analysis

Table 15 shows the calculated Particle Size Distribution (PSD) for the discrete sampling depths (0.5 to 3.0 mbgl) across the study area. Figure 28 shows the Soil Texture Classes for the available soil texture data for the eight sampling locations at the various depths.

Table 15. Particle Size Distribution at discrete depths (0.5m) within the Rietvlei Wetland

Soil Sample	Latitude (Degree Decimal)	Longitude (Degree Decimal)	Particle Size Distribution (%)					Soil Class
			Clay	Silt	Fine Sand	Medium Sand	Coarse Sand	
RV1-0,5	18,49075	-33,83307	0,00	0,68	10,68	50,42	38,23	Sand
RV2-0,5	18,49815	-33,85250	0,78	11,13	18,48	47,12	22,55	Sand
RV3-0,5	18,50093	-33,85247	0,00	0,90	12,55	47,20	40,06	Sand
RV4-0,5	18,49545	-33,84310	0,91	6,38	30,92	39,53	22,27	Sand
RV5-0,5	18,49377	-33,86123	0,55	9,77	18,84	36,34	34,43	Sand
RV6-0,5	18,50205	-33,83983	0,39	8,63	10,54	58,70	21,77	Sand
RV7-0,5	18,51188	-33,83958	1,34	19,30	49,01	26,49	3,88	Loamy Sand
RV8-0,5	18,51915	-33,83765	0,58	9,34	13,67	42,08	34,34	Sand
RV1-1,0	18,51594	-33,84213	0,93	23,00	30,57	30,30	15,22	Loamy Sand
RV2-1,0	18,51914	-33,84150	0,23	6,07	14,10	50,06	29,53	Sand
RV3-1,0	18,52234	-33,84088	No data					*Sand
RV4-1,0	18,52555	-33,84026	No data					*Sand
RV5-1,0	18,52875	-33,83964	0,40	6,17	16,31	36,74	40,36	Sand
RV6-1,0	18,53196	-33,83901	1,01	12,17	21,90	41,86	22,77	Sand
RV7-1,0	18,53516	-33,83839	1,53	21,03	58,62	16,17	2,63	Loamy Sand
RV8-1,0	18,53836	-33,83777	0,39	6,47	18,19	44,34	30,53	Sand
RV1-1,5	18,49075	-33,83307	2,65	49,45	45,92	1,98	0,00	Silt Loam
RV2-1,5	18,49815	-33,85250	0,26	5,75	19,09	39,32	35,62	Sand
RV3-1,5	18,50093	-33,85247	0,77	12,04	27,31	39,81	20,01	Sand
RV4-1,5	18,49545	-33,84310	1,53	15,59	46,26	27,24	9,39	Loamy Sand
RV5-1,5	18,49377	-33,86123	0,20	4,08	13,40	40,95	41,36	Sand
RV6-1,5	18,50205	-33,83983	1,25	46,87	33,85	32,12	15,96	Loamy Sand
RV7-1,5	18,51188	-33,83958	0,97	13,31	50,28	28,52	6,91	Sand
RV8-1,5	18,51915	-33,83765	0,88	12,61	22,42	43,47	20,59	Sand
RV1-2,0	18,51594	-33,84213	2,75	35,32	24,05	27,21	10,68	Sandy Loam
RV2-2,0	18,51914	-33,84150	No data					*Sand
RV3-2,0	18,52234	-33,84088	No data					*Sand
RV4-2,0	18,52555	-33,84026	7,64	53,96	38,37	0,00	0,00	Silt Loam
RV5-2,0	18,52875	-33,83964	0,22	3,45	12,43	40,29	43,52	Sand
RV6-2,0	18,53196	-33,83901	0,11	4,49	8,13	67,60	19,38	Sand
RV7-2,0	18,53516	-33,83839	0,70	13,55	44,43	30,78	10,53	Sand
RV8-2,0	18,53836	-33,83777	0,54	9,83	26,25	44,90	18,49	Sand
RV1-2,5	18,51594	-33,84213	1,96	48,04	41,63	6,28	2,11	Sandy Loam
RV2-2,5	18,51914	-33,84150	No data					*Sand
RV3-2,5	18,52234	-33,84088	No data					*Sand
RV4-2,5	18,52555	-33,84026	0,72	8,87	13,81	43,04	33,59	Sand
RV5-2,5	18,52875	-33,83964	0,11	3,01	8,77	43,38	44,72	Sand
RV6-2,5	18,53196	-33,83901	0,27	6,75	21,13	51,51	20,29	Sand
RV7-2,5	18,53516	-33,83839	0,61	9,61	44,76	37,71	7,28	Sand
RV8-2,5	18,53836	-33,83777	0,00	0,00	0,20	34,18	65,63	Sand
RV1-3,0	18,51594	-33,84213	4,34	60,40	33,08	2,17	0,00	Silt Loam
RV2-3,0	18,51914	-33,84150	No data					*Sand
RV3-3,0	18,52234	-33,84088	0,83	16,45	17,99	27,14	37,59	Loamy Sand
RV4-3,0	18,52555	-33,84026	1,28	11,92	16,33	43,67	26,84	Sand
RV5-3,0	18,52875	-33,83964	0,20	4,26	21,95	40,16	33,44	Sand
RV6-3,0	18,53196	-33,83901	0,23	6,92	20,87	52,70	19,26	Sand
RV7-3,0	18,53516	-33,83839	0,30	6,74	35,41	45,31	12,22	Sand
RV8-3,0	18,53836	-33,83777	No data					Sand

*where no data is available texture class is inferred from drilling logs.

*RV refers to the wells present within the Rietvlei Wetland

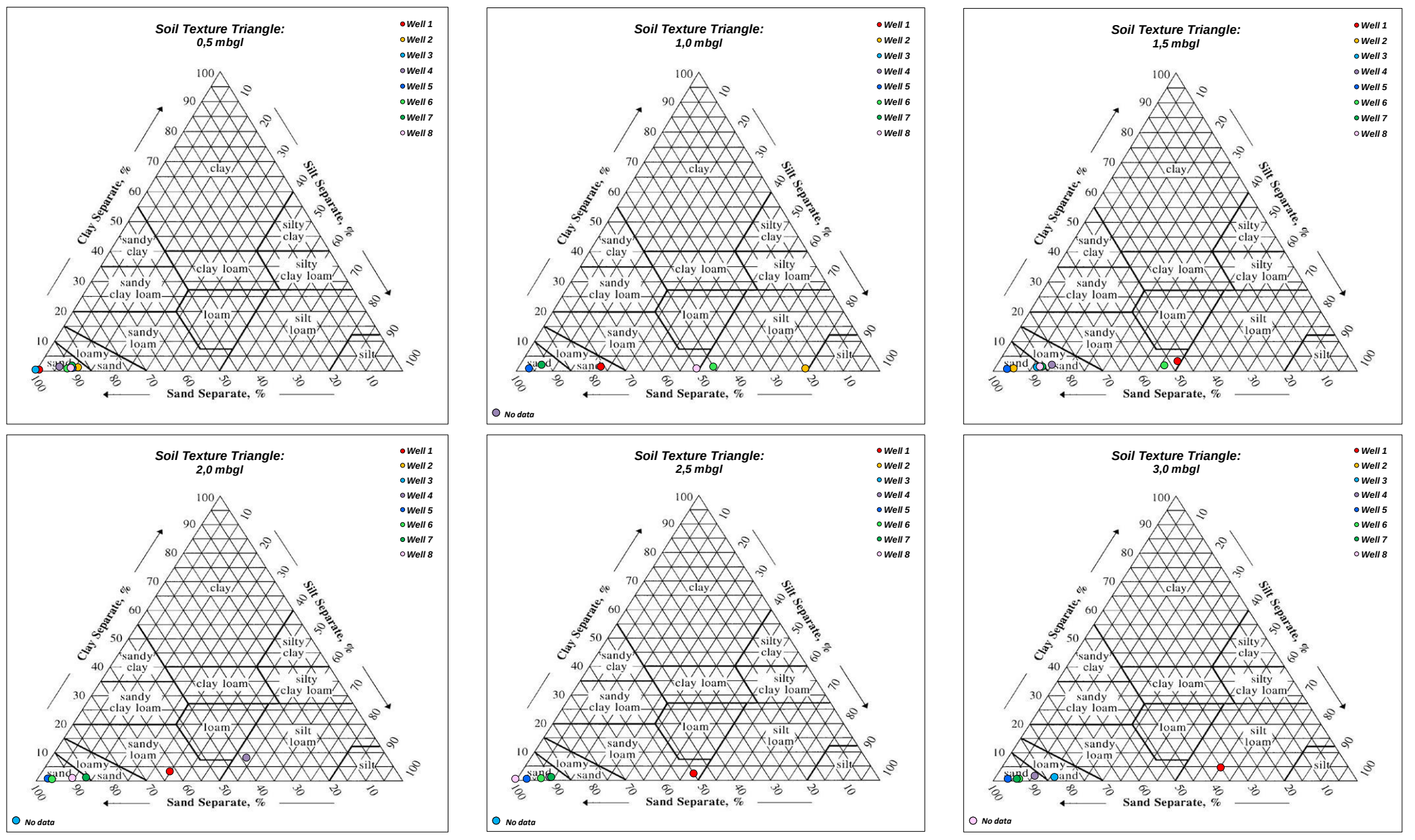


Figure 28. Soil Texture Distribution and Soil Classification: Wells 1 - 8 (Soil Survey Division Staff, 1993)

Soil textures were dominated by medium-coarse grained sands. A homogenous layer of sand is noted above 0.5 mbgl across the wetland. Sandy loam, loamy sand and silty loam textures are noted above the average groundwater level which indicates a heterogeneous soil distribution below 0.5 mbgl. This would influence the percolation of surface water infiltration to groundwater and potentially result in preferential flow pathways, e.g. the increasing loam (sandy to silt loam) texture observed at well 1, indicates that the movement of surface water (which would include dissolved salts) are staggered compared to the sandy textures observed at well 4 and well 6. The salinities at well 4 and well 6 are on average 20 000 $\mu\text{S}/\text{cm}$ higher than that of well 1. Well 7 presents sandy loam textures at shallower depths accompanied by lower salinities, as is this case at well 1. Although well 7 is similarly situated near storm water trenches, the groundwater presents a salinity of approximately 17 000 $\mu\text{S}/\text{cm}$ lower than that of well 6, located just 910 meters west of the well; with the only difference being the soil texture. Well 8 on the other hand presents low salinities with a sandy profile; the lower salinity observed at this well might be attributed to the contribution of freshwater from the nearby river canal moving through the transmissive porous media.

As mentioned, sandy textures dominate across the wetland which is indicative of less restrictive water movement within and through the porous media. Thus, the primary unconfined to semi-confined aquifer is hydrologically conductive and water moves freely across the shallow unconfined aquifer. This supports the observations made from the groundwater contours:

- Groundwater movement is similar throughout the year although the groundwater level is shallower (closer to the surface) during the second half of the year due to the porous media being highly conductive and responsive to local rainfall/recharge events;
- Preferential flow pathways may occur due to the depth-dependent and spatial variability of soil textures (and associated porosity), which support the assumption made by Campbell *et al.* (2017) that the wetland is divided into sub-catchments.

5.4.2 Soil texture distribution interpolation

Utilizing the PSD data, separate continuous surfaces were interpolated at various depths (0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 m) for the following soil types:

- (1) Clay,
- (2) Silt,
- (3) Fine sand,
- (4) Medium sand, and
- (5) Coarse sand.

All results are presented in the percentage (%) of the volume of the soil. The soil texture maps interpolated from the PSD data are presented in Annexure C. The resultant Soil Texture Class maps are presented in Figure 29. Soil texture was rather homogenous at shallower depths and presented more heterogeneity with depth.

Clay contents ranged between 0.0% to 7.64% (with the highest fraction recorded 2 mbgl at well 5), and was generally present in percentages below 1%. Silt contents ranged between 0.0% to 60.40% (with the highest fraction recorded at 3 mbgl at well 1), and on average made up 15% of the grains observed at the depths sampled.

Fine sand contents ranged between 0.20% to 58.62% (with the highest fraction recorded at 1 mbgl at well 7), and on average made up 25% of the grains observed at the depths sampled. Medium sand contents ranged between 0% to 67.60% (with the highest fraction recorded at 2 mbgl at well 6), and on average made up 36% of the grains observed at the depths sampled. Coarse sand contents ranged between 0.0% to 65.63% (with the highest fraction being recorded at 2.5 mbgl at well 8), and on average made up 23% of the grains observed at the depths sampled.

The distribution of clay and silt across the wetland indicated similarities. Both soil textures are present in higher percentages in the north eastern portion of the wetland at shallower depths, and tends toward the west at depths surpassing 1.0 mbgl.

The distribution of fine and medium sand indicated an inverse relationship, i.e. where the fine sand soil textures dominate, the medium grained sand textures are less prevalent. Finer soil textures dominate in the eastern and western portions of the central wetland area, whilst the medium grained textures are prevalent in the central wetland. Coarse grained sands are predominantly in the southern portion of the wetland.

Table 16 presents the typical hydraulic properties associated with the identified soil textures presented in figure 29; thus, these values indicate which zones are hydraulically conductive. In the case of Sand, coarse grained sand would be more conductive but have a lower porosity.

Table 16. Typical hydraulic properties of identified textural classes (Schultze, 1995; Todd, 1980)

Soil Texture Class	Saturated Hydraulic Conductivity (mm/h)	Effective Porosity, Subsoil (m^3 / m^3)	Porosity (%)
Clay	0.6	0.470	45 – 55
Loam (Silt)	13	0.464	35 – 50
Sand	210	0.430	25 – 45
Loamy Sand	61	0.432	-
Sandy Loam	28	0.448	-
Silty Loam	6.8	0.495	-

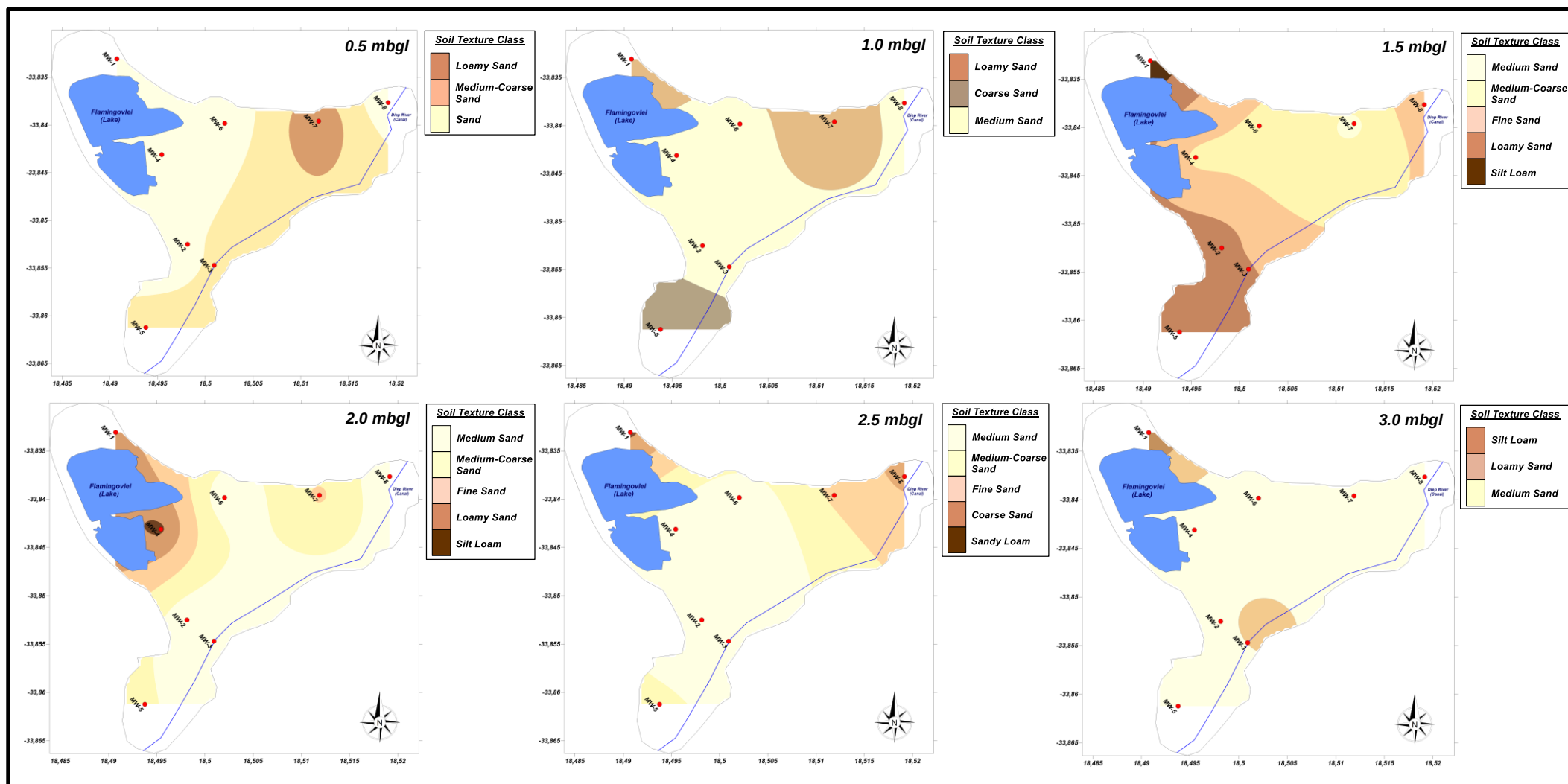


Figure 29. Soil Texture Distribution within and across the Rietvlei Wetland: 0.5 - 3.0 mbgl

5.5 Assessment of environmental impacts

5.5.1 Environmental Impacts highlighted in previous reports

During 2015 to 2017 the City of Cape Town commissioned a study aimed at designing a strategy to better understand the hydrology and geohydrology of the Diep Estuary. The main deliverables stemming from the study and subsequent reports were:

- (1) Observations with regards to the hydrology of the estuary which improved the understanding of the circulation of surface water and the reduction of flows from the catchment (Ally *et al.*, 2017a),
- (2) Description of the geohydrological characteristics of the estuary, specifically groundwater flows directions, groundwater gradients, groundwater quality variations, groundwater depth and seasonal fluctuations (Campbell *et al.*, 2017), and
- (3) The compilation of a Hydrodynamic model using Mike21FM and HEC-RAS software to determine the extent of salinity intrusion upstream of the estuary mouth, which modelled present day flows and modified effluent release flows from the Potsdam WWTW (Ally *et al.*, 2017b).

The result of these reports, relevant to this study, is the identification of key environmental and ecological aspects impacted by hydrological and geohydrological change. Table 17 presents these key aspects, the resulting impacts and potential repercussion of these factors on the environment. This review provides a platform to compare and assess the findings presented within this study.

Some key aspects were highlighted within these reports and are discussed in context with the observations made during the course of the current study:

- **Inflows and outflows**

These aspects define the inputs required to quantify the water balance as per Eq. 1 (section 3.2.2). Major inflows to the system include the Potsdam WWTW, river flows (from the Diep River catchment) and oceanic tides at the estuary mouth. The hydraulics of the system are, however, dominated by Potsdam WWTW flow. In addition to this, the high responsiveness to rainfall/runoff events observed (i.e. groundwater recharge and movement), accounts for a major hydrological input to the local aquifer.

Water loss from the seasonal pans and permanent water bodies occur as a result of evaporation and not necessarily due to drainage to the aquifer, as the surface of the pans are covered by very fine sediment which is impermeable to water (Campbell *et al.*, 2017).

Table 17. Environmental impacts highlighted within the reports compiled for the City of Cape Town (Ally *et al.*, 2017a; Campbell *et al.*, 2017)

Aspect	Impact	Potential environmental/Ecological degradation
(a) Natural environment, including ecosystem health and sustainability	(1) Changes in seasonal cycles of pan inundations as the result of altered surface and groundwater flows due to anthropogenic change over time, (2) Tidal flows and salinity levels are not natural due to freshwater effluent entering the system via the Potsdam WWTW	i. Migration of water birds might be staggered, and nutrients that made seasonal pans attractive to these birds are not in sync with seasonal fluctuations ii. High nutrient loads and evaporation rates during dry season may lead to algal blooms in estuary iii. Species disappear from upper canals of Milnerton Lagoon toward the end of October when water starts to dry up and salinities increase, potentially leading to water becoming hypersaline
(b) Salinity	(1) Classified as freshwater dominated estuary due to high volumetric flow rate of the Potsdam WWTW effluent entering the system (2) Storm water runoff from the residential areas (via trenches) influences the salinity of the northern boundary of the wetland	i. Loss of habitat for sand prawn communities due to the salinity gradient declining below optimal breeding conditions (17 PSU) down gradient of the Otto Du Plessis Bridge ii. Vegetation (exotic invader species) less tolerant to saline waters dominate the northern boundary of the wetland
(c) Water level	(1) Altered seasonal fluctuation in groundwater levels (2) Dust problems in summer due to extended dry periods (3) Potsdam WWTW drainage canal drains the riverine system faster than would naturally occur	i. Loss of ecological characteristics of pans ii. Fine sediments cover surface and may cause decreased infiltration, and as a result in increased runoff and risk of flooding iii. Siltation due to increase of sediment being transported downstream
(d) Flooding	(1) Damage to properties constructed below the 1:50 year flood-line (2) Addition of industrial and other contaminants to surface water and groundwater	i. Disturbance to natural surface water flow regime ii. Vegetation loss which may in short to medium term increase runoff iii. Soil and water contamination
(e) Estuary mouth conditions	(1) Transition from temporarily open / closed system to permanently open due to the addition of effluent from the Potsdam WWTW	i. Decreased salinity gradient, refer to (b) for ecological impact
(f) Sediment management	(1) Build-up of fine-grained sediment resulting in siltation (2) Heavy metal contamination (3) Sediment-rich water is stored within wetland during floods, and alters flood characteristics by allowing the water level to gradually drop via drainage	i. Long term siltation (build-up of sediments) within the Rietvlei may cause it to lose its characteristics as a wetland ii. Rate of sedimentation is enhanced by vegetation, especially in the north-eastern area where treated sewage water is released
(g) Water flows	(1) Riparian zone is heavily utilized by domestic stock (upstream) (2) Impoundments of natural flows in the river has caused the riverine system to change from a perennial to an intermittent flowing system (3) Stagnant water may result in anoxic conditions	i. Heavy invasion by weeds and invader species during dry months ii. Decrease in flushing of the system and an increase in exotic vegetation encroachment within riverbed iii. Nutrient enrichment as a result of farming practises, effluent release and poorly serviced human settlements which has negatively impacted aquatic and riparian vegetation

- **Surface water**

The water depths and salinity of the Rietvlei Wetland are directly influenced by groundwater. The conductivity profile of the Flamingo Vlei lake shows a uniform salinity, and no halocline or distinguishing vertical stratification (Ally *et al.*, 2017a).

Two distinct flood regimes are present with regards to the Diep River and Rietvlei system (Ally *et al.*, 2017b). The first presents in the upper Rietvlei and is dependent on river flow. The second is present at the lower Milnerton Lagoon and is dependent on opening of the estuary mouth. Maximum salinity intrusion into the lagoon occurs during spring low tides and reduced river flows.

Due to significant changes to the hydrodynamics of the Rietvlei over the years, the groundwater of the vlei and the surface water of the Diep River and constructed bypass canal are not as closely related as would be expected. Campbell *et al.* (2017) noted that the Rietvlei itself might be divided into its own sub-catchments, as the drainage and response varies across the wetland.

- **Groundwater**

The groundwater within the Rietvlei wetland supports the surface hydrology dynamics and plays a vital role in the management of the desiccation of the central pans during summer periods. According to Campbell *et al.* (2017), a clear connection between groundwater and the surface water at Blaauwberg Road Bridge and the Flamingo Vlei deep water lake exists. No clear connection exists between the bypass canal or the upper estuary. The Bayside canal north-east of the Flamingo Vlei lake contributes to the inflow toward the lake during winter months. The inflow contribution of this canal has been reported as 1000 m³ per day during summer months, with an average inflow ranging between 7000 – 10 000 m³ per day (Moorcroft, 2019).

Campbell *et al.* (2017) state that the aquifer may not be continuous, but rather separated from one another by man-made or natural features, e.g. storm water trenches, roads and natural topography.

The soils and sediments within the vlei were described as mainly sand in the outer vlei and finer grained profiles with higher clay and silt content are observed closer to the centre of the vlei (Ally *et al.*, 2017a). Campbell *et al.* (2017) performed a chemical analysis on these soils and sediments and found that the sodium content provides a useful guide to soluble salt content of sediment. This study observed that the inner wells 2, 3 and 4 show the highest salt content at depths of 1 and 2 mbgl, which is near the average groundwater levels. This is indicative of a good correspondence between sediment and groundwater salinity. A trace element analysis was also

performed and compared against the soil screening values – all land uses protective of water resources (SSV1), and showed:

- Well 1: Copper (Cu) was equal to SSV1 at 3 mbgl,
- Well 4: Vanadium (V), Copper (Cu) and Lead (Pb) exceeded SSV1 at 2 mbgl,
- Well 5: Nickel (Ni) exceeded the SSV1 at 0.5 mbgl, which may be the result of the sandy soil texture and historic dumping (Campbell *et al.*, 2017).

Campbell *et al.* (2017) observed that wells with lower average salinities tend to show an increase in salinity over the winter followed by a decrease and levelling out during summer (wells 1, 5, 7 and 8), whilst wells with higher salinities indicated the opposite pattern (wells 2, 3, 4 and 6). In this study Campbell *et al.* (2017) also collected pH readings during September and November, which indicated no clear seasonal trend and that variations are minor. Groundwater temperature follows a natural seasonal trend. The average temperatures observed in the outer wells 1, 5, 6, 7 and 8 were 14 – 16 °C during winter and 19 – 21 °C during summer. The lower lying central area was warmer on average, with a maximum temperature of 25 °C observed at well 2, due to the shallower water level and warmer soil temperature.

Campbell *et al.* (2017) attributes the rapid rise in water level observed at well 2 and well 3 to the inundation over the surface rather than groundwater rising from below, as groundwater permeation is slow.

Groundwater within the Rietvlei is affected by several processes, specifically recharge and discharge, interaction with surface water bodies and the movement of dissolved salts. These three processes are discussed below:

- **Groundwater recharge and discharge**

The Rietvlei's groundwater system is dynamic and responds rapidly to rainfall events over short periods of time, which results in the flooding of the seasonal pans, observed at wells 2 and 3. Recharge occurs within the pans via flooding, and provide a source of groundwater discharge over summer months alongside evaporation losses.

Falling groundwater levels correspond with groundwater discharge, which is more gradual over longer time frames. The groundwater within the vlei flows toward lower lying areas where it discharges either as seepage into surface water bodies or capillary action to surface followed by evaporation and evapotranspiration in seasonal pans and groundwater use by plants (Campbell *et al.*, 2017).

- **Groundwater interactions**

The Diep River has a direct interaction with groundwater alongside the river canal, as evident from the similar water levels observed from the groundwater in well 8 and the surface water logger at the Blaauwberg Bridge, indicating close hydraulic connectivity (Campbell *et al.*, 2017).

The groundwater is more saline than the water flowing within the river. Salinity, however, shows no clear relationship, although both show constant salinities over summer months and an increase during winter. Groundwater temperature indicates less short-term variability than the surface water. Groundwater and surface water temperatures are similar during summer, suggesting some river flow is due to groundwater infiltration (Campbell *et al.*, 2017).

The data observed at well 2 and the Otto du Plessis Bridge shows no clear hydraulic connectivity between groundwater and the artificial, unlined canal that drains the effluent from the Potsdam WWTW.

The Flamingo Vlei lake is more saline than well 1, but less so than wells 2 and 4. Similar groundwater levels and seasonal trends are observed, although the temperature changes occur faster in the lake than in the groundwater. The lake also experiences water losses that lower the water level to below the surrounding groundwater levels, which causes the hydraulic gradient to tend toward the lake (Campbell *et al.*, 2017).

Numerous storm water outlets are present along the northern border of the wetland which drain the runoff from the adjacent residential areas via trenches. These trenches often hold standing water that influence groundwater levels and quality, which is evident from the vegetation; as less saline tolerant vegetation is found in this area (Campbell *et al.*, 2017). Many residents have well points at their homes that are frequently used for irrigation, which lowers groundwater levels at wells 6 and 7, as compared to well 8 situated near the river. Not all residents register these abstraction points with the NGA, however those identified are shown in Annexure B.

- **Salinity: Soil, sediment and groundwater**

Recharge events flush salts into the groundwater by means of preferential flow. These salts originate as the dry deposition of marine aerosols from the ocean settling and accumulating on the surface of the vlei over summer, which result in an increase in salinity not necessarily associated with the intrusion of saltwater. According to the Ghyben-Herzberg scenario presented for the Rietvlei by Campbell *et al.* (2017), intruding marine water would occur at depths of 40 – 80 mbgl, which is a far less relevant mechanism of salinity as the groundwater-surface water dynamics are limited to far shallower depths of approximately 0 – 10 mbgl.

Vertical stratification occurs at well 2 and 3 as saline water in denser environments would be present at greater depths. Salts are flushed through the soil during recharge events, thus higher salinities are found deeper within the soil profile and wells at lower elevations.

The outer wells are dominated by sand, and are thus more permeable which allows rapid water level increases and enhanced movement of salts down to groundwater. Over time, all available salts are leached from the upper soil profile and groundwater salinity levels decrease and stabilize over summer. The inner wells consist of an aquifer that is less permeable, thus recharge tends to take place via surface flooding with freshwater. Campbell *et al.* (2017) made the observation that freshwater enters the inner wells and dilutes the saline groundwater, which causes the rapid decreases in the measured salinities.

Discharge from the Potsdam WWTW would ideally need to be managed to re-establish natural estuarine faunal communities. By decreasing the amount of freshwater effluent released into the system, the salinities would increase and salt water intrusion would extend further up the estuary, at least to the Otto DU Plessis Bridge to a minimum salinity of 17 PSU to allow sand prawns to breed. Ally *et al.* (2017b) found that even by reducing the input by 50%, the natural salinity would not reach these levels up to the bridge.

The salinity across the northern boundary of the wetland is influenced by storm water canals which discharge runoff from the adjoining suburb into the reserve. No clear seasonal pattern is observed from the salinity data.

5.5.2 Environmental impacts identified throughout the course of the study

5.5.2.1 Salinity and tidal influence

Soil and groundwater chemistry plays a significant role in the environmental and ecological sustainability of any environment, none more so than in wetlands. The locality of the Rietvlei Wetland increases the relevance of the influence of tidal fluctuation and saltwater intrusion, making water level fluctuation and salinity profiles important aspects to consider.

To establish the extent of expected higher salinities, the available Electrical Conductivity (EC) data from wells 1 to 8 is interpolated for the same period of analysis used in the conceptualizing the groundwater flow: January to June 2016 and July to December 2016 (Table 18). Table 19 presents the average EC for the surface water monitoring points across the same period.

Figures 30 to 32 present the maps generated from this data. This presents a visualization of the distribution of the groundwater chemistry within the wetland, and provides some insight into the hydrodynamics of the groundwater regime and surface water connectivity.

Table 18. Average electrical conductivity (EC) for the period July 2015 – December 2016, Wells 1 - 8

Well	Average EC ($\mu\text{S/cm}$) – Jul to Dec 2015	Average EC ($\mu\text{S/cm}$) – Jan to Jun 2016	Average EC ($\mu\text{S/cm}$) – Jul to Dec 2016
MW-1	1 401.59	1 765.52	4 269.70
MW-2	52 063.00	56 249.00	52 474.00
MW-3	73 106.64	77 469.02	79 077.64
MW-4	25 323.82	24 339.09	25 680.07
MW-5	10 422.68	6 849.92	6 218.12
MW-6	23 266.90	23 316.05	23 362.26
MW-7	5 230.69	3 096.41	5 090.65
MW-8	4 174.60	3 372.90	5 562.37

Table 19. Average Electrical Conductivity (EC) for the period July 2015 - December 2016, surface water monitoring points

Surface water monitoring point	Average EC ($\mu\text{S/cm}$) – Jan to Jun 2016	Average EC ($\mu\text{S/cm}$) – Jul to Dec 2016
Blaauwberg Bridge	1 727.77	2 092.01
Flamingo Vlei	4 167.59	4 273.06
Otto du Plessis Bridge	915.65	1 038.59
Woodbridge	21 874.87	14 086.28

The following observations were made upon comparison of the EC values against the groundwater levels observed in wells 1 to 8 (section 5.2):

- (1) Groundwater EC levels decline following a rainfall / recharge event,
 - The addition of freshwater from surface water runoff (rainfall) temporarily decreases the salinity of groundwater within the wetland,
- (2) Groundwater level fluctuations and movement drive the observed changes in the distribution of EC within the wetland itself, and
- (3) Surface water salinities increase at all surface monitoring points toward the second half of the year, apart from the monitoring point at Woodbridge – which shows a decrease. This might be due to the flow during this period being mainly from the freshwater WWTW effluent and resultant runoff from rainfall from the upper catchment.

Figure 30 presents the EC for wells 1 to 8 for the period July to September 2016. This period has been highlighted as a hydrologically responsive period as a result of increased rainfall. Figure 31 presents the EC variation at the surface water monitoring points, and clearly shows the tidal influence on salinities closer to the estuary mouth, however further upstream of the Otto Du Plessis Bridge and within the wetland no clear tidal influence on salinity is noted.

The EC observed at wells 1 – 8 indicates no tidal influence. From the period highlighted in these figures, no clear connection of the surface water and groundwater salinity trends is evident. The higher observed salinities within the groundwater was observed within the central seasonal pans

in well 2 and well 3, whereas the higher salinities associated with the surface water was observed downstream of the Otto du Plessis Bridge toward the estuary mouth. EC values were generally higher during the second semester of the year, indicating that the rainfall/recharge events flush and distribute dissolved salts across the surface and shallow sub-surface.

Wells 1, 5, 7 and 8 (referred to by Campbell *et al.*, 2017 as the outer wells) show a similar EC trend which tends to be below 10 000 $\mu\text{S}/\text{cm}$. Wells 4 and 6 (upper central wells) showed a similar EC trend and ranged between 20 000 – 30 000 $\mu\text{S}/\text{cm}$. The highest observed EC values were at the central wells 2 and 3, where the highest values were observed at well 3 and ranged between 70 000 – 80 000 $\mu\text{S}/\text{cm}$. This is the lowest point within the wetland which results in a pressure gradient (which induces groundwater flow toward this area) and elevation different (which results in surface water draining toward this area).

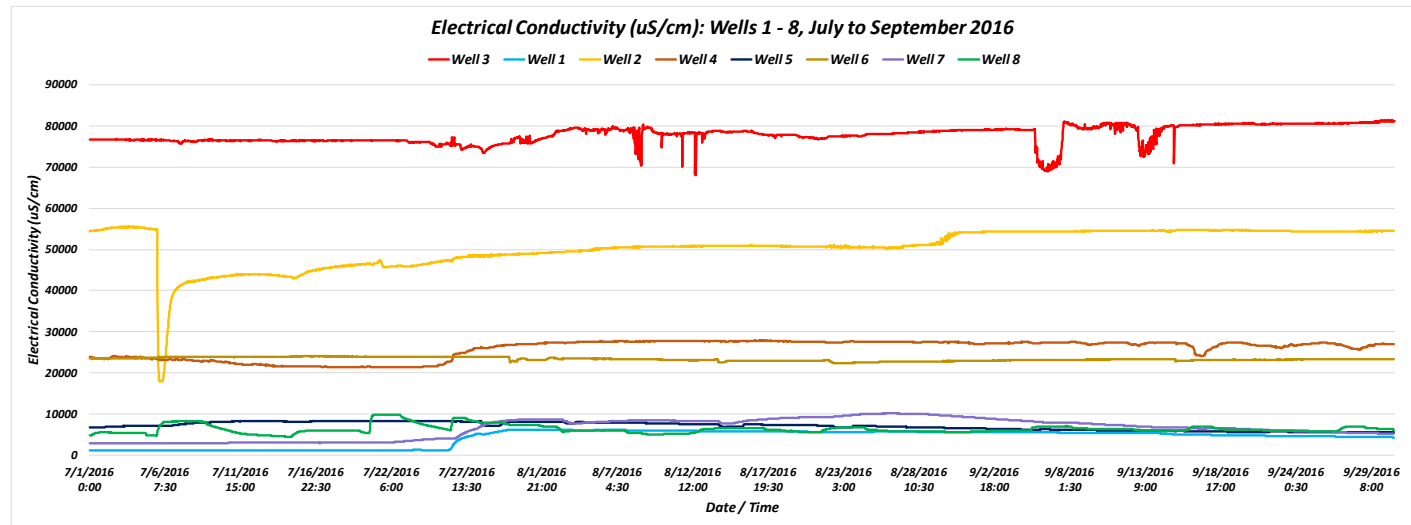


Figure 30. Electrical conductivity ($\mu\text{S}/\text{cm}$): Wells 1 - 8, July to September 2016

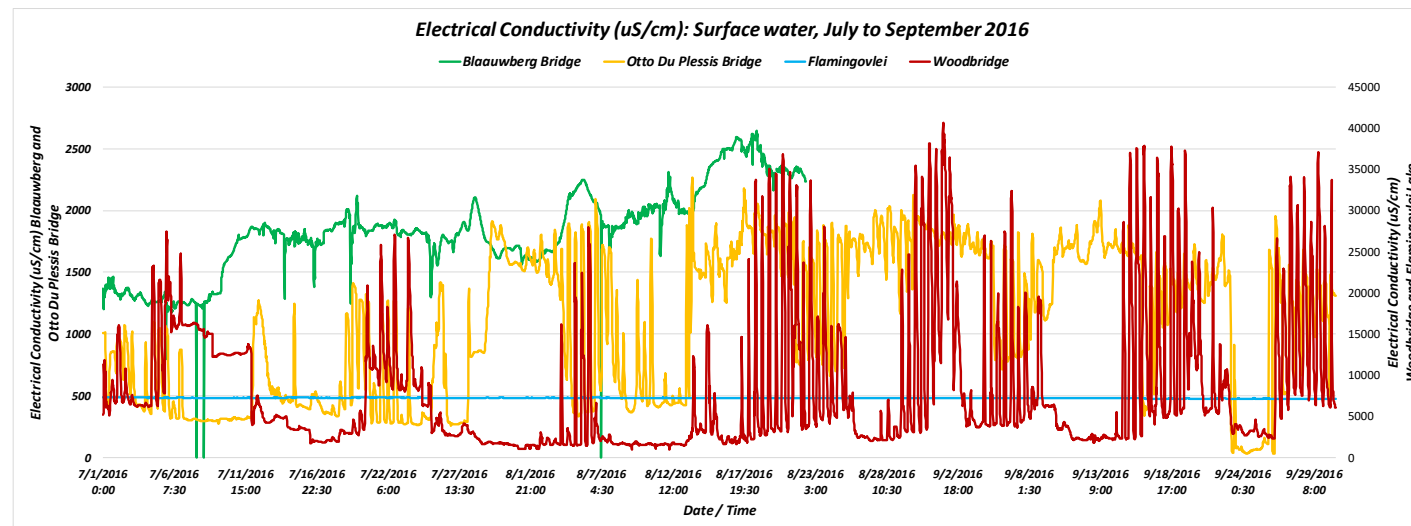


Figure 31. Electrical conductivity ($\mu\text{S}/\text{cm}$): Surface water, July to September 2016

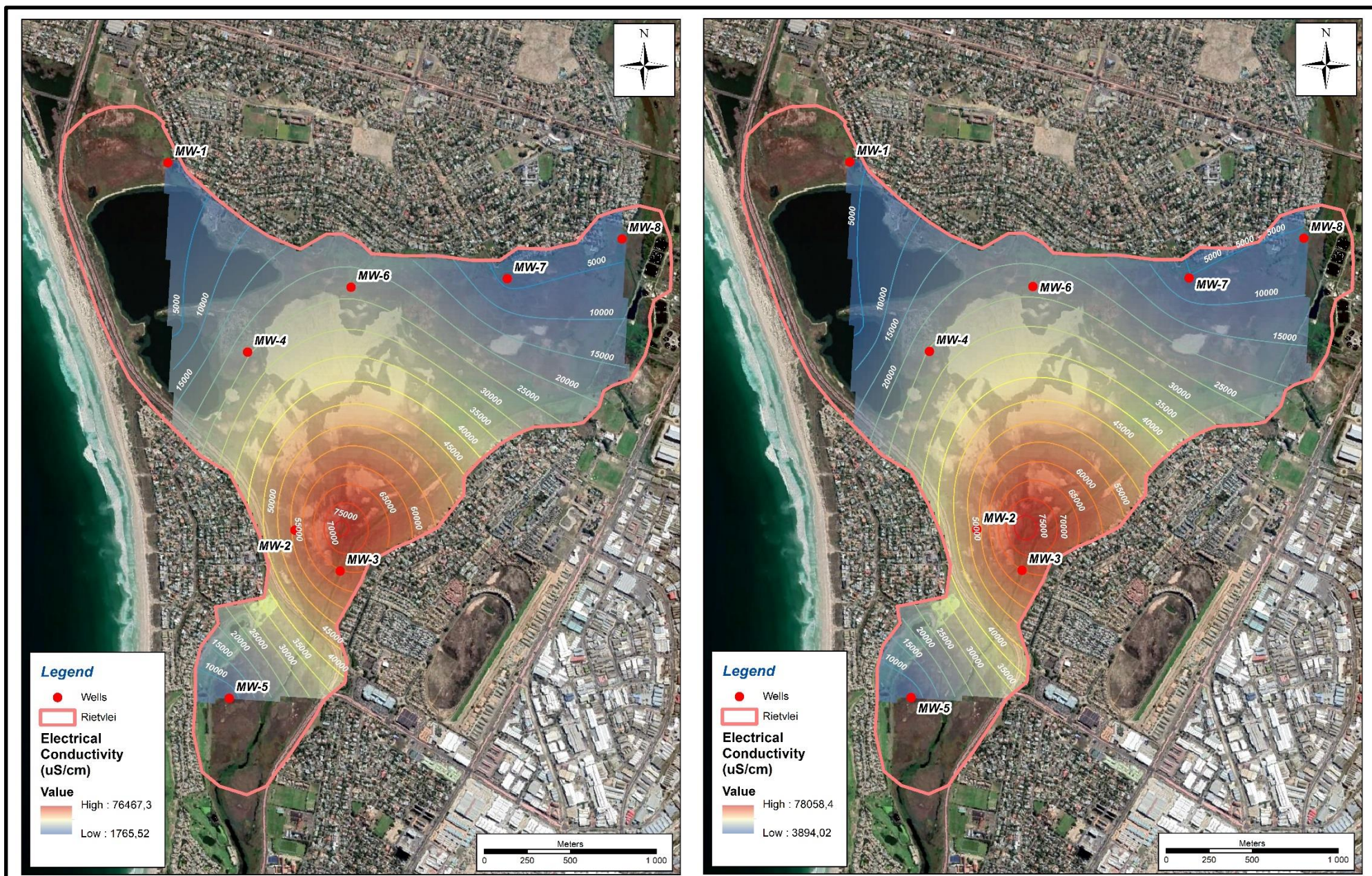


Figure 32. Electrical Conductivity ($\mu\text{S}/\text{cm}$) Contours: January to June 2016 (left) and July to December 2016 (right)

Other than EC, the possible influence of tidal fluctuation will require validation, as the response of the wetland to these aspects is crucial in understanding its hydrodynamics. The tidal data obtained from WxTide is compared to the groundwater levels of the eight groundwater wells and four surface monitoring points for the month of July (Figure 33 and Figure 34). The reasoning behind examining this aspect across a shorter timeframe is to better highlight any response to the tidal fluctuations. Noting this influence would make it paramount to the effective development of a complex numerical hydrological model.

From these observations, no clear influence of tidal fluctuation on groundwater was noted during the highlighted period. The groundwater hydrodynamics of the system seem to respond to rainfall/runoff (recharge), evaporation (discharge) and seepage (discharge).

A clear influence on the water level at the surface water monitoring points at Woodbridge and Otto du Plessis Bridge is noted. The Flamingo Vlei lake and the monitoring point at Blaauwberg bridge show no clear tidal influence, and a more similar response to rainfall/runoff than that of the groundwater monitoring wells in the vicinity.

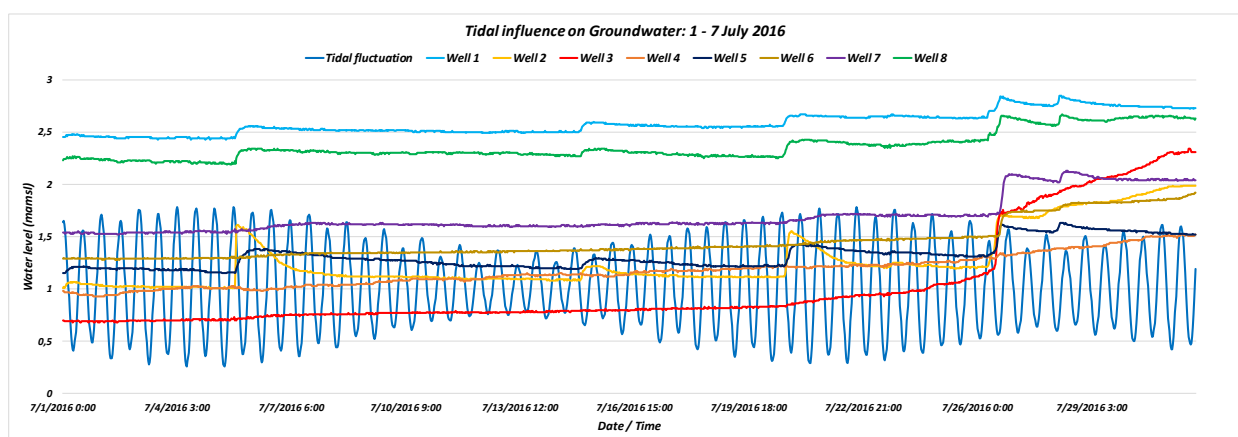


Figure 33. Tidal influence on groundwater: 1 - 7 July 2016

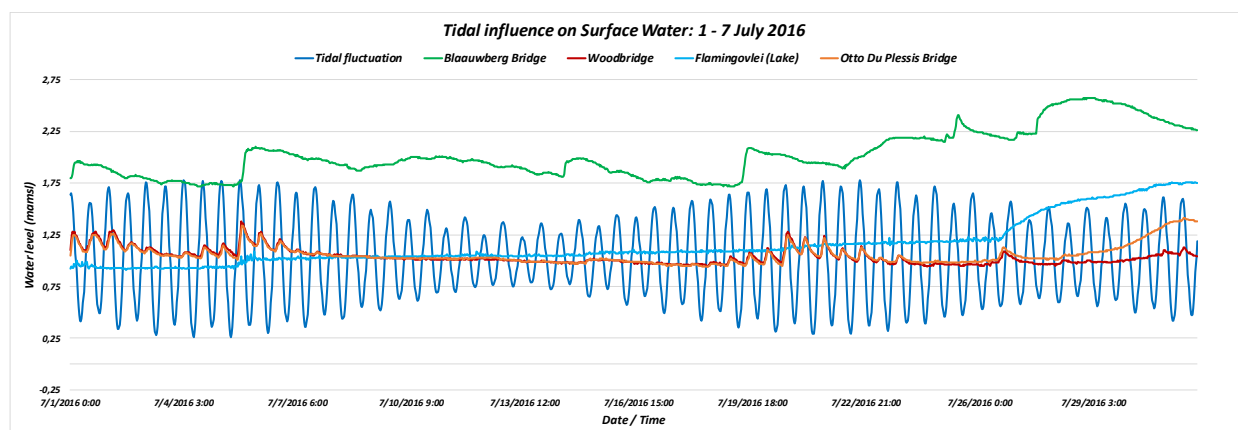


Figure 34. Tidal influence on surface water: 1 - 7 July 2016

5.5.2.2 Utilizing the analysis of Key Wetland Attributes and soil characteristics to establish potential environmental impacts

Upon review of both the groundwater movement and soil characteristics of the wetland, it is clear that – although not homogeneous – the wetland’s characteristics are linked across and below the surface (Table 20).

The identification of environmental impacts was based on the quantification of aspects related to the groundwater attributes and soil texture within the wetland. Thus, a qualitative assessment is launched based on the observations made from the:

- (1) Groundwater flow and wetland residence time,
- (2) Groundwater level fluctuation and wetland hydroperiod,
- (3) Groundwater salinity,
- (4) Groundwater-surface water connectivity,
- (5) Estuary mouth conditions,
- (6) Soil texture classification and distribution.

Additionally, important aspects identified throughout the review of the study area, relevant data and literature are also considered, which include:

- Tidal influence,
- Discharge of freshwater effluent from the Potsdam WWTW,
- Historic alteration to the geomorphology of the wetland, and
- Point and non-point source pollution.

Table 20 presents this in accordance with the methodology proposed in section 4.3, and provides a common platform to assess the significance of these aspects and their potential to enact change and impact the sustainable functioning of the Rietvlei Wetland.

Table 20. Environmental Aspects and Impacts identified throughout the course of the study

Theme	Aspect	Impact	Scale / Frequency of change	Significance of change
a. Groundwater	(i) Flow	(1) Change in hydrological regime - Flamingo Vlei lake acts as sink for the surrounding groundwater, resulting in preferential flow of groundwater toward the lake within the north-western area of the wetland due to the difference in hydraulic gradient (i.e. groundwater level is at a higher elevation than the water level within the lake). - Groundwater flow generally tends toward the seasonal pans north of the Otto du Plessis Bridge; this results in a seasonal high-water table, which together with surface water flooding (due to a difference in elevation as the result of the alteration made to the natural drainage canal) gives rise to a distinct hydropattern. - No contribution to base flow from / to the Diep River is present under current conditions due to the upstream abstraction of groundwater and surface water, however during the course of the study base flow contribution to and from the unlined canal that drains the eastern border of the wetland was noted. - The majority of groundwater abstraction in the vicinity of the wetland is from the primary aquifer which governs the groundwater characteristics of the wetland, thus the potential for local change in water level exists. (2) Pan inundation and ecological change - Irregular pan inundation or changes in response to natural seasonal trends may lead to changes in water-bird migration patterns and affect the composition and distribution of vegetation across the wetland. - Groundwater flow is responsible for the distribution of dissolved salts which has resulted in higher observed salinities within the Marsh/Vlei area (see a.v. <i>Salinity</i>)	(1) Regional / Permanent (2) Local / Seasonal	(1) Medium (2) High
	(ii) Hydroperiod	(1) Extended periods of saturation - Shallow surface pans form at low gradients where surface water ponds, groundwater discharges or the groundwater-surface water interface meets; which, should the depth exceed the tolerance level of the vegetation, could potentially result in the loss of vegetation. - The shallow pans increase the area exposed to the effects of evaporation, i.e. water (groundwater) is lost through evaporation instead of being stored / transported within the sub-surface porous media. - The highly saline nature of the pans coupled with high evaporation rates may result in the pans becoming hypersaline. (2) Depth of water rise above ground level - Should the depth of the hydroperiod exceed the tolerance level of the local vegetation, the conditions might be detrimental to some hydrophytic plant species.	(1) Local / Seasonal (2) Local / Permanent (event-based)	(1) High (2) High

	(iii) <i>Residence Time</i>	(1) Filter and flush of water through the central pan (Marsh/Vlei) area - Although wetlands offer a natural purification effect to the catchment, the higher residence times associated with wetlands may result in contamination from the surrounding environment being present within the wetland for extended periods of time. This could increase the adverse effects thereof – which may result in soil and groundwater contamination and ecological degradation over the long-term. - The residence time within the Rietvlei wetland is notably longer under its current flow conditions than would occur naturally thus, the wetland has experienced an increase in residence time due to decreased inflow from the upper catchment, which results in a less active surface and shallow sub-surface flow. This could result in stagnant ponds of water and the anoxic conditions. (2) Flood buffer - Floodplain wetlands, such as the Rietvlei, decrease the flow rate of their river systems by dispersing the inflow over a larger surface area covered in vegetation and saturated soil - and as such, the loss of energy results in the deposition of sediment which may result in siltation, loss of vegetation and altered wetland characteristics.	(1) Local / Permanent (2) Local / Event-based	(1) High (2) Medium
	(iv) <i>Recharge</i>	(1) Rainfall dependent - Recharge within the wetland is governed by rainfall, rather than contributions from surface water or tidal influence. - High volumes of rainfall over the saturated surface of the wetland (i.e. shallow pans) would result in an increase in the flow of water across the surface and shallow sub-surface, and an event-based decrease the residence time within the wetland. (2) Decrease due to saturated zones and fine sediment over surface - Fine sediment (clay) is spread across the surface of the wetland as a result of siltation from upstream river flows, which decreases the natural recharge rate of the wetland by establishing impermeable areas that may restrict natural recharge. - During hydroperiods, the porous media is saturated to such an extent that the groundwater level rises to and above the wetland surface – thus an addition of water would result in a sporadic decrease in wetland residence time and subsequently increase the distribution of water across the surface and increase the risk of flooding.	(1) Regional / Event-based (2) Local / Permanent	(1) Medium (2) Medium
	(v) <i>Salinity</i>	(1) Specialized vegetation (salt-tolerant plants, halophytes; saturation-tolerant plants, hydrophytes) - Halophytic and hydrophytic plants dominate the central wetland as the result of the saline water and saturated soils. These plants are sensitive to change; should the reverse salinity gradient noted within the estuary extend to this area, the sustainable functioning of these plants would be affected. Even though this is unlikely under current conditions, overbank flooding of freshwater from the adjacent canal may influence the salinity of this area.	(1) Local / Permanent (2) Local / Permanent	(1) High (2) Medium

		- A decrease in salinity has been noted across the northern border of the wetland due to the presence of storm water trenches – this has led to a decrease in these plants, and the invasion of other plant species that are more tolerant to current conditions. (2) Dissolution of aerosolized salts from the ocean - Oceanic salt is aerosolized as a spray, and is windblown across the surface of the wetland. These salts accumulate during summer time (or periods where no rainfall recharge occurs). During winter months (or periods of rainfall) these salts are dissolved and either percolates through the porous soil media and increases the salinity of the groundwater, or joins the surface water runoff and flows toward the seasonal (or permanent) pans. These pans are hydrogeologically connected to groundwater, and would thus lead to an increase in groundwater salinity within these areas.		
	(vi) Surface water connectivity	(1) Surface water (overbank) flooding resulting in hydroperiods - Stagnant water may result in anoxic conditions (<i>see iii.1 Hydroperiod</i>). - The resultant ponded water depth could exceed the depth required to sustain the hydrophytic vegetation across the wetland surface (<i>see iii.2 Hydroperiod</i>). (2) Decline in base flow contribution - Groundwater and surface abstraction have resulted in the natural base flow of the hydrologic system being altered that no (or negligible) base flow is present during dry summer months (<i>see i.1 Flow</i>). (3) Changes in salinity - Surface water salinities within the Diep Estuary (apart from the Flamingo Vlei) have decreased due to the addition of freshwater effluent from the Potsdam WWTW. - Groundwater salinities within the Rietvlei Wetland are not influenced by saltwater intrusion or tidal fluctuations, but rather dissolved salts originating from the aerosolized salts from the ocean accumulating on the surface during dry months (<i>see v.2. Salinity</i>). - No clear link of regional influence between groundwater and surface water salinities is observed; however seasonal fluctuations in water levels and salinities are evident.	(1) Local / event-based (2) Regional / Permanent (current conditions) (3) Local / Permanent (Seasonal)	(1) Medium (2) Low (3) High
b. Soil	(i) Soil texture and spatial distribution	(1) Hydraulic conductivity (Highly responsive to flooding and recharge events) - Medium-coarse grained sands dominate the soil texture within the wetland; thus, a high hydraulic conductivity as the result of the associated porosity invites the potential for the distribution of contaminants from residential and commercial storm water drains through the sub-surface. (2) Altered surface water runoff characteristics - Responsiveness to rainfall/runoff may contribute to flooding (<i>see iv.2. Recharge</i>). (3) Siltation - Siltation will result in a decrease in the storage capacity (volume) of the wetland which directly affects the wetland residence time, i.e. a decrease in volume will decrease the residence time. - Siltation could result in a change in estuary dynamics due to prolonged periods of saturation, and may result in anoxic conditions.	(1) Local / Permanent (depth-dependent) (2) Local / Permanent (3) Regional / Permanent	(1) Medium (2) Medium

		- The addition of sediment from the upstream catchment has resulted in an increase in clay-content across the surface of the Marsh/Vlei (see a.iv.2).		
c. Environmental setting	<i>(i) Estuarine mouth conditions and tidal influence</i>	(1) Saltwater intrusion - The unknown extent of groundwater exploitation surrounding the wetland has resulted in a level of uncertainty when it comes to the impact of groundwater abstraction surrounding the wetland; however, it has been noted that the freshwater-salt water interface is deep (approximately 80 mbgl) and would thus require significant abstraction volumes to result in saltwater intrusion of the secondary aquifer (see a.i.1. and a.vi.3). - Increase in salinity may affect the vegetation and local ecology (see a.v.1). (2) Declining salinity gradient - The observed declining salinity gradient within the estuarine region is the result of the discharge of high volumes of freshwater effluent from the Potsdam WWTW (see c.ii.1) (3) Change in estuarine system - The estuarine system has transitioned from a permanently open to a temporarily open/closed system (see c.ii.1)	(1) Regional / Permanent (depth-dependant) (2) Regional / Permanent (current conditions) (3) Regional / Permanent (event-based)	(1) Low (2) High (3) Medium
	<i>(ii) Potsdam WWTW</i>	(1) Addition of high volumes of freshwater effluent: - This has resulted in changes to the natural salinity profile of the Diep River, Milnerton Lagoon and Rietvlei Wetland due to the resultant declining salinity gradient. - Loss of habitat (specifically sand prawns) and a change in the vegetation composition and distribution within the wetland (see a.v.1). (2) Construction of a canal diverting flow from the Diep River and WWTW - Alteration to the natural groundwater and surface water flow regime (see a.i.1).	(1) Local / Permanent (2) Local / Permanent	(1) High (2) Medium
	<i>(iii) Geomorphological changes</i>	(1) Use of natural resources - The dredging of the freshwater lake has irreversibly altered the hydrodynamics of the wetland, and the resultant works has affected the ecological functioning of the wetland via physical disturbance and changes in chemistry due to pumping seawater into the pans (see a.i.1). (2) Encroachment - General pollution of the Rietvlei Wetland, which includes litter (wind-blown waste), storm water runoff (water pollution), emissions (air pollution) and the addition of toxic metals (trace- and heavy metals) resulting in soil pollution as the result of historic dumps (see c.iv.1) - Loss of physical habitat due to urban developments (incl. housing, roadworks and industry)	(1) Local / Permanent (2) Local / Permanent	High
	<i>(iv) Point and non-point source pollution</i>	(1) Alteration of groundwater and surface water chemistry - As the result of fertilizers (non-point) from upstream agriculture, and other chemical runoff/discharge from the adjacent industrial area (point). Notable also is the contribution of the storm water drains (see a.v.1). The addition of nutrient-rich chemicals has in the past resulted in algal blooms, and subsequent anoxic conditions which are detrimental to flora.	Regional / Permanent	High

5.5.3 Conceptualizing the hydrodynamics of the Rietvlei Wetland

During the course of the study various hydrological inputs, outputs and processes within the Rietvlei Wetland were reviewed and assessed. From this analysis, the key hydrological inputs and outputs, governing hydrogeological conditions and associated environmental impacts of the surrounding environment on the Rietvlei Wetland (and vice versa) were identified. Figures 35 and 36 provide a conceptualization of these analyses. Here follows an overview of the aspects presented within these conceptualizations.

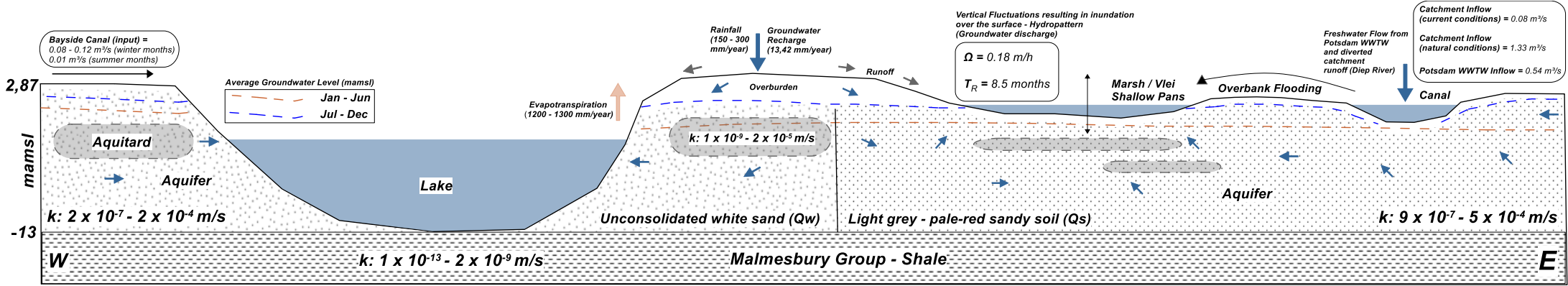
The three key wetland attributes identified by the U.S. EPA (2008) were quantified and conceptualized; this includes the groundwater flow within the wetland, the hydroperiod (Ω) (and subsequent identification of hydropatterns) and the wetland residence time (T_R).

The geological cross-section presents the distinct hydrogeological units underlying the wetland (Figure 35), as well as the associated estimated saturated hydraulic conductivity (k) in meters per second (m/s). This parameter reflects the rate at which water will flow through the saturated porous media (Domenico & Schwartz, 1990). The western section of the wetland is associated with finer grained sediments, whilst the eastern section is associated with medium-coarse grained sediment and will thus present a higher hydraulic conductivity. Aquitards (silt-loam / sandy loam textures) were identified via the interpolation of the soil texture associated with the wetland (chapter 5.3); these zones represent areas where the groundwater flow may be impeded and its distribution altered. Key hydrological inputs and wetland attributes are also presented.

Figure 36 provides a conceptualization of the aspects reviewed and presented within the study; this includes:

- The flow of the hydrological processes within the wetland (top left-hand corner), as identified by this study, to conceptualize the wetland water budget;
- The spatial variability of groundwater salinity (bottom left-hand corner);
- A simplified geological cross-section (bottom right-hand corner);
- A 2-D conceptualization of the Rietvlei Wetland, which includes:
 - o Areas of interest, and the associated environmental impacts;
 - o Hydrological inputs and losses;
 - o Wetland attributes;
 - o Hydrogeological conditions, including groundwater flow.

Through this conceptualization, a framework identifying the processes and interactions within the wetland, as well as the environmental impacts, was developed.



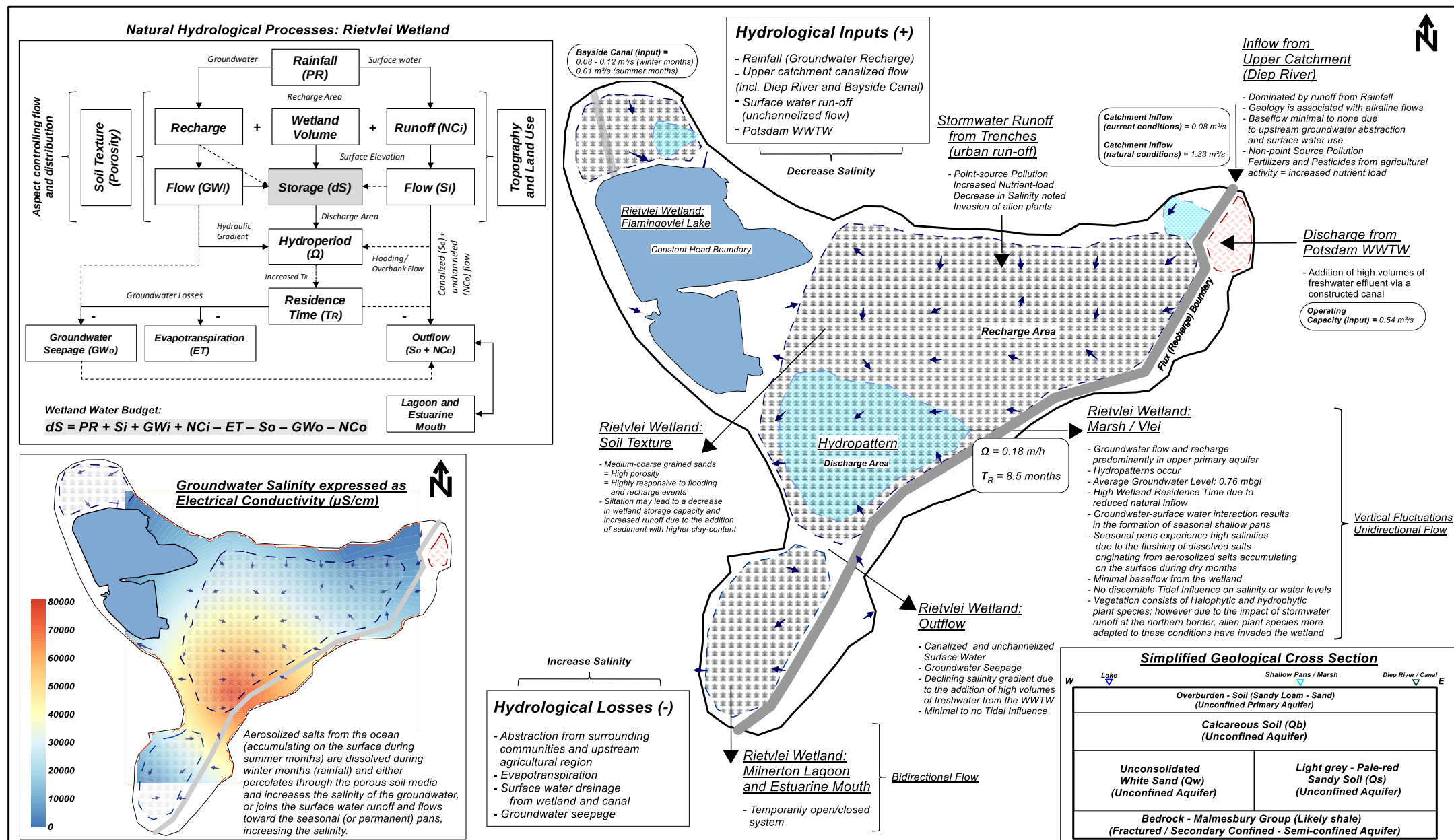


Figure 36. Conceptual Model of the Hydrological Inputs and Outputs (Water Budget), Hydrological Processes and Environmental Impacts associated with the Rietvlei Wetland

CHAPTER 6 CONCLUSION

6.1 An evaluation of utilizing Hydrological Analyses to conceptualize the Rietvlei Wetland's attributes and identify significant Environmental Impacts

Throughout the course of this study, the importance of conserving the Rietvlei and its characteristics as a wetland has been overwhelmingly pertinent, not only for its own ecological health but to the sustainable functioning of the entire Diep Estuary.

Thus, the natural environment was assessed by way of a review of scientific information relevant to the functioning of the wetland system to date, the changes the system has undergone due to anthropogenic stressors and the impact these changes have had on the hydrodynamics of the wetland itself.

It is evident that the wetland has undergone tremendous change over the last century which has caused irreversible ecological degradation and changes to the overall hydrodynamics of the system:

- i. What is now known as the Flamingo Vlei Lake is the result of the dredging of the northern portion of the wetland for raw materials needed in the process of constructing Cape Town harbour,
 - a. During this process the seasonal pans were pumped full of seawater (which is highly saline), and as a result irreversible ecological damage was caused;
- ii. Inflow from the upper catchment has been reduced over time due to upstream groundwater and surface water abstraction,
 - a. This has caused reduced natural inflow to the system, resulting in a change in wetland characteristics, most notably an increase in wetland residence time;
- iii. Freshwater effluent discharged from the Potsdam WWTW has resulted in a change in the natural salinity regime of the estuary,
 - a. A declining salinity gradient upstream of the estuary mouth has caused habitat loss and unfavourable mating conditions for sand prawns,
 - b. The addition of large quantities of freshwater has resulted in a change of the estuarine system, resulting in the system transitioning from a temporarily open/closed system to a permanently open system.

These changes have led to a need to fully comprehend the hydrodynamics of the Diep Estuary, and specific to this study - the Rietvlei Wetland. This study aimed to contribute to this cause by providing insight into the hydrogeological connectivity of the groundwater and surface water of

the wetland by conceptualizing the groundwater flow within the wetland, defining the hydroperiod and residence time of the wetland, and the distribution of soil texture across the wetland; which all contribute to the hydrodynamic functioning of the wetland and larger Diep Estuary.

The objectives of the study were met. The particle size distribution data was utilized, and the soil types and texture across the wetland defined. Pan inundation (or hydroperiod) could be defined upon review of the trends associated with the historic groundwater level fluctuations, and quantified by way of numerical integration. An observable hydropattern was identified just north of the Otto du Plessis Bridge within the area described as the seasonal pans as part of the central Marsh/Vlei.

Lastly, by combining the observation made with regards to soil characteristics (texture) and groundwater fluctuations (water levels, flow direction and quality), potential environmental impacts were identified:

- Observed groundwater flow substantiates the point raised by Campbell *et al.* (2017) that the wetland consists of sub-catchments (i.e. the wetland is not homogeneous and groundwater flow and its interaction with surface water is dynamic and complex),
- Altered water flows have caused a change in the wetland's hydrological regime, and influenced its natural hydropattern and residence time,
- Soil textures and water levels point to a hydrological system that is highly responsive to rainfall/recharge events,
- Tidal fluctuations do not enact an apparent impact on the groundwater levels or salinity of the wetland itself; the changes observed with regards to the salinity and water levels within the wetland have been the result of anthropogenic change, mentioned above, and the dissolution and percolation of aerosolized salts from the ocean;
- Tourism and encroachment present a risk to the conservation and the effective management of the wetland itself, as the impacts may range from minor (such as litter) to major (such as the addition of fertilizer and industrial chemicals via unmonitored storm water trenches).

Through realizing these objectives - a coalition of tangible data relating to the hydrodynamics of the wetland could be defined, and the conceptualization of the hydrogeological system and its natural response made possible. Thus, through this conceptualization – key wetland attributes were defined, and significant environmental aspects and possible impacts identified, which aids in the understanding of this complex and dynamic system in its current state.

6.1.1 Recommendations: Developing a complex hydrodynamic model for the Rietvlei Wetland using the insights gained from the current study

Developing a complex hydrodynamic model of the Rietvlei wetland that describes and includes the groundwater and surface water interaction would be a complex endeavour without first conceptualizing the hydrological processes present within the wetland. From the study the following aspects are highlighted as pertinent to developing a complex hydrodynamic model:

1. The groundwater interaction of the upper aquifer relevant to the wetland is within the top ten meters below ground level (mbgl),
 - a. The geology of the upper 3mbgl is described within this report, and logs of neighbouring well points exist that describe the geology in the northern portion up to 10mbgl;
 - b. The geology underlying the upper calcareous soils are split between unconsolidated white sand to the east and light grey pale-red sandy soils to the west; these layers are potentially underlain by siltstone and shale from 10 mbgl.
2. Groundwater data availability varied across the eight wells; thus, two periods were identified as viable modelling periods:
 - a. July to December 2015, a portion of data for well 6 is missing;
 - b. July to December 2016, most complete set of data across all wells.
3. Tidal influence on groundwater levels and salinities is not as prominent within the wetland according to the observations made within this report as no definite tidal influence has been observed,
4. Interactions with surface water bodies are limited to:
 - a. Discharge of freshwater effluent from Potsdam WWTW, noted as $0.54 \text{ m}^3/\text{s}$,
 - b. Flamingo Vlei lake (water levels and electrical conductivity data available),
 - c. Blaauwberg Bridge (water levels and electrical conductivity data available, portion of data during September to November 2016 missing),
 - d. Unlined bypass canal east of the wetland (potential discharge/base flow of groundwater to canal),
 - e. Bayside canal contributes to the inflows of the Flamingo Vlei, noted as 1000 m^3 per day during summer months and ranging between $7000 - 10\,000 \text{ m}^3$ per day during winter months.
 - f. Base flow from the upstream (catchment) inflow is considered as negligible (under current conditions) as the river dries up completely over summer months.

5. The system is highly responsive to rainfall/recharge events and is susceptible to water losses via evaporation, evapotranspiration and seepage to the lake, river and unlined canal;
 - a. Climate data is available and stretches continuously from 2015 – present (2019).
6. Important to note is that surface water inflow data at Blaauwberg Bridge and outflow data at Otto du Plessis Bridge is unavailable, and as such discharge (Q) is not available at this point. However, Ally *et al.* (2017b) successfully used data from an upstream flow gauge (G2H014) and tidal data for the year 1980 to develop a surface water model for the larger Diep Estuary and the Milnerton Lagoon. Catchment runoff was excluded from the aforementioned model, and the contribution of the Potsdam WWTW used as the major surface water input for the Diep Estuary.
7. The hydraulic conductivity of the horizontal and vertical layers can be calculated from the PSD data presented in this report, or inferred from the soil textural classes:
 - a. 0.5 mbgl: Medium-coarse grained sandy textures dominant across all wells,
 - b. 1.0 mbgl: Loam sand / sandy loam textures dominant, apart from sandy textures bordering the southern (well 5) and northern (well 7) borders of the wetland,
 - c. 1.5 – 2.5 mbgl: Sandy textures dominant, apart from sandy loam textures observed north and east of the Flamingo Vlei lake,
 - d. 3.0 mbgl: The same trend as 1.5 – 2.5 mbgl, apart from the presence of silt loam north-west of the Flamingo Vlei lake.
 - e. According to historic logs, peat underlies these soils (4 – 6 mbgl), followed by alluvium (6 – 10 mbgl) underlain by siltstone and shale (>10 mbgl).
8. Unknown inputs and losses to the system include:
 - a. Groundwater abstraction from surrounding communities,
 - b. Contribution of storm water trenches (quantity and quality),
 - c. Current discharge / flow upstream inputs of the Diep River and outflow from the wetland.

Although it would be difficult to simulate the current condition of the wetland and its complex environment, it is important. This study provides a conceptualization of the dynamic system and should be utilized as such.

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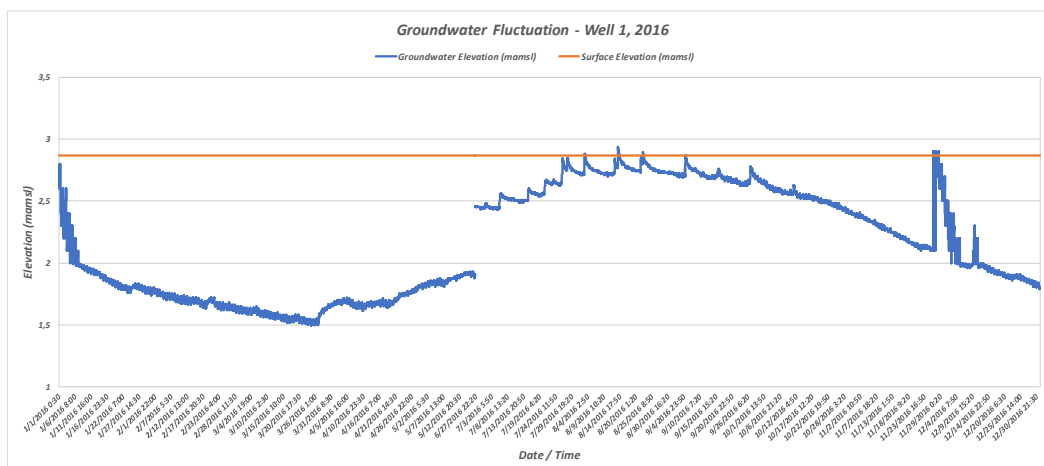
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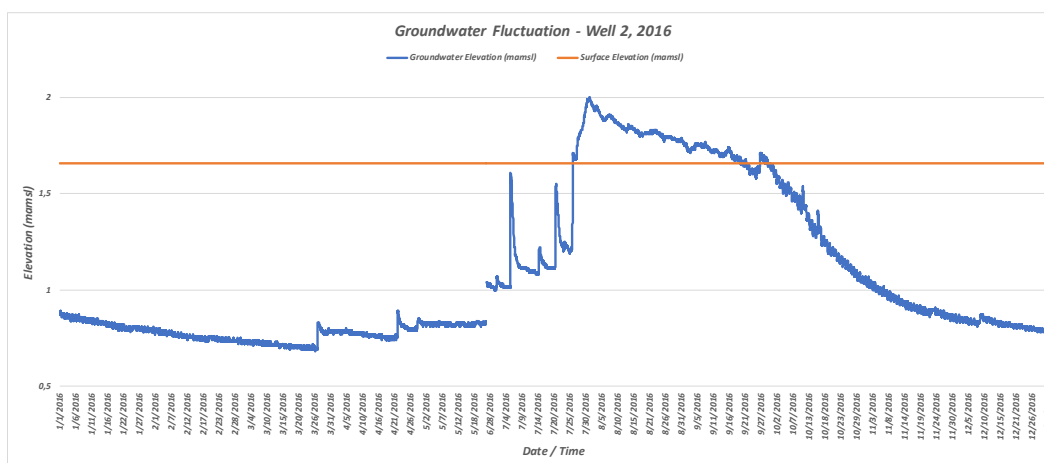
ANNEXURES

LAST UPDATED: 12 NOVEMBER 2019

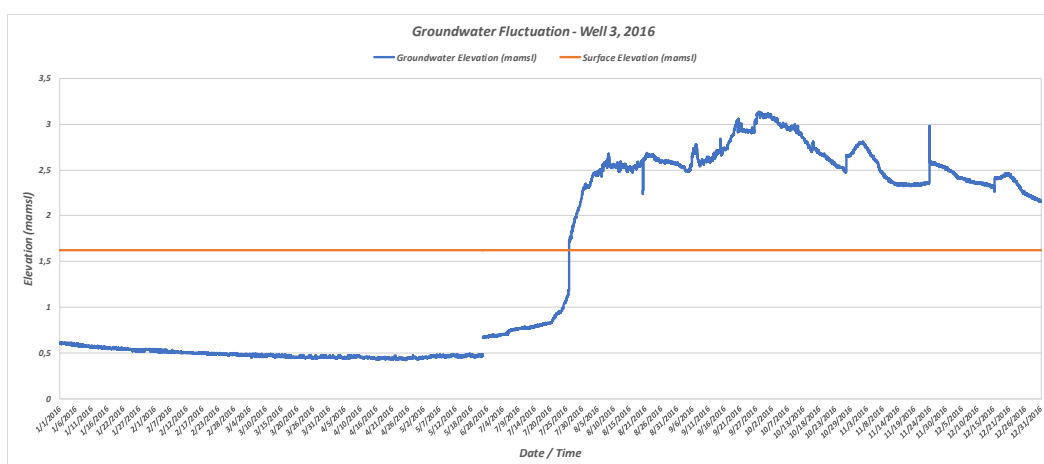
Annexure A: Additional Groundwater Fluctuation Figures, Wells 1 - 8



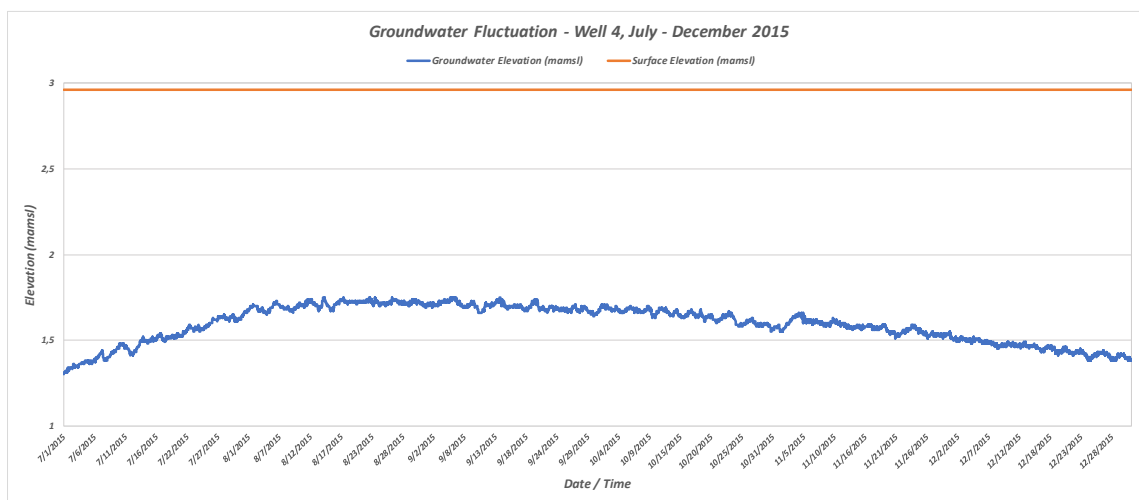
Groundwater fluctuation – Well 1, 2016



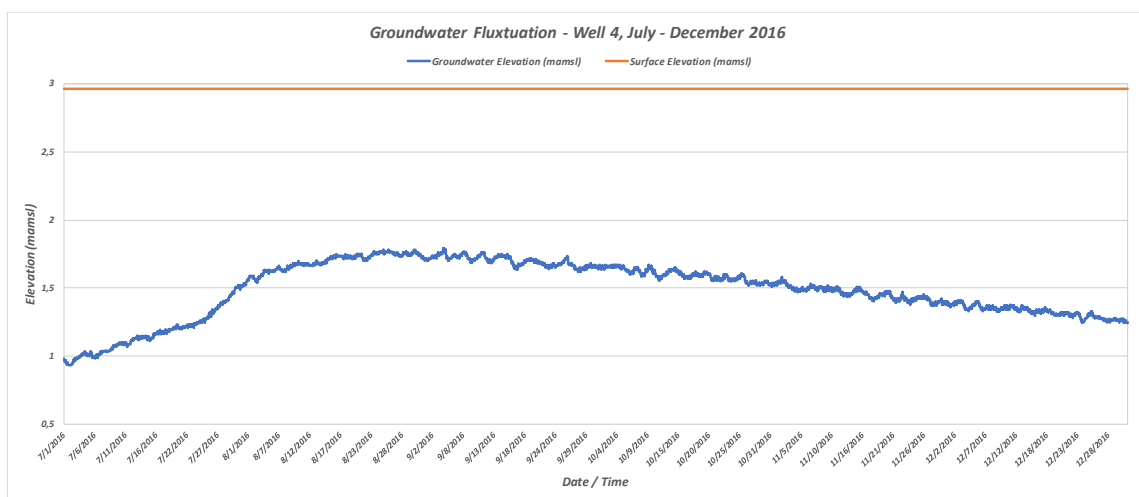
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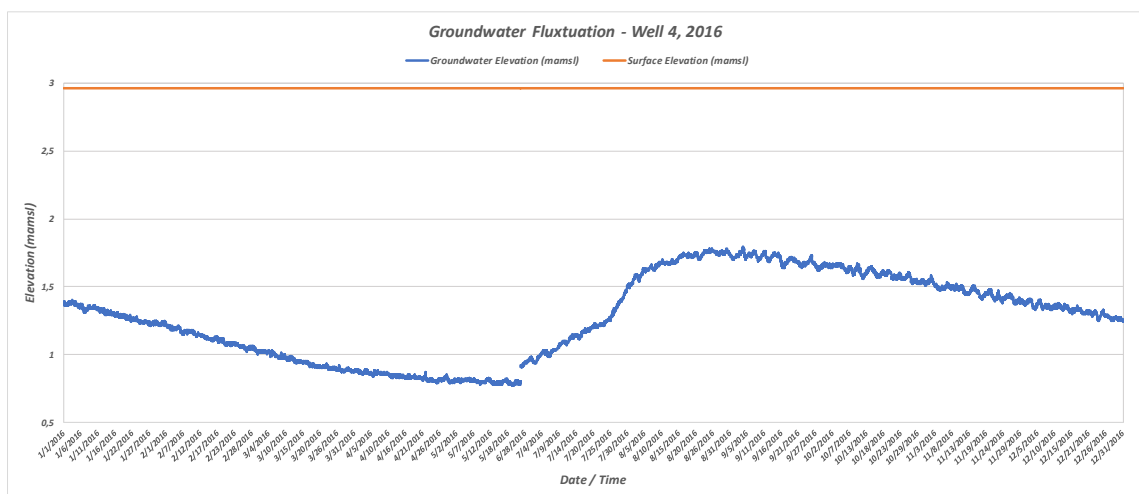
Groundwater fluctuation – Well 3, 2016



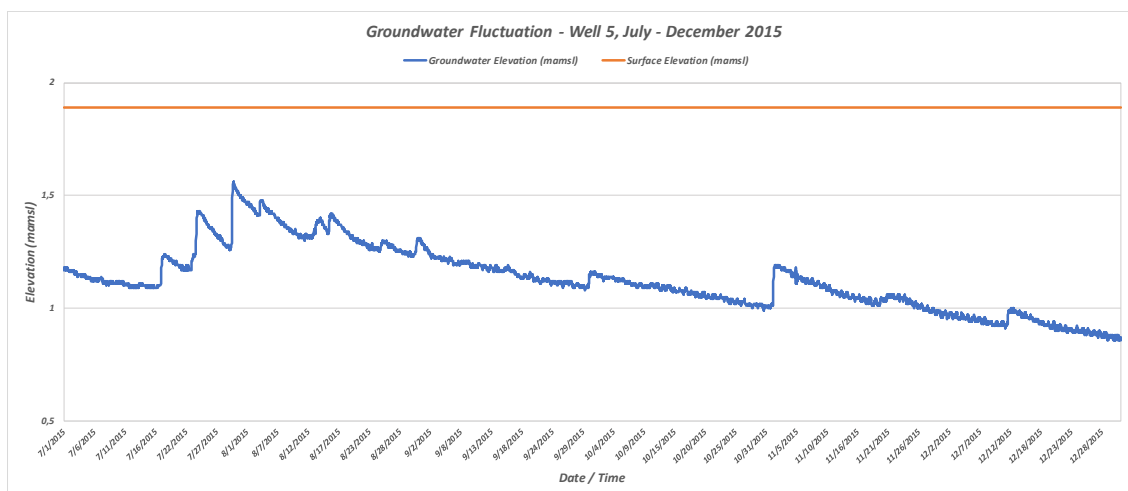
Groundwater fluctuation – Well 4, July – December 2015



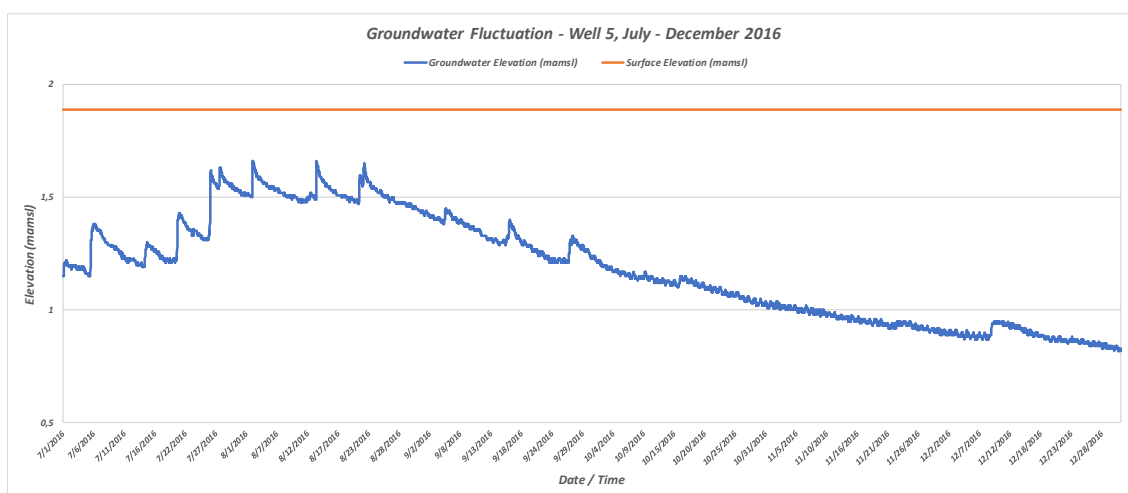
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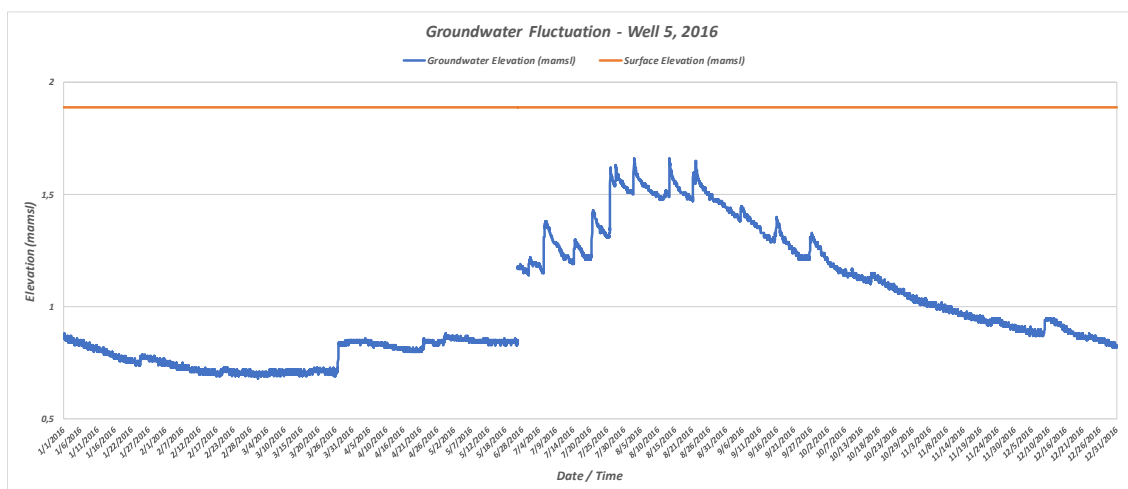
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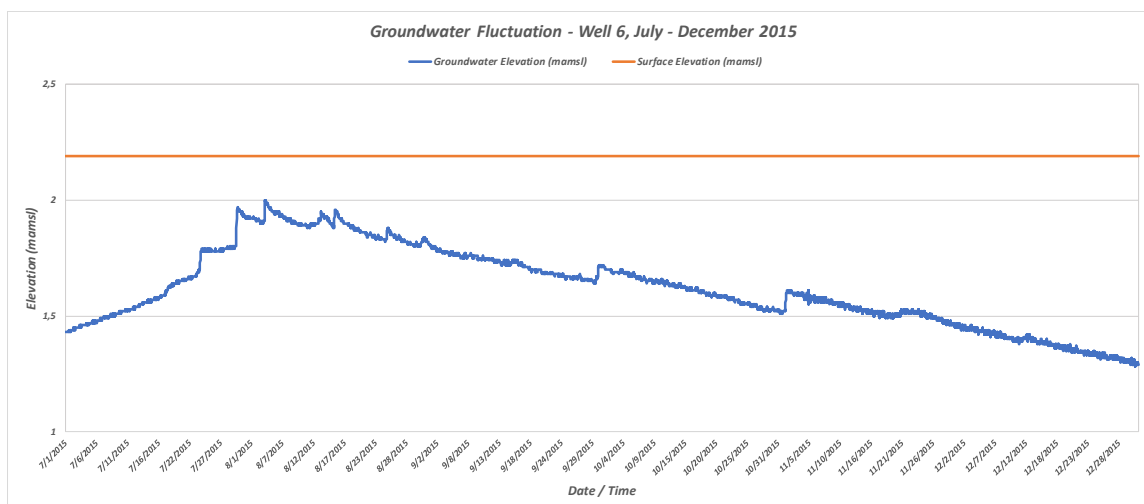
Groundwater fluctuation – Well 5, July – December 2015



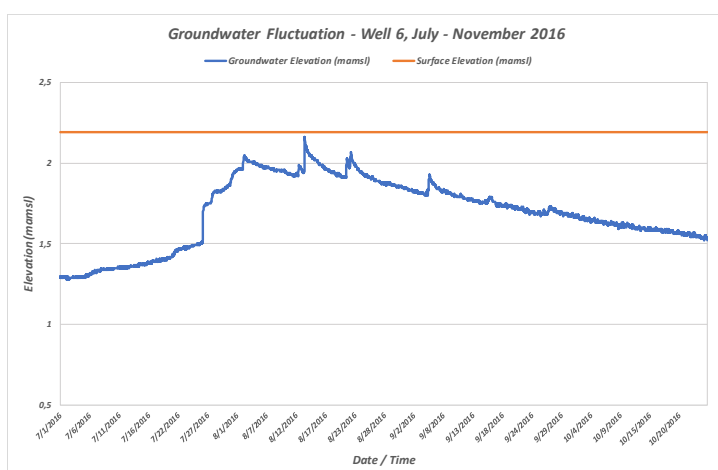
Groundwater fluctuation – Well 5, July – December 2016



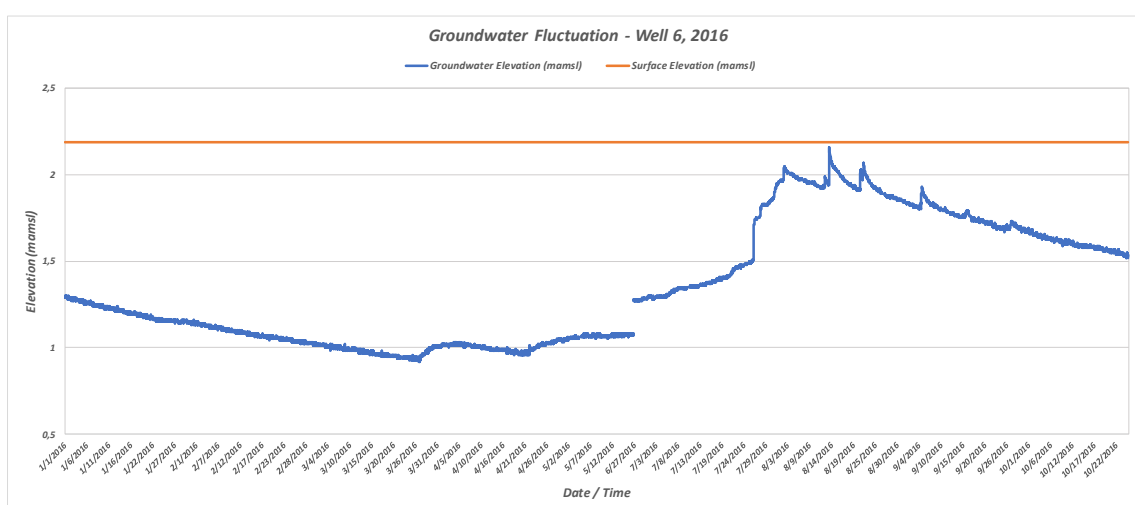
Groundwater fluctuation – Well 5, 2016



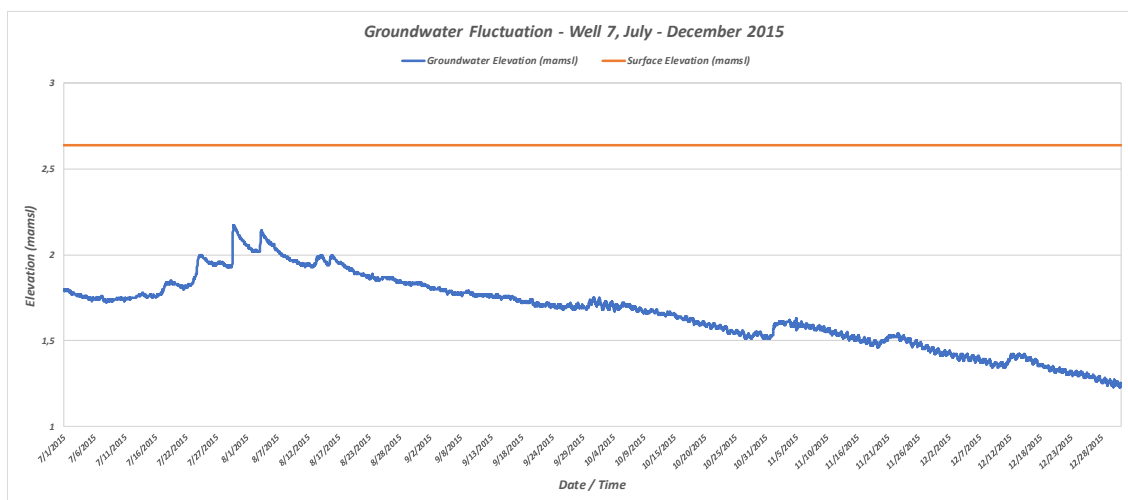
Groundwater fluctuation – Well 6, July – December 2015



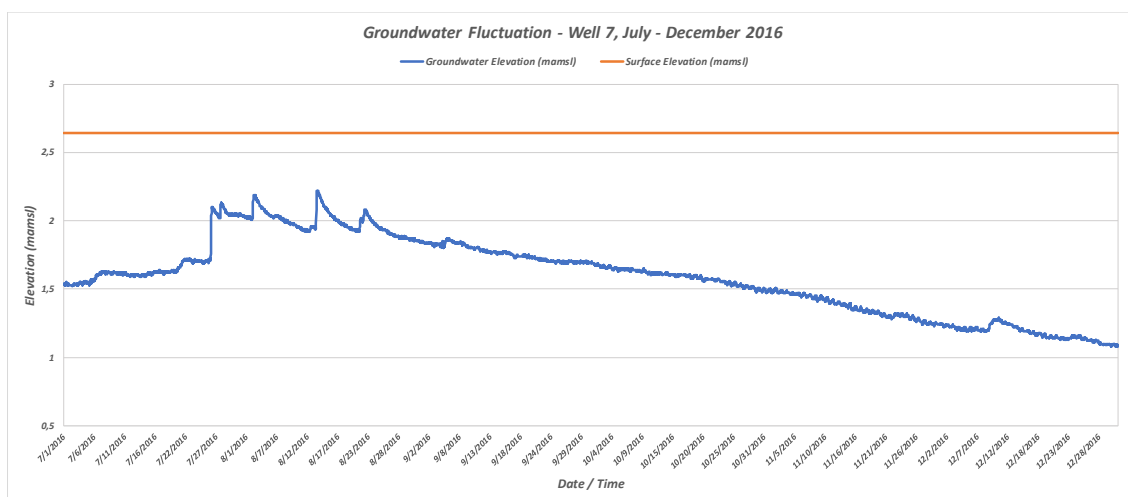
Groundwater fluctuation – Well 6, July – November 2016



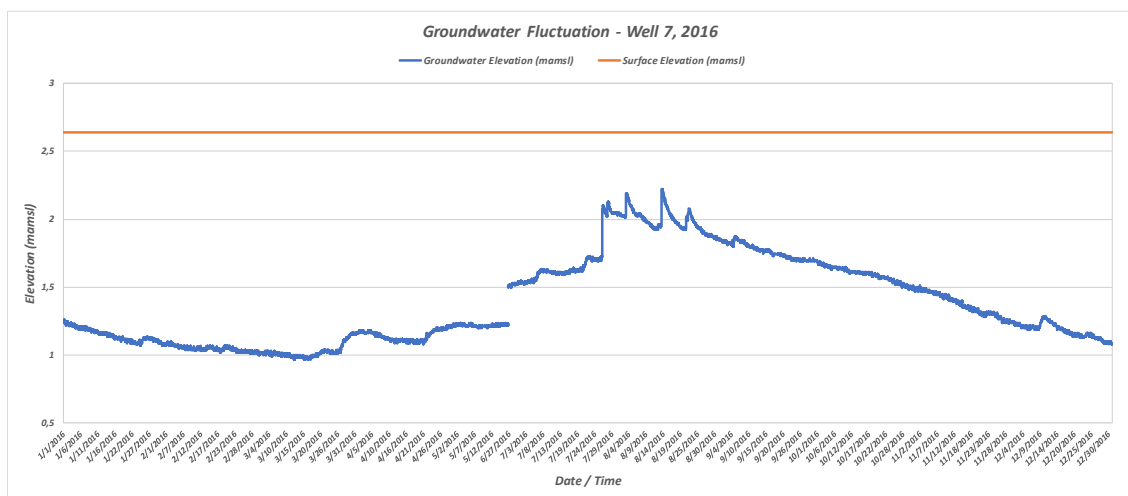
Groundwater fluctuation – Well 6, 2016



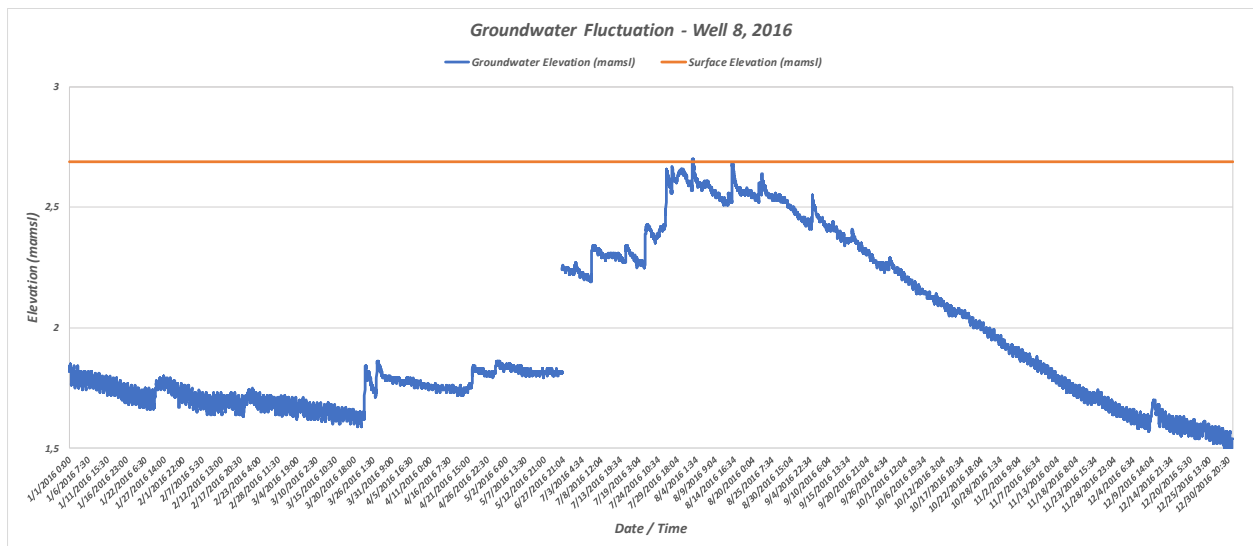
Groundwater fluctuation – Well 7, July – December 2015



Groundwater fluctuation – Well 7, July – December 2016

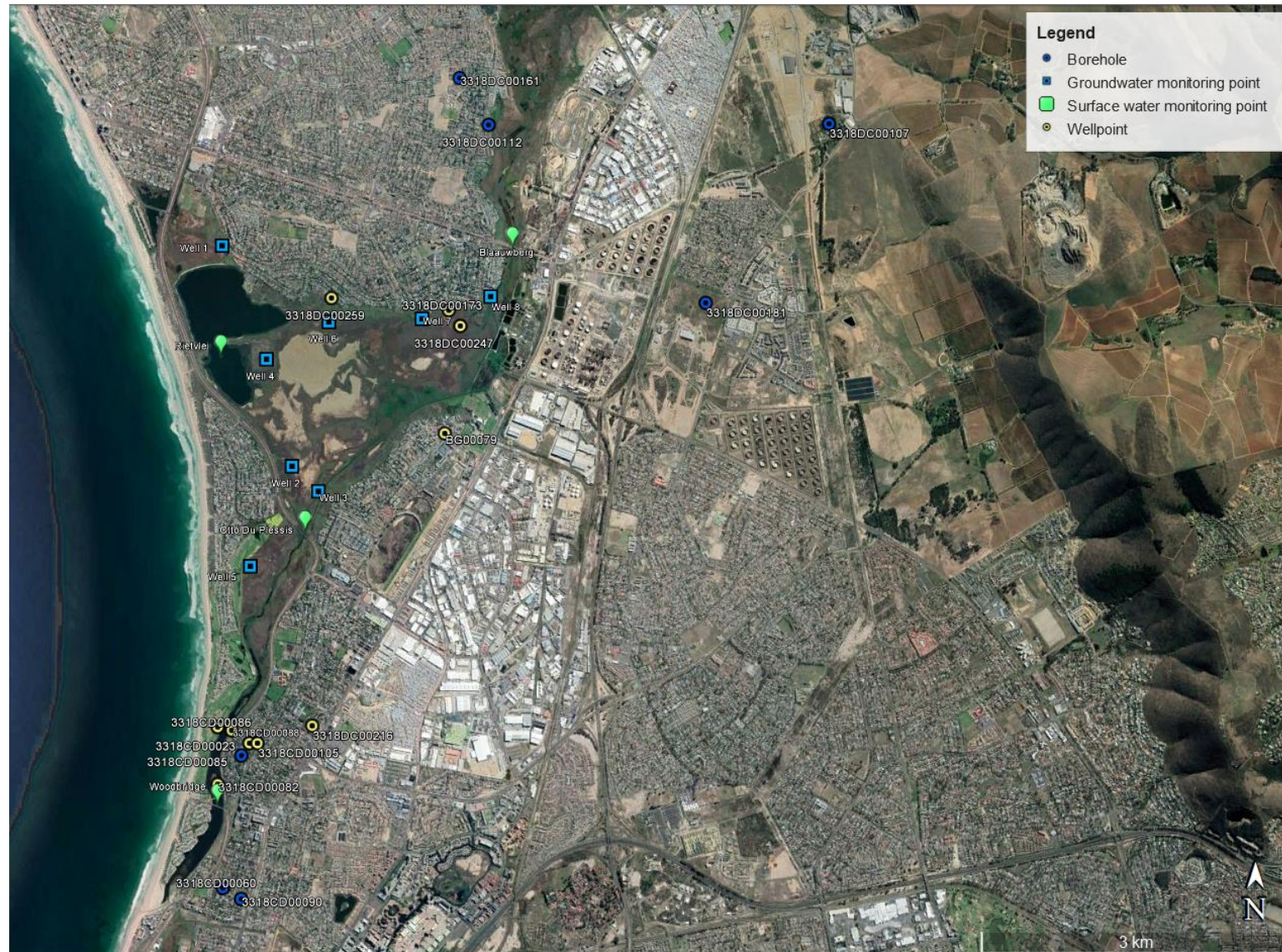


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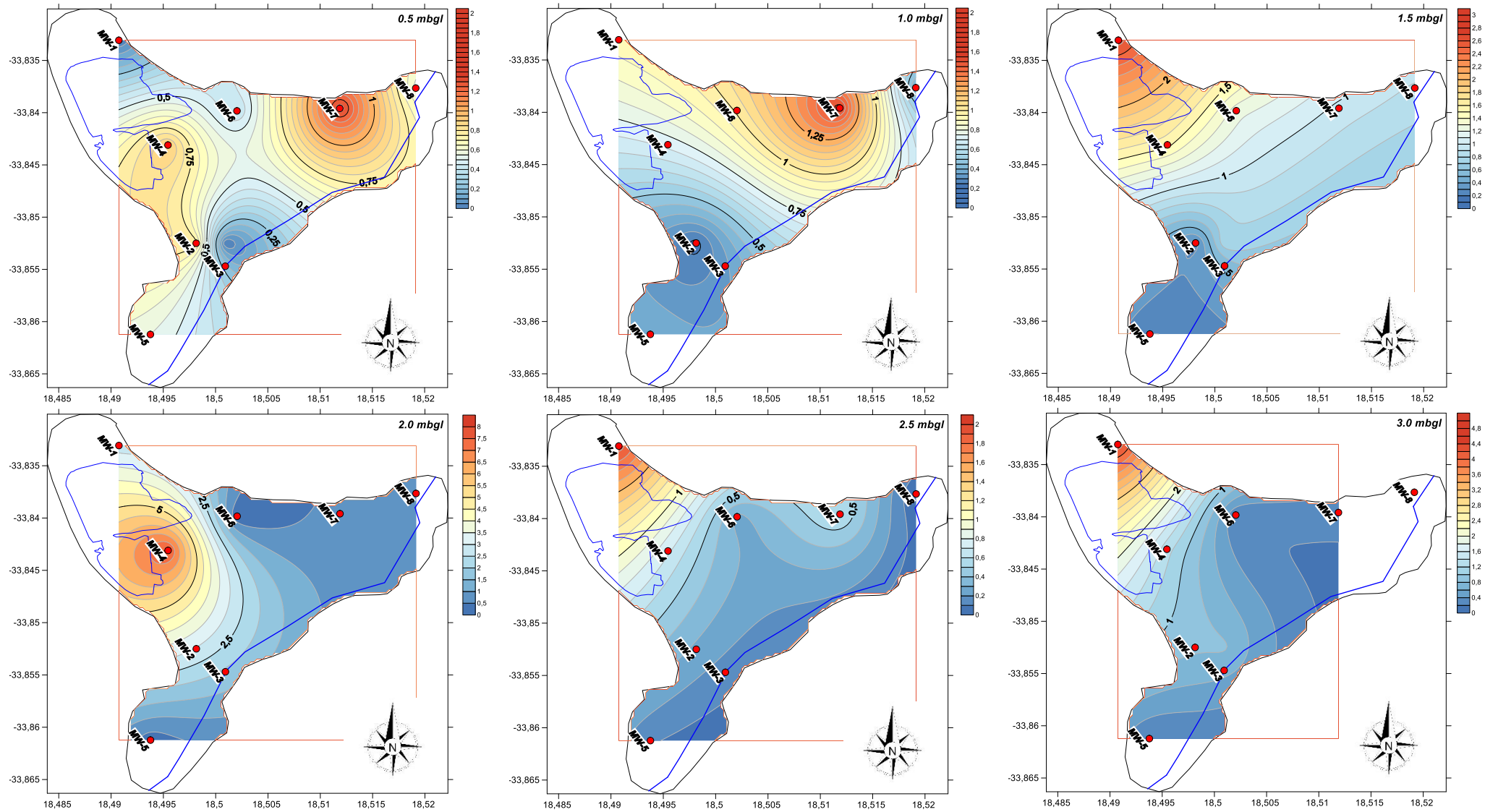
Groundwater fluctuation – Well 8, 2016

Annexure B: Hydrocensus of the Rietvlei Wetland and its immediate vicinity (National Groundwater Archive, Department of Water and Sanitation)

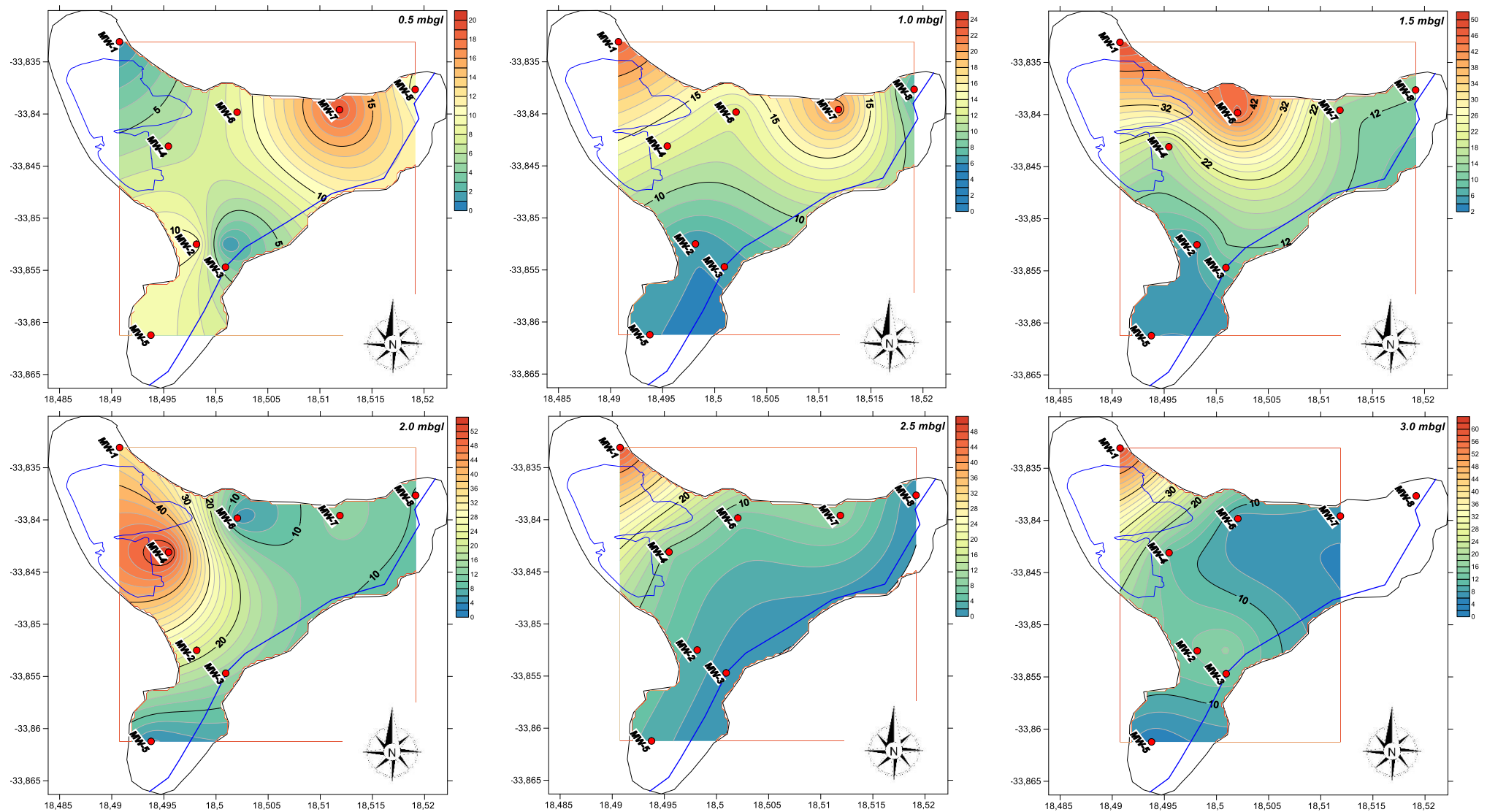


Annexure C

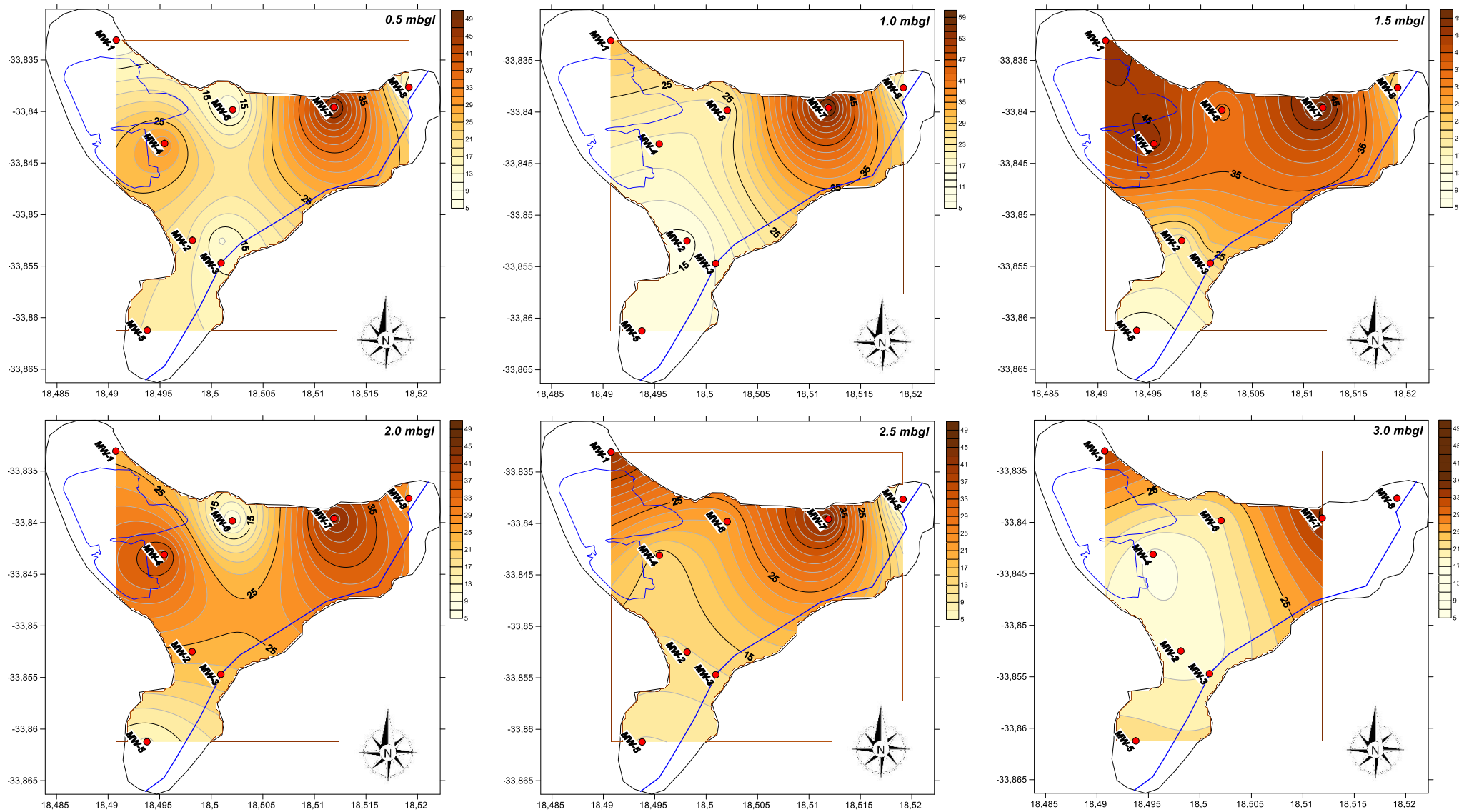
- ***Soil Texture interpolation, 0.5 – 3.0 mbgl:***
 - ***% Clay content***
 - ***% Silt content***
 - ***% Fine sand content***
 - ***% Medium sand content***
 - ***% Coarse sand content***



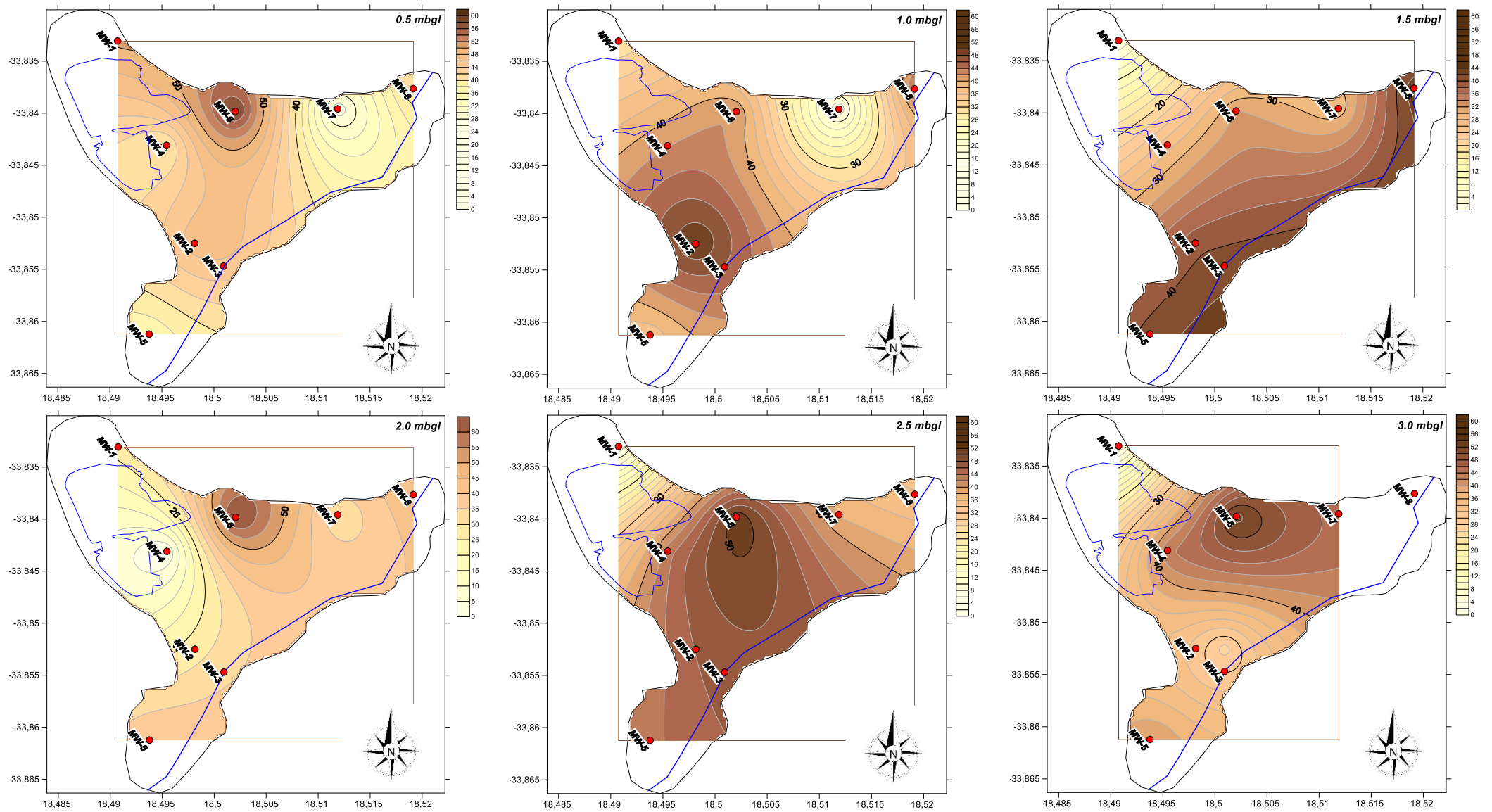
Soil Texture Interpolation 0.5 - 3.0 mbgl: Clay content (%)



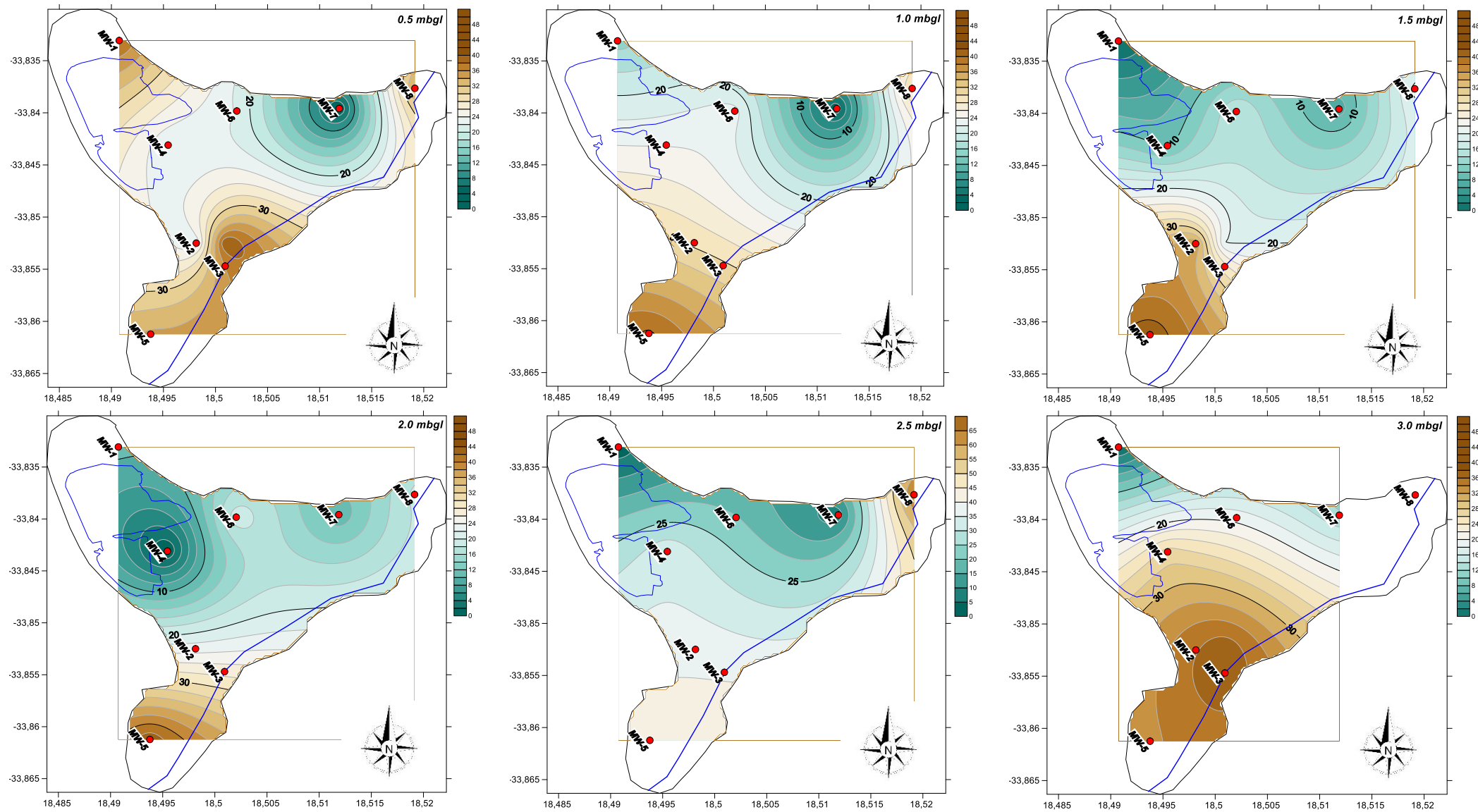
Soil Texture Interpolation 0.5 - 3.0 mbgl: Silt content (%)



Soil Texture Interpolation 0.5 - 3.0 mbgl: Fine Ssnd content (%)



Soil Texture Interpolation 0.5 - 3.0 mbgl: Medium sand content (%)



Soil Texture Interpolation 0.5 - 3.0 mbgl: Coarse sand content (%)

Declaration

This is to declare that I, Annette L Combrink, accredited language editor and translator of the South African Translators' Institute, have language-edited the dissertation

AE van Staden



orcid.org/0000-0003-1320-7142

with the title

**Hydrological Modelling of the Rietvlei Wetland,
Western Cape, South Africa: Identifying
possible Environmental Impacts**

A handwritten signature in purple ink, appearing to read 'Annette L Combrink'.

Prof Annette L Combrink

Accredited translator and language editor

South African Translators' Institute

Membership No. 1000356

Date: 25 November 2019