# Groundwater assessment and sustainable management of the coastal alluvial aquifers in Namib Desert, Namibia: Omdel Aquifer as case study

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# Abstract

The study addressed the groundwater assessment and sustainable management of the coastal alluvial aquifers in Namib Desert, the Omaruru River Delta Aquifer (Omdel Aquifer) was used as a case study. Sustainable utilization of groundwater in parts of hyper-arid Sub-Saharan Africa, like the Namib Desert, is always a challenge due to lack of resources and data. Understanding of hydrogeological characteristics of the Omaruru Delta Aquifer System is a pre-requisite for the management of groundwater supply in the Central Namib area (Namib Desert). For the Omdel Aquifer in the Omaruru catchment, Namibia, issues to investigate include the lack of information on the geology and hydrogeological setting, the hydraulic properties and geometry of the aquifer at the inflow and outflow sections, groundwater recharge conditions upstream of the aquifer, and the impact of artificial recharge. Omdel Aquifer occurs in a desert environment with less than 20 mm of rainfall per annum, it's regarded to receive no direct groundwater recharge from rainfall, only from occasional (inconsistent) flooding of the Omaruru River, due to periodic thunderstorms in the upstream catchment. Since the Omdel Aquifer does not receive direct recharge from rainfall, an artificial recharge scheme was implemented to augment the water supply. One of the objectives of the study is to integrate artificial recharge with hydrogeological understanding of the Omdel Aquifer to establish a conceptual framework for assessment of groundwater recharge and discharge, water chemistry and balanced water supply.

In this desert environment, the methods applied are hydrogeological surveys and site visits, together with interpretation of geological, hydrological and geomorphological data from investigations carried out to define the hydrogeological characteristics of the Omdel Aquifer. Geological information obtained from the borehole completion reports were used to draw geological cross sections, using Arc-Map software to have a better conceptual understanding of the Omdel Aquifer. Test pumping data were analysed using the Aquifer Test Curve Fitting and Aquifer Test 3.5 analyses to determine the aquifer parameters of the Omdel Aquifer. Hydrochemical data of selected boreholes of the Omdel Aquifer were analysed using WISH and HamVer2Dot softwares to determine the groundwater facies, water types and fingerprints.

Groundwater recharge estimation at groundwater supply schemes upstream of Omdel Aquifer in the Omaruru catchment was estimated by Water Table Fluctuation (WTF) and Chloride Mass Balance (CMB) methods. Groundwater flow from the upper river bed (upstream of Omdel Aquifer), OMAP, SEC and groundwater supply schemes upstream in the Omaruru catchment were conceptualized and estimated by using Darcy's law. The groundwater numerical model of the Omdel Aquifer was constructed using modelmuse (modflow software) to assist in better understanding of the conceptual model of the Omdel Aquifer.

It is confirmed that the alluvial aquifer comprises unconsolidated coarse sand and gravel (unconfined aquifer), clay rich sand and cemented sand (aquitard) and predominantly coarse sand and gravel (major groundwater reservoir), which were successively deposited within four palaeochannels that were incised in bedrock of mainly mica schist and granite. The bedrock geometry of the Omdel Aquifer indicates that the MC is the largest reservoir of stored fresh groundwater, estimated at about 133 $Mm^3$, and is deeper than the other three channels, with an average sediment thickness of 80 m.

All groundwater chemistry facies of the selected boreholes tapping the Omdel Aquifer reveal a NaCl character, indicating a coastal environment. The water type of the majority of the groundwater chemical data of the selected boreholes of the Omdel Aquifer is chloride and sodium indicating an end point in a water evolution sequence. The recharge over rainfall ratio at different localities in the Omaruru catchment (Nei-Neis, Okombahe and Omaruru) is relatively small indicating that rainfall contributed a small portion to the water level rise (recharge), therefore run-off plays a very important role in the water level rise (groundwater recharge) in the Omaruru River bed alluvial aquifers. The estimated groundwater recharge upstream in the catchment plays a significant role; it contributes to groundwater flow upstream in the catchment, which in turn contribute to groundwater flow in the delta aquifer downstream.

The study focuses on the understanding of hydrogeological characteristics of the Omaruru Delta Aquifer System in terms of groundwater recharge and discharge, groundwater dynamics within the aquifer and groundwater chemistry in order to assess if the current abstraction is operating within the hydrogeological limits of sustainability. The total annual recharge increased from 5.8 $Mm^3$/year to 7.87 $Mm^3$/year (after construction of the dam). The yield of the Omdel Aquifer is estimated to have increased from 2.8 $Mm^3$/year before construction of a recharge enhancement dam to 4.6 $Mm^3$/year after the construction. The Omdel Aquifer has been over abstracted by an average rate of 1.7 $Mm^3$/year during the past 22 years period, resulting in clearly observed declining trends in groundwater levels. The normalized root mean square error (nRMS) for a calibrated steady state model of the Omdel Aquifer is 2.252% and the $R^2$ of the observed and simulated heads is about 0.9965, which is about 99.65% good correlation indicating that the steady state model calibration of the Omdel Aquifer has been achieved. The simulated steady state model revealed high evapotranspiration rate at low abstraction rate and the simulated heads are much deeper at high abstraction rate. The calibrated steady state model also indicated that the change of abstraction rate affects the groundwater balance components and the simulated heads.

The results provide a sound reference for application to similar aquifer systems prevailing in the Namib Desert, e.g. the Ugab River Delta, Swakop River, Kuiseb River Delta, etc.

## Keywords

Hydrogeological characteristics
Artificial recharge
Coastal aquifer
Groundwater numerical modelling
Ephemeral river
Recharge
Episodic recharge
Groundwater chemistry
Groundwater balance
Sustainable yield
Sub-Saharan Africa
Namib Desert
Namibia

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# Declaration

I declare that **Groundwater assessment and sustainable management of the coastal alluvial aquifers in Namib Desert, Namibia: Omdel Aquifer as case study** is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted are indicated and acknowledged by complete references.

Brian Munihango Matengu

March 2020

Signature……………………

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# Chapter 1: Introduction

## 1.1 Background

Namibia, the driest country in Africa south of the Sahara, depends mainly on groundwater for domestic, agricultural and industrial use (Christelis and Struckmeier 2001). Groundwater resources have played a vital role in the development of Namibia and have been used for drinking purposes since people settled in the country. More than 100 000 boreholes have been drilled for groundwater over the past century in the Country, whilst half of these boreholes are still in operation and supply groundwater to industries, municipalities, rural water supply, livestock, game, irrigation and mines. The advantage of using groundwater is that it can supply water to scattered communities and economic activities such as mining, agriculture and tourism that are located far from surface water sources. Over 80% of the Country's annual water consumption is supplied from groundwater resources (Christelis and Struckmeier 2001).

Geological unconsolidated surface deposits that have potential for porous aquifers cover about 48% of the country and the remaining 52% is made up of hard impervious rocks which are partially fractured to develop secondary aquifers (Christelis and Struckmeier 2001). Furthermore, these authors are of the opinion that only 42% of the country overlies aquifers; 26% of consisting of porous (primary) aquifers, with 16% consisting of fractured (secondary) aquifers.

Generally many parts of Namibia have serious limitations to groundwater supply. These may be due to insufficient amounts, unreliable groundwater recharge, low borehole yields, deep groundwater level depths, high risks of contamination and poor groundwater quality. However other areas have high yielding, very productive aquifers with more groundwater than the local farmers and communities presently need. Since every drop of water counts in Namibia, groundwater resources should be preserved, protected and controlled as an underground treasure for future use and during extended periods of drought. Furthermore, groundwater resources should be identified and mapped over the entire country in order to provide a comprehensive basis for utilization in planning development. The constitution of Namibia includes the proper and sustainable use of all natural resources (including groundwater resources), to utilize the water needed without damaging the environment for the future generations.

Christelis and Struckmeier (2001) point out that the distribution of rainfall is the lowest along the south-western Atlantic coast of the Southern African Subcontinent, an area covered mainly by the Namib Desert in Namibia. The high temperature during the rainy season (January to April) and high evaporation losses make Namibia the driest country in Southern Africa and probably in the entire Southern Hemisphere. Dams have been constructed in some of the main river courses to capture surface run-off and store water from the floods during rainy season, however, their sustainable safe yields depend on unreliable and unfavourable hydro-climatic conditions.

Groundwater is regarded as the preferred cost effective way to provide water in most parts of the Country. In Namibia, about 45% of the water supply to towns, villages and farms comes from boreholes or springs and 45% of the water used in agriculture comes from groundwater sources (Christelis and Struckmeier 2001).

**Table 1.1** indicates that the consumer groups in Namibia, stock and domestic, used more groundwater than surface water (about 78% and 48% respectively) in the year 2000. The consumer group that indicated less groundwater used is irrigation (about 26%). The source of supply that was used more in 2000 is groundwater (135 Mm$^3$), which is about 45% compared to 22% and 33% of Ephemeral rivers and Perennial rivers respectively.

**Table 1.1** Utilization of Namibian water resources per consumer group in 2000 (Modified after Christelis and Struckmeier 2001)

| Consumer group | Demand (Mm$^3$) | Source of supply | | | | | |
|---|---|---|---|---|---|---|---|
| | | Perennial rivers | | Ephemeral rivers | | Groundwater | |
| | | Mm$^3$ | % | Mm$^3$ | % | Mm$^3$ | % |
| Domestic | 73 | 18 | 25 | 20 | 27 | 35 | 48 |
| Stock | 77 | 14 | 18 | 3 | 4 | 60 | 78 |
| Mining | 14 | 8 | 57 | 1 | 7 | 5 | 36 |
| Irrigation | 136 | 60 | 44 | 41 | 30 | 35 | 26 |
| Total | 300 | 100 | 33 | 65 | 22 | 135 | 45 |

During the Cretaceous and the Tertiary, southern Africa separated completely from the neighbouring parts of Gondwanaland. The whole subcontinent went through various stages of upliftment due to these isostatic movements and the present interior was subjected to erosion. Such isostatic upliftment is most prominent along the edges of a continent, where erosion is most intense, and as a result, the Great Escarpment developed (Fig. 1.1). Some of the highest peaks in Namibia occur along the Great Escarpment. The Great Escarpment marks the beginning of the Central Plateau east of the Namib Desert with altitude difference of more than 1000 m, it’s formed by mountain ranges or single mountains that are much higher than the Central Plateau, and it separate the Namib Desert from the Central Plateau (Christelis and Struckmeier 2001). Between the northern and the southern parts there is an area that has been deeply eroded as a result the ground rises gradually to the height of the Central Plateau.

The Namib Desert is the world's most arid region underlain by sands of a proto-Namib phase which developed about 35 million years ago (Christelis and Struckmeier 2001). This desert stretches along the entire Atlantic coast of Namibia, with an average width of 100 km and rises with a very gradual slope from the coastline to an elevation of about 800 m at the foot of the Great Escarpment in the east (Fig. 1.1). It is characterized by several distinct types of landforms such as a vast sand sea, flat plains of gravel and bedrock, mountains of bare rock and areas with surfaces fretted into strange sandblasted forms (Keen 1997). Most parts of the desert consist of a broad platform, eroded into bedrock of monotonous flatness. According to Christelis and Struckmeier (2001), the Namib Desert landscapes range from mountainous red dunes in the south-east part of the interior plains and flat-topped to steep sided inselbergs in the central region. There are bare dunes, stony and rocky plains in the northern part of the Namib Desert (Skeleton coast). Dry ephemeral river beds pass through the Namib Desert from the Central Plateau (east) to the coast (west), but only flow after good rainfall in the upper catchment areas. The average annual rainfall in the Namib Desert ranges between 20 mm and 50 mm.

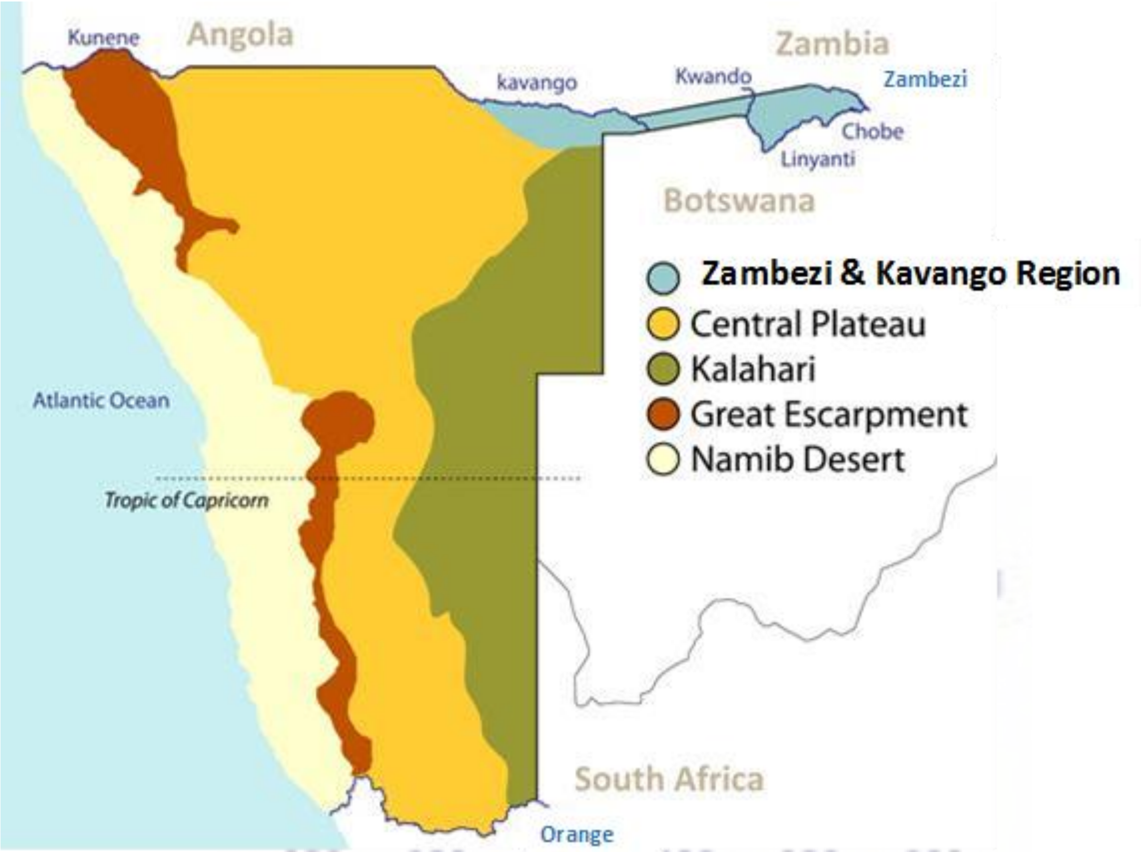

**Fig. 1.1** Map depicting the Namib Desert, Great Escarpment, Central Plateau, Zambezi & Kavango Region (Info Namibia 2019)

River catchment basins in the Namib Desert are Koichab, Orange, Tsaris, Tsauchab, Tsondab, Kuiseb, Swakop, Omaruru, Ugab, Huab, Koigab, Uniab, Hoanib, Hoarusib and Khumib (Fig. 1.2). Almost all the above river catchments form delta aquifers or aquifers in close proximity to Atlantic Ocean. Current aquifers developed and used commercially in the Namib Desert are the Omaruru River Delta Aquifer (Omdel Aquifer), Kuiseb River Delta Aquifer and Koichab Pan Aquifer. The other known aquifers that are less developed are Tsaris, Tsauchab, Tsondab, Ugab, Swakop, Huab, Koigab, Uniab, Hoanib, Hoarusib, Orange and Khumib.

Omdel Aquifer is situated about 80 km north of Swakopmund and extends from the coast to about 35 km inland with an altitude rise of 230 mamsl (metres above mean sea level) across the relatively flat Namib Plain (Geyh and Ploethner 1995). The total catchment area of the Omaruru River covers approximately 15 700 km$^2$ and reaches an altitude of 1450 mamsl inland with a mountainous peak area at 2100 mamsl (Fig. 1.2). In the mountainous inland region of the catchment, with an average altitude of 1000 mamsl, a mean annual rainfall of between 200 and

450 mm/year is recorded (Geyh and Ploethner 1995). Groundwater from the Omdel Aquifer is supplied to Henties Bay, Swakopmund, Arandis, Rossing uranium mine, Langer Heinrich mine and many other consumers in the Central Namib area. The location of Omdel Aquifer in Fig. 1.2 also represent the location of Henties Bay.

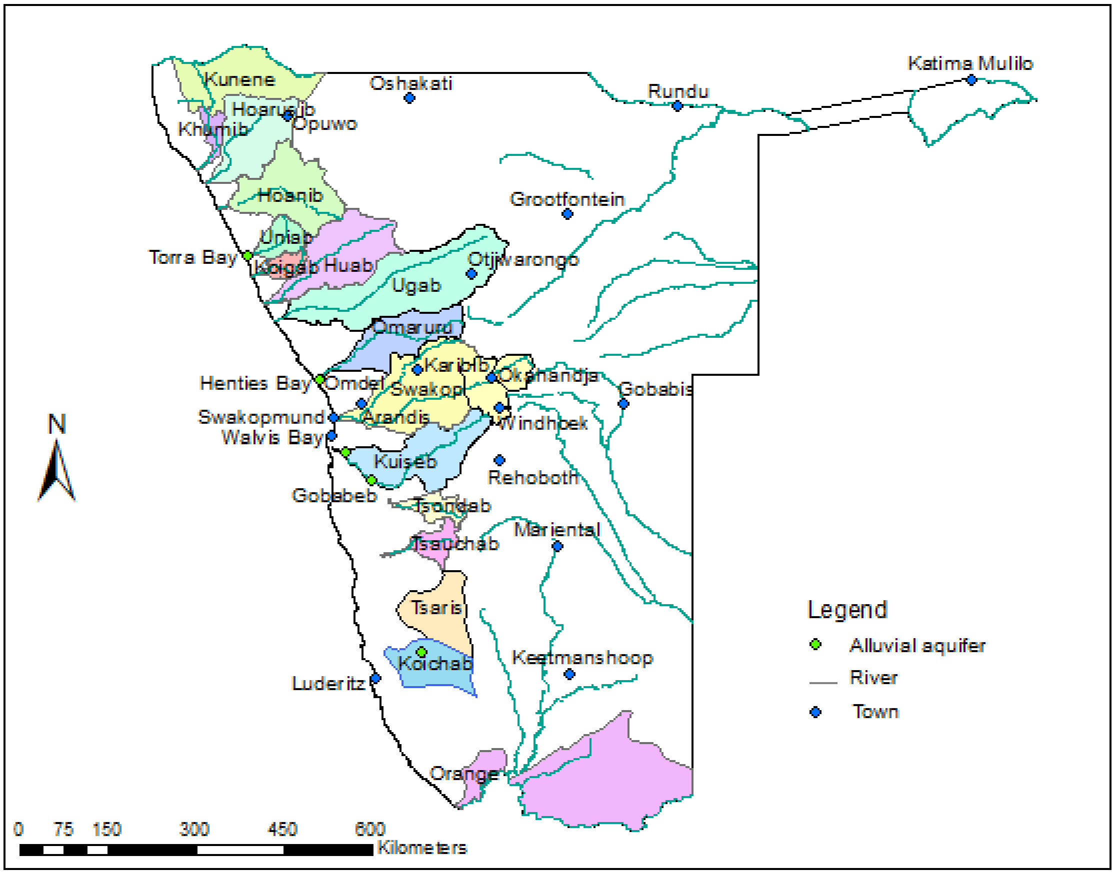

**Fig. 1.2** Map depicting catchments and alluvial aquifers in the Namib Desert, rivers and towns

The ephemeral Swakop River is an important source of surface water to the Central part of Namibia, since two major storage dams occur in its upper catchment area, i.e. the Von Bach and Swakoppoort Dams. However, flow of flood water only reaches the coast when exceptionally high rainfall occurs. Downstream of each dam the river course is characterized by a dry river bed with patches of perennial or temporary wet areas particularly where bedrock is exposed at the surface (Matengu 2011). Leaching of salt in the alluvial riverbed is expected to occur when the Namib Desert receives occasional high rainfall, resulting in a temporary bad water quality developing farther downstream in the river. Lenses of gypsum and other salts are often located in the river bed alluvium.

The Swakop River is considered to be a losing system since the water table in the river bed is elevated above the regional groundwater table. In addition, subsurface inflow does occur from adjoining tributaries, which is considered to be the source of groundwater mineralization in the vicinity of the Langer Heinrich. There are no production boreholes operating in the Swakop River Delta Aquifer. Only monitoring boreholes are installed here to monitor the potential groundwater pollution influence of mining activities from uranium mines upstream.

There are two boreholes drilled in the Uniab River Delta Aquifer that supply water to Namibia Wildlife Resorts (NWR) at Torra Bay, which is a campsite situated within the Skeleton Coast Park, well known for its fishing retreat. The location of Uniab River Delta Aquifer in Fig. 1.2 also represent the location of Torra Bay.

Another important west-flowing river that produces essential groundwater from its alluvial beds is the Kuiseb River which is approximately 350 km in length with the catchment area of about 14 000 km$^2$. It originates in the Khomas Highlands approximately 23 km west of Windhoek with an elevation of about 1600 mamsl and the long-term mean annual rainfall in this source area is about 360 mm (Wessels 2001). The area is mountainous, composed mainly of mica schist. Farther downstream, the river drains the escarpment region where the mean annual rainfall drops from 250 mm to 100 mm (middle Kuiseb River) and farther west, the rainfall decreases to about 20 mm/annum (Namib Desert; Lower Kuiseb River). Gobabeb research station is located upstream of Kuiseb Aquifer, and water supply is from two boreholes drilled in the alluvial aquifer of the Kuiseb River System in the Kuiseb catchment (Fig. 1.2).

South of the Kuiseb River Basin lies the Koichab River Catchment, which is defined by the escarpment to the north and east and the mountains to the south east around Aus. A watershed between the Koichab River and its major tributary (the Garub River), subdivides the catchment. The ephemeral Koichab River originates east of Aus, about 80 km from Koichab Pan and runs along the dune line forming the southern border known as Namib Sand Sea (van Vuureen and Zeelie 2004). Along the dunes the river course is not well defined and consists of a series of pans and depressions with no signs of recent fluvial activity. The average annual rainfall over the catchment is about 80 mm. Run-off in the upper Koichab River occurs after heavy rains but does not occur frequently, sometimes pools of water will be visible in the desert and it’s believed not to be a significant source of recharge to groundwater.

## 1.2 Research objectives and Approach

The aim of this study is to discuss groundwater assessment and sustainable utilization of groundwater of the coastal alluvial aquifers in the Namib Desert. Groundwater recharge plays an important role towards the groundwater balance component of the coastal alluvial aquifers in the Namib Desert. Omdel Aquifer is used as a case study with the following objective: to integrate artificial recharge with hydrogeological understanding of the Omdel Aquifer to establish a conceptual framework for assessment of groundwater recharge and discharge, water chemistry and balanced water supply.

The specific objectives are:

- Determine the groundwater quality facies of selected boreholes of the Omdel Aquifer.
- Estimate the groundwater recharge of the Omdel Aquifer.
- Estimate groundwater recharge of groundwater supply schemes upstream of the Omdel Aquifer in the Omaruru catchment.
- Estimate the groundwater discharge of the Omdel Aquifer.
- Determine the groundwater balance of the Omdel Aquifer.
- Construct and run the groundwater numerical model of the Omdel Aquifer.

The issues/challenges investigated in the study are:

- Lack of understanding of geology and hydrogeological settings of the Omdel Aquifer.
- Little information on the hydraulic properties and geometry of the aquifer at the inflow and outflow sections.
- No groundwater recharge study done upstream of the Omdel Aquifer in the Omaruru catchment.
- Little information on the impact of artificial recharge as well as the effect of flood events for the hydrological seasons of 1996/97/98, 1999/00, 2007/08, 2008/09 and 2010/11 on groundwater levels of the Omdel Aquifer.

## 1.3 Methodology of research

The research was to assess the groundwater and sustainable utilization of groundwater in the Namib Desert, using Omdel Aquifer as an example. Hydrogeological surveys were carried out during the site visits at Omdel Aquifer (study area) and groundwater supply schemes (Okombahe, Nei-Neis, Omaruru, Tubussis and Spitskoppe) upstream of the Omdel Aquifer in the Omaruru catchment. Site visits were conducted to familiarize with the study area (Omdel Aquifer), the artificial recharge infrastructure, groundwater supply schemes upstream in the Omaruru catchment and observe the geological structures (dykes) and different outcrops or formations. The pictures of the outcrops taken at Nei-Neis along Omaruru River and Spitskoppe in the Omaruru catchment during the site visit are indicated in Fig. 1.3.

The study looked at the geological setting using different sources to come up with detailed geological features of the Omdel Aquifer. Geological information obtained from the borehole completion reports were used to draw geological cross sections, using Arc-Map software to give detailed hydrostratigraphy and a better understanding of geometry of the Omdel Aquifer. The effect of abstraction from production boreholes on groundwater level (water table) was assessed. Test pumping data were analysed by using the Aquifer Test Curve Fitting and Aquifer Test 3.5 analyses to determine the aquifer parameters of the Omdel Aquifer. The groundwater level elevations of the Omdel Aquifer boreholes gave an indication of groundwater flow. Hydrochemical data of selected boreholes of the Omdel Aquifer were analysed using WISH and HamVer2Dot softwares to determine the groundwater facies, water types and fingerprints.

Groundwater recharge estimation at groundwater supply schemes upstream of Omdel Aquifer in the Omaruru catchment was estimated by Water Table Fluctuation (WTF) and Chloride Mass Balance (CMB) methods. The study looked at the effect of run-off on groundwater recharge (episodic recharge) of the alluvial aquifers in the Omaruru catchment compared to rainfall. Groundwater flow from the upper river bed (upstream of Omdel Aquifer), OMAP, SEC and groundwater supply schemes upstream in the Omaruru catchment were conceptualized and estimated by using Darcy's law. The groundwater balance of the Omdel Aquifer before and after dam construction was estimated. The overall understanding of the conceptual model of an aquifer (Omdel Aquifer) in arid environment (Namib Desert) was assessed. The groundwater numerical model was constructed using modelmuse (modflow software) to assist in better understanding of the conceptual model of the Omdel Aquifer.

**Fig. 1.3 a** Outcrop at Nei-Neis along Omaruru River, **b** outcrop at Spitskoppe

## 1.4 Thesis outline

The thesis outline has five (5) chapters.

Chapter 1: describes the introduction chapter of the study and highlights on the background of groundwater focus in Namibia (Sub Saharan Africa). The background also presents an overview on the alluvial aquifers in the Namib Desert. Research objectives and approach as well as methodology of research are described in the introduction chapter. Previous work done has also been reviewed in this chapter.

Chapter 2: describes the water resources found in the Namib Desert, the developed alluvial aquifers, episodic recharge, desalination plant and water demand situation. The chapter highlights on the groundwater quality and estimated groundwater reserves of the developed coastal alluvial aquifers.

Chapter 3: presents a published paper on hydrogeoological characteristics of the Omaruru Delta Aquifer system in Namibia. The paper focuses on the geology and hydrogeological settings, groundwater quality, groundwater recharge, artificial recharge, groundwater discharge, and groundwater balance of the Omdel Aquifer.

Chapter 4: presents the groundwater numerical modelling, constructed to assist in a better understanding of the conceptual framework of the Omdel Aquifer system. The calibrated steady state model is used to present the results of different abstraction rate scenarios of the Omdel Aquifer.

Chapter 5: describes the sustainable groundwater management strategies of the Omdel Aquifer, these strategies may be applied to other coastal alluvial aquifers in the Namib Desert.

## 1.5 Previous work

There is lack of recent publications in Namibia on groundwater issues, particularly on groundwater assessment and sustainable management use of the coastal alluvial aquifers in Namib Desert, therefore, the development methodology to carry out such assessment and sustainable groundwater utilization of the coastal alluvial aquifers in Namib Desert or similar environment forms part of the study. The floodwater is not considered a sustainable water resource, but floodwater infiltrating the alluvial aquifers is a traditional source of water supply in arid areas (Benito et al. 2010). The alluvial aquifers of ephemeral rivers are characterized by dynamic interactions and the link between human consumption, surface hydrology, the geological environment and ecosystems. The alluvial aquifers gets recharge via vertical infiltration during the run-off event of the Kuiseb River and from groundwater flow upstream within the alluvial aquifers (Schmitz 2004). Dahan et al. (2008) conducted a study on dynamics of flood water infiltration and groundwater recharge in hyper arid deserts, the study revealed the effect of flood water infiltration on groundwater recharge of the local alluvial aquifers along ephemeral channels like Kuiseb River in Namib Desert. Ephemeral rivers and associated alluvial aquifers of the arid to hyper-arid western and southern regions in Namibia are important water resources that sustain populations, economic activities and ecosystems (Sarma and Xu 2017). The Department of Water Affairs, Namibia introduced an artificial recharge project at Omdel Aquifer in 1989 (Nawrowski 1994). The aim of the project is to contain the surface water in a dam after a significant run-off where the silt is allowed to settle, after that the water is released via a canal into recharge infiltration ponds where it infiltrate the aquifer.

Seawater intrusion in coastal aquifers tend to be a common problem in almost all coastal aquifers and is encountered, with different degrees (Sefelnasr and Sherif 2014). It is regarded as a natural process that might be influenced by external factors such as change in groundwater abstraction, irrigation, recharge practices, land use, and possible seawater rise due to climate change.

It is important to note that the sustainable yield of an aquifer should always be considered less than recharge, in order to retain enough water to sustain and preserve the quantity and quality of natural streams, springs, wetlands and groundwater dependent ecosystems (Sophocleous 2000). Good management of water resources should not be approached only from the viewpoint of focusing on the volume of water available for sustainable use, but also the impact of groundwater exploitation on the environment should be considered. The numerical modelling has become a decision and planning tool in sustainable groundwater management. According to Sophocleous (2000), the models can generate the transition curve from storage depletion to induced recharge from surface water bodies in order to manage the plans and planning horizons. However, the use of these models for water resource management purposes should include land, vegetation, climate and water interactions. Groundwater modelling is a tool which can be used for prediction and planning purposes and is also capable to bring all available data together to formulate a logical holistic picture on a quantitative basis (Kinzelbach et al. 2003). This tool is extensively used to study the sustainability of groundwater abstraction.

A sustainable yield of the Omdel Aquifer system depends strongly on the artificial recharge events and production history (Bittner et al. 2014). The developed numerical groundwater model of the Omdel Aquifer can help to gain a better understanding of the system, therefore it can play an important role in managing the groundwater resources and can be used to predict the potential impacts of abstraction. All over the World there is a lack of groundwater management sustainability; the evidences are falling of water tables, drying wetlands, increasing sea water intrusion and deterioration of water quality (Kinzelbach et al. 2003). Sustainable water management involves a management practice that avoids an irreversible damage to the water resource and other natural resources that depend on it, like soil and ecosystems. When the groundwater table declines very rapidly, roots of trees that rely on groundwater may not be able to follow the decline and as a result will end dying off. This scenario is particularly critical and common in dry areas.

# Chapter 2: Water resources in Namib Desert

## 2.1 Introduction

Groundwater is used as the main source of freshwater in many countries around the globe, especially in arid and semi-arid regions, where rainfall is very low and insignificant and surface water bodies are limited and sometimes absent (as in the case of the Namib Desert; Sefelnasr and Sherif 2014). As an important source for water supply, groundwater, if available must be used sustainably, in such a way that the mean abstraction rates do not exceed the long term recharge values under present and future climatic conditions (Schmitz 2004). For this reason accurate and reliable recharge estimates formulate the most important parameter for sustainable groundwater management.

Due to fishing and mining industries at the coastal towns of Namibia, such as Henties Bay, Swakopmund, Walvis Bay and Lüderitz, the population density is proportionally high and the coastal aquifers are generally exposed to extensive groundwater abstraction. Often such abstraction exceeds the natural replenishment rates.

Groundwater plays an important role in supplying water to towns and mines located in the Namib Desert, e.g. Omdel Aquifer, Kuiseb Aquifer and Koichab Pan Aquifer in the Central and Southern Namib Desert respectively.

In the Central Namib Desert the Areva desalination plant (also called the Erongo desalination plant) was constructed in 2010 to augment industrial water supply, particularly to the developing uranium mines. Episodic recharge plays an important role to replenish groundwater in arid environments, therefore it will be explored in more details in this chapter.

The water demand situation of the Namib Desert in comparison to the available water resources will be elaborated on in more details.

## 2.2 Alluvial aquifers

Developed alluvial aquifers are Omdel Aquifer, Kuiseb Aquifer and Koichab Pan Aquifer, which supply water to Henties Bay, Swakopmund, Arandis, Rössing uranium mine, Langer Heinrich mine, Walvis Bay and Lüderitz respectively. Only Kuiseb Aquifer and Koichab Pan Aquifer will be discussed here, since Omdel Aquifer is discussed in chapter 3.

Alluvial strip aquifers, associated with ephemeral rivers, are important groundwater supply sources to various settlements and ecological systems in arid Namibia, and more than 70 % of the population in the western and southern regions depend on the alluvial aquifers associated with ephemeral rivers (Sarma and Xu 2017). Groundwater recharge to such aquifers occurs through infiltration during occasional flood events resulting from higher rainfall in the form of thunderstorms farther upstream in the river catchment. Varying thunderstorm rainfall patterns in arid regions like Namibia, however, make recharge assessments of the aquifers difficult to manage in a sustainable way, usually resulting in the aquifers being over-utilised.

Total aquifer storage of linear alluvial aquifers depends mainly on the connectivity of the aquifer along the ephemeral river bed (Benito et al. 2010). The Kuiseb Aquifer is a good example of a linear set of interconnected alluvial reaches. In arid regions the water quality and quantity cannot be separated in alluvial channels of the ephemeral rivers.

Conceptual models of an ephemeral river indicate the water balance composed of upstream inflow, flood recharge, evaporation, transpiration, pumping, lateral flow, vertical flow, and downstream outflow. As a result changes in storage volume (water level) will occur, accompanied by a solute and salt balance (Benito et al. 2010; Fig. 2.1)

When pumping takes place in an alluvial aquifer the storage volume and water level are directly affected, but other impacts such as surface evaporation losses, transpiration rates and flood recharge also play a role.

Evapotranspiration is a major component of groundwater especially in arid environments and has direct and indirect impact on groundwater resources. The direct impact is related to groundwater evapotranspiration, where groundwater is lost due to trees with deep roots and evaporation from groundwater table (Obakeng 2007). The indirect impact is the evapotranspiration of water from surface and from unsaturated zone (water that has not reached water table). The other evapotranspiration is the moisture uptake by plant roots in the unsaturated zone and evaporation from unsaturated zone. The depth of roots for most of the local vegetation results in evapotranspiration, Acacias (Camelthorn Trees) and Acanthosicyos horrida (Nara Plants) can grow roots up to 60 m and 50 m respectively (Beranek et al. 2018).

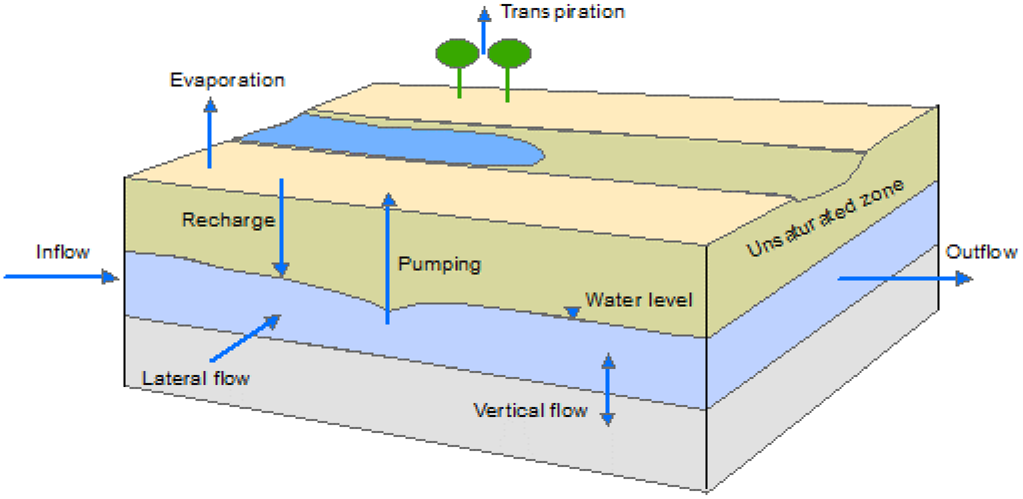

**Fig. 2.1** Conceptual model of an ephemeral river indicating the hydrological balance (different flows of water and atmospheric vapour; after Benito et al. 2010)

### 2.2.1 Kuiseb Aquifer

Bulk groundwater is supplied to Walvis Bay, Swakopmund, Topnaar communities, Rooikop airport, Military base and quarries (in close proximity) from the Kuiseb Aquifers. The Lower Kuiseb Aquifers are divided into two main aquifer compartments, namely the Swartbank-Rooibank A compartment and the Rooibank B-Dorop South compartment, whilst the two compartments are separated by a distinct bedrock high (Fig. 2.2). Palaeochannels in both compartments are filled with sand, gravel, silt (slightly consolidated by a carbonaceous cement) up to 120 m and are in hydraulic contact with the active Kuiseb River Plain (Wessels 2001). The average saturated thickness of the palaeochannel fill is about 50 m, and the palaeochannels are preferred pathways directing groundwater flow to the coast. Unconsolidated alluvial clastics sediments of the Kuiseb River, up to 50 m thick, present the best hydraulic conditions.

Although the Kuiseb River Plain is described as one continuous aquifer, there are several basement barriers that partially separate a number of compartments, thus affecting the groundwater flow at certain localities downstream. An impermeable crystalline basement outcrop on the northern boundary acts as a groundwater barrier. Wessels (2001) mentions that the alluvial aquifer displays poor aquifer characteristics to the west below the dune covers, where it's in hydraulic contact with the Tsondab Sandstone and palaeochannel fill.

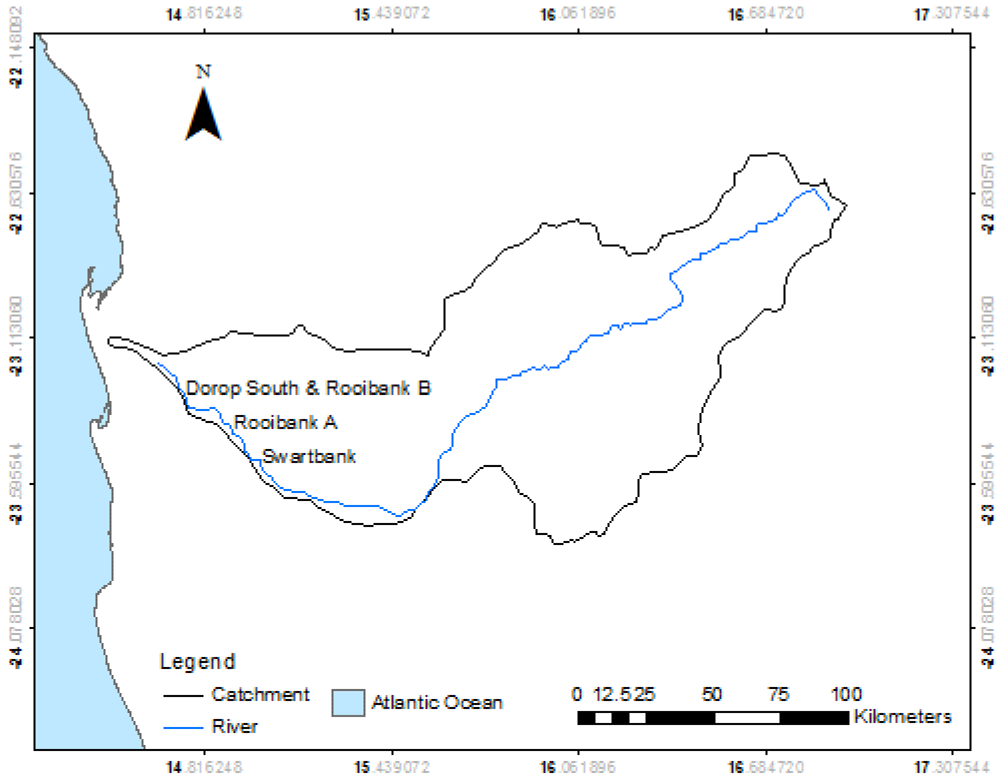

**Fig. 2.2** Map depicting lower Kuiseb Aquifers in the Kuiseb catchment

Geological material encountered during 2017 drilling at Kuiseb River Delta Aquifer (Dorop South); the sediments at most sites comprise of a fine to medium grained sand with intercalated clay-rich layers. Layers of coarse sand and gravel are located at the bottom of the sedimentary succession, just above the bedrock and are considered to be the most productive part of the aquifer. The presence of shell fragments in the sand and gravel at most sites indicate a marine environment (Fig. 2.3). A semi-confined aquifer is expected here, due to the presence of a clay layer observed at some boreholes during drilling. Bedrock is mainly mica schist and granite of the Damara Sequence, which is encountered at an average depth of 55 m.

**Fig. 2.3** The presence of shell in the sand at Dorop South Delta Aquifer (Kuiseb Aquifer)

The groundwater recharge to the Kuiseb Aquifer occurs during flood events when there is significant inflow upstream in the Kuiseb catchment and subsequent groundwater flow upstream of the Kuiseb Aquifer. The best way to assess the impact of recharge to the aquifers is based on the estimated run-off losses in the Kuiseb River between Swartbank and the Kuiseb Delta and the volume of water infiltrated as a result of these events that reaches the groundwater table (Wessels 2001). A principal source of water in arid environments like the Kuiseb Aquifer is related primarily to floods in the ephemeral rivers, caused by intense rainstorms of relatively short duration inland (Benito et al. 2010). The floodwater is not considered a sustainable water resource, but floodwater infiltrating the alluvial aquifers is a traditional source of water supply (Benito et al. 2010).

Lateral and vertical restrictions to the alluvial channel constitute possible barriers to groundwater flow (Schmitz 2004). Recharge to the alluvial aquifers occurs through vertical infiltration of run-off when the Kuiseb River flows and through groundwater flow within the alluvial aquifers.

During the period between December 2003 and April 2004, the aquifer responded with a rise in water table of about 89 cm in reaction to the first flood and 8 cm as a result of the second flood (Schmitz 2004). The rate of vertical advance of the wetting front was estimated to be between 0.3 m/h and 0.15 m/h in the two flood events. Schmitz (2004) also estimated the infiltration rates to be between 0.26 mm/h and 0.89 mm/min. Estimated smaller rates at Kuiseb are mainly associated with silt layers on the surface which reduce the infiltration. Flood events of the 1996/97 season had an impact on the rest water levels of boreholes, particularly at the Swartbank-Rooibank A Aquifer compartment. The impact of the exceptional 2011 flood event was not observed in the boreholes of the Dorop south well field, because the boreholes there are covered by at least 1 to 2 m thick sand/silt deposits.

Figure 2.4 indicates a picture taken during the 48-hours constant discharge test (CD) of about 80 $m^3/h$ on borehole WW100292 at Dorop South in 2017.

**Fig. 2.4** Picture taken during CD test on borehole WW100292 at Dorop South

The sustainable yield of the Kuiseb Aquifer is estimated at 11.4 $Mm^3/a$, with 8.7 $Mm^3/a$ and 2.7 $Mm^3/a$ allocated to the Rooibank A – Swartbank Compartment and Rooibank B – Dorop South Compartment respectively (Beranek et al. 2018). They further estimated the worst case scenario sustainable yield for the next 10 years (until 2028) to be about 9 $Mm^3/a$, taking no further recharge into consideration. Run-off recharge to the Kuiseb Aquifer, estimated to be 2.7 to 27 $Mm^3/a$ with an average of 12 $Mm^3/a$, occurs only when there is significant inflow. Variations to the amount of recharge are directly related to the duration and volume of run-off in the river (Beranek et al. 2018). The main source of recharge is related to flood waters in the middle-lower Kuiseb River and the water table of the shallow aquifer decreases during the dry periods, resulting in an increase of the storage capacity (potential recharge) when flood events subsequently occur (Benito et al. 2010).

There is a small lateral saline inflow of groundwater from the northern bank to Kuiseb River, representing about 5% of flood recharge. This implies that a slow increase of salinity can be expected during long periods when there are no floods (Benito et al. 2010). The Kuiseb alluvial

Aquifer in certain sections feeds groundwater into the southern bank (palaeochannels covered with dunes).

Production boreholes in the Kuiseb Aquifer supply at least Group B groundwater quality (according to the Namibian Standards for Drinking Water), with the exception of 3 boreholes (WW22129 (A5), WW29412 (A10B) at Rooibank A and the Fehlman Well (WW10657) at Swartbank, which produce Group C and D groundwater quality respectively (Shinana 2018). The Group A is water with excellent quality, Group B is water with acceptable quality, Group C is water with low health risk and Group D is water with a high health risk or water unsuitable for human consumption (Department of Water Affairs 1988). Groundwater chemistry facies indicate that the concentrations of cations and anions reveal mostly no dominant water type, varying from calcium/magnesium bicarbonate to calcium/magnesium sulphate/chloride water types. The groundwater quality from boreholes WW100292, WW100293, WW100294, WW100295, WW100296, WW100297, WW100300, WW100301, WW100303, WW100304, WW100305, WW100307, WW100308, WW100309, WW100310, WW100311, WW100313, WW100314, drilled at Dorop South Aquifer (Kuiseb River Delta Aquifer) during the 2017 project, is classified as Group B (Fig. 2.5; Matengu 2018). From boreholes WW100298, WW100302 and WW100315 the water quality is classified as Group C, while boreholes WW100299, WW100306 and WW100312 are classified as Group D.

In the case of the above borehole water samples, Group B determinants are sodium, nitrate, conductivity, chloride, total hardness, manganese, iron, turbidity and sulphate. The Group C determinants are chloride, sodium, conductivity and total hardness, while the Group D determinants are cadmium, iron, magnesium, total hardness, chloride, sulphate, sodium and conductivity.

Old boreholes at Dorop South, WW100198, WW100197, WW100196, WW36782 and WW36781 have a water quality classified as Group B, while borehole WW36786 is classified as Group C (Fig. 2.5). Group B determinants, in this case, are conductivity, sodium and total hardness, while the Group C determinant is manganese. The new and old boreholes have both Group B and Group C water quality. None of the old boreholes have the water quality of Group D.

According to the total dissolved solids (TDS) classification (Usher 2002), the water of boreholes WW100292, WW100293 and WW100313 is classified as fresh water due to recharge of groundwater flow (upstream). The water of boreholes WW100294, WW100295, WW100296, WW100297, WW100298, WW100300, WW100301, WW100302, WW100303, WW100304, WW100305, WW100306, WW100307, WW100308, WW100309, WW100310, WW100311, WW100314 and WW100315 is classified as brackish (moderately saline). Water in borehole

WW100312 is classified as sea water (saline water), and the water in borehole WW100299 is classified as brine. The Piper diagram indicates that the groundwater chemical signature of the boreholes drilled at Dorop South in 2017 is dominated by chloride and sodium, typical of a coastal environment (Fig. 2.6).

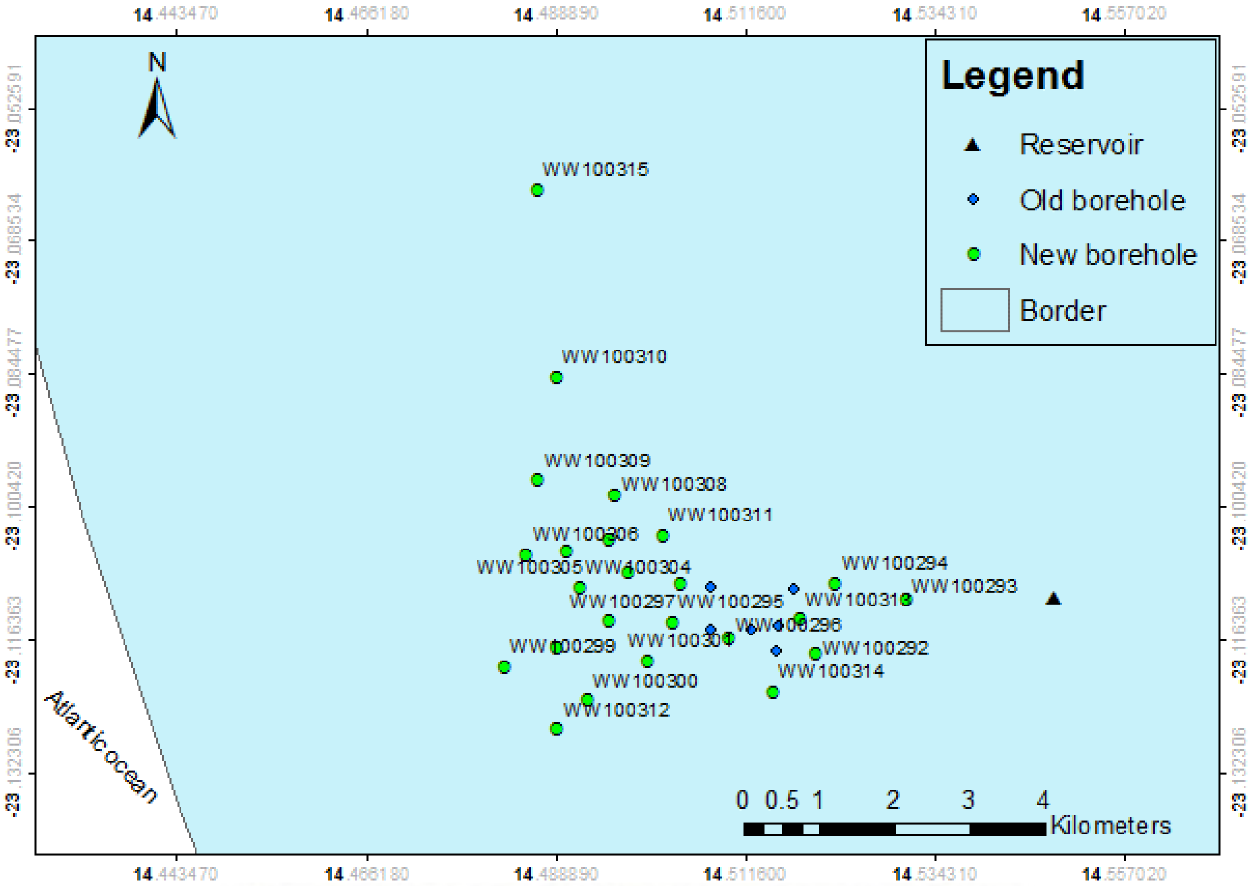

**Fig. 2.5** Map depicting new and old boreholes at Dorop South

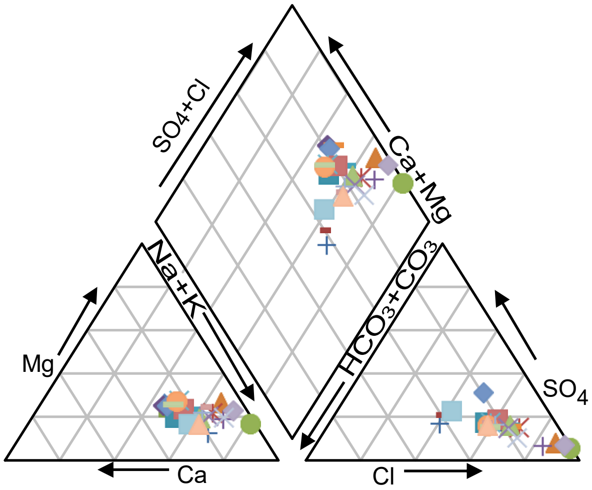

**Fig. 2.6** Piper diagram of boreholes drilled in 2017 at Dorop South

### 2.2.2 Koichab Pan Aquifer

The Koichab Pan Aquifer is located about 120 km north east of Lüderitz in the //Karas Region of southern Namibia and has been proved, through numerous investigations, to host quite a substantial groundwater resource. A water supply scheme was developed which supplies water to the town of Lüderitz since 1969.

The Koichab valley consists of a belt of alluvial fans formed due to erosion of the Great Escarpment and other mountainous features in the catchment (van Vuuren and Zeelie 2004). Distribution of grain size in the alluvial fans begins with the coarse gravel fractions close to the mountains (proximal fan) and the finer material at the downstream end (distal fan), where silt and clay are deposited in pans. Coarser material can be expected, closer to the distal fan, during periods of high rainfall (strong flooding), but such a scenario will result in clearly defined layers of various grain size. Porosity and permeability values are high in the upper catchment, decreasing downstream. As a result groundwater becomes progressively more "confined" towards the Koichab Pan area, due to the increasing number of semi-permeable to impermeable (clay) layers. The aquifer is described as semi-confined or leaky in nature, overlain by semi-permeable layers (aquitards), consisting of a mixture of sand and clay. Van Vuuren and Zeelie (2004) mention that when abstraction of groundwater occurs the water is released from the elastic storage, developing a cone of de-watering which induces leakage through the overlying semi-permeable layers. This results in the water to move freely upward or downward through the aquitard.

Groundwater recharge occurs mainly along the small river courses in the upper catchment of the piedmont. Clay and silt reduces groundwater recharge in the lower part of the piedmont. Groundwater contained in the tertiary sediments is collected in the bedrock depressions and gravitates towards the coast where it forms springs (van Vuuren and Zeelie 2004). During the January 2019 drilling project, it was revealed that the geology comprises of semi-consolidated sand with clay, quartz gravel, calcrete, quartz and gneiss, and the bedrock encountered is gneiss. The latest water quality chemical analysis for the production boreholes of Koichab Pan Aquifer is classified as Group A. Average actual abstraction (past five years) and the total recommended abstraction of production boreholes at Koichab Pan Aquifer is 1 090 155 $m^3$/year and 2 232 000 $m^3$/year respectively. Estimated groundwater stored reserves amount to 1 600 $Mm^3$ and 150 $Mm^3$ for the entire aquifer and the well field respectively (van Vuuren 2000).

The two pictures taken during drilling which took place in January 2019 are indicated in Fig. 2.7.

**Fig. 2.7** Pictures depicting drilling at Koichab Pan Aquifer in January 2019

## 2.3 Episodic recharge

Flood events are regarded as a principal source of water in arid environments around the world in ephemeral rivers (Benito et al. 2010). Significant floods especially in dry lands are caused by intense rain storms that may last for a short period from minutes to days depending on the area of drainage basin system. The recharge of groundwater in arid environments is controlled by two main mechanisms: direct regional infiltration of rain water in the mountains and inter drainage areas and infiltration of flood water through ephemeral channel beds (transmission loss) (Dahan et al. 2008; Osterkamp et al. 1994; Schwartz 2001; Shentsis and Rosenthal 2003; Walter et al. 2000). Direct infiltration is relatively ineffective in arid environments due to rare rain storms, low mean average precipitation and high evaporation potential, it’s therefore regarded as nonexistent in many desert areas (Dahan et al. 2008; Scanlon 2004). The groundwater quality in many deserts in the world have relatively high salinity due to high evaporation potential relative to precipitation which results in soil salinity and the rare deep infiltration of rain water (Dahan et al. 2008; Simmers 1997).

Flood water infiltration through beds of ephemeral rivers known as transmission loss, depends on water flow usually last for short period in stream channels (Dahan et al. 2008; Shentsis and Rosenthal 2003). The transmission loss recharges partially the local alluvial aquifers below the stream channels and the aquifers connected to them. Borehole WW26483 is the monitoring borehole in the Omaruru River bed located at Nei-Neis (local alluvial aquifer) upstream in the Omaruru catchment, the details of the borehole are described in chapter 3. Sarma and Xu (2017) reported that infiltrated water flow is vertical underneath streambed and lateral distributed underground flow. According to Dahan et al. (2008) and Scanlon (2004), flood water is usually characterized by low salinity because of the streambed and its alluvium which are more frequently flushed by floods. Therefore, the shallow alluvial aquifers along the stream channels in arid environments usually have groundwater of acceptable quality (Dahan et al. 2008; de Vries and Simmers 2002; Gee and Hillel 1988). The seepage rates for a particular flow duration are controlled by streambed hydraulic conductivity and width, however, stream flow depth has limited effect on seepage rates (Dahan et al. 2008; Sarma and Xu 2017). Therefore, the water resource management in arid environments must depend on quantifying the flood water infiltration and percolation that recharge the shallow alluvial aquifers.

## 2.4 Water demand situation

The water demand situation in the Central Namib area for the past 20 years (1998 to 2018) is based on the average actual water consumption of 14 108 323 m$^3$/year (Fig. 2.8**)**. Omdel and Kuiseb Aquifers were the only source of water in the Central Namib before August 2013, with the average of 12 550 907 m$^3$/year. More water is supplied to Walvis Bay, Swakopmund and Rossing with an average of 5 441 011 m$^3$/year, 3 470 292 m$^3$/year and 3 442 554 m$^3$/year respectively, while the least water is supplied to Henties Bay at an average of 429 522 m$^3$/year. Water supplied to Walvis Bay and Swakopmund includes the towns and other small customers. Supplies of water to Rossing include Rossing Mine and Arandis Township (domestic). Langer Heinrich mine water supply started in 2007 when its operation started. Due to the increased water demand as a result of Langer Heinrich mine and Husab mine operations, the Areva desalination plant started supplying the required volume of water in August 2013 with an average of 5 906 585 m$^3$/year. Omdel Aquifer could not sustainably produce the increased volume of water required. Water consumption at Husab mine increased from 589 046 m$^3$ (2014) to 5 928 634 m$^3$ (2018; Fig. 2. 8). The projected water demand from 2019 to 2023 is estimated to be between 22 958 979 and 24 319 938 m$^3$ in the Central Namib area However, due to the reduction of  mining operations, the projected water demand decreased from 2018 to 2019.

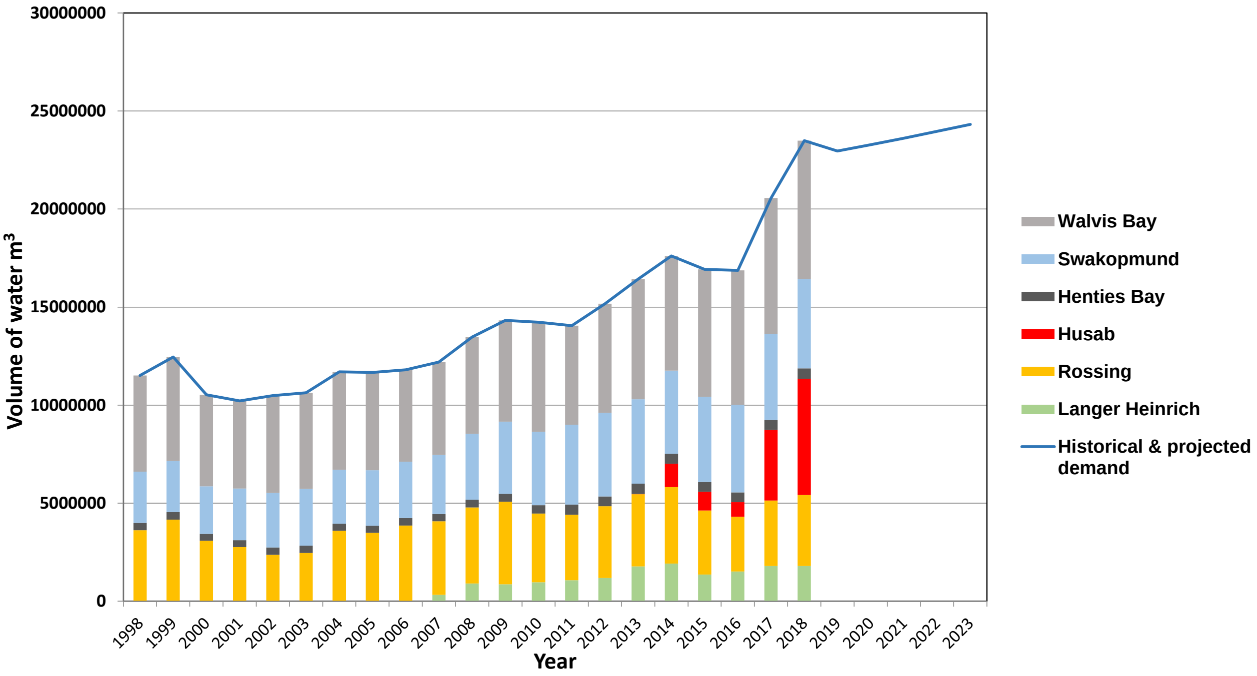

**Fig. 2.8** Historical water consumption and projected water demand for Central Namib (after Shinana 2018)

The total water consumption for the Central Namib,  between 2014 to 2018 from Omdel Aquifer, Kuiseb Aquifers and Areva desalination plant,  was 65 927 343 m$^3$ (69%) and 29 532 923 m$^3$ (31%) respectively, amounting to about 95 460 266 m$^3$ total water consumption from both aquifer and desalination sources (Fig. 2.9). Note should be taken of the fact that more water was from Omdel and Kuiseb Aquifers (groundwater sources) than from Areva desalination plant (desalination source) over the same period. The anticipated growth in water demand for the town of Lüderitz is predicted to be in the order of 1% per annum depending on future development. Compounded over the next 5 years, the predicted demand in the year 2020 is estimated to be in the order 1.00 Mm$^3$ (Fig. 2.10). There was a decrease in water consumption in 2005 and 2010 and an increase in 2004 and 2008, fluctuations being associated with fishing industries at Lüderitz.

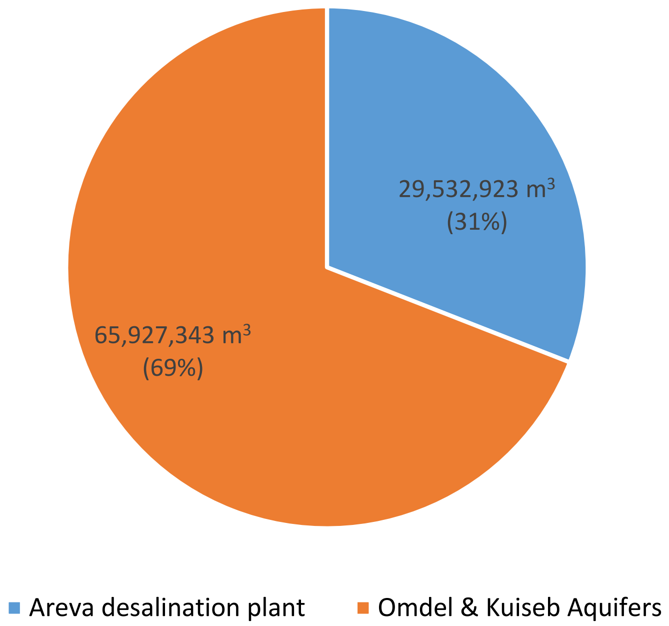

**Fig. 2.9** Total water consumption for the Central Namib from aquifers (Omdel and Kuiseb) and desalination plant (after Shinana 2018)

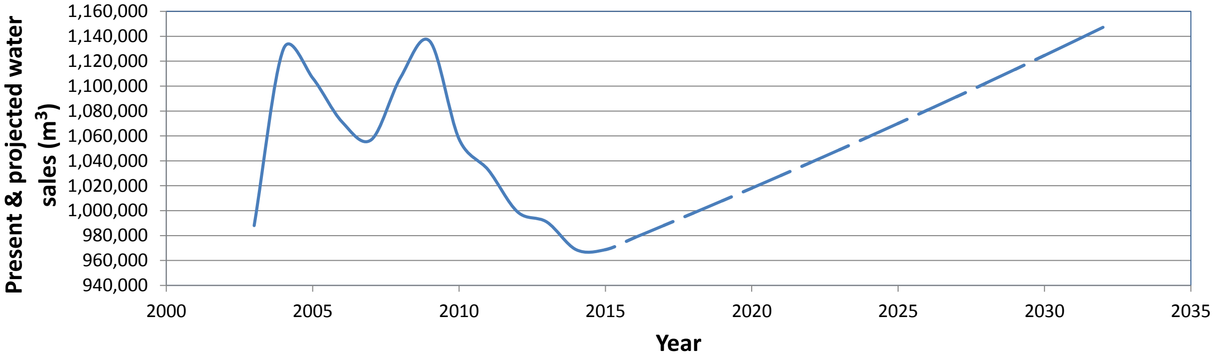

**Fig. 2.10** Total present and projected water sales at Koichab Pan Aquifer

The total water consumption for the Namib Desert (excluding water consumption from two boreholes at Torra bay and water consumption for October 2018, November 2018 and December 2018 from Koichab Pan Aquifer) is 70 580 093 m$^3$ (71%) and 29 532 923 m$^3$ (29%) from Omdel, Kuiseb and Koichab Pan Aquifers and Areva desalination plant respectively for the period 2014 to 2018 (Fig. 2.11), amounting to a total of about 100 113 016 m$^3$ from the two sources for 2014 to 2018.

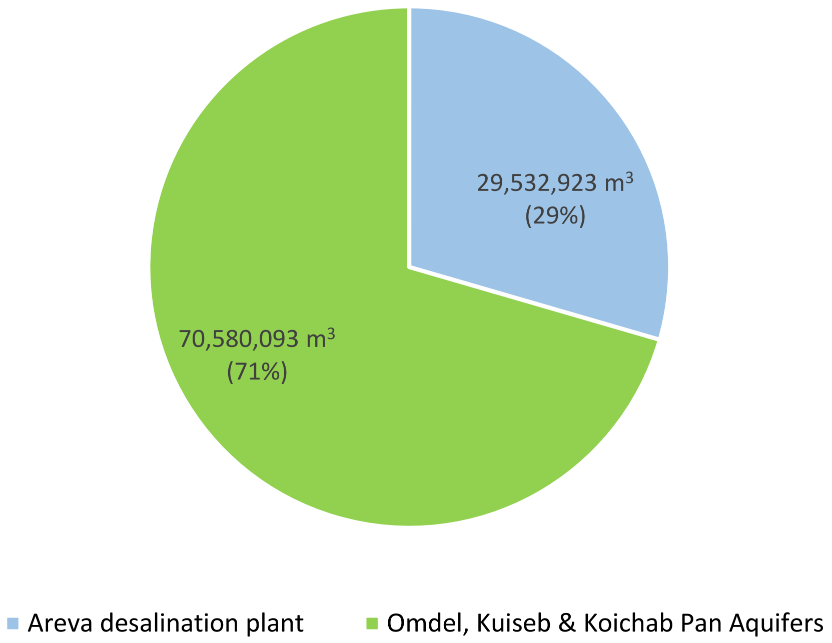

**Fig. 2.11** Total water consumption for the Namib Desert from aquifers (Omdel, Kuiseb & Koichab Pan) and desalination plant

## 2.5 Conclusions

The Omdel, Kuiseb & Koichab Pan Aquifers are three major aquifers developed to supply groundwater in the Namib Desert. Estimated sustainable yields of Omdel, Kuiseb and Koichab Pan Aquifers are 4.6 Mm$^3$/year, 11.4 Mm$^3$/year and 2.232 Mm$^3$/year respectively. Total sustainable yield of groundwater resources in the Namib Desert (excluding two boreholes at Torra Bay in Uniab catchment) is estimated at about 18.232 Mm$^3$/year.

Benito et al. (2010) describes floodwater that recharges into alluvial aquifers is controlled by the regulated maximum flux rate through the riverbed (sand channel beds about 1 to 15 mm/h), duration of the flood, flood frequency and groundwater storage capacity at the time the flood is taking place (flood time). Such factors are determined by the width of the aquifer and the unsaturated zone thickness. They further mention that appropriate management strategies can increase the groundwater storage capacity, hence enhancing final volume of flood water recharge, and groundwater quality. The episodic recharge usually occur after significant run-off, it contribute immensely to groundwater recharge of the alluvial aquifers in Namib Desert. A stable groundwater level limits the storage capacity of the aquifer during flood periods and prevents a high replenishment of groundwater, resulting in poor hydrochemical quality and brackish groundwater during long drought periods (Benito et al. 2010).

The alluvial aquifers in the Namib Desert that have the potential to be developed are in catchments such as the Khumib, Hoarusib, Hoanib, Uniab, Koigab, Huab, Ugab, Swakop, Tsondab, Tsauchab, Tsaris and Orange river systems (Fig. 1.2). Some of these alluvial aquifers can be developed to supply the local communities, e.g. the two boreholes drilled in the Uniab River Delta Aquifer to supply NWR at Torra bay. Other alluvial aquifers are considered to have huge potential for development to supply water to larger towns with a high population growth. The projected water demand in Namib Desert for the year 2023 is about 25.369 Mm$^3$, the difference between the projected water demand and the total estimated sustainable yield being about 7.137 Mm$^3$, which could be supplied from those alluvial aquifers that have potential to be developed in the Namib Desert. In such a case, the possibility exists to reduce the use of expensive water from the Areva desalination plant.

# Chapter 3: Hydrogeological characteristics of the Omaruru Delta Aquifer System in Namibia

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## Abstract

Sustainable utilization of groundwater in parts of hyper-arid Sub-Saharan Africa, like the Namib Desert, is always a challenge due to lack of resources and data. For the Omdel Aquifer in the Omaruru catchment, Namibia, issues to investigate include the lack of information on the geology and hydrogeological setting, the hydraulic properties and geometry of the aquifer at the inflow and outflow sections, groundwater recharge conditions upstream of the aquifer, and the impact of artificial recharge. In this desert environment, the methods applied are hydrogeological surveys and site visits, together with interpretation of geological, hydrological and geomorphological data from investigations carried out to define the hydrogeological characteristics of the Omdel Aquifer. The bedrock geometry of the aquifer indicates that the Main channel (one of four palaeochannels) is the largest reservoir of stored fresh groundwater, estimated at 133 Mm$^3$, and it is deeper than the other three channels, with an average sediment thickness of 80 m. All groundwater chemistry facies of the selected boreholes tapping the Omdel Aquifer reveal a NaCl character, indicating a coastal environment. The yield of the Omdel Aquifer is estimated to have increased from 2.8 Mm$^3$/year before construction of a recharge enhancement dam to 4.6 Mm$^3$/year after the construction. This paper focuses on the understanding of hydrogeological characteristics of the Omaruru Delta Aquifer System in terms of groundwater recharge and discharge, ground-water dynamics within the aquifer and groundwater chemistry, in order to assess whether the current abstractions are operating within the hydrogeological limits of sustainability.

**Keywords**: Hydrogeological characteristics, Artificial recharge, Coastal aquifer, Sub-Saharan Africa, Namibia

## 3.1 Introduction

As one of the coastal aquifers in the Namib Desert in Namibia (Fig. 3.1), the Omaruru River Delta Aquifer (Omdel Aquifer) supplies groundwater to Henties Bay, Swakopmund, Arandis, Rossing uranium mine, Langer Heinrich mine and many other consumers in the Central Namib area. Since groundwater resources can be used as a stable water supply for coastal areas in Africa, they should be managed appropriately to ensure sustainable water supply, and furthermore they should be protected and monitored regularly (Steyl and Dennis 2010). Omdel Aquifer is described as an alluvial aquifer consisting of four palaeochannels, i.e. the Main channel (MC), Northern channel (NC), Northern elevated channel (NEC) and Southern elevated channel (SEC; Fig. 3.1). The MC aquifer is located between the two elevated bedrock channels, i.e. the SEC to the south and the NEC to the north. Further to the north from the NEC is the deeper NC. These palaeochannels are defined mainly by their bedrock elevation, groundwater quality and relative position to the current flow-path of the Omaruru River (Fig. 3.1). The MC is the only channel with potable groundwater. A total of 174 boreholes have been drilled in the Omdel Aquifer, of which 42 are production boreholes, mainly found in the MC. Monitoring boreholes amount to 96, whilst 34 boreholes are reported dry and 2 boreholes are blocked. Water quality from production boreholes in the MC appears to have changed with time; particularly, the total dissolved solids (TDS) is reported to have increased in some of the production boreholes (Seimons and Muundjua 2011). Increase in drawdown usually causes salinization in coastal aquifers (Bocanegra et al. 2010). Some of these boreholes have been in operation for a long time (before 1986). Groundwater resources can be protected from overutilization and contamination by implementing enhanced groundwater recharge systems (dams; Sargaonkar et al. 2011).

Groundwater recharge to the Omdel Aquifer occurs mainly from occasional ephemeral run-off in the Omaruru River. According to Nawrowski (1994) only 1 Mm$^3$/year of surface water recharges the Omdel Aquifer during occasional flood events and about 14 Mm$^3$/year escapes into the sea, based on mean annual run-off data. It should, however, be mentioned that these figures are based mainly on the one major flood event which occurred in 1985. Later long-term average run-off of the river, based on the flood events of the past 56 years, before the construction of the recharge enhancement dam in 1994, is estimated to be 13 Mm$^3$/year. It was furthermore calculated that groundwater recharge amounts to 2.3 Mm$^3$/year as a result of the run-off events, whilst the remaining 10.7 Mm$^3$/year flows out to sea without contributing to recharge, Consultants for Water and Environment (IWACO 2001). In order to prevent any run-off from entering the sea, and to retain the run-off water, the Department of Water Affairs introduced an artificial recharge project (Omdel Dam Project) in 1989, and the construction of the Omdel Dam in the Omaruru River, about 30 km inland from the coast, was completed in 1994. The Omdel Dam was constructed to enhance groundwater recharge by first impounding the silt loaded flood waters and allowing the fine suspended sediment to settle. After sufficient time is allowed for the silt settlement, the clear water is then released downstream to infiltrate into the aquifer under controlled conditions.

Downstream of the dam, two infiltration sites (sites 1 and 2; Fig. 3.1) were selected and prepared for the release and infiltration of silt-free water from the dam into the MC. A further advantage of this system is that whilst the silt from any particular flood event settles as a result of the impoundment, some of water already starts infiltrating the MC from the dam.

Nawrowski (1994) found that at site 1 the average hydraulic conductivity (K) is 145 m/day; below the water table the hydraulic conductivity is 142 m/day and above the water table it is 148 m/day. The alluvium at site 1 was also found to be more permeable laterally along the bedding plane than across the bedding plane, indicating an anisotropic behavior with respect to hydraulic conductivity. According to Nawrowski (1994), the effects of aquifer anisotropy are observed in the aquifer behavior during discharge and recharge events, mainly revealed as delayed yield or delayed drainage. The eastern portion of the site 1 aquifer indicates high values of lateral conductivity, with an average of 218 m/day, whilst the western portion of the site 1 aquifer, has K values ranging between 203 and 204 m/day (Nawrowski 1994). Groundwater flows paths revealed by the water level and water quality trends suggest that entry of groundwater from the Omaruru River bed into the MC occurs about 30 km inland from the coast. At site 1 the water flows partly through a sub-channel into a larger secondary channel aquifer and then converges farther downstream into the MC aquifer. Site 1 aquifer is therefore regarded as a favourable infiltration and conduit system for recharging water to be directed into the secondary and MC aquifers for storage and later abstraction (Nawrowski 1994). After the construction of the dam, IWACO (2001) estimated that 6.2 Mm$^3$/year would be the long term average spill, whilst the natural recharge from the river bed was estimated to be 1.1 Mm$^3$/year (17.5%) based on the dam capacity of 38 Mm$^3$. They also estimated the potential recharge volume (PRV) as 7.1 Mm$^3$, defined as the average annual volume available for enhanced recharge over the long term.

Zeelie (2001) estimated that about 18 Mm$^3$ of run-off water were retained in the dam during the 1999/2000 rainy season and flood event. Of this inflow, about 4.9 Mm$^3$ evaporated, 4.8 Mm$^3$ were released for enhanced infiltration, 4.5 Mm$^3$ directly infiltrated the aquifer within the dam basin and about 3.8 Mm$^3$ remained in the dam. Therefore about 9.3 Mm$^3$ effectively recharged the aquifer from this single event, as compared to the previous events (1997/1998) of the same magnitude.

The problems investigated are: the lack of understanding of the geology and the hydrogeological setting of the Omdel Aquifer; little information on the hydraulic properties and geometry of the aquifer at the inflow and outflow sections; no groundwater recharge study done upstream of the Omdel Aquifer in the Omaruru catchment; little information on the impact of artificial recharge; and the effect of flood events for the hydrological seasons of 1996/1997/1998, 1999/2000, 2007/2008, 2008/2009 and 2010/2011 on groundwater levels of the Omdel Aquifer.

The objective of the paper is to integrate artificial recharge with hydrogeological understanding of the Omdel Aquifer to establish a conceptual framework for assessment of groundwater recharge and discharge, water chemistry and balanced water supply.

## 3.2 Study site

Figure 3.1 is a map of the Omaruru River Catchment Basin, showing the locality of the study area (Omdel Aquifer), the Omaruru Alluvial Plain Aquifer (OMAP), the main tributaries within the catchment, rainfall gauge stations, location of the Omdel Dam and groundwater supply schemes in the Omaruru catchment. The Omdel Aquifer in Namibia is situated about 80 km north of Swakopmund and extends from the Omaruru River mouth at Henties Bay to about 35 km inland, with the elevation reaching 230 m above mean sea level (mamsl) at its eastern extremity across the relatively flat Namib Plain (Geyh and Ploethner 1995; Fig. 3.1). Since the Omdel Aquifer is located at the outflow end of the Omaruru River, it is important to note, from a hydrogeological perspective, that the total catchment area of the river covers approximately 15,700 km$^2$ and reaches an elevation of 1,450 m amsl at its source, with a peak area of 2,216 m amsl in the Erongo Mountains downstream of Omaruru town (Geyh and Ploethner 1995). It should also be noted that the mountainous region of the catchment, with an average elevation of about 1,000 m amsl receives a mean annual rainfall between 200 and 450 mm (Geyh and Ploethner 1995). In the area around the Omdel Aquifer the climate is, however, hyper-arid with an average precipitation of less than 50 mm/year. Brandberg Mountain (to the north, at 2,278 m amsl), Grootspitskop (at 1,728 m amsl) and Erongo Mountains (at 2,216 m amsl) to the east are the highest protruding peaks near the study area.

Groundwater supply schemes along the Omaruru River flow-path are Omaruru, Okombahe, Nei-Neis, Tubussis, Spitskoppe and Lêe Water. Within the delta area the outline of the production well field with two infiltration sites (sites 1 and 2) are indicated. The only main towns within the catchment are Omaruru and Henties Bay, whilst a number of formal and informal settlements occur within and outside the catchment. The rain gauging stations have sufficient historic rainfall data that can be used to estimate groundwater recharge and station ID numbers are used to identify them. The positions of boreholes used for the water-table-fluctuation calculations are indicated in Fig. 3.1. Three lines on the map of Fig. 3.1 indicate that there might be some tectonic geological control influencing the flow pattern of the Omaruru River. This flow pattern may be controlled by the Omaruru, Erongo and Autseib lineaments described by Corner (1983).

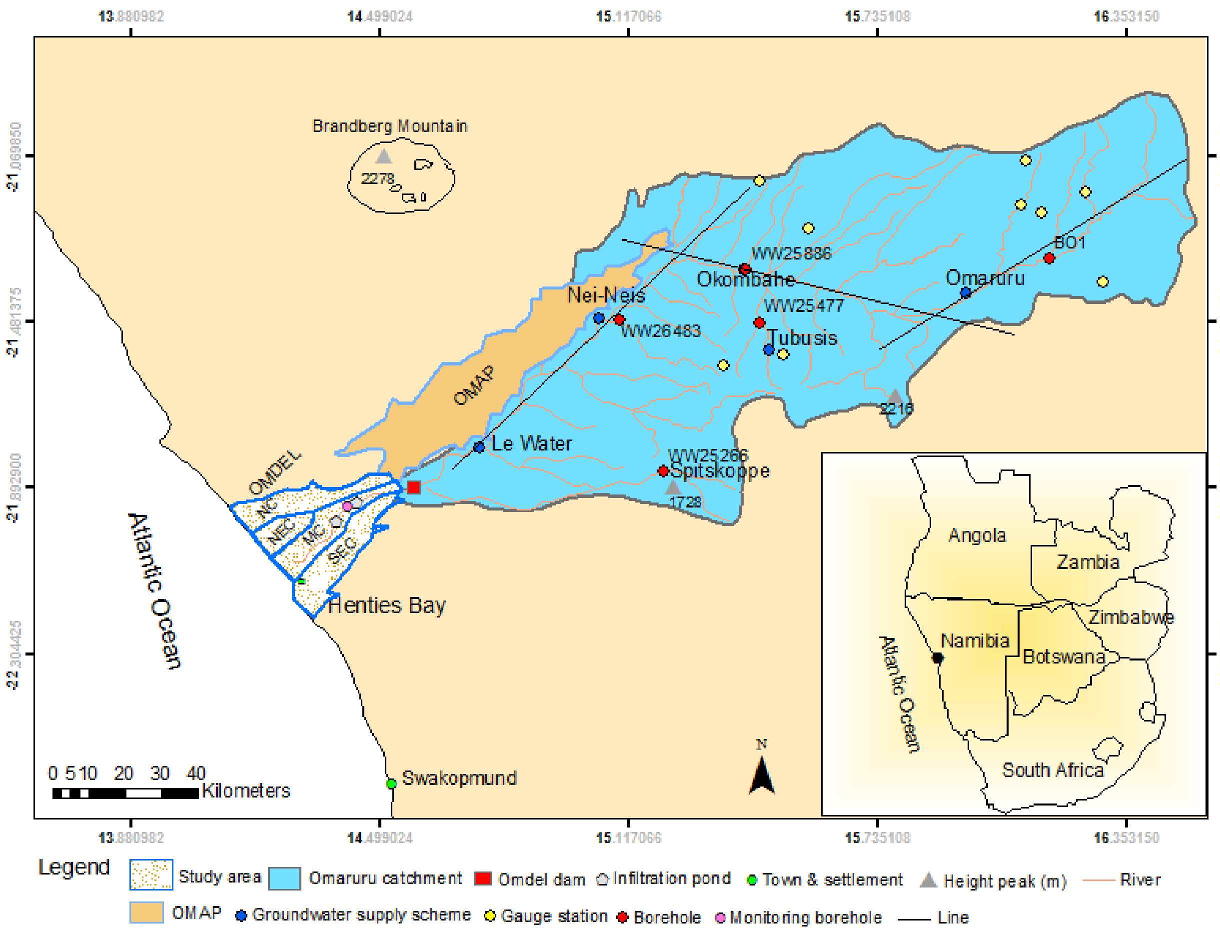


**Fig. 3.1** Map indicating the study area and Omaruru catchment in Namibia

## 3.3 Geological setting

The geological setting of the study area is described in more detail here. Geologically the oldest rocks of the Omdel Aquifer and the surrounding area are the Neoproterozoic quartzite of the Naauwpoort Formation (Nosib Group, ±850–750 Ma), phyllite of the Amis Formation (Zerrissene Group, ±740–600 Ma), marble of the Karibib and Arandis Formations and mica schist of the Kuiseb Formation of the Swakop Group (±770–600 Ma), all part of the Damara Orogen within the Namibian age (Geological Survey of Namibia 1997; Miller 2008). Deposition and deformation of the rock-types in the Damara Orogen are attributed to ancient continental rifting, collision and subduction. Miller (2008) states that the beginning of rifting and thus the base of the Nosib Group is not known, but may be as old as 900 Ma. Dates for the deposition of the Swakop Group vary between 711 and 658 Ma, while ages for continental collision and subduction (deformation and metamorphism) are estimated at 650–633 Ma. Associated and followed by the deformation and metamorphism processes were the intrusion of granitic rocks, dated between 550 and 450 Ma. It was also during this period of deformation that the lineaments (Omaruru, Erongo and Autseib) developed. The metasedimentary and metavolcanic rocks are intruded by diorite (early syn-tectonic to post-tectonic), granite (syn-tectonic, post-tectonic to late-tectonic), and red granites (post-tectonic to late-tectonic; Fig. 3.2). The granites are described as medium to fine grained and coarse grained, whilst the diorite is coarse grained. Mudstone, siltstone, sandstone and shale, overlying the intrusive rocks, are sedimentary rocks of the Gai-as, Huab and Verbrande Berg Formations of the Karoo Sequence (300–180 Ma). Basalt of the Awahab Formation of the Etendeka Group (Cretaceous age, 132 Ma) overlies the sedimentary rocks of the Karoo Sequence. The stratigraphy is further intruded by granite and gabbro rocks of the Cretaceous intrusive complexes, further intruded by parallel north-westerly trending dolerite sills and dykes of Cretaceous age. Finally, surficial deposits (alluvium, sand, gravel, calcrete, scree, gypcrete) of the Quaternary period overlie all the aforementioned rock formations, in places (Fig. 3.2). There are also Quaternary age salt pan deposits along the coast. The surficial deposits are divided into two main aquifer systems: the Omaruru River Delta Aquifer (OMDEL) and the Omaruru Alluvial Plain Aquifer (OMAP), the latter extending approximately 120 km inland from the coast (Fig. 3.1). Located in the downstream portion of the Omaruru River, known as the delta area of the Omaruru alluvial bed, the Omdel occurs as a roughly triangular shape (about 526,000,000 $m^2$).

| **Period/ Era** | **Age Ma** | **Sequence** | **Group** | **Formation** | **Lithology** | **Hydrogeological Control** |
|---|---|---|---|---|---|---|
| Quaternary | 70 and younger | | Kalahari & Namib | | Alluvium<br>Sand<br>Clay<br>Gravel<br>Calcrete<br>Scree<br>Gypcrete | Unconsolidated deposits of sand and gravel in palaeochannels allow infiltration of surface run-off in riverbed (Unconfined aquifer).<br>Clay rich sand acts as confining layer (delayed yield effect).<br>Gravel layers act as main aquifer. |
| Cretaceous | 137-125 | Damaraland igneous suites; mainly granite (Messum, Brandberg, Erongo) | | | | Related tectonic action resulted in scouring of several palaeochannels in underlying bedrock |
| | 132 | | Etendeka | Awahab | Basalt & dolerite dykes | Dolerite dykes react as semi-pervious and /or screening barriers |
| Permian to Triassic | 300-180 | Karoo | Ecca | Huab<br>Gai-as<br>Verbrande Berg | Mudstone siltstone sandstone shale | Eroded or scoured away during tectonic activities during intrusion of Damara igneous suites |
| Namibian/ Cambrian to Ordovician | 550-450 | Salem-type granite & red granite intrusions associated with tectonic activity (Syn- and post-tectonic) | | | | Bedrock of the aquifer (impermeable layer). Water bearing capabilities are only limited to fractured or decomposed portions |
| Namibian/ Neoproterozoic | 770-600 | Damara Orogen | Swakop | Kuiseb | Mica schist | |
| | | | | Arandis Karibib | Marble | |
| | 740-600 | | Zerrissene | Amis | Phyllite | |
| | 850-750 | | Nosib | Naauwpoort | Quartzite | |

**Fig. 3.2** Summary of geological features of the Omdel Aquifer (After Nawrowski 1990, Geological Survey of Namibia 1997 and Miller 2008)

## 3.4 Materials and methods

To realize the objective set for this research, the following methods are duly considered: Hydrogeological surveys and site visits, together with the detailed interpretation of geological, hydrological and geomorphological of the area, carried out to define the hydrogeological characteristics of the Omdel Aquifer. Two photographs, taken during a site visit, depict the abstraction tower at Omdel Dam and the infiltration ponds at Omdel Aquifer (Fig. 3.3). Existing data on geology, climate, hydrogeology, hydrology, rainfall, test pumping and hydrochemistry were collected from different sources such as books, reports, maps, remote sensing images and databases. From the existing data, the hydrogeological data such as depth to water table, borehole depth, water bearing formations and corresponding geomorphological units were determined.

Geological information obtained from the borehole completion reports were used to draw geological cross sections, using Arc-Map software. The maps were also created using Arc-Map software. Test pumping data were used to determine the aquifer parameters of the Omdel Aquifer by using the Aquifer Test Curve Fitting and Aquifer Test 3.5 analyses. Hydrochemical data were used to determine the groundwater facies, water types and fingerprints, using WISH and HamVer2Dot softwares.

Borehole WW26483 is one of the monitoring boreholes in the Omaruru River bed at Nei-Neis. Historic water levels of borehole WW26483 and the historic rainfall data at both Usakos and Etendero gauge stations were used to estimate groundwater recharge at Nei-Neis, upstream in the Omaruru catchment, where there is significant rainfall (Fig. 3.4). From the records, there appears to be a clear relationship between the rise in groundwater levels in the borehole and significant rainfall. Also the decline in groundwater levels with low or no rainfall should be noted. It is also important to note that the rainfall peaks indicate sporadic thunderstorms which often result in flood run-off lasting a short period of time. Very few such floods, however, reach the Omdel Aquifer.

Usakos gauge station has historic rainfall data up to March 2002, while Etendero gauge station has historic rainfall data starting from January 2001 up to present. The historic water levels of boreholes and the historic rainfall data of gauge stations were used to estimate groundwater recharge at Okombahe, Nei-Neis, Omaruru, Tubussis and Spitskoppe. Water table fluctuation (WTF) and chloride mass balance (CMB) methods were used to estimate groundwater recharge at different localities in the Omaruru catchment (Okombahe, Nei-Neis, Omaruru, Tubussis and Spitskoppe). Once the significant inflow (flood) reaches the Omdel Dam, some water infiltrates into the dam basin, some will be lost in the process through evaporation at the dam. When the water is released through the abstraction tower, some water infiltrates along the Omaruru River part 1, some water infiltrates at infiltration ponds at site 1, and some will be lost through evaporation. If the water goes beyond the infiltration ponds at site 1 (significant inflow), some water will infiltrate the Omaruru River part 2, some water will infiltrate at infiltration ponds at site 2 and some will be lost through evaporation (Fig. 3.1). Five major run-off events for the hydrological seasons of 1996/1997/1998, 1999/2000, 2007/2008, 2008/2009 and 2010/2011 were used to evaluate the effect of artificial recharge on groundwater of the Omdel Aquifer.

Groundwater flow from the upper river bed (upstream of Omdel Aquifer), OMAP and SEC were conceptualized and estimated by using Darcy’s law. This contributes to the water balance of the Omdel Aquifer in question.

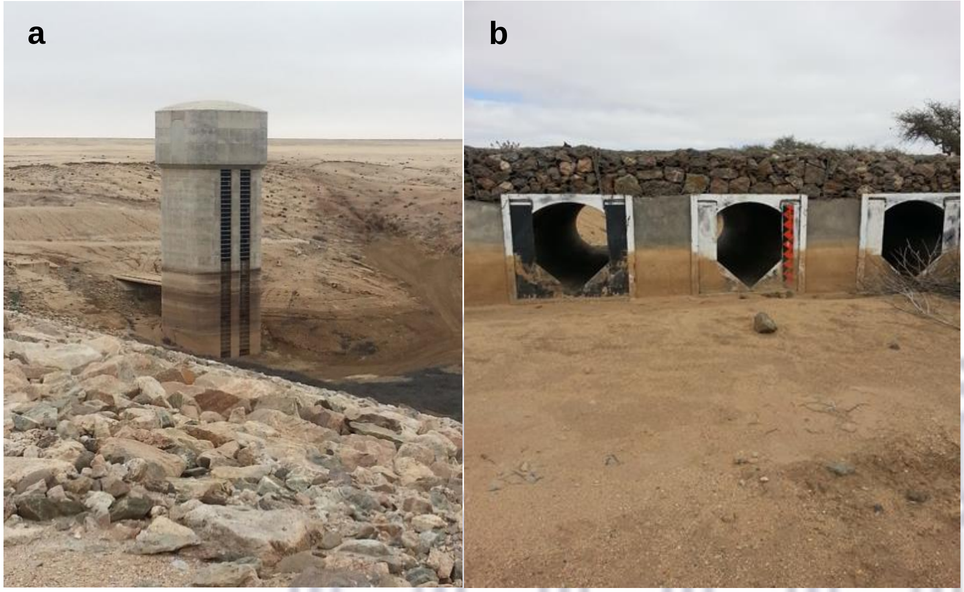


**Fig. 3.3 a** Abstraction tower at Omdel Dam and **b** infiltration ponds at Omdel Aquifer

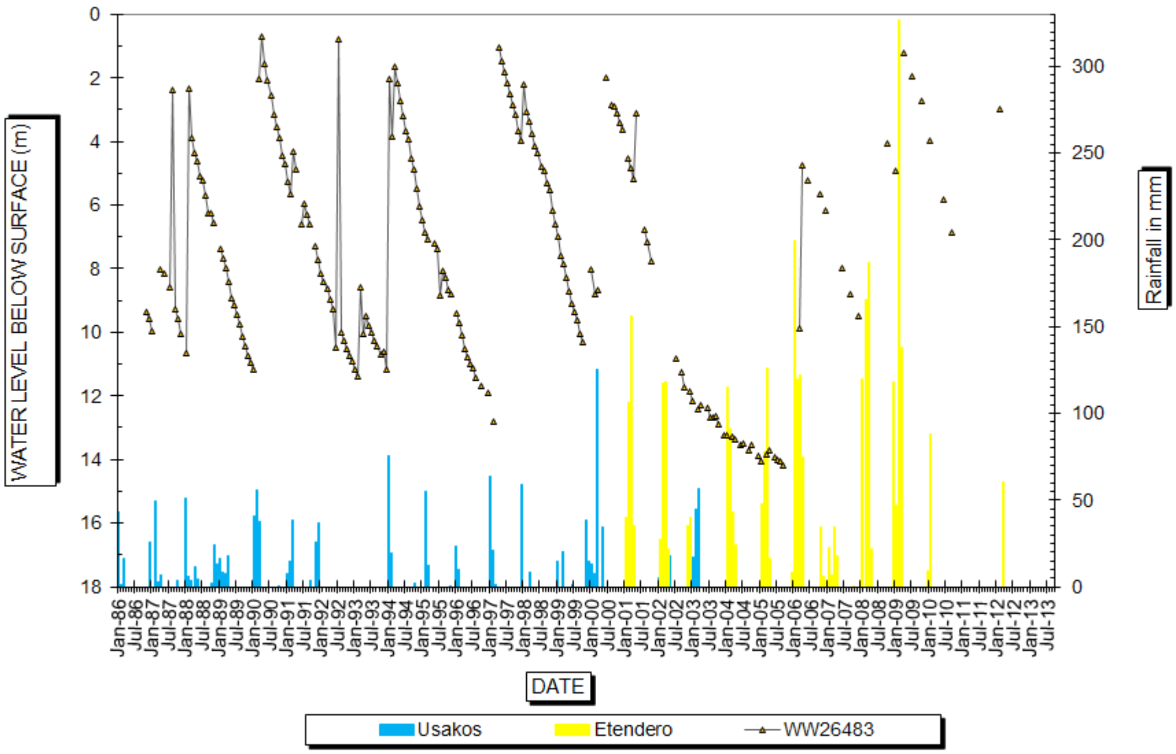


**Fig. 3.4** Graph indicating water levels of borehole WW26483 and rainfall of Usakos and Etendero gauge stations

The relief of the bedrock of the multi-channel aquifer system in the Omaruru Delta plays an important role for the delineation of flow direction (flow paths), groundwater storage and quality (Nawrowski 1990). It is therefore necessary to identify aquifer boundaries, recharge areas and discharge areas, as well as to describe the composition of the aquifer material. All the data and information gathered are critically reviewed and interpreted to establish a framework within which the hydrogeological characteristics of the Omaruru Delta Aquifer System are evaluated.

## 3.5 Results

### 3.5.1 Subdivision of Omdel Aquifer

According to lithological borehole logs, nine geological cross-sections were drawn across the Omdel Aquifer, ranging from the dam to the coast, and are located in Fig. 3.5. Cross sections AB, CD and EF are referred to as downstream; GH, IJ and KL as center/middle; and MN, OP and QR as upstream.

Lithologically this alluvial aquifer consists of unconsolidated coarse sand and gravel (unconfined aquifer), clay rich sand and cemented sand (aquitard) and predominantly coarse sand and gravel (major groundwater reservoir), which were successively deposited within the different palaeochannels that were incised in bedrock of mainly mica schist and granite. The Omdel Aquifer is characterised by lithology (Table 3.1):

**Table 3.1** Hydrostratigraphy of the Omdel Aquifer

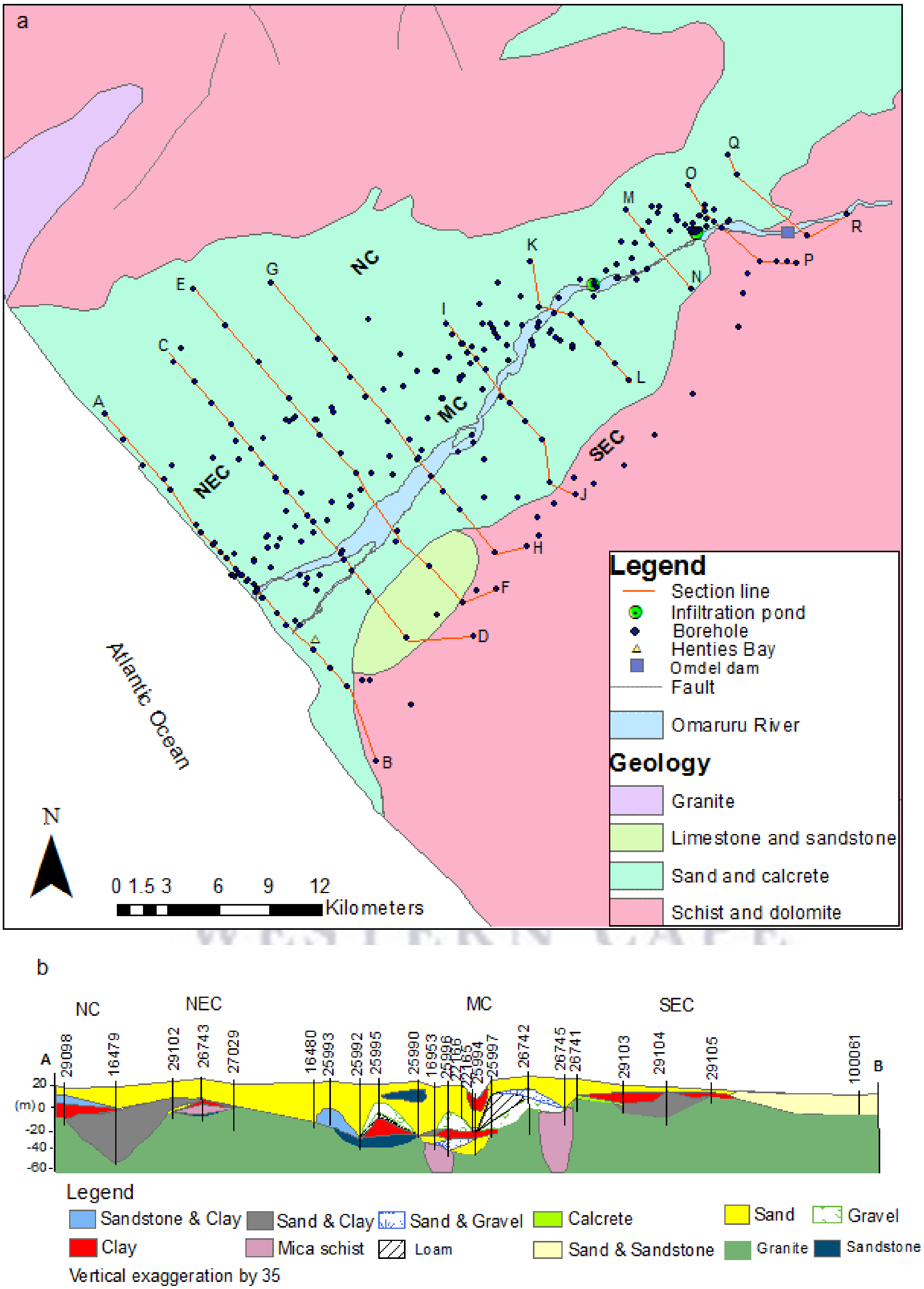
| Lithology | Description | Hydrostratigraphic units and Properties |
|---|---|---|
| Sand | Unconsolidated, porous sand (medium or fine grained, rounded or angular) | Mostly unconfined primary aquifer |
| Sandstone | Consolidated and cemented, semi-porous (medium or fine grained) | Aquitard, normally semi-confined |
| Sand and clay | Unconsolidated sand with subordinate amounts of clay (or otherwise). | Clay between sand grains reduces transmissivity |
| Sandstone, granite, mica schist, quartzite and dolerite | Bedrock of the aquifer (impermeable layer) | Water-bearing capabilities are only limited to fractured or decomposed portions |

- Saturated alluvial deposits, mainly sand and gravel, represent the productive aquifer. Interbedded layers of clay, silt and calcareous cemented sand are also part of the alluvial deposits, acting as leaky confining layers above or within the primary aquifer. Furthermore, the surface geology of the Omdel Aquifer comprises alluvial deposits, mainly consisting of coarse sand and gravel (of granitic origin), interbedded with thin layers of clay and locally cemented with calcrete. Minor dune sand partially covers the surface at the coast and in the river bed, forming low mounds.
- A sand layer covers most of the upper section of the Omdel Aquifer system, with average thicknesses of about 40, 65 and 20 m in the downstream, middle and upstream sections of

the aquifer, respectively. Such sand beds have the potential to allow flood water to infiltrate into the aquifer. According to different cross-sections, the sand layer overlies varying layers of clay, sandstone, sand and clay, gravel, sand and gravel, calcrete, sandstone and clay, loam, with granite or mica schist as bedrock (Fig. 3.5). Gravel, calcrete, gravel and clay, gravel and calcrete, sand and gravel lithologies dominate the MC of the Omdel Aquifer system. Unconsolidated sand with local thin lenses of partially calcareous material of the deepest alluvial layer within the MC, represent the major aquifer. Clay layers found in all four channels, indicate periods of low energy sediment transport.

- Sandstone within and at the base of the MC is found mainly in the downstream part of the aquifer. In the NEC and NC the sandstone layer occurs in the central part, and in the SEC it occurs in the central and upstream part of the aquifer.
- Interbedded layers of the alluvial deposits are prominent in the central and upstream part of the Omdel Aquifer.

  Calcrete layers, interbedded in the alluvial deposits of up to 25 m in thickness, occur mainly in the central part of the MC. The widespread layer of cemented sand and gravel and lenses of unconsolidated sand and gravel are found at depths down to the basement. It also appears that greatest cemented thicknesses of the alluvial deposits occur in the central part of the MC. Further upstream in the MC a decrease in calcareous material is found, whilst the downstream part has varying degrees of calcareous material, less than 30% of the aquifer thickness (Nawrowski 1990). The less permeable calcareous material layer acts as an aquitard (semi-confined horizon) and displays delayed yield effect characteristics. In the centre of the MC, a dolerite dyke was intercepted at a depth of approximately 85 m.
- The underlying bedrocks of the Omdel Aquifer are quartzite, mica schist and granite of the Damara Orogen (bedrock geometry indicated in Fig. 3.5). Granite bedrock is mainly found in the downstream part of the aquifer, while mica schist is mainly found in the central and upstream part. Quartzite bedrock is only observed in the central part of the aquifer.


a
Atlantic Ocean
NC
NEC
MC
SEC
A
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0 1.5 3 6 9 12
Kilometers
Legend
Section line
Infiltration pond
Borehole
Henties Bay
Omdel dam
Fault
Omaruru River
Geology
Granite
Limestone and sandstone
Sand and calcrete
Schist and dolomite
b
NC
NEC
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SEC
A
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Legend
Sandstone & Clay
Sand & Clay
Sand & Gravel
Calcrete
Sand
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Clay
Mica schist
Loam
Sand & Sandstone
Granite
Sandstone
Vertical exaggeration by 35

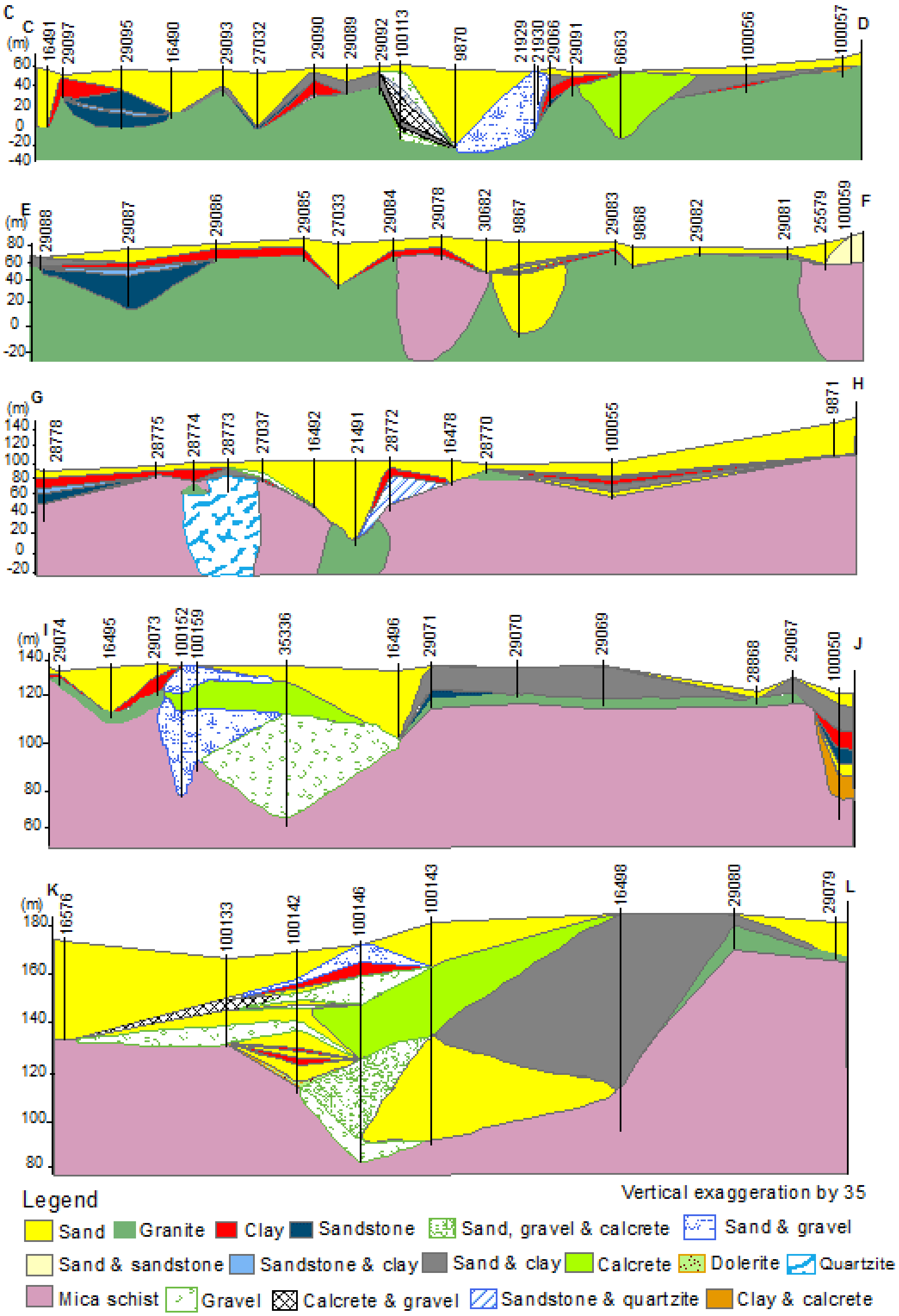

**Fig. 3.5 a** Simplified geological map depicting cross-section locations, **b** geological cross-section A-B, displaying the palaeochannels, **c** other geological cross-sections

### 3.5.2 Aquifer parameters

The transmissivity (*T*), hydraulic conductivity (*K*) and storativity (*S*) were determined from test pumping data of boreholes in the Omdel Aquifer. Most of these boreholes are located in the MC, with a few of them in the SEC. There are neither pumping test data nor information on the transmissivity and storativity values from the NEC and NC. Transmissivity values range between 17 and 3,916 $m^2$/day, the lowest value (17 $m^2$/day) is recorded at borehole WW35338 in the central part of the MC, whilst the highest value (3,916 $m^2$/day) is recorded at borehole WW35344, located in the upstream part of the MC (Table 3.2). Borehole WW35344 is located north-west of infiltration ponds site 1 and the Omdel Dam (Fig. 3.6). The coarse sediments, deposited during high energy transport at that part of the aquifer, are the reason for the high T value. During deposition of the sediments in the Omdel Aquifer, fine materials such as clay were deposited in some parts of the aquifer due to low transport energy conditions, thus accounting for the low T values in these parts of the aquifer (Fig. 3.6). The boreholes with high T values are WW21490, WW33068, WW33069, WW100049, WW100142, WW100155 and WW100157. Most of them are located in the upstream and central part of the MC, where high energy run-off water deposited the coarser sediments as it flowed towards the ocean. The hydraulic conductivity (*K*) values range between 1 and 302 m/day with an average value of 20 m/day. Storativity (*S*) values range between 0.0001 and 0.01.

Boreholes with high storativity values (0.01), in this case the specific yield ($S_y$), are WW21501, WW100095 and WW21490, found in the central part of the MC. The distribution of transmissivity, hydraulic conductivity and storativity of the Omdel Aquifer boreholes from downstream to upstream are indicated in Figs. 3.7, 3.8 and 3.9 respectively.

**Table 3.2** Statistical assessment of aquifer parameters of boreholes at Omdel Aquifer

| Aquifer parameters | Number of datasets | Minimum | Maximum | Standard deviation | Mean | Median |
|---|---|---|---|---|---|---|
| Transmissivity ($m^2$/day) | 57 | 17 | 3916 | 709 | 463 | 208 |
| Hydraulic conductivity (m/day) | 53 | 1.0 | 302 | 48 | 20 | 4.6 |
| Storativity | 57 | 0.0001 | 0.01 | 0.002 | 0.0006 | 0.0001 |

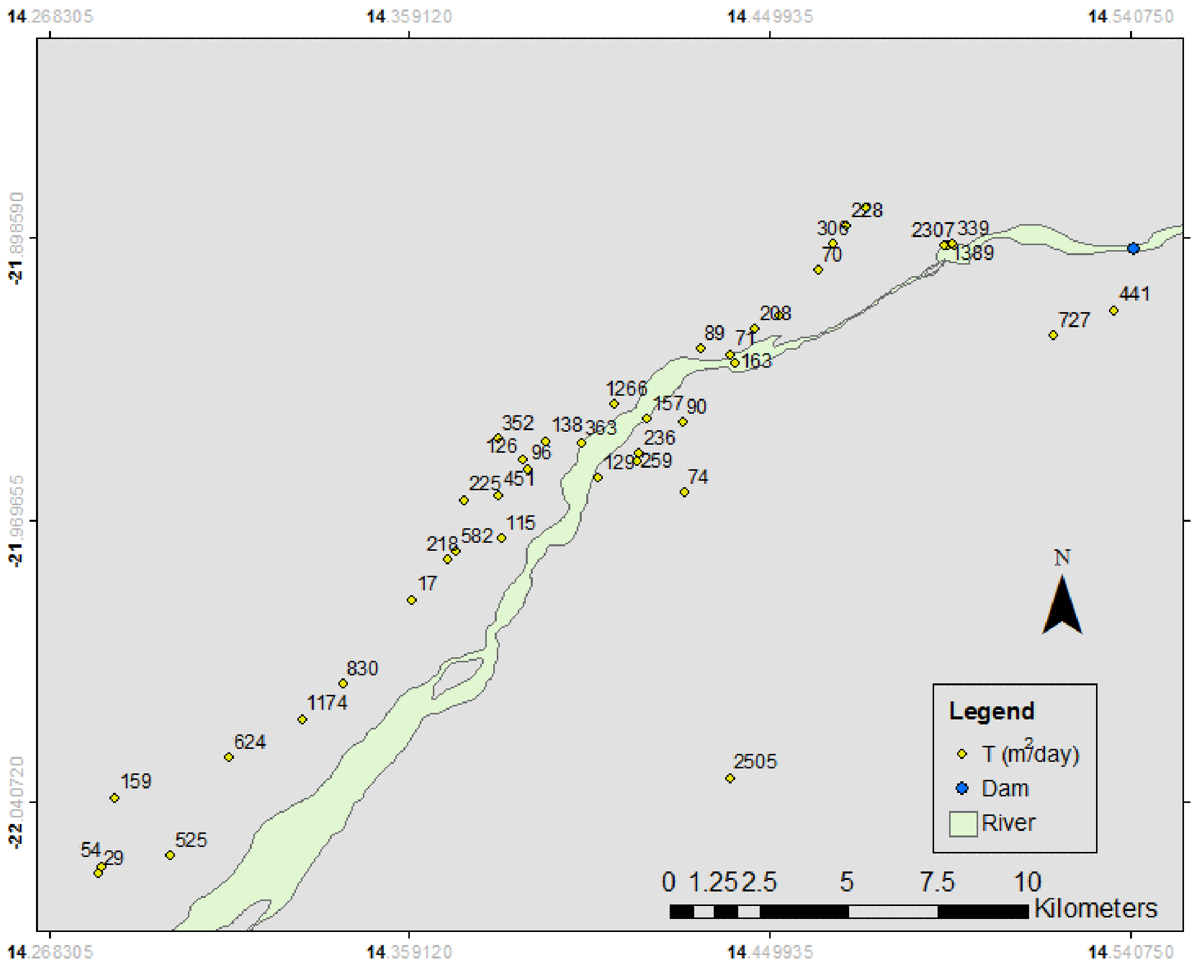

**Fig. 3.6** Map depicting the distribution of transmissivity (*T*) values in MC and SEC

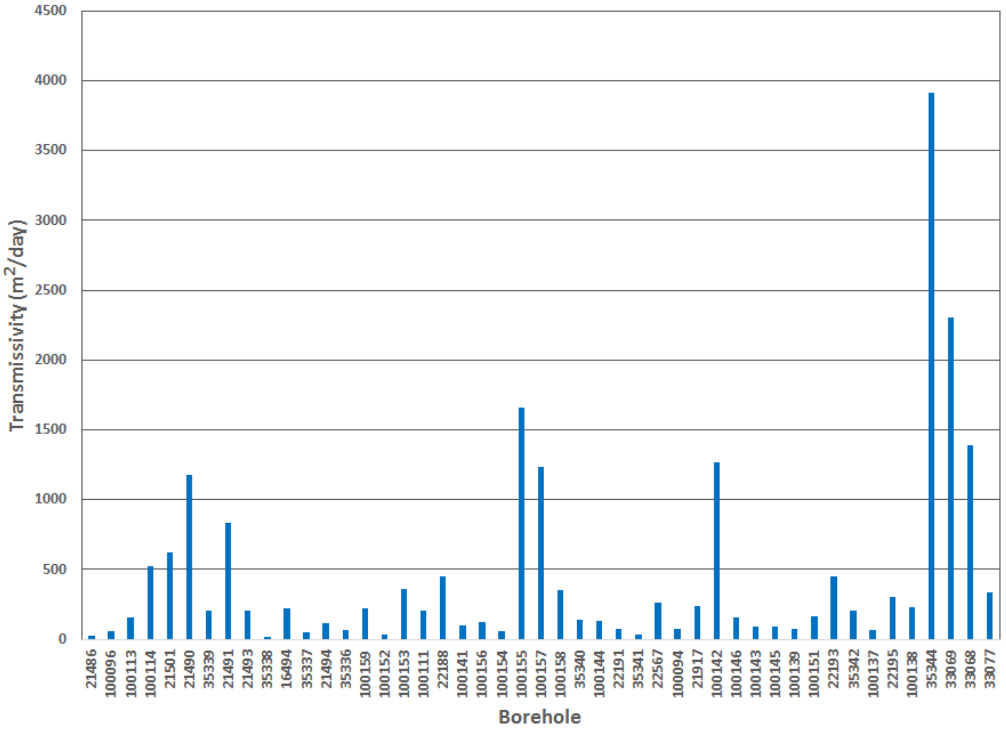

**Fig. 3.7** The distribution of transmissivity values of Omdel Aquifer boreholes (downstream to upstream)

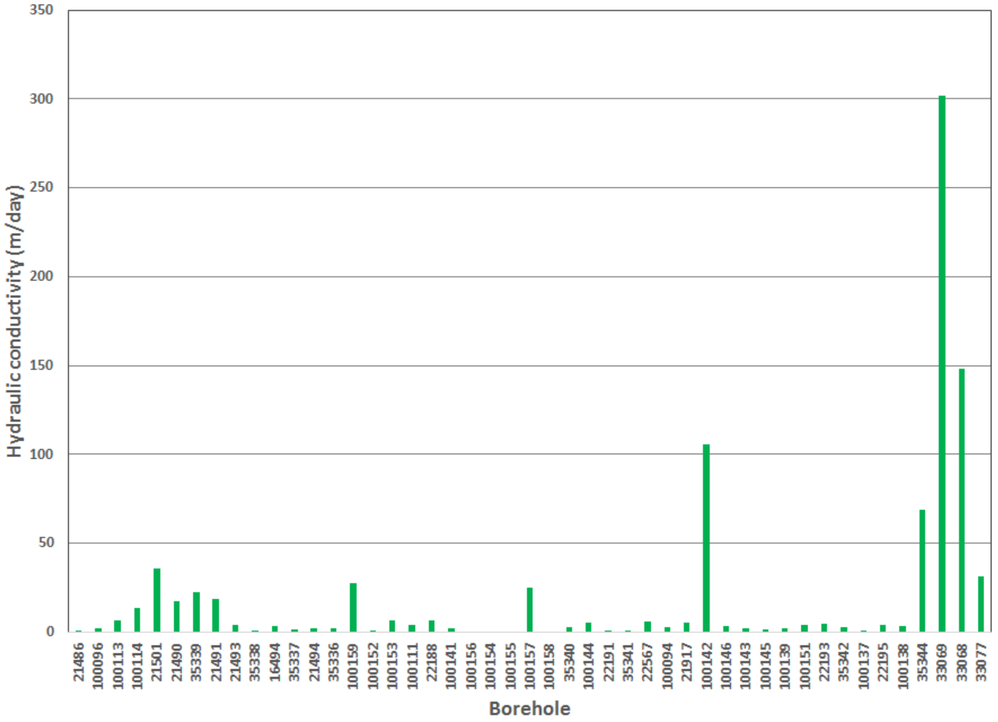

**Fig. 3.8** The distribution of hydraulic conductivity values of Omdel Aquifer boreholes (downstream to upstream)

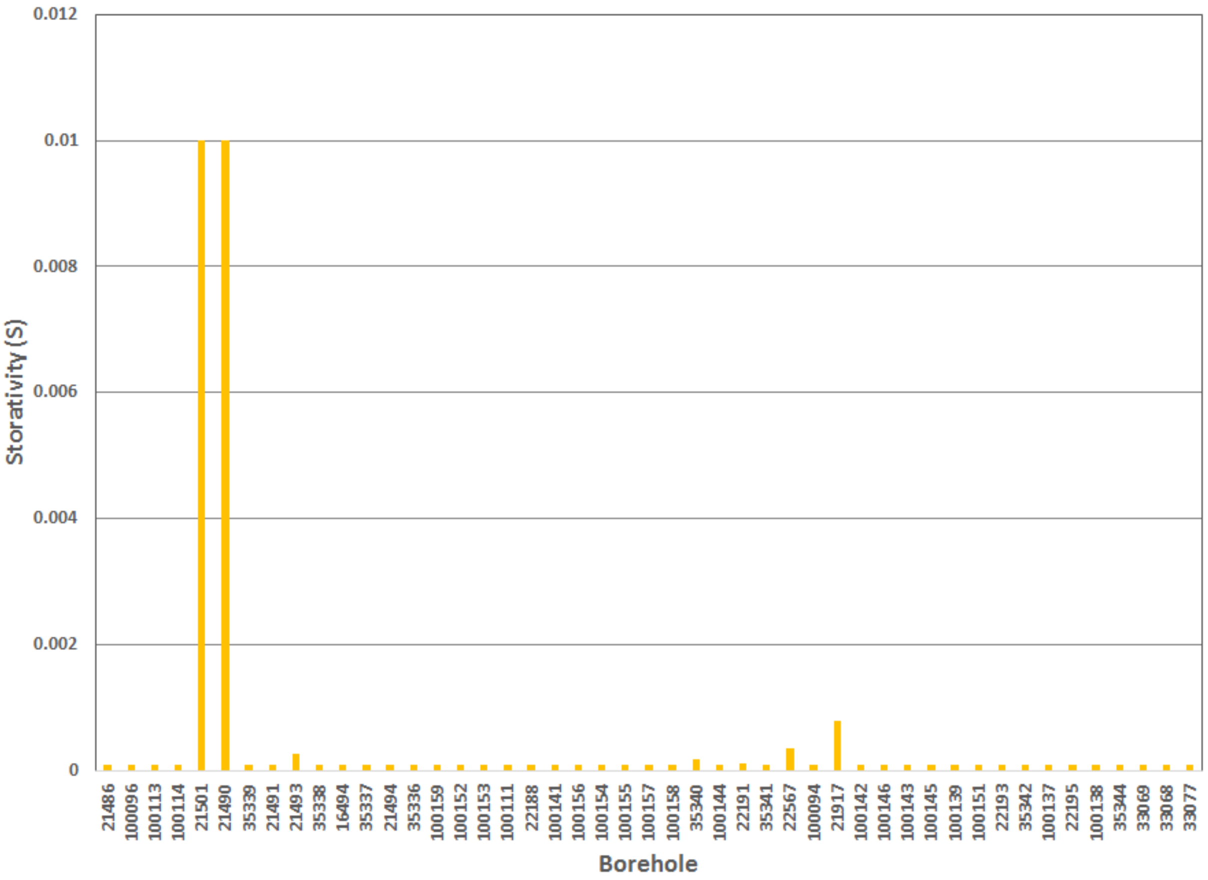

**Fig. 3.9** The distribution of storativity values of Omdel Aquifer boreholes (downstream to upstream)

### 3.5.3 Groundwater level characteristics

The groundwater flow direction is towards the Atlantic Ocean (flowing from north east to south west), with the Omaruru River acting as the base-level of drainage. A total of 154 groundwater level measurements of boreholes were available for assessments of the groundwater flow regime. There is good correlation between surface elevation (topography) and the groundwater level elevation ($R^2$ = 0.97, about 97%; Fig. 3.10). The good correlation indicates that the water table follows a trend of surface topography.

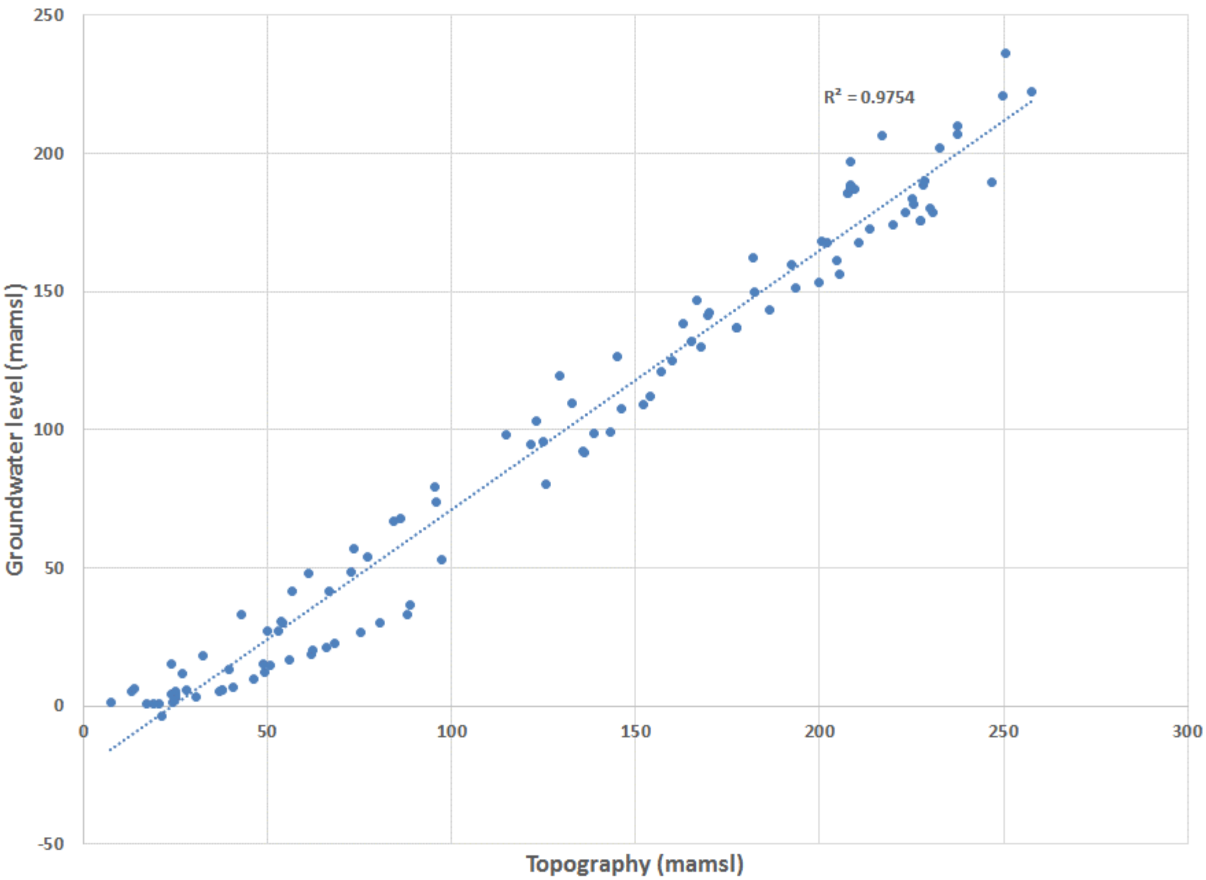

**Fig. 3.10** Correlation between surface topography and groundwater level elevations

The statistical analysis of the 154 groundwater levels is presented in Table 3.3, revealing a minimum value of 6.31 m below surface and maximum value of 57.46 m with an average groundwater level of 31.0 m below surface. The groundwater level elevation contours of the Omdel Aquifer boreholes for June 2016 ranges between 235 to 0 (m amsl; Fig. 3.11). Since it is obvious that the groundwater levels fluctuate with time, it was important to compile Fig. 3.11 with data within the same timeframe. The highest elevation is for borehole WW100035 located upstream next to the Omdel Dam while the lowest elevations are for the boreholes next to the coast line. Contour lines of the upstream aquifer range between 235 to 135 m amsl, the middle aquifer between 135 to 50 m amsl and the downstream aquifer be-tween 50 to 0 m amsl. Over abstraction of the aquifer is illustrated by the upstream curving of the contour lines in the middle of the MC. The converging contour lines at the downstream section of the middle aquifer suggests a submerged bedrock high between this aquifer and the downstream aquifer. The contour lines of the downstream aquifer appear to have slightly greater spacing, suggesting a flatter water table.

**Table 3.3** Recent groundwater level measurements

| Groundwater level measurements, number | Groundwater level (m below surface) | | | |
|---|---|---|---|---|
| | Minimum | Maximum | Standard deviation | Mean |
| 154 | 6.31 | 57.46 | 12 | 31.0 |

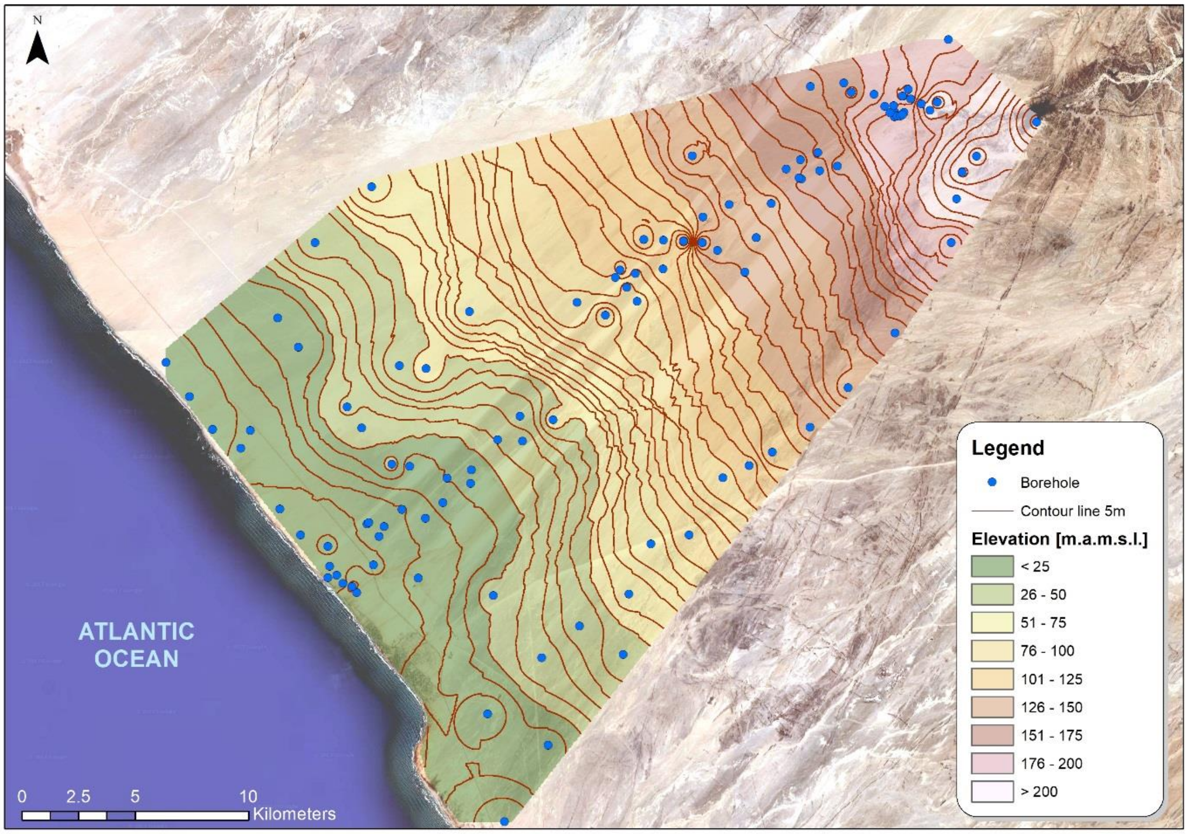

**Fig. 3.11** Groundwater level elevations of Omdel Aquifer boreholes

### 3.5.4 Groundwater chemistry

The groundwater cation chemistry fingerprint of the Omdel Aquifer is dominated mainly by the concentrations (meq/l) of Na and Ca, whilst other cations such as Mg and K occur in lesser concentrations (Fig. 3.12; Appendices 1 and 2). About 22% of the groundwater samples of the aquifer indicate that Na is the predominant cation.

The groundwater anion chemistry fingerprint of the Omdel Aquifer is dominated mainly by the concentration (meq/l) of Cl, whilst other anions such as $HCO_3$ and $SO_4$ occur in lesser concentrations. About 70% of the groundwater samples of the aquifer indicate that Cl as the predominant anion.

Boreholes WW25992, WW100060, WW16484, WW100050 and WW100045 mainly contain $Cl^-$ with no dominant cation. This water type suggests reverse ion exchange according to the expanded Durov diagram, and the boreholes are located in the downstream part of the NEC, as well as in the downstream, central and upstream parts of the SEC. The majority of the groundwater chemical data of the selected boreholes of the Omdel Aquifer plot in the dominance field of $Na^+$ and $Cl^-$, usually indicating an end point in a water evolution sequence.

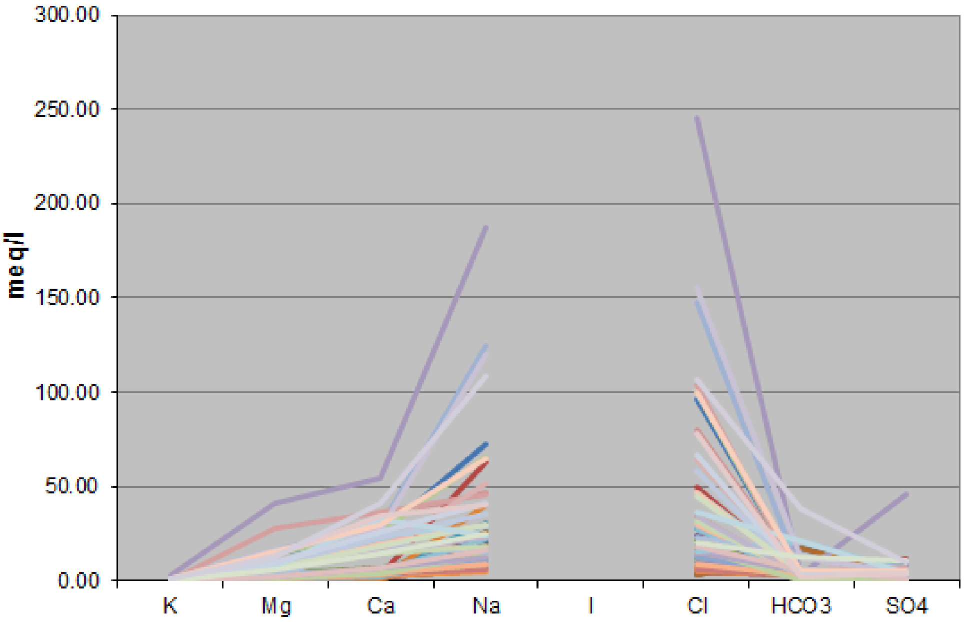

**Fig. 3.12** Groundwater fingerprint of selected boreholes of Omdel Aquifer

The ratio rCa/($rHCO_3$ + $SO_4$) of the water samples collected from the Omdel Aquifer during the 1993 to 2012 period shows changes with time (Fig. 3.13). Most of the water samples had ratios of rCa/($rHCO_3$ + $rSO_4$) close to 1.

The TDS and chloride are important parameters that can be used to study seawater intrusion. Figure 3.14 indicates the change of TDS and $Cl^-$ over time from 1993 to 2012. The two parameters shows similar trend patterns. The three highest peaks observed over this period are at 1998, 2000 and 2004. The graph also indicates the average TDS values of freshwater (less 1,000 mg/l) in 1994, 2005 and 2010, while the rest of the data indicate brackish water (more than 1,000 mg/l).

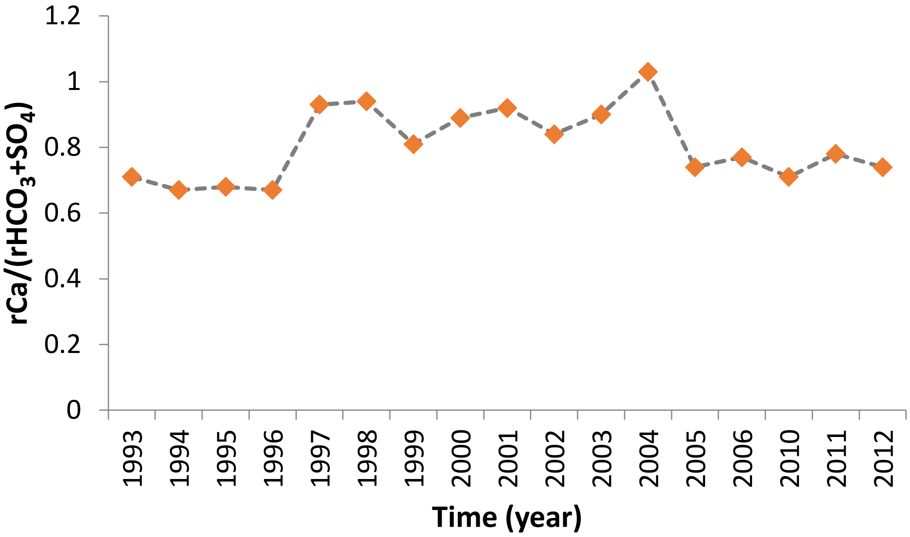

**Fig. 3.13** Average values of rCa/(rHCO$_3$+rSO$_4$) of Omdel Aquifer showing change over time

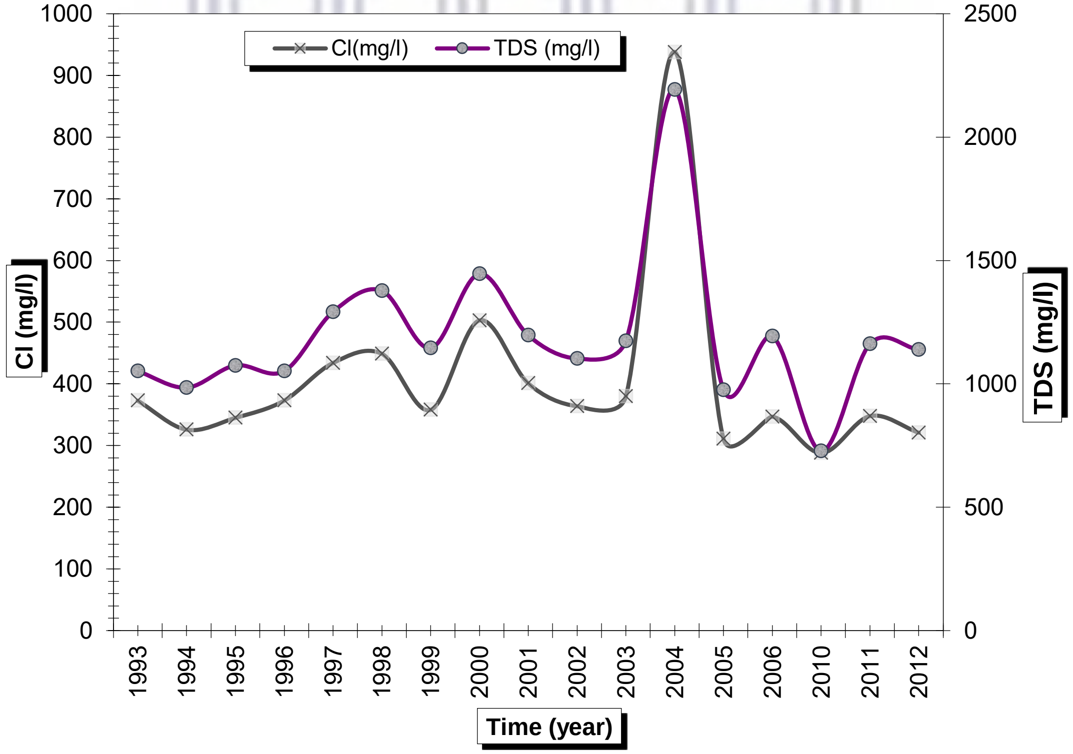

**Fig. 3.14** Chloride and total dissolved solids (TDS) concentrations in groundwater of the Omdel Aquifer between 1993 and 2012

Seven groundwater quality facies of selected boreholes in the Omdel Aquifer are recognized in the Piper diagram (Fig. 3.15), and these are Na+K-$HCO_3$-Cl+$SO_4$ of borehole WW22188 (located in the centre of the MC), Na+K-Cl+$SO_4$ of Borehole WW21926 (located upstream in the MC, Fig. 3.16), Ca+Mg-Na+K-Cl+$SO_4$ (some boreholes), Na+K-Ca+Mg-Cl+$SO_4$ (some boreholes), Ca+Mg-Na+K-Cl+$SO_4$-$HCO_3$ (some boreholes), Na+K-Ca+Mg-Cl+$SO_4$-$HCO_3$ (majority of the boreholes) and Ca+Mg-Na+K-$HCO_3$-Cl+$SO_4$ of borehole WW100044, located upstream in the SEC. The absence of $HCO_3$ in the groundwater of boreholes suggests that there is a lack of recharge in that part of the aquifer. The presence of $HCO_3$ in groundwater of borehole WW100044 suggests seepage flow from the dam. All groundwater facies of selected boreholes of the Omdel Aquifer have NaCl indicating a coastal environment.

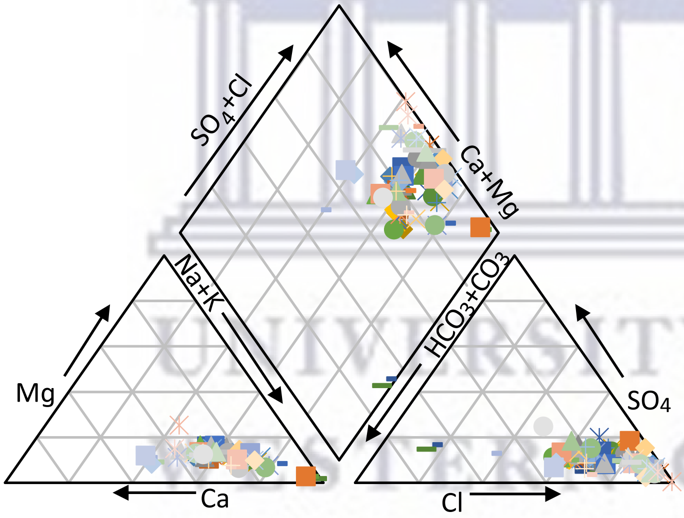

**Fig. 3.15** Groundwater quality facies of selected boreholes of the Omdel Aquifer (Piper plot)

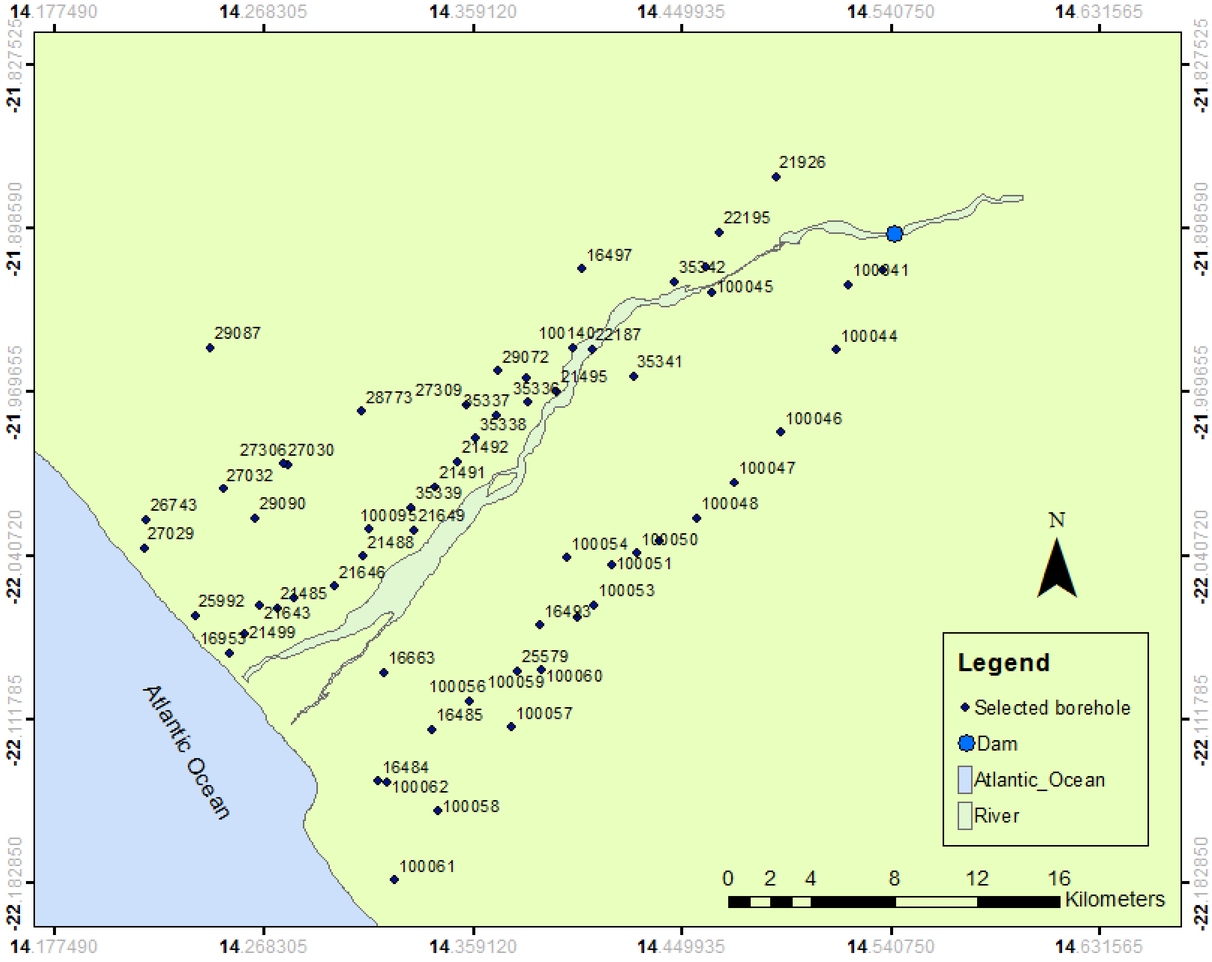

**Fig. 3.16** Map depicting locations of the selected boreholes of the Omdel Aquifer

### 3.5.5 Groundwater recharge

Groundwater recharge estimated to take place in the Omaruru catchment was evaluated by the WTF and CMB methods. The rainfall rate decreases towards the coast and increases inland, i.e. a significant amount of rainfall is recorded upstream in the Omaruru catchment. Spitskoppe, Nei-Neis, Okombahe, Tubussis and Omaruru are groundwater supply schemes where groundwater recharge was estimated. Groundwater recharge (R) estimated by the WTF method for the period between 1986 and 2006 was calculated by using Equation 1 (Shamsudduha et al. 2011) and is discussed in more detail (Fig. 3.17).

$$R = \Delta S^{gw} = S_y \partial h/\partial t = S_y \Delta h/\Delta t \qquad (1)$$

$\Delta S^{gw}$ is the change in groundwater storage, $S_y$ is specific yield, $\Delta h$ is change in water table head (between minimum and maximum), $\Delta t$ is time period.

The WTF method is based on the response of groundwater levels that rise in unconfined aquifers due to recharge arriving at the water table (Healy and Cook 2002). Recharge is determined as the change in water level over time multiplied by the specific yield. It is best applied to shallow water table systems that display sharp rises and declines in groundwater levels.

Historic groundwater data, between 1986 and recent times, are available for most of the groundwater supply schemes. The groundwater levels of borehole WW26483 and rainfall recorded at Usakos and Etendero gauge stations from January 1986 to 2012 used to estimate groundwater recharge at Nei-Neis are indicated in Fig. 3.4. During the rainfall season when it is significant, groundwater levels rise, and groundwater levels decline during low rainfall periods. For the period 1988 to 2000, Nei-Neis, Spitskoppe and Tubussis localities indicated high groundwater recharge, estimated to be between 5 and 21 mm rise in water level (Fig. 3.17). Omaruru groundwater supply scheme is the first location upstream in the catchment, and the groundwater recharge estimation is between 2 and 6.5 mm. The average groundwater recharge estimations are 9.54 mm at Nei-Neis, 3.71 mm at Okombahe, 4.9 mm at Omaruru, 5.84 mm at Spitskoppe and 11.69 mm at Tubussis. This actually means more water is recharged at Nei-Neis, Spitskoppe and Tubussis than at Okombahe and Omaruru, which may be due to topographical differences and aquifer dimensions.

Rainfall recharge estimated at Omaruru, Okombahe and Nei-Neis over 1 km$^2$ is 560, 580 and 780 m$^3$ respectively (Table 3.4). The recharge over rainfall ratio at different localities in the Omaruru catchment is relatively small indicating that rainfall contributed a small portion to the water level rise (recharge). Therefore, run-off plays a very important role in the water level rise (groundwater recharge) in the Omaruru River bed alluvial aquifers.

**Table 3.4** Recharge over rainfall ratio at different localities: Omaruru catchment

| Location | Rainfall recharge (m$^3$ per km$^2$) | Rainfall (m$^3$ per km$^2$) | Recharge/rainfall | |
|---|---|---|---|---|
| | | | Ratio | (%) |
| Nei-Neis | 780 | 116 000 | 0.0067 | 0.67 |
| Okombahe | 580 | 143 000 | 0.0040 | 0.41 |
| Omaruru | 560 | 189 000 | 0.0030 | 0.30 |

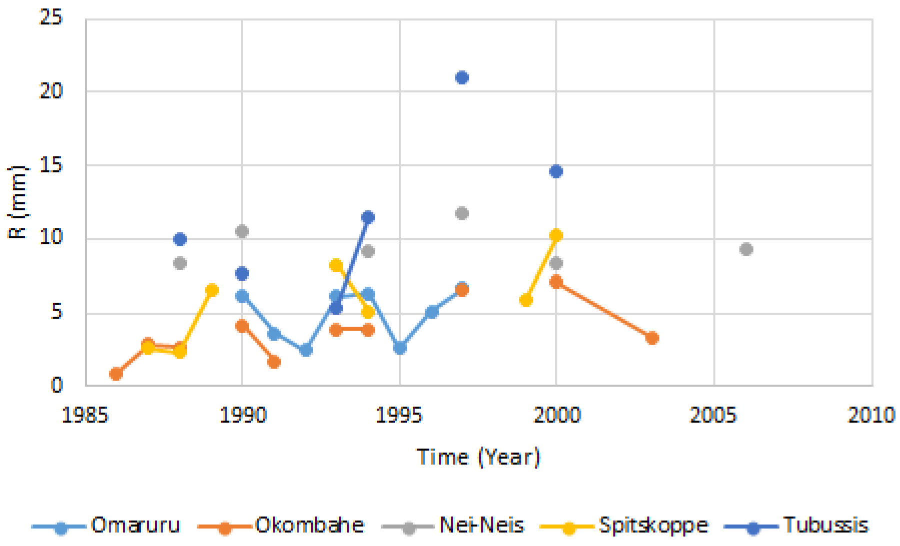

**Fig. 3.17** Groundwater recharge estimation by the WTF method

The groundwater recharge estimated by using the CMB method ranges between 0.19 and 9.23% Equation (2),

*R* = Clp × rainfall/Clg (2)

Clp is chloride in precipitation and Clg is chloride in groundwater.

Recharge estimates by using CMB method considered TDS increases in groundwater with time after a run-off event. Such delayed TDS increases are considered to suggest retarded groundwater flow with high TDS emanating from the surrounding bedrock and mixing with low TDS groundwater contained in the alluvial aquifers. It appears that direct rainfall contributes more to recharge at Okombahe compared to the other localities (Table 3.5). Chloride concentration in groundwater increases towards the coast and is higher in tributaries than in the Omaruru River itself. The data are for the year 2000, due to the fact that some rain gauge stations have no recent rainfall data. The concentration of chloride in precipitation was a projected estimate from chloride concentration distribution in precipitation in the northeastern Namibia map by Klock (2001). It should also be noted that run-off has a greater influence on groundwater recharge of the river bed alluvium at these different localities.

**Table 3.5** Groundwater recharge ($R$) estimation by CMB method at different localities in the Omaruru River catchment (year 2000)

| Location | Chloride in groundwater (mg/l) | Chloride concentration in precipitation (mg/l) | Rainfall (mm) | Groundwater recharge $R$ | |
|---|---|---|---|---|---|
| | | | | (mm) | (%) |
| Nei-Neis | 92 | 1.3 | 125.1 | 1.77 | 1.41 |
| Okombahe | 13 | 1.2 | 117.1 | 10.81 | 9.23 |
| Spitskoppe | 700 | 1.3 | 125.1 | 0.23 | 0.19 |
| Tubussis | 169 | 1.2 | 161.5 | 1.15 | 0.71 |

There was no rainfall station at Omdel Dam in the past, but at the beginning of 2014 a rain gauge was installed. So far no rainfall has been recorded at the new station. Due to absence of rainfall stations at the coast, there are also no historical rainfall data for the coastal region. The rainfall at the coast is regarded as insignificant to direct recharge in the Omdel Aquifer, since high evaporation still plays a major role. From this perspective, therefore, the Omdel Aquifer is assumed not to receive any direct recharge from local rainfall, but is rather recharged through artificial recharge (significant run-off), seepage underneath the dam and groundwater flow from the upper river bed (Omdel upstream), OMAP and SEC. The groundwater flow is assumed to play a major role in the recharge of the Omdel Aquifer, since significant run-off only reaches the Omdel Dam occasionally. To estimate groundwater flow, Darcy's law was applied (Kruseman and de Ridder 1994):

$$Q = KAi \quad (3)$$

$Q$ is the volume rate of groundwater flow (length$^3$/time), $K$ is a constant proportionality also referred to as hydraulic conductivity (length/time), $A$ is the cross-sectional area normal to the flow direction (length$^2$) and $i$ is the hydraulic gradient which is dimensionless (Kruseman & de Ridder 1994).

By applying Darcy's law, the groundwater flow from the upper river bed (Omdel upstream) was obtained; $K$ (110 m/day), $A$ (15,000 m$^2$) and $i$ (0.0044), thus $Q = 110 \times 15{,}000 \times 0.0044 = 7{,}260$ m$^3$/day (July 2013).

Therefore, the annual groundwater flow from the upper river bed (Omdel upstream) according to the preceding calculation amounts to about 2.6 Mm$^3$/year (Table 3.6). IWACO (2001) estimated a value of about 3.0 Mm$^3$ /year. Groundwater flow from OMAP was estimated as follows: $K$ (6.8 m/day), $A$ (40 000 m$^2$) and $i$ (0.0032), thus $Q = 6.8 \times 40{,}000 \times 0.0032 = 870$ m$^3$/day suggesting an annual groundwater flow from OMAP of 0.3 $Mm^3$/year (September 2014). Previous studies estimated *Q* as 0.5 $Mm^3$/year (IWACO 2001) and 0.2 $Mm^3$/year (Zeelie 2001).

Groundwater flow from the SEC to the MC near borehole WW16662 was estimated, using the following values: *K* (4.6 m/day), *A* (10,581 $m^2$) and *i* (0.007), thus $Q = 4.6 \times 10{,}581 \times 0.007 = 341$ $m^3$/day (November 2015), suggesting an annual groundwater flow from the SEC of about 0.12 $Mm^3$/year. Zeelie (2001) estimated it to be about 0.23 $Mm^3$/year.

The average saturated thickness of production boreholes for February 2016 in the central wellfield and downstream wellfield of Nei-Neis Water Supply Scheme is 6.9 m and 7.0 m respectively, whilst the average saturated thickness of production boreholes for May 2011 in the central wellfield was 19.5 m, due to the significant run-off during that period. The estimated groundwater flow at Okombahe and Nei-Neis for the period between April 1996 and April 2016 is presented in Figs. 3.18 and 3.19. At Okombahe and Nei-Neis the estimated groundwater flow for April 2016 is 775,990 $m^3$/year (*K* is 29.9 m/day, *A* is 4,941 $m^2$ and *i* is 0.01439, thus $Q = 29.9 \times 4{,}941 \times 0.01439 = 2{,}126$ $m^3$/ day) and 389,455 $m^3$/year (*K* is 36.9 m/day, *A* is 1,555.8 $m^2$ and *i* is 0.01858, thus $Q = 36.9 \times 1{,}555.8 \times 0.01858 = 1{,}067$ $m^3$/day) respectively.

The groundwater flow estimated at Tubussis (a north flowing tributary) and Spitskoppe for November 2015 is 13,724 $m^3$/year (*K* is 5.5 m/day, *A* is 976.9 $m^2$ and *i* is 0.007, thus $Q = 5.5 \times 976.9 \times 0.007 = 37.6$ $m^3$/day) and 2,081 $m^3$/year (*K* is 0.229 m/ day, *A* is 4,963.2 $m^2$ and *i* is 0.005, thus $Q = 0.229 \times 4{,}963.2 \times 0.005 = 5.7$ $m^3$/day) respectively.

**Table 3.6** Groundwater flow (*Q)* estimated for Omdel upstream, OMAP, WW16662, Okombahe, Nei-Neis, Tubussis and Spitskoppe

| Location | *K* (m/day) | *A* (m$^2$) | *i* | Flow rate *Q* | |
|---|---|---|---|---|---|
| | | | | (m$^3$/day) | (Mm$^3$/year) |
| Omdel upstream | 110 | 15 000 | 0.0044 | 7 260 | 2.6 |
| OMAP | 6.8 | 40 000 | 0.0032 | 870 | 0.3 |
| WW16662 (SEC to MC) | 4.6 | 10 581 | 0.007 | 341 | 0.12 |
| Okombahe | 29.5 | 5 023.5 | 0.014 | 2 075 | 0.76 |
| Nei-Neis | 28.3 | 1 847.2 | 0.027 | 1 411 | 0.52 |
| Tubussis | 5.5 | 976.9 | 0.007 | 37.6 | 0.014 |
| Spitskoppe | 0.229 | 4 963.2 | 0.005 | 5.7 | 0.002 |

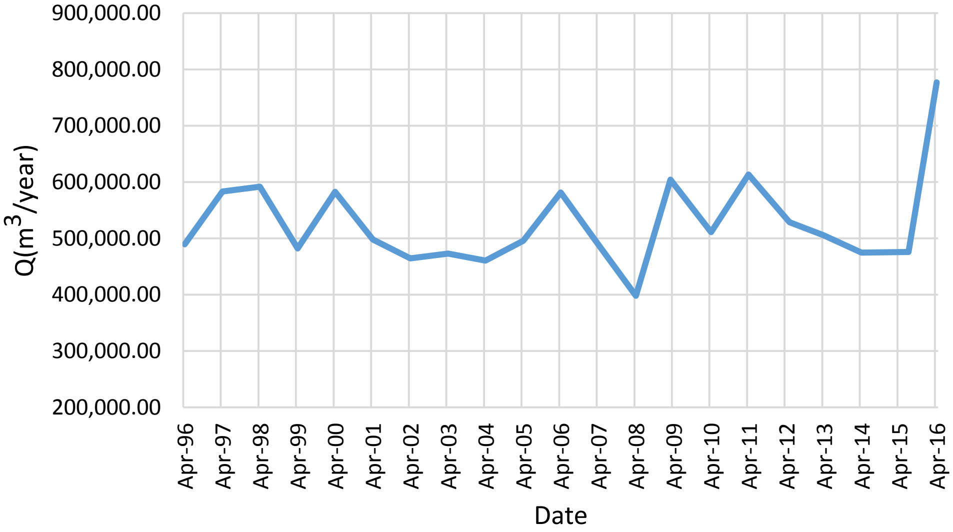

**Fig. 3.18** Groundwater flow at Okombahe (Q = flow rate)

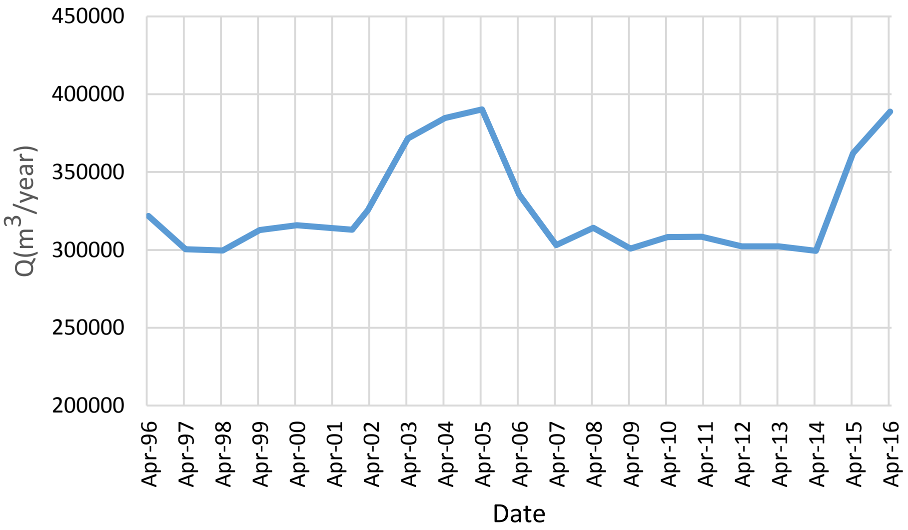

**Fig. 3.19** Groundwater flow at Nei-Neis (Q = flow rate)

The schematic diagram Fig. 3.20 indicates the Omdel Dam, Omaruru River and infiltration ponds (sites 1 and 2). If a significant inflow (run-off) reaches the Omdel Dam, the accompanied silt is first allowed to settle. Efforts are also made to prevent silt from being deposited around the abstraction tower, which blocks the outlet valves. Clear water is released from the tower and flows about 6 km (part 1) and 12 km (part 2) downstream before it reaches and directly recharges the aquifer through infiltration ponds at site 1 (ponds A, B, C and D) and site 2 (ponds E and F) respectively; sites 1 and 2 are situated in the MC.

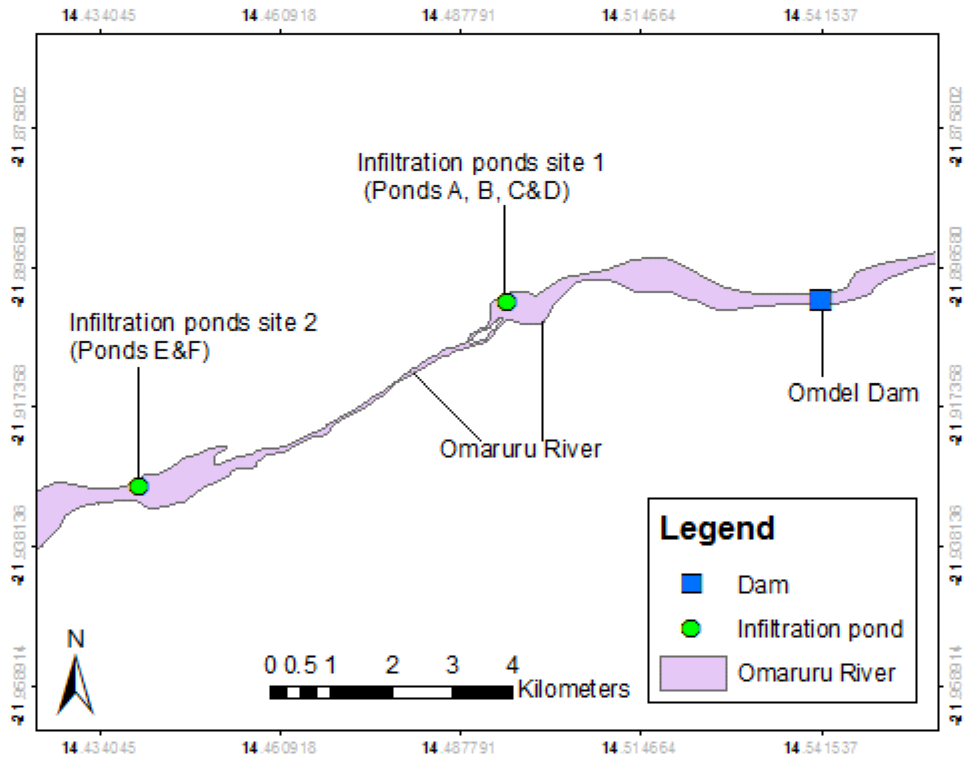

**Fig. 3.20** Schematic diagram indicating Omdel Dam, Omaruru River and infiltration ponds (sites 1 and 2)

Once the significant inflow (flood) reaches the Omdel Dam, some water infiltrates into the dam basin, some will be lost in the process through evaporation at the dam, whilst the remaining water will be available for release through the abstraction tower and enhanced recharge processes. The silt content is estimated to be about 10% of the total inflow.

If the inflow (flood) is significant enough, it will continue to travel down to infiltration ponds at site 2. Some water will infiltrate the river channel along this course, whilst some water will evaporate. During the hydrological season 2008/2009, about 2.506 Mm$^3$ travelled the Omaruru River beyond sites 1 and 2. Of this flow, 0.050 Mm$^3$ infiltrated the river channel and 0.040 Mm$^3$ was lost through evaporation. Excess water flows to the infiltration ponds E and F at site 2 through pond C at site 1. Inflow of 2.416 Mm$^3$ reached the infiltration ponds at site 2 during the hydrological season 2008/2009, 2.398 Mm$^3$ infiltrated and about 0.018 Mm$^3$ evaporated (Muundjua 2010).

According to Table 3.7 “infiltration” represents the water infiltrated at the dam basin, river channel (parts 1 and 2) and the infiltration ponds at sites 1 and 2. This “infiltration” indicates the artificial recharge for each hydrological season. The artificial recharge for the hydrological season between 1996/1997/1998 and 2010/2011 ranges between 52 to 89% of the total inflow, representing a significant component towards the Omdel Aquifer recharge. It should however be noted that artificial recharge occurs only during major flood events. The most water inflow recharged into the aquifer is for the hydrological season 2010/2011 and the least water inflow recharged into the aquifer is for the hydrological year 1999/2000. However, the hydrological season 1996/1997/1998 has more infiltrated water (9.55 $Mm^3$) compared to other hydrological seasons. The sum of infiltration at the dam, river section and infiltration pond(s) is estimated on average to be about 2.262 $Mm^3$/year, whilst the average volume infiltrated at sites 1 and 2 (infiltration ponds) is estimated at about 1.487 $Mm^3$/ year (Mostert 2014). These estimations take into account a 10% silt content and an average release rate of 19.2 $Mm^3$/year.

According to the preceding estimates, it is obvious, therefore, that artificial recharge (enhanced) at the infiltration ponds plays a major role at the Omdel Aquifer, since at least 60% of the infiltration occurs there. The effect on groundwater level of the monitoring boreholes (WW33066, WW31366, WW33069 and WW31243) in the surroundings of the infiltration ponds were observed during the recorded flood events (Fig. 3.21).

**Table 3.7** Information on the major flood events (After Zeelie 2001, Muundjua 2010 & Mostert 2014)

| Hydrological season | Total inflow ($Mm^3$) | Infiltration ($Mm^3$) | % of Artificial recharge |
|---|---|---|---|
| 1996/97/98 | 18.027 | 9.55 | 53 |
| 1999/00 | 18.0 | 9.3 | 52 |
| 2007/08 | 2.853 | 2.0 | 70 |
| 2008/09 | 10.423 | 8.61 | 83 |
| 2010/11 | 5.716 | 5.07 | 89 |

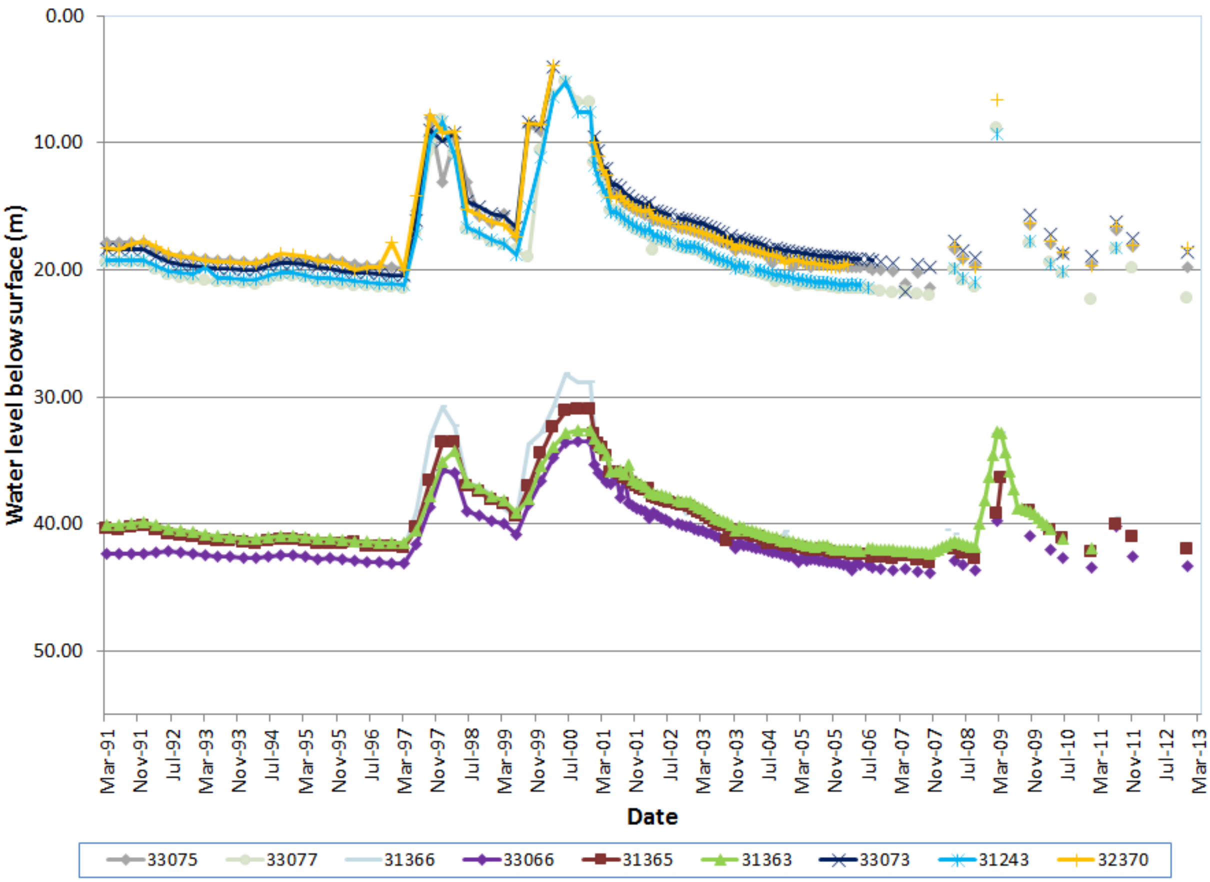

**Fig. 3.21** Groundwater levels of selected monitoring boreholes

## 3.6 Discussion

### 3.6.1 Four palaeochannels of Omdel Aquifer

As can be seen in Fig. 3.5, the bedrock geometry of the Omdel Aquifer reveals that the MC is relatively deeper than the other three elevated channels (Fig. 3.5). This confirms a hypothesis by Nawrowski (1990) that the aquifer geometry is defined mainly by the deepest Omaruru River palaeochannel known as the MC, which extends farther north-eastwards into the alluvium bed. According to the bedrock geometry it is clear that the MC is the largest reservoir of stored fresh groundwater. The MC is filled with varying interbedded layers of sand, gravel, calcrete and clay, with a total thickness ranging between 70 m near the coast to 110 m at its upstream limit (Fig. 3.5). It should, however, be noted that cross-sections IJ (central part of the aquifer) and OP (upstream part of the aquifer) each indicate a sediment thickness of about 70 m, therefore suggesting an average sediment thickness of 80 m for the MC. The saturated thickness of the MC aquifer ranges from 20 to 60 m. Near the coast (downstream part of the MC) the saturated thickness is on the order of 50 m, decreasing towards the central part and increasing again upstream to about 60 m. The IJ and OP cross-sections indicate a saturated thickness of about 30 and 20 m respectively, therefore suggesting an average saturated thickness of about 40 m for the MC. It should be noted that the saturated thickness obviously declines as the groundwater levels in the aquifer decline.

The NC system, with saline groundwater and also described as the deeper channel sub-system, occurs farther northwards of the NEC (Fig. 3.22). This channel is also filled with sand, clay, sandstone, gravel and calcrete, with total alluvium thicknesses ranging between 20 and 75 m. Sediments deposited in the NC near the coast are about 70 m thick, decreasing towards the centre of the channel to about 20 m and increase again upstream to about 75 m. From these observations it is estimated that the average thickness of the sediments in the centre of the NC is about 35 m, whilst the average thickness of the sediments upstream is about 60 m. Saturated thicknesses of the NC ranges between 5 and 54 m. Near the coast the saturated thickness is about 54 m, decreasing towards the center and increasing again upstream to about 18 m. The EF cross-section indicates a saturated thickness of about 5 m and the average saturated thickness of the NC is estimated at about 20 m, which is half the average saturated thickness of the MC.

Nawrowski (1990) mentioned that the two elevated channels are almost parallel to each other, suggesting that their flow direction may be controlled by north-easterly trending dolerite dykes. Throughout the Namib Desert, in the study area, dolerite dykes appear as prominent ridges. This is due to the fact that the dolerite is more resistant to weathering than the surrounding rocks. The channels in question are therefore perceived to be limited valleys (channels) incised in the bedrock between parallel dolerite dykes and later filled with sediments. Borehole WW100142 intercepts a dolerite dyke before reaching the mica schist bedrock. A conclusion, confirmed by water table elevations, is that subsurface ridges, caused by dolerite dykes in the basement surface, form partial barriers on both sides of the MC.

River migration, of the pre-Omaruru River, obviously caused the development of the previously mentioned palaeochannels and the subsequent sediment infilling thereof. During the infilling of the channels there must have been also an ingress of subsurface water flow. It is also conceivable that the perceived river migration was caused by geological tectonics related to crustal uplift and subsidence; the elevated channels described previously, suggest such a process. Since the NEC is reported to contain saline to brackish groundwater (as in the case of the other channels elevated above the MC), the conclusion must be made that they do not currently receive recharge from local flood events, as in the case of the MC. Only during extreme flood events may some recharge to these elevated channels occur. The thickness of sediments deposited in the NEC ranges between 25 and 30 m, with an average thickness of 26 m and near the coast it is about 30 m. In the NEC the saturated thickness ranges between 1 and 9 m, the CD cross-section indicating a saturated thickness of about 1 m, whilst the EF cross-section indicates a thickness of about 9 m. From these observations the average saturated thickness of the NEC is estimated at about 7 m. This channel has the least saturated thickness, compared to the other palaeochannels.

In the SEC the sediment thickness ranges between 20 and 65 m, increasing upstream, the exception being cross-section KL which indicates a thickness of 15 m. From these observations it is, therefore, assumed that the average thickness of the sediments deposited in the SEC is about 40 m. The SEC has a saturated thickness ranging between 5 and 40 m, with the CD cross-section indicating a thickness of about 5 m. From this observation the average saturated thickness of the SEC is estimated at 21 m, which is equivalent to the average saturated thickness of the NC. The volume of groundwater estimated in the MC is about 133 Mm$^3$. Geyh and Ploethner (1995) estimated the total groundwater reserve in the Omdel Aquifer to be 1.6 Mm$^3$, 50% is considered abstractable.

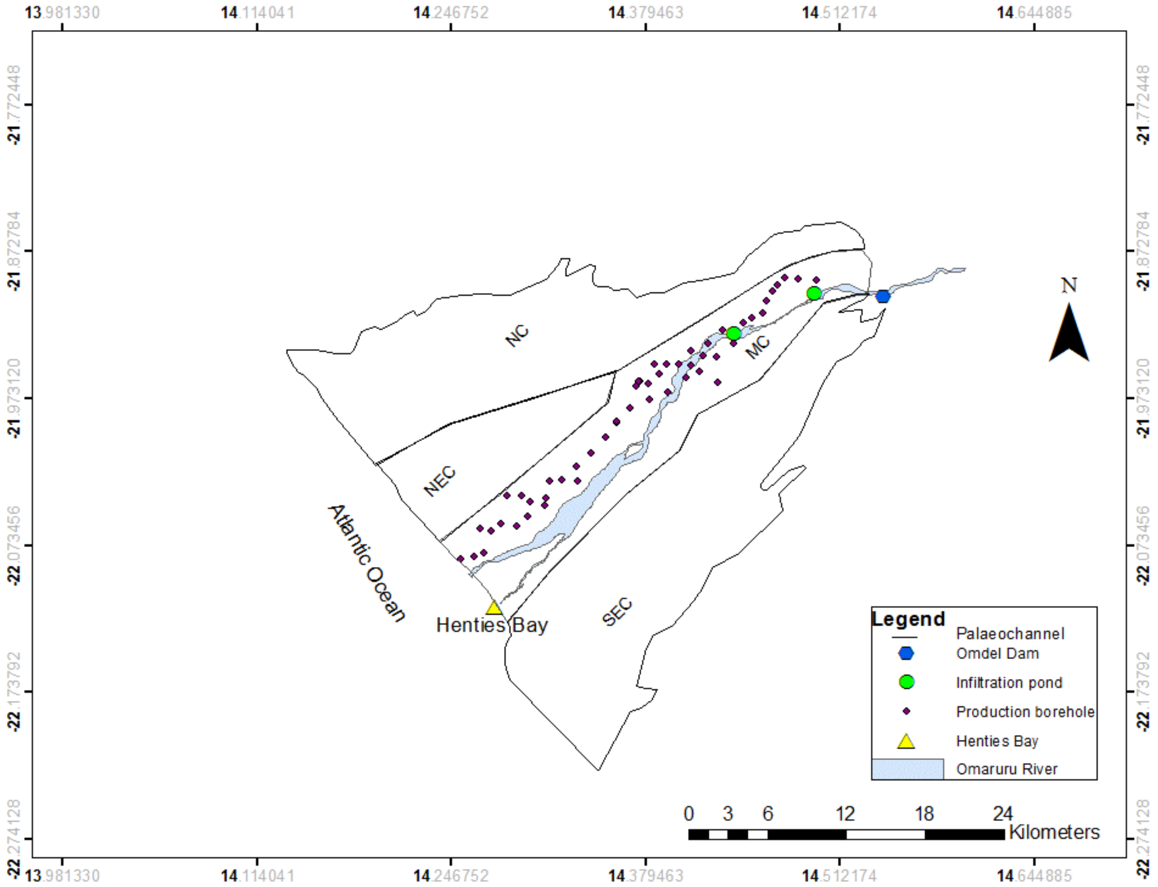

**Fig. 3.22** Map depicting the four palaeochannels

### 3.6.2 Water table characteristics

The water table of the MC of the Omdel Aquifer shows a significant decline with time, which is observed from the groundwater levels in the production boreholes. According to the historic borehole production data of the aquifer, the water table has declined ever since abstraction operations started, indicating over abstraction. Hydraulic head loss in the MC ranges from 2.0 to 31.0 m over the period from January 1986 to December 2012 (approximately 26-year period). This severe decline of the water table is observed in the central part of the MC, where excessive abstraction occurs (WW21649, about 31.0 m; Fig. 3.23). Geyh and Ploethner (1995) mentioned that the oldest groundwater is abstracted from the northeastern part of the Omdel Aquifer with $^{14}$C ages of up to 17,000 years BP. Near the coastline the observed decline in water levels is on average 2.0 m (WW16953 and WW21499). It is estimated that the water levels decline by about 0.08 m/year near the coastline; furthermore, it is estimated that the water levels (water table) of the central part of the MC decline by an average of about 1.08 m/year. A plot of time series depicting groundwater level changes of boreholes WW16953, WW21499, and WW21649 presented in Fig. 3.23 date back from 1986 to May 2018. Masterson and Walter (2009) report that withdrawals of groundwater from the coastal aquifers of southeastern Massachusetts (USA) change the water levels, the flow directions and the groundwater discharge rate into streams and coastal water bodies. They further mentioned that the potential effects of increased groundwater abstraction will result in declines in pond levels, increases in the depth to the water table beneath inland wetlands, reductions in streamflow, reductions in groundwater discharge to the coast and hence increased saltwater intrusion.

The average groundwater drawdowns in production boreholes of the Omdel Aquifer range between 0.8 and 20.03 m, the average drawdown being 0.8 m for borehole WW16953, located near the coast, and 20.03 m for borehole WW22186 in the central part of the MC. Production boreholes with average drawdowns greater than 10 m are WW21495, WW21649, WW22186, WW22187, WW22188/100111, WW22192, WW22194, WW22567/100094, WW35336, WW35337, WW35341, WW35343 and WW35346. The significant drawdowns (>10 m) observed in these production boreholes are due to the cemented alluvial thickness (semi-confined horizon) found in the central part of the MC. Average yields of the production boreholes range between 4.7 and 91.5 $m^3$/h; the lowest average yield of 4.7 $m^3$/h is in production borehole WW21495 and the highest average yield of 91.5 $m^3$/h is observed in WW100157, located in the central part of the MC.

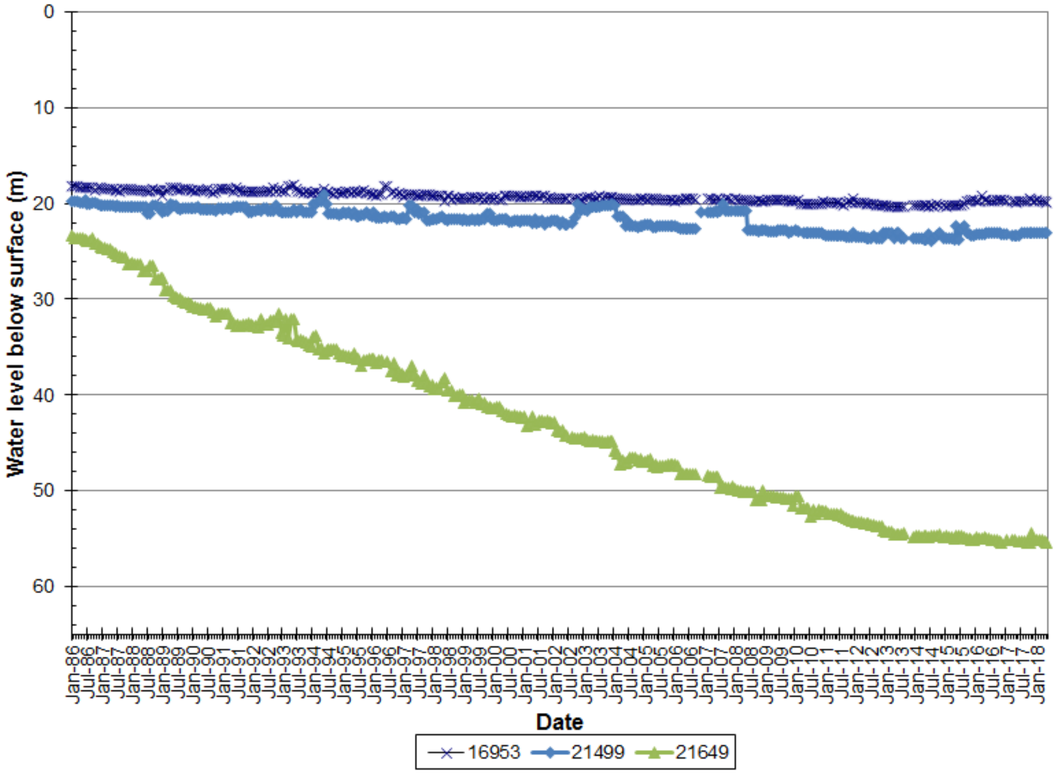

**Fig. 3.23** Plot of time series depicting groundwater level changes of boreholes WW16953, WW21499 and WW21649

### 3.6.3 Groundwater chemistry

According to Chen and Jiao (2007), the depletion of sodium in the groundwater is believed to be due to cation exchange when seawater intrudes the fresh groundwater. $Na^+$ is taken up by the soil exchanger and replaced by $Ca^{2+}$ leaving chloride in excess.

$$2Na^+ + Ca^{2+} - X_2 = Ca^{2+} + 2Na - X \qquad (4)$$

X indicates the soil exchanger; $Na^+$ is taken up the exchanger during the processes and $Ca^{2+}$ is released into the water. The excess of Na occurs when the fresh groundwater flushes the previously saline groundwater, resulting in $Na^+$ being released to the solution.

$$Ca^{2+} + 2Na - X = Ca - X_2 + 2Na^+ \qquad (5)$$

Seven groundwater quality facies of selected boreholes in the Omdel Aquifer are recognized in the Piper diagram (Fig. 3.15) and are $Na+K-Cl+SO_4$, $Ca+Mg-Na+K-Cl+SO_4$, $Na+K-HCO_3-Cl+SO_4$,

$Ca+Mg-Na+K-Cl+SO_4$, $Na+K-Ca+Mg-Cl+SO_4$, $Ca+Mg-Na+K-Cl+SO_4-HCO_3$, and $Ca+Mg-Na+K-HCO_3-Cl+SO_4$. The presence of $HCO_3$ in some of the groundwater quality facies suggests recharge at that part of the aquifer through seepage at the dam, groundwater flow upstream of Omdel Aquifer and through the OMAP. The absence of $HCO_3$ in the groundwater of some boreholes suggests that there is lack of recharge in that part of the aquifer. All groundwater facies of selected boreholes of the Omdel Aquifer have NaCl indicating a coastal environment.

According the expanded Durov diagram, there are six water types for the selected boreholes of the Omdel Aquifer: calcium bicarbonate, bicarbonate sodium, sulphate or (anions) and sodium, chloride and calcium dominant, chloride and no dominant cation, and chloride and sodium (Fig. 3.24). Calcium bicarbonate water type indicates recharged or recharging water (Usher 2002), and borehole WW100044 located upstream of SEC has this water type (Fig. 3.16). Bicarbonate sodium water type indicates ion exchanged water; borehole WW22188 located in the centre of MC contains this water type. Borehole WW100061 located downstream of SEC contain sulphate or (anions) and sodium water type, which may be due to mixing influences. Chloride and calcium dominant water type indicates that reverse ion exchange is taking place, and this water type is found in boreholes WW100057 and WW100046 located downstream and upstream of SEC respectively. Boreholes WW25992, WW100060, WW16484, WW100050 and WW100045, located downstream of the NEC as well as downstream, central and upstream of the SEC, have chloride and no dominant cation water type suggesting reverse ion exchange is taking place. The water type of the majority of the selected boreholes of the Omdel Aquifer is chloride and sodium, indicating an end point in a water evolution sequence. About 89% of the selected boreholes of the Omdel Aquifer have chloride concentrations in the groundwater that exceed the World Health Organization (WHO) drinking water standard (250 mg/l).

Spatial distribution patterns suggest that the boreholes located near or along the River Tugela have high concentrations of Na and Cl (Ntanganedzeni et al. 2018). mNa/Cl and chloro alkaline indices (CAI1 and CAI2) indicate that reverse ion exchange reactions are dominating over cation exchange in the Tugela catchment (Ntanganedzeni et al. 2018). The concentration of TDS, total hardness (TH), Na, Ca, and Cl observed in boreholes that are in Tugela catchment exceeded the drinking water standards recommended by WHO (80%) and South African drinking water standards (SAWQG; 90%) according to groundwater suitability assessment (Ntanganedzeni et al. 2018). Offenborn (1999) found that the hydraulic contact between the MC and NEC has been proved at boreholes WW 21501 and WW 22188, while the hydraulic contact between the MC and NC has been provided at borehole WW 22195, due to brackish groundwater observed in these boreholes. Borehole WW21501 was replaced by WW100095 in 2002; therefore, borehole WW100095 indicates the location of borehole WW21501 in Fig. 3.16.

The study revealed that about 38% of 101 groundwater samples collected in 2004 had ratios of $rCa/(rHCO_3+rSO_4) > 1$ (Fig. 3.13), which suggests that the Omdel Aquifer suffered the seawater intrusion in 2004 (Chen and Jiao 2007).

The $rCa/(rHCO_3+rSO_4)$ ratios were average 0.94 for the groundwater samples collected in 1998, with about 33% of the samples having ratios >1. It is also observed that the $rCa/(rHCO_3+rSO_4)$ ratios of the groundwater samples of the Omdel Aquifer collected between 1993 and 2012 are <1, except for 2004, and only a few water samples have a ratio >1.

The decreasing trend of the $rCa/(rHCO_3+rSO_4)$ ratios indicates that the Omdel Aquifer experienced gradual freshening after 2004 and between 1993 and 2003. The decrease in the ratio suggests that the saline front moved seaward and as a result the $Ca^{2+}$ was adsorbed by the aquifer.

The three highest peaks observed over this period are for 1998, 2000 and 2004, however the 2004 sample remains the highest peak of TDS and chloride recorded, and it agrees with the $rCa/(rHCO_3+rSO_4)$ ratio for the year 2004, suggesting possible seawater intrusion (Fig. 3.14). The ionic ratios $HCO_3/Cl$, Na/Ca, Ca/Cl, Mg/Cl and $Ca/SO_4$ can be efficiently used to delineate seawater intrusion (Lee and Song 2007). The Cl and TDS values greater than 316 and 1,260 mg/l respectively, indicate strongly the effect of saline water intrusion (Lee and Song 2007). About 76 and 63% of Cl and TDS values, respectively, of the selected boreholes of the Omdel Aquifer have values greater than 316 and 1,260 mg/l, respectively, suggesting possible seawater intrusion. In coastal areas, a saline water body would intrude the fresh groundwater and forms an interface or a transition zone in the subsurface, even if there is no pumping taking place (Lee and Song 2007). According to Geyh and Ploethner (1995), the variability of $^{14}C$ values indicates that the occasional flash-flood recharge and the pumping action together yield a confusing temporal and spatial $^{14}C$ distribution pattern. Geyh and Ploethner (1995) said that the clustering of the $^{14}C$ data of the tritium-free water samples indicates that there is flash-flood recharge in the Omaruru catchment in areas with surface geology dominated by volcanic rocks and calcretes. There is no temporal or spatial trend of the $^{14}C$ values in the MC where groundwater abstraction is taking place and the groundwater is recharged by groundwater flow and ephemeral river run-off (Geyh and Ploethner 1995). However, the distinct values of $^{14}C$ and $\delta^{13}C$ rule out mixing of the groundwater from flash flood events or recharge conditions (Geyh and Ploethner 1995). Geyh and Ploethner (1995) stated that the $\delta^{18}$O value of NEC groundwater at –6.87‰ differs significantly from the young groundwater abstracted in the production boreholes of MC (–7.38 ± 0.1‰).

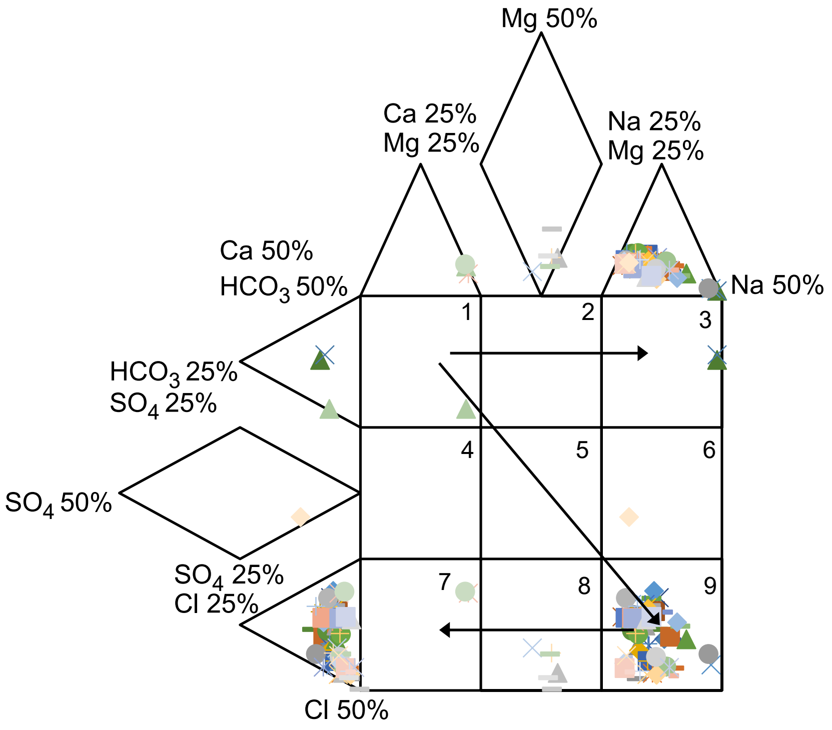

**Fig. 3.24** Expanded Durov diagram of selected boreholes of the Omdel Aquifer

### 3.6.4 Groundwater recharge

The groundwater recharge estimation by the WTF method indicates that more water is recharged at Nei-Neis, Spitskoppe and Tubussis than at Okombahe and Omaruru, and this may be due to topographical differences and aquifer dimensions. Adelana (2010) mentioned that the WTF method is capable of identifying relative changes in seasonal recharge due to differences in rainfall. The WTF method is only capable of estimating recharge when water is arriving at the water table at a higher rate than it is leaving, producing a water level rise (Healy and Cook 2002). It is observed that the recharge over rainfall ratio at different localities in the Omaruru catchment is relatively small indicating that rainfall contributed a small portion to the water level rise (recharge, Table 3.4). Therefore, run-off plays a very important role in the water level rise (groundwater recharge) in the Omaruru River bed alluvial aquifers. Surface run-off occurs when the soil's infiltration capacity is exceeded by the precipitation rate and increases with increasing amounts of precipitation (Adelana 2010).

The groundwater recharge estimation by CMB method indicates that direct rainfall contributes more to recharge at Okombahe compared to the other localities such as Nei-Neis, Spitskoppe and Tubussis. The rainfall at the coast is regarded as insignificant to direct recharge in the Omdel Aquifer, since high evaporation is expected and plays a major role. From this perspective, the Omdel Aquifer is assumed not to receive any direct recharge from local rainfall, but is rather recharged through artificial recharge (significant run-off), seepage underneath the dam and groundwater flow from the upper river bed (Omdel upstream), OMAP and SEC. The groundwater flow is assumed to play a major role in the recharge of the Omdel Aquifer, since significant run-off only reaches the Omdel Dam occasionally. The groundwater flow estimated at Okombahe between April 1996 and February 2016 is more than the groundwater flow estimated at Nei-Neis (Figs. 3.18 and 3.19), may be due to aquifer dimensions. The significant groundwater flow estimated at Okombahe and Nei-Neis contributes to the significant groundwater flow estimated at Omdel upstream (about 2.6 Mm$^3$/year; Table 3.6), and hence contributes to the groundwater recharge of the Omdel Aquifer.

The artificial recharge (enhanced) at the infiltration ponds plays a major role at the Omdel Aquifer, since at least 60% of the infiltration occurs there; the evidence is the effect on groundwater level of the monitoring boreholes (WW33066, WW31366, WW33069 and WW31243) in the surroundings of the infiltration ponds (Fig. 3.21).

### 3.6.5 Groundwater discharge

The groundwater discharge from the Omdel Aquifer is considered to be abstraction from production boreholes, evapotranspiration and groundwater outflow to the sea. A total average groundwater abstraction from the 42 production boreholes at the Omdel Aquifer amounts to 5.2 Mm$^3$/year. Groundwater is also discharged from the aquifer through evapotranspiration from open water, trees, reeds and other vegetation and is estimated to be about 0.2 Mm$^3$/year (IWACO 2001). The groundwater outflow to the sea was estimated by Darcy's law: $K$ (18.5 m/day), $A$ (190,077 m$^2$) and $i$ (0.0024), thus $Q = 18.5 \times 190{,}077 \times 0.0024 = 8{,}439$ m$^3$/day, therefore suggesting an annual groundwater outflow to the sea to be about 3.08 Mm$^3$/year (Table 3.8). Zeelie (2001) and IWACO (2001) estimated Q to the sea to be 3.0 Mm$^3$/year, while Bittner et al. (2014) estimated it to be 3.05 Mm$^3$/year.

**Table 3.8** Estimated groundwater outflow to the sea

| Location | *K* (m/day) | *A* ($m^2$) | *i* | *Q* ($m^3$/day) | *Q* ($Mm^3$/year) |
|---|---|---|---|---|---|
| Sea | 18.5 | 190 077 | 0.0024 | 8 439 | 3.08 |

### 3.6.6 Groundwater balance

The groundwater balance of the Omdel Aquifer was estimated before the construction of the dam and again after its construction. According to the water balance estimated before construction, the total amount of annual recharge was estimated at 5.8 $Mm^3$/year (Table 3.9). Such estimates considered groundwater flow upstream of Omdel, groundwater flow (OMAP) and natural recharge which was regarded to be 17% of a 13 $Mm^3$ average flood. The total annual groundwater discharge by groundwater outflow to the sea and direct pumping (abstraction) was estimated at 8.0 $Mm^3$/year, whilst evapotranspiration losses were regarded as zero due the water-table depth and sparse vegetation. Average abstraction from the production boreholes was 5.0 $Mm^3$/year, which exceeds the sustainable yield of 2.8 $Mm^3$/year of the Omdel Aquifer by 2.2 $Mm^3$/year.

According to the water balance estimated after the dam construction, the total amount of annual recharge from groundwater flow (Omdel upstream), groundwater flow (OMAP), natural recharge (17.5% of 6.2 $Mm^3$/a long-term average spill), sum of infiltration at the dam, river section and ponds, average volumes infiltrated at sites 1 and 2 (recharge ponds) as well as groundwater flow from the SEC near WW16662, is estimated at 7.87 $Mm^3$/year (Table 3.10). The total annual groundwater discharge by groundwater outflow to the sea, direct pumping (abstraction) and through evapotranspiration is estimated at 8.48 $Mm^3$/year.

Abstraction from the production boreholes for the past year was 5.2 $Mm^3$, which exceeds the sustainable yield of 4.6 $Mm^3$/ year of the Omdel Aquifer by 0.6 $Mm^3$/year. After the construction of the Omdel Dam, the annual recharge increased from 5.8 to 7.87 $Mm^3$/year and the estimated sustainable yield increased from 2.8 to 4.6 $Mm^3$/year. Figure 3.25 shows the schematic diagram of groundwater balance components.

For the past 22 years, since 1994 (after the construction of Omdel Dam), the Omdel Aquifer has been operating at an average yield of 6.3 $Mm^3$/year. This exceeds the sustainable yield of 4.6 $Mm^3$/year by 1.7 $Mm^3$ and such over-abstraction is clearly observed in the continued downward trends in water levels of the monitoring boreholes and production boreholes. The temporal changes of the $^{14}C$ values observed in the boreholes between the border of MC and NEC, may be due to over-exploitation of the Omdel Aquifer (Geyh and Ploethner 1995). Saltwater intrusion is actually caused by abstracting more groundwater than is sustainable via recharge, and as a result adjacent bodies of salt water are drawn into the abstraction zone of influence (Ezzy 2005). In order to maintain the sustainable yield of the Omdel Aquifer, the storage capacity of Omdel Dam should be maintained by regular silt removal. Such an exercise may not be possible for practical and economic reasons; furthermore, the sustainable yield could be maintained if significant run-offs are received more frequently. Coastal aquifers can be used as a sustainable source of freshwater if managed correctly and exploited according to recharge, well pattern and local hydrogeological characteristics (Adelana 2010). According to Bredehoeft (2002), sustainability of groundwater development takes place when the pumping captures an equal amount of virgin discharge.

$$P = \Delta D_0 \tag{6}$$

$P$ is pumping and $\Delta D_0$ is a change in the virgin rate of discharge.

Mitigation for the continued over abstraction may be attributed to an increase in water demand by the various consumers and also the opening of new uranium mines such as Langer Heinrich. Enhanced recharge from the Omdel Dam also did not materialize to the extent that it was expected; however, the aforementioned data clearly indicate that drastic measures need to be implemented to reduce over abstraction from the aquifer and at least maintain its groundwater levels above some critical point.

**Table 3.9** Groundwater balance of Omdel Aquifer before dam construction (after Zeelie 2001)

| **Balance components** | **Q (Mm$^3$/year)** | **Comments** |
|---|---|---|
| *Main Channel inflow* | | |
| Groundwater flow (Omdel upstream) | 3.0 | Darcy calculations |
| Groundwater flow (OMAP) | 0.5 | Darcy calculations |
| Natural recharge | 2.3 | 17.5% recharge of 13 Mm$^3$ flood |
| Subtotal inflow | 5.8 | - |
| *Main Channel outflow* | | |
| Abstraction | 5.0 | |
| Outflow to sea | 3.0 | Darcy calculations at sea interface |
| Subtotal outflow | 8.0 | - |
| *Overall balance components* | | |
| Over-exploitation | 2.2 | - |
| Sustainable yield | 2.8 | - |

**Table 3.10** Groundwater balance of Omdel Aquifer after dam construction

| **Balance components** | ***Q* (Mm$^3$/year)** | **Comments** |
|---|---|---|
| *Main Channel inflow* | | |
| Groundwater flow (Omdel upstream) | 2.6 | Darcy calculations |
| Groundwater flow (OMAP) | 0.3 | Darcy calculations |
| Natural recharge | 1.1 | Average contribution from spills (IWACO 2001) |
| Sum of infiltration at dam, river section & pond(s) | 2.26 | Mostert 2014 |
| Average volumes infiltrated at Sites 1 and 2 (recharge ponds) | 1.49 | Mostert 2014 |
| SEC | 0.12 | Darcy calculations near WW16662 |
| Subtotal inflow | 7.87 | - |
| *Main Channel outflow* | | |
| Abstraction | 5.2 | - |
| Outflow to sea | 3.08 | Darcy calculations at sea interface |
| Evapotranspiration | 0.2 | IWACO 2001 |
| Subtotal outflow | 8.48 | - |
| *Overall balance components* | | |
| Over-exploitation | 0.6 | - |
| Sustainable yield | 4.6 | - |

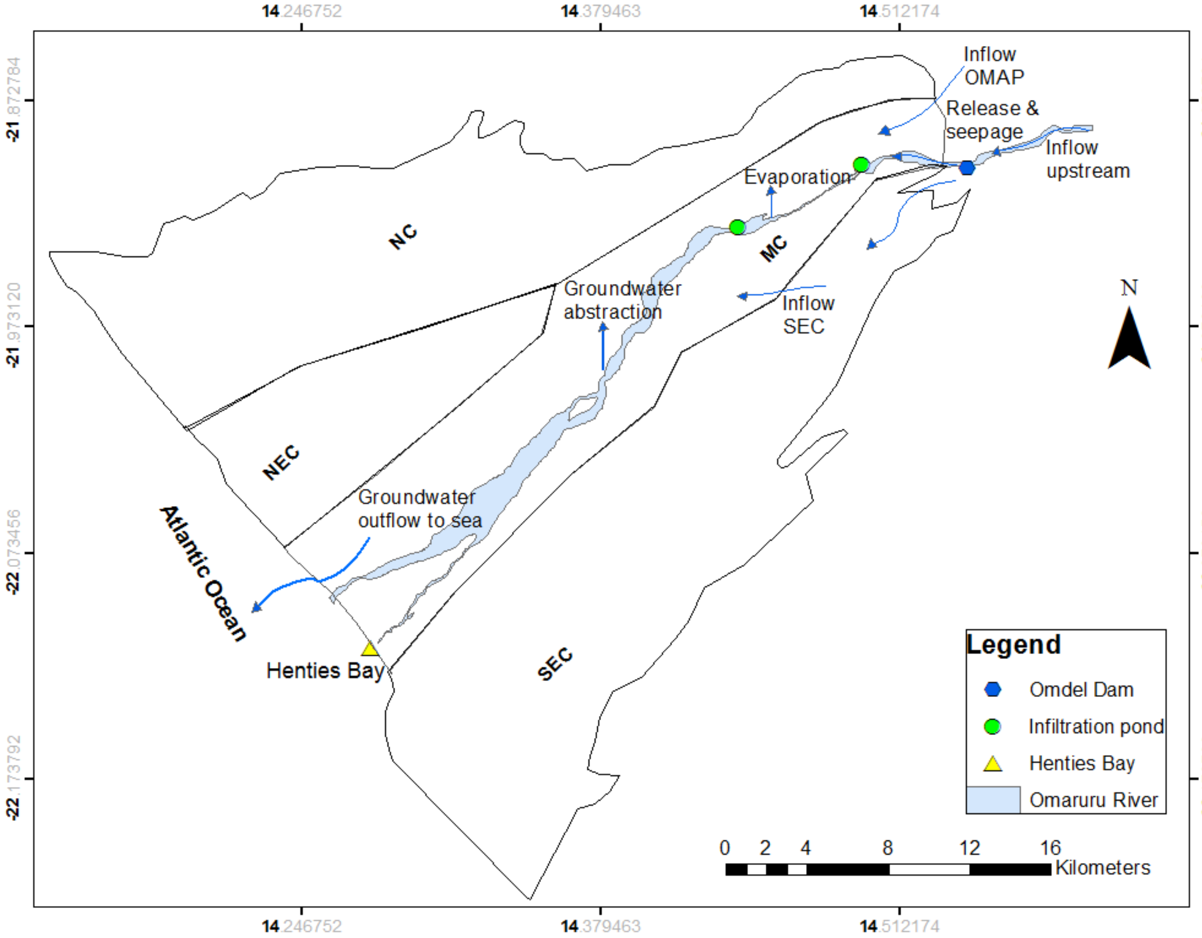

**Fig. 3.25** Groundwater balance components of the study area

## 3.7 Conclusions

The Omdel Aquifer is an alluvial aquifer with four palaeochannels (MC, NC, NEC and SEC). Bedrock geometry of the Omdel Aquifer indicates that the MC is the largest reservoir of stored fresh groundwater estimated at about 133 Mm$^3$ and is deeper than the other three channels with an average sediment thickness of 80 m.

Aquifer parameters were estimated with high T values associated with coarse sediments and low T values associated with the presence of clay materials. All groundwater chemistry facies of the selected boreholes of the Omdel Aquifer reveal a NaCl character, indicating a coastal environment. The water type of the majority of the groundwater samples of selected boreholes of the Omdel Aquifer is chloride and sodium, indicating an end point in a water evolution sequence. The recharge over rainfall ratio at different localities in the Omaruru catchment is relatively small indicating that rainfall contributed a small portion to the water level rise (recharge). Therefore, run-off plays a very important role in the water level rise (groundwater recharge) in the Omaruru River bed alluvial aquifers. Recharge estimation confirms that groundwater in the aquifer is replenished mainly by seepage underneath the dam, enhanced by artificial recharge (significant run-off) and groundwater flow from upstream, OMAP and SEC. The major flood events after the construction of the Omdel Dam took place during the hydrological seasons of 1996/1997/1998, 1999/200, 2007/2008, 2008/2009 and 2010/2011 and the artificial recharge ranges between 52 and 89% of the respective flood events (52% in 1999/2000 and 89% in 2010/2011). However, the hydrological season 1996/1997/1998 shows more infiltrated water (9.55 $Mm^3$) compared to the other hydrological seasons.

The total annual recharge to the Omdel Aquifer after construction of the dam is estimated at 7.87 $Mm^3$/year, with a total groundwater discharge rate estimated at 8.48 $Mm^3$/year. Therefore, the total annual recharge increased from 5.8 $Mm^3$/year (before the dam construction) to 7.87 $Mm^3$/year (after construction of the dam). Groundwater abstraction amounts to 61% of the estimated annual discharge. The sustainable yield of the Omdel Aquifer increased from 2.8 $Mm^3$/year (before the dam construction) to 4.6 $Mm^3$/year (after the dam construction), which can be maintained if the storage capacity of Omdel Dam is maintained by regular silt removal. Artificial recharge (enhanced) therefore contributes significantly towards the increase of the sustainable yield of the Omdel Aquifer. The groundwater system will reach a new equilibrium by means of capture, and the principal tool to carry out such investigations is the groundwater model (Bredehoeft 2002). According to Kalf and Woolley (2005), the law of conservation of mass plays an important role when assessing sustainable yield of an aquifer. They also mention that any groundwater system may reach equilibrium at some time. Groundwater was abstracted from the Omdel Aquifer at an average abstraction of 6.3 $Mm^3$/year for the past 22 years (1994-2016), an over-abstraction of 1.7 $Mm^3$/year. As a result, continued downward trends in water levels of the monitoring and production boreholes were observed. Saltwater intrusion is actually caused by abstracting more groundwater than is sustainable via recharge, and as a result adjacent bodies of saltwater are drawn into the abstraction zone of influence (Ezzy 2005). The groundwater flow dynamics along the Omaruru River suggest that it has a different impact on recharge to the Omdel Aquifer with time. Effective groundwater level monitoring, done by the Department of Water Affairs and Forestry, is in place and plays a vital role. It is against this background that the Omdel Aquifer needs to be carefully operated on a sustainable basis in order to strive for a state of equilibrium. The results provide a sound reference for application to similar aquifer systems prevailing in the Namib Desert, e.g. the Ugab River Delta, Swakop River, Kuiseb River Delta.

## 3.8 Acknowledgements

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# Chapter 4: Groundwater numerical model

## 4.1 Introduction

Groundwater model is described as a means of using a simplified form to represent a complicated field reality for people to understand and manage the resource. Ezzy (2005) mentioned that groundwater model try to represent an actual groundwater system with a mathematical counterpart. Groundwater numerical simulation has gradually become an important tool for investigating and managing of groundwater resources in both theoretical and practical aspects of hydrogeology (Xu 2013). The three-dimensional movement of groundwater of constant density through a porous earth material may be described by the partial-differential equation 7 (McDonald and Harbaugh 1988; Ezzy 2005).

$$\partial/\partial x\ (Kxx(\partial h/\partial x)) + \partial/\partial y\ (Kyy(\partial h/\partial y)) + \partial/\partial y\ (Kzz(\partial h/\partial z)) - W = Ss\ (\partial h/\partial t) \qquad (7)$$

Where Kxx, Kyy and Kzz are values of hydraulic conductivity along the x, y and z coordinate axes ($Lt^{-1}$), h is the potentiometric head (L), W is the volumetric flux per unit volume and represents sources and/or sinks of water ($t^{-1}$), Ss is the specific storage of the porous material ($L^{-1}$) and t is time (t). Equation 7 together with the specification of flow and/or head conditions at the boundaries of an aquifer system and specification of initial head conditions, it constitutes a mathematical representation of a groundwater flow system (McDonald and Harbaugh 1988). Analytically, a solution of equation 7 is an algebraic expression giving h(x,y,z,t) such that, when the derivatives of h with respect to space and time are substituted into equation 7, the equation, its initial and the boundary conditions are satisfied (McDonald and Harbaugh 1988). A time-varying head distribution of this nature, characteristics the flow system, where it measures both the energy of flow and the volume of water in storage, and can be used to calculate directions and rates of movement (McDonald and Harbaugh 1988). The sum of all flows into and out of the cell must be equal to the rate of change in storage within the cell (McDonald and Harbaugh 1988). Equation 8 is expressing the balance of flow for a cell under the assumption that the density of groundwater is constant (McDonald and Harbaugh 1988).

$$\sum Qi = Ss\ (\Delta h/\Delta t)\Delta v \qquad (8)$$

Where Qi is the flow rate into a cell ($L^3t^{-1}$), Ss (specific storage) is the volume of water that can be released from storage per unit volume of aquifer material per unit change in hydraulic head ($L^{-1}$), Δv is the volume of the cell ($L^3$) and Δh is the change in head over a time interval of length Δt.

Equation 8 is described as equivalent to the volume of water taken into storage over a time interval $\Delta t$ given a change in head $\Delta h$. The inflow and storage gain describes Equation 8. The outflow and loss are described as negative inflow and negative gain respectively. In steady state model simulations it is assumed that the hydrogeological system is in equilibrium, the change of groundwater storage is equal to zero and all the components of the groundwater balance are time independent (equation 9; Lubczynski 2000).

$$Q_{Gin} + R = Q_{Gout} + Eg \qquad (9)$$

Where $Q_{Gin}$ is groundwater inflow (lateral inflow), R is groundwater recharge from rainfall, $Q_{Gout}$ is groundwater outflow (lateral outflow) and Eg is groundwater evapotranspiration.

Modflow is the industry standard code for finite difference modelling (McDonald and Harbaugh 1988).

Ezzy (2005) states that modflow is designed to simulate the aquifer systems in which: the saturated flow conditions exist, Darcy’s law applies (groundwater flow is defined by hydraulic conductivity by cross-sectional area by the groundwater gradient), the density of groundwater is constant and the principal directions of horizontal hydraulic conductivity or transmissivity does not change within the system. This chapter describes the results of a steady state groundwater model of the Omdel Aquifer. The purpose of the model is to have a better conceptualization understanding, predict behaviour and assess the impact of groundwater abstraction scenarios on Omdel Aquifer. Modflow uses the finite-difference method to solve the groundwater flow equation. Under steady state conditions, the groundwater flow equation 7 reduces to equation 10 (Beranek et al. 2018).

$$\partial/\partial x\,(K_{xx}(\partial h/\partial x)) + \partial/\partial y\,(K_{yy}(\partial h/\partial y)) + \partial/\partial y\,(K_{zz}(\partial h/\partial z)) \pm W = 0 \qquad (10)$$

## 4.2 Conceptual understanding

The Omdel Aquifer consists of four palaeochannels, the MC, NEC, NC and SEC (Fig. 3.1). The bedrock geometry of the aquifer indicates that the MC is deeper than the other three channels with an average sediment thickness of 80 m. The hydrostratigraphy and the geological features of the Omdel Aquifer are described in Table 3.1 and Fig.3.2 respectively and the detailed constructed cross-sections are indicated in Fig.3.5. The groundwater flow direction is towards the Atlantic Ocean (flowing north east to south west), with the Omaruru River acting as the base-level of drainage (Fig.3.11 & Fig.3.25). The groundwater flow (Omdel upstream), groundwater flow (OMAP), natural recharge (average contribution from spills), infiltration at the dam, river section and ponds, average volume infiltration at sites 1 & 2 as well as groundwater flow from SEC (near WW16662) contribute to the recharge of the Omdel Aquifer. The groundwater discharge of the Omdel Aquifer are groundwater outflow to the sea, the direct pumping (abstraction) and evapotranspiration. The constant head boundary conditions are upstream of Omdel, OMAP and sea while the rest of the model domain have no inflow boundary condition (impermeable bedrock). The location of production boreholes, monitoring boreholes, Omarurur River, infiltration ponds and dam are indicated in Fig. 4.1 (Appendices 3 and 4).

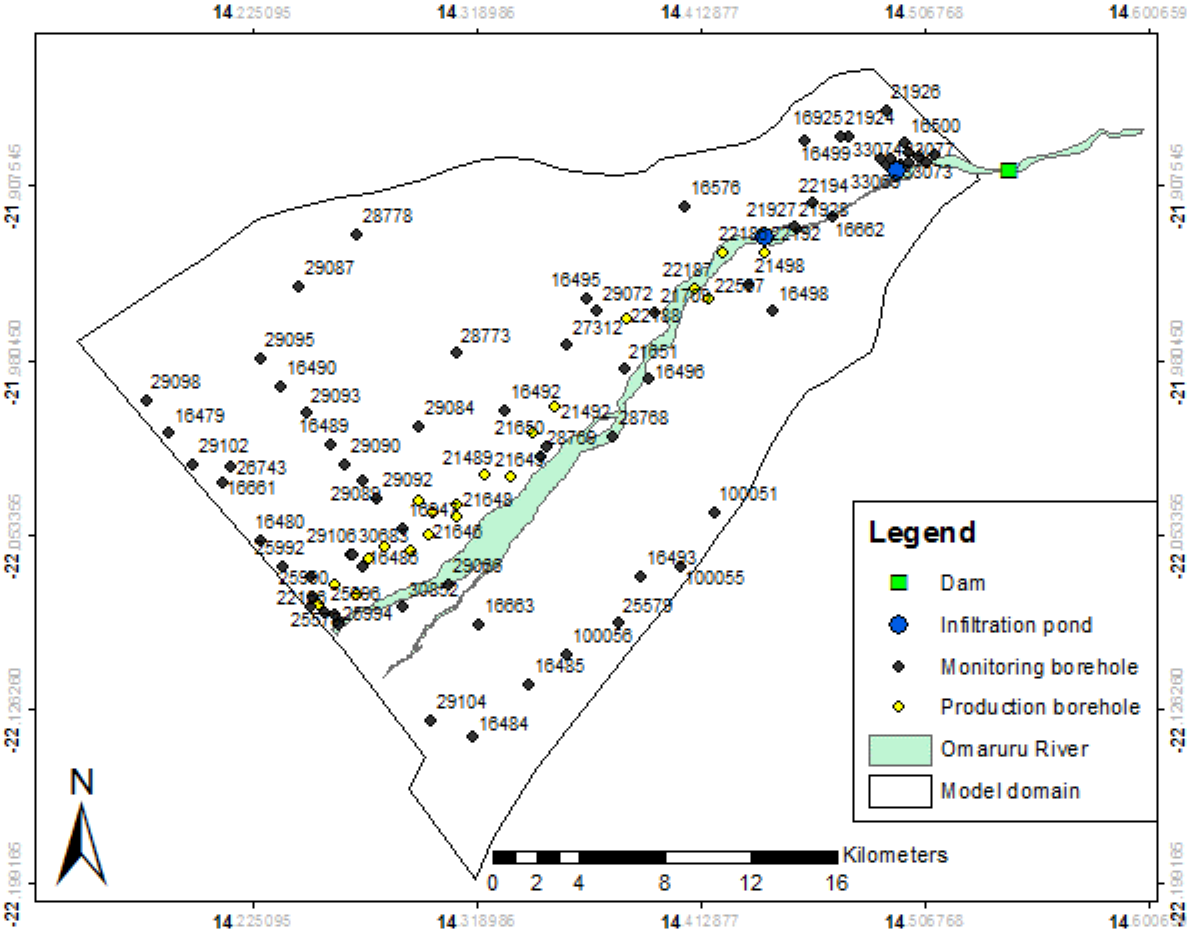

**Fig. 4.1** Map depicting production boreholes, monitoring boreholes, infiltration ponds, Omaruru River, Omdel dam and model domain

## 4.3 Model construction

MODFLOW is described as a computer program that simulates three dimensional groundwater flow through a porous medium by using a finite difference method (McDonald and Harbaugh, 1988). Furthermore, MODFLOW was designed to have a modular structure that facilitates two primary objectives such as ease of understanding and ease of enhancing (Harbaugh et al. 2000). The finite difference groundwater numerical flow model of the Omdel Aquifer was built using MODFLOW-NWT and UPW (Upstream-Weighting) solver package (Niswonger et al. 2011) implemented by using ModelMuse 3.10.0.11 (Winston 2009). MODFLOW-NWT is a standalone program that is intended to solve problems involving drying and rewetting nonlinearities of the unconfined groundwater flow equation (Niswonger et al. 2011). MODFLOW-NWT must be used with the UPW package which is the alternative package to the BCF (Block-Centered Flow), LPF (Layer Property Flow), and HUF (Hydrogeologic-Unit Flow) packages for calculating all terms in the discretized groundwater flow equation. However, the UPW package treats nonlinearities of cell drying and rewetting by using a continuous function of groundwater head, instead of the discrete approach used by the BCF, LPF, and HUF packages (Niswonger et al. 2011). They further mentioned that, the UPW package do smooth the horizontal conductance function and the storage change function during wetting and drying of a cell to provide continuous derivatives for solution by the Newton method. ModelMuse is a graphical user interface to create the input files for MODFLOW-NWT/MODFLOW–2005, the spatial data for the model is independent of the grid and the temporal data is independent of the stress periods (Winston 2009). The aquifer top was determined using 30 m digital elevation model (ASTER) and the bottom of the aquifer was determined from borehole depths obtained from the borehole logs.

The data processing was done in ArcGIS, the created shapefiles were imported into Modelmuse. The data such as locations of boreholes (production and monitoring boreholes) and infiltration ponds as well as the borehole depths in excel were first brought to ArcGIS, converted to shapefiles and imported into Modelmuse. The digital elevation data (ASTER) were converted to ASCII in ArcGIS and imported as aquifer top into Modelmuse.

## 4.4 Grid discretisation

The model domain is set up with one convertible (unconfined) layer discretised into 1000 m by 1000 m grid cells (Fig. 4.2). The grid consists of 36 columns and 28 rows. The model domain is a roughly triangular shape with an area of about 526 000 000 m$^2$. The inactive grid cells are due to shallow bedrock depths. Several dry boreholes were drilled in these areas (Bittner et al. 2014).

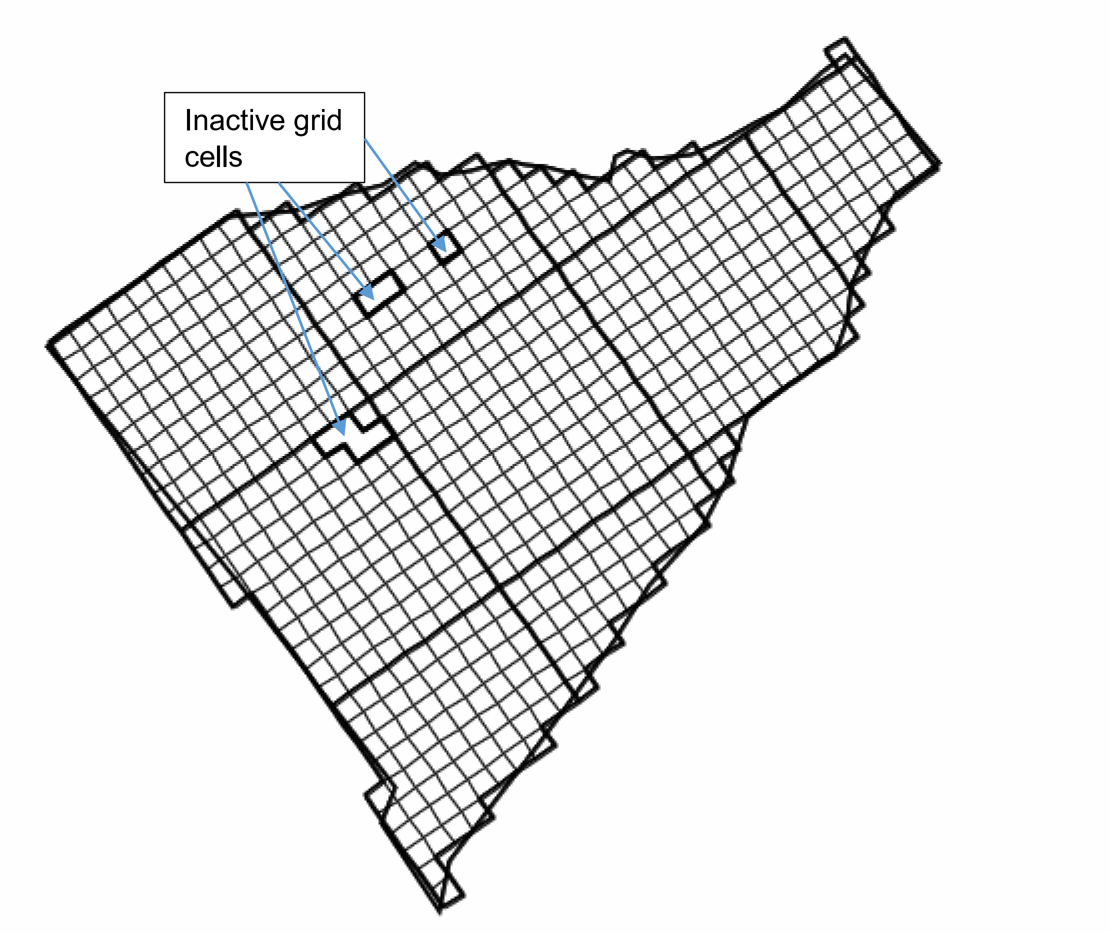

**Fig. 4.2** Map depicting model grid discretisation and inactive grid cells

## 4.5 Model parameters and inputs

The horizontal hydraulic conductivity of the model is divided into 7 zones, such as MC zone 1, MC zone 2, MC zone 3, MC zone 4, NC zone, NEC zone and SEC zone (Fig. 4.3; Table 4.1), assigned in Modelmuse under model/MODFLOW packages and programs/flow/UPW. The hydraulic conductivity data of the MC were estimated from test pumping data, the MC is divided into four zones (downstream to upstream) according to the hydraulic conductivity data which were grouped into four zones (Appendix 5). The hydraulic conductivity of NC zone, NEC zone and SEC zone were estimated from literature because there is no test pumping data in these palaeochannels, this makes hydraulic conductivity to be the uncertainty in the input data of the model.

**Table 4.1** Hydraulic conductivity (*K*) of each zone

| Hydraulic zone | Initial *K* values (m/day) |
|---|---|
| MC zone 1 | 3.21 |
| MC zone 2 | 23.51 |
| MC zone 3 | 5.18 |
| MC zone 4 | 27.4 |
| NC zone | 2.0 |
| NEC zone | 2.51 |
| SEC zone | 2.51 |

The evapotranspiration and recharge were assigned to the entire model domain. IWACO (2001) estimated evapotranspiration and the natural recharge (average contribution from spills) as 0.2 $Mm^3$/year and 1.1 $Mm^3$/year respectively. The recharge was assigned to the entire model domain for stability and to prevent cells from drying, if the steady state model heads are considered to be used as initial heads for a transient model (Bittner et al. 2014). The Evapotranspiration package (EVT) was used to simulate the evapotranspiration from the top convertible (unconfined) layer with evapotranspiration extinction depth of 5 m while the recharge package (RCH) was used to simulate the recharge of the model. The Time-Variant Specified-Head package (CHD) was used to simulate the boundary conditions upstream of Omdel (213 m amsl ), OMAP (175.8 m amsl) and sea (0 m amsl) (Fig. 4.3), while the rest of the model domain boundary condition is a no flow, due to the impermeable bedrock found in the surrounding of the aquifer. The abstraction of production boreholes was assigned and simulated by Well package (Well) while the Head Observation package (HOB) was used to simulate the hydraulic head of the observation boreholes. The initial hydraulic heads used was after the dam construction but before the first flood event when the water levels was slightly stable. It's difficult to have a steady state condition in this environment.

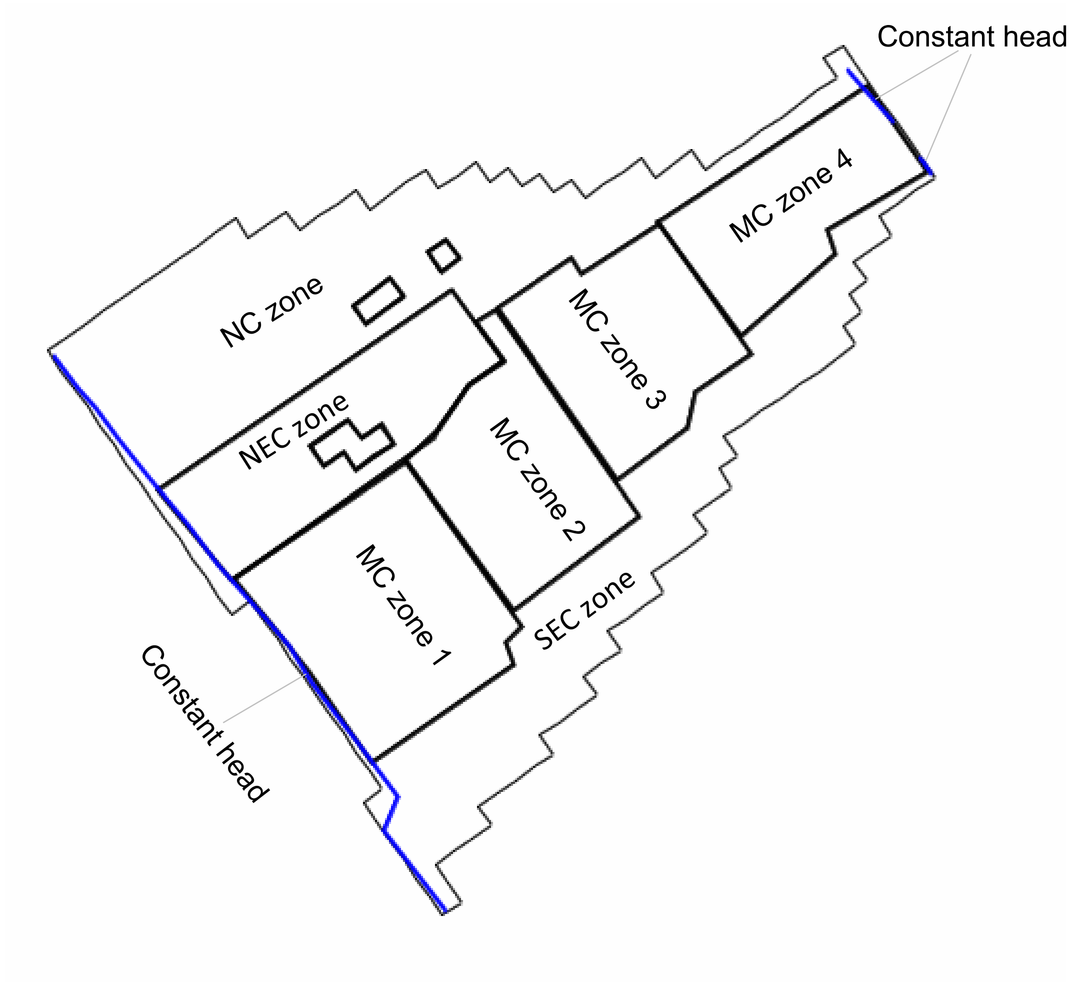

**Fig. 4.3** Map depicting hydraulic zones and boundary conditions

## 4.6 Steady state calibration

Calibration is a process whereby model input parameters are adjusted within a reasonable range in a systematic way and the model is run repeatedly until the model output matches with the observed values within some acceptable error criteria (U.S. Army Corps of Engineers 2011). Model calibration is described as the modification of model input data by making the model to match more closely with the observed heads and flows (Reilly and Harbaugh 2004). They further mentioned that groundwater model can be calibrated by trial and error or by automatic parameter estimation techniques, by using nonlinear regression statistical techniques. The calibration by trial and error technique was used in the study whereby hydraulic conductivity for different zones, recharge and evapotranspiration were manually adjusted within the reasonable range, in order for the simulated heads to match with the observed heads. The groundwater model calibration methods were developed to allow the modeler to estimate values of input parameters such as K, porosity and the boundary conditions (Sovinsky 2017). The estimated values are used to run the groundwater model to obtain the model outputs (for example heads and travel times) that are compared to the actual field measurements. Sovinsky (2017) said depending on the results, the inputs can be further adjusted within a reasonable range to try to match the field observations better. This process continues until the model outputs and the field observations is very close and satisfies the criteria established by the investigator (Sovinsky 2017).

The hydraulic conductivity of different zones, recharge and evapotranspiration of the Omdel Aquifer were adjusted within the reasonable range during the calibration, for the simulated heads to match with observed heads (Table 4.2 & 4.3). The initial values and the estimated values of hydraulic conductivity for all the zones are close to each other except for MC zone 2 that has a huge difference between the initial and the estimated values, this may be due to the quality of test pumping data used to estimate the initial hydraulic conductivity of MC zone 2. The initial and estimated values of recharge and evapotranspiration are close to each other indicating that both were adjusted within the acceptable range (Table 4.3). The estimated values of hydraulic conductivity of different zones, recharge and evapotranspiration were obtained during the calibration of the steady state model.

**Table 4.2** The initial and estimated values of hydraulic conductivity (*K*) of different zones

| Hydraulic zone | Initial values (m/day) | Estimated values (m/day) |
|---|---|---|
| MC zone 1 | 3.21 | 5.016 |
| MC zone 2 | 23.51 | 7.896 |
| MC zone 3 | 5.18 | 7.968 |
| MC zone 4 | 27.40 | 25.920 |
| NC zone | 2.00 | 4.704 |
| NEC zone | 2.51 | 1.416 |
| SEC zone | 2.51 | 6.672 |

**Table 4.3** The initial and estimated values of recharge and evapotranspiration

| Parameter | Initial values (m/day) | Estimated values (m/day) |
|---|---|---|
| Recharge | 0.00000473 | 0.00000441 |
| Evapotranspiration | 0.000000860 | 0.000000802 |

The groundwater balance of Omdel Aquifer after a steady state model calibration is indicated in Table 4.4, the inflows that brings water into the model are constant heads and recharge while the outflows responsible for taking water out of the model are constant heads, wells and evapotranspiration. There is no change of storage under steady state condition. The difference between the total inflow and total outflow indicate the percentage discrepancy of about -0.00%, contributing to the confidence level of the steady state model calibration. The calibrated steady state model revealed that there is more inflow than outflow at the constant head, indicating that some water flow out of the aquifer through abstraction and some were lost through evapotranspiration.

**Table 4.4** Groundwater balance of Omdel Aquifer after steady state model calibration

| Item | Inflow ($m^3$/day) | Outflow ($m^3$/day) |
|---|---|---|
| Storage | 0.000 | 0.000 |
| Constant head | 41 185.394 | 27 851.215 |
| Wells | 0.000 | 15 962.400 |
| Evapotranspiration | 0.000 | 2.312 |
| Recharge | 2 630.506 | 0.000 |
| Total | 43 815.900 | 43 815.927 |
| In-Out | | -0.027 |
| Percent discrepancy | | -0.00% |

The quality of the steady state calibration can be evaluated in different ways such as error statistics, calibration target figures, gradient analysis of well clusters and compare to other published information. The calibration of a model is measured mathematically by using error statistics. The simulated heads accuracy were judged by comparing the mean error, mean absolute error and the root mean square error estimated.

The mean error (ME), mean absolute error (MAE), and the root mean square (RMS) error are the three criteria and are defined by the following equations respectively (U.S. Army Corps of Engineers 2011).

$$\text{ME}=\sum_{i=1}^{n}(Ci-Oi)/\text{n} \qquad (11)$$

The mean error is the average of the differences between the observed and simulated heads and can also indicate the overall comparison between simulated and observed data.

$$\text{MAE}=\sum_{i=1}^{n}|Ci-Oi|/\text{n} \qquad (12)$$

The mean absolute error is the average of the absolute values of the residuals.

RMSE=$\sqrt{\sum_{i=1}^{n}(Ci-Oi)^2/n}$ (13)

The root mean square error is the square root of the average of the squares of the residuals.

Whereby:

*Ci* is the simulated head at observation point *i*, *Oi* is the observation head at observation point *i*, and *n* is the number of observation points.

The mean error, mean absolute error and the root mean square error of the Omdel Aquifer are estimated as -0.277 m, 2.855 m and 4.305 m respectively, after applied equations 11, 12 and 13. The negative mean error means the model is simulating too low. The normalized root mean square error (nRMSE) is the ratio expressed as a percentage of the root mean square error divided by the difference between the maximum and minimum values of the observed data, and is defined by equation 14.

nRMSE=RMSE/$n_{max}$-$n_{min}$ (14)

Where $n_{max}$ is maximum observed head and $n_{min}$ is minimum observed head.

Therefore, the normalized root mean square error for a calibrated steady state model of the Omdel Aquifer is 2.252%. Bittner et al. (2014) estimated the normalized root mean square error as 4.36%, and said that this value should be less than 10% for a good calibrated model. Therefore, the steady state model of the Omdel Aquifer has been well calibrated.

There is a good correlation between the observed heads and simulated heads of the Omdel Aquifer after the steady state model calibration (Fig. 4.4; Appendix 6). The $R^2$ measures the degree in which two variables are linearly related (simulated and observed heads; Huo et al. (2011). The best fit between observed and simulated heads under ideal conditions would be $R^2$ is equal to 1 (Mohanty et al. 2013). The $R^2$ of the observed and simulated heads is 0.9965, which is close to 1 (good correlation) indicating that the steady state model calibration of the Omdel Aquifer has been achieved.

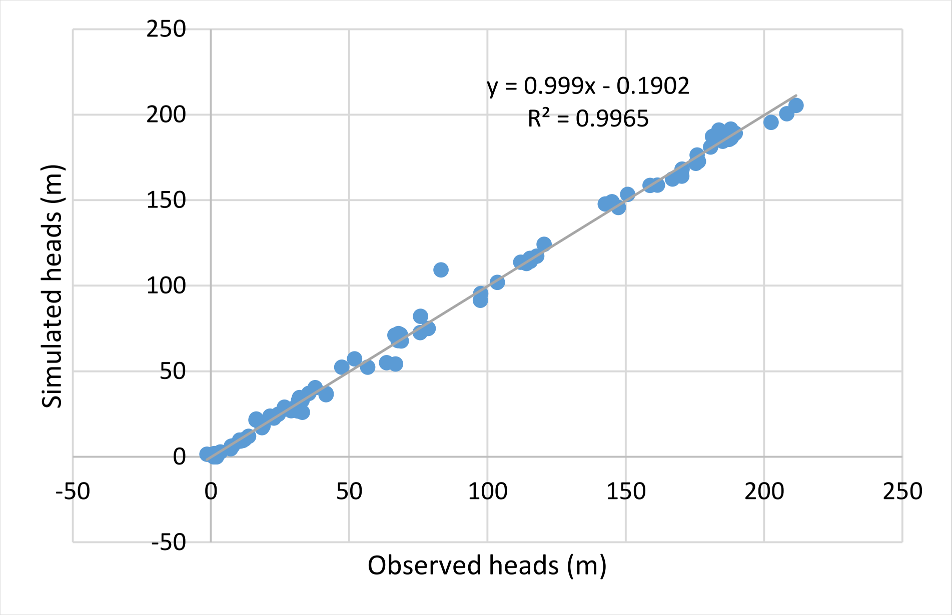

**Fig. 4.4** Good correlation between observed and simulated heads

## 4.7 Abstraction scenarios

Two abstraction scenarios were applied to the calibrated steady state model, such as half abstraction rate scenario and 30% increase abstraction rate scenario to assess the impact different abstraction scenarios have on the groundwater balance components and groundwater levels (simulated heads). The constant head inflow of the calibrated steady state model, half abstraction rate scenario and 30% increase abstraction rate scenario are 41 185.394 $m^3$/day, 40 951.776 $m^3$/day and 41 693.026 $m^3$/day respectively suggesting that more groundwater flow in through the constant head boundary at high abstraction rate (Table 4.5). The constant head outflow of the calibrated steady state model, half abstraction rate scenario and 30% increase abstraction rate scenario are 27 851.215 $m^3$/day, 35 556.622 $m^3$/day and 23 577.970 $m^3$/day respectively suggesting that more groundwater flow out through the constant head boundary at low abstraction rate (half abstraction rate scenario). The high evapotranspiration rate of half abstraction rate scenario indicates that more groundwater was lost through evapotranspiration since the simulated heads are high close to the surface due to low abstraction rate. The evapotranspiration is zero for 30% increase abstraction rate scenario, because the simulated heads are too deep due to high abstraction rate. The inflow components are constant head and recharge while the outflow components are constant head, wells and evapotranspiration. The percent discrepancies for the calibrated steady state model, half abstraction rate scenario and 30% increase abstraction rate scenario are -0.00%, 0.00% and -0.00% respectively. The water balance with less than 0.1% is regarded as an ideal error, an error of about 1% is considered acceptable (Elkrail and Ibrahim 2008).

**Table 4.5** Groundwater balance of the calibrated steady state model and different abstraction rate scenarios

| **Calibrated steady state model** | Inflow (m$^3$/day) | Outflow (m$^3$/day) |
|---|---|---|
| Constant head | 41 185.394 | 27 851.215 |
| Wells | 0.000 | 15 962.400 |
| Evapotranspiration | 0.000 | 2.312 |
| Recharge | 2 630.506 | 0.000 |
| Total | 43 815.900 | 43 815.927 |
| In-Out | | -0.027 |
| Percent discrepancy | | -0.00% |
| **Half abstraction rate scenario** | | |
| Constant head | 40 951.776 | 35 556.622 |
| Wells | 0.000 | 7 981.200 |
| Evapotranspiration | 0.000 | 44.448 |
| Recharge | 2 630.506 | 0.000 |
| Total | 43 582.282 | 43 582.270 |
| In-Out | | 0.0120 |
| Percent discrepancy | | 0.00% |
| **30% increase abstraction rate scenario** | | |
| Constant head | 41 693.026 | 23 577.970 |
| Wells | 0.000 | 20 745.600 |
| Evapotranspiration | 0.000 | 0.000 |
| Recharge | 2 630.506 | 0.000 |
| Total | 44 323.532 | 44 323.570 |
| In-Out | | -0.038 |
| Percent discrepancy | | -0.00% |

The simulated heads of the calibrated steady state model, half abstraction rate scenario and 30% increase abstraction rate scenario are indicated in Figs. 4.5, 4.6 and 4.7. The lowest simulated heads of the calibrated steady state model and half abstraction rate scenario is 0 m indicating similar simulated heads pattern. The simulated heads of the 30% increase abstraction rate scenario indicates that the lowest simulated groundwater heads are in the order of -6 m due to high abstraction rate, this may cause sea water intrusion.

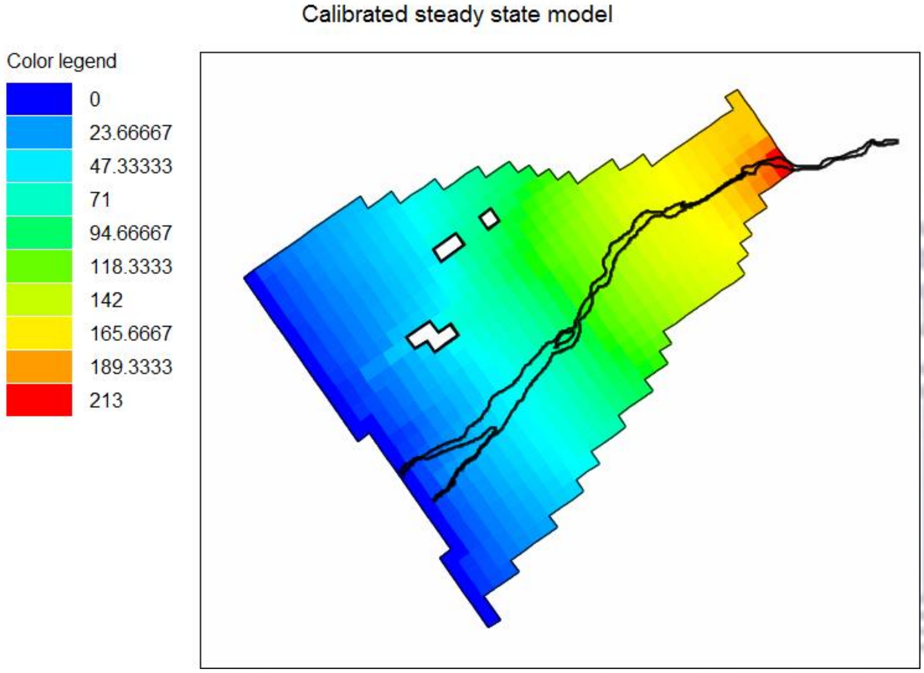

**Fig. 4.5** Simulated heads of calibrated steady state model

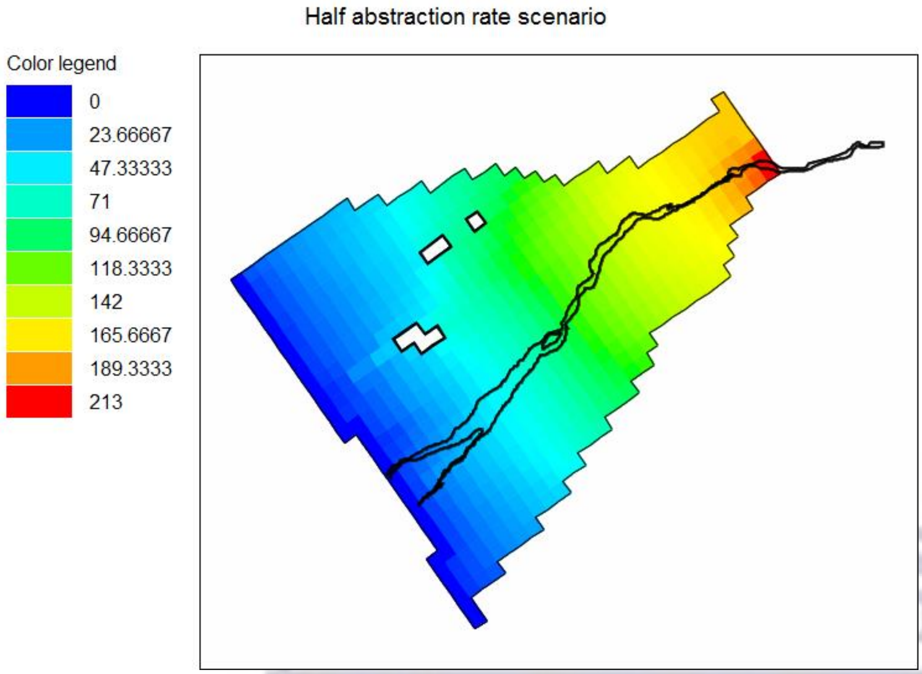

**Fig. 4.6** Simulated heads of half abstraction rate scenario

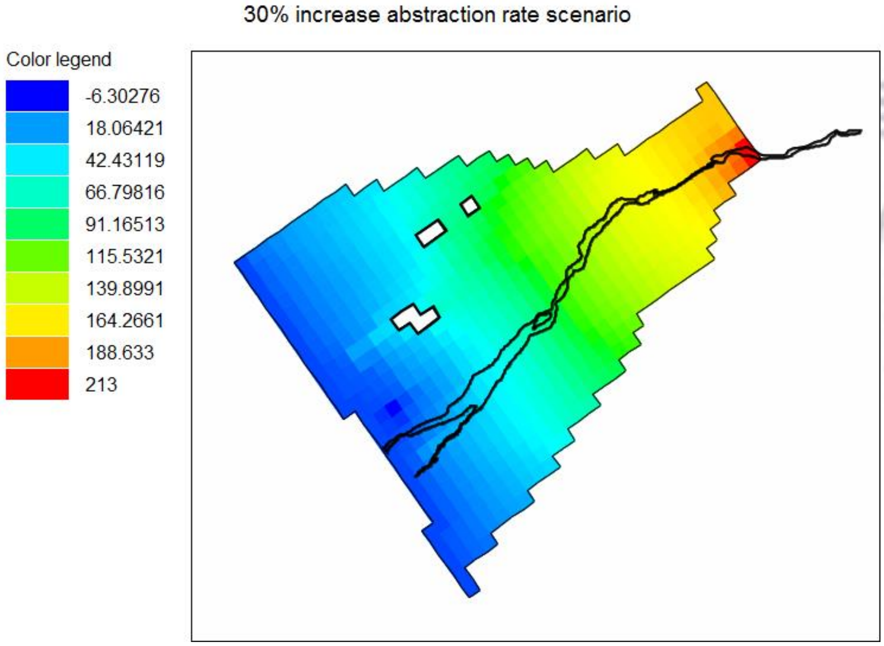

**Fig. 4.7** Simulated heads of 30% increase abstraction rate scenario

## 4.8 Conclusions

This chapter presented and discussed the results of a finite difference steady state groundwater model of the Omdel Aquifer which was developed using MODFLOW-NWT and UPW (Upstream-Weighting) solver package and implemented by using ModelMuse 3.10.0.11. The hydraulic conductivity of different zones, recharge and evapotranspiration were adjusted within the reasonable range during calibration for the simulated heads to match the observed heads. The uncertainty of the model is the estimated hydraulic conductivity of some hydraulic zones (NC zone, NEC zone and SEC zone). The Aim was to present the calibrated steady state model result of the Omdel Aquifer with two abstraction rate scenarios. The change in storage is zero under steady state condition. The calibrated steady state model heads can be used as the initial heads for a transient model of the Omdel Aquifer. The mean error, mean absolute error and the root mean square error of the calibrated steady state model of the Omdel Aquifer are estimated as -0.277 m, 2.855 m and 4.305 m respectively, therefore, the model calibration is more acceptable. The normalized root mean square error of the calibrated steady state model of the Omdel Aquifer is 2.252%, indicating a good model calibration. The normalized root mean square error estimated is well within the 10% norm (Elkrail and Ibrahim 2008). The $R^2$ of the observed and simulated heads is 0.9965, which indicate good correlation (close to 1) suggesting that the steady state model calibration of the Omdel Aquifer has been achieved.

The half abstraction rate scenario indicates high evapotranspiration rate compared to 30% increase abstraction rate scenario due to low abstraction rate. The different abstraction scenarios revealed that the higher abstraction rate, the less the evapotranspiration loss. The simulated heads of the 30% increase abstraction rate scenario indicates that the lowest simulated groundwater heads are in the order of -6 m due to high abstraction rate. This actually means that if the Omdel Aquifer system operates at a high abstraction rate, the groundwater level will decline. The 30% increase abstraction rate scenario was to assess the impact the high abstraction rate has on the groundwater balance components and the simulated heads under steady state condition.

# Chapter 5: Sustainable groundwater management strategies

## 5.1 Introduction

The main objective of this study is to assess groundwater and sustainable management use of the coastal alluvial aquifers in the Namib Desert. Hydrogeological characteristics and artificial recharge are considered to be the most appropriate sustainable groundwater management strategies that will be summarized. A water budget concept which is part of the hydrogeological characteristics is described as the rate of change in water storage of an area, such as a watershed and is balanced by the rate at which groundwater flows into and out of the system (Healy et al. 2007). They further mentioned that a better understanding of water budgets and underlying hydrologic processes leads to a sound effective water resource, environmental planning and management. The changes in water budgets of an area that is observed over time, can be used to assess the effects of climate change and human activities on water resources.

Sustainable resource management is described as managing groundwater for both present and future generations and provide enough quantities of water for the environment. Good management of water resources should not be approached only from the viewpoint of focusing on the volume of water available for sustainable use but also the impact of groundwater exploitation on the environment should also be considered (Sophocleous 2000).

## 5.2 Hydrogeological characteristics

The hydrogeological characteristics of the Omdel Delta Aquifer System in chapter 3 described the geological setting, aquifer parameters, groundwater level, groundwater chemistry, groundwater recharge (including the estimated recharge at different localities upstream in Omaruru catchment) and components of groundwater balance to give a better understanding of the Omdel Aquifer system.

The approach for sustainable coastal aquifer management, should include the true source of salinity and understanding of salinization dynamics which is a starting point key for management decisions, protection and remedial measures (Nwankwoala 2011).

Healy et al. (2007) describes a water budget as the difference between the rates of water flowing into and out of an accounting unit, which is balanced by a change in water storage:

$$\text{Flow In} - \text{Flow Out} = \text{Change In Storage} \qquad (15)$$

The groundwater budget for a basin is described in equation 16 (Healy et al. 2007).

$$P = ET + \Delta S + RO + Q^{bf} \quad (16)$$

Where P is precipitation,

ET is evapotranspiration (sum of evaporation from soils, surface water bodies, plants and aquifer),

$\Delta S$ is change in water storage,

RO is surface run-off

$Q^{bf}$ is baseflow (groundwater discharge)

One of the lesson learnt during the current study is that the estimated recharge at different localities upstream in the Omaruru catchment contributed significantly to the estimated groundwater flow at each specific locality, which then contributed to the groundwater flow of about 2.6 Mm$^3$/year upstream into the Omdel Aquifer.

The results of hydrogeological characteristics of the Omdel Delta Aquifer System provide a sound reference for application to similar aquifer systems prevailing in the Namib Desert, for sustainable utilization of groundwater resources. Benito et al. (2010) regards the shallow alluvial aquifers of the ephemeral rivers as limited water resource systems. Therefore, there is a need to understand the groundwater system and quantify the inputs and outputs in order to optimize the sustainable recharge volume for both ecosystems and human consumption. The ephemeral rivers have different types of alluvial aquifers that have different characteristics of recharge, the water quality changes due to pumping and floods (Benito et al. 2010).

Groundwater model is constructed after better understanding of the conceptual model of an alluvial aquifer in arid environment to enhance the understanding and used as investigating and groundwater management tool. Groundwater flow model is an important tool used for studies of groundwater systems (Reilly and Harbaugh (2004).

## 5.3 Artificial recharge

The sustainable yield of an aquifer should be considered less than recharge to have enough water in order to sustain quantity and quality of streams, springs, wetlands and groundwater dependent ecosystems (Sophocleous 2000). Recharge is irregular making the aquifers difficult to manage sustainably due to temporal variability of rainfall in arid regions, and are usually over utilized. The artificial recharge has been projected as the apparent means of increasing water supply reliability in arid regions (Sarma and Xu 2017), therefore it’s very important to make use of ephemeral rivers as artificial recharge and groundwater storage sites.  Infiltration through the streambed occurs at rates dependent on factors such as flow rate, flow duration, channel morphology, sediment texture and composition during run-off events. It’s difficult to attain steady state conditions in arid environments whereby recharge events are followed by prolonged periods of groundwater storage depletion. Therefore, artificial recharge can play a vital role for sustainable use of aquifers in arid environments, by controlling the natural rapid run-off and increase storage in aquifers (Sarma and Xu 2017). The most suitable areas for artificial recharge are highly porous media with a thick unsaturated zone and no impeding bedrock layers. Sayit and Yazicigil (2012) reported in their study that the average thickness of the unsaturated zone of 45 m and saturated hydraulic conductivity varies between 3.7 to 20.4 m/day, with geometric of 9.6 m/day.

The managed aquifer recharge is an important water management strategy together with demand management, to maintain, enhance, to secure groundwater that is already stressed, protect and improve water quality (Dillon et al. 2019). They further mentioned that managed aquifer recharge will exceed 10% global extraction to sustain quantity, quality and reliability of water supply.

Managed aquifer recharge techniques involves well, shaft and borehole recharge whereby water is directly infiltrated into the saturated zone or released to travel some distance along the river drainage system and recharged by gravitation (Glass et al. 2018; Hannappel et al. 2014). They further reported that infiltration into unsaturated zone is done by spreading methods through infiltration ponds and basins. The leakages from lakes and rivers is enhanced by abstraction through means of induced bank filtration (Glass et al. 2018; Dillon 2005). The depth of infiltration ponds or basins should be shallow enough to allow quick draining especially if cleaning of the ponds or basins by drying or scraping is needed (Gale 2005). Water levels in the ponds or basins should be managed to prevent vegetation growth that will be resistance to the water flow. Applying a rotational system of water spreading and drying followed by scrapping will restore infiltration rates (Gale 2005).

The water that enters an aquifer as groundwater recharge is described by equation 17 (Healy et al. 2007)

$$R = \Delta S^{gw} + Q^{bf} + ET^{gw} + \Delta Q^{gw} \tag{17}$$

Where

$\Delta S^{gw}$ is recharge arriving at the water table to augments groundwater storage, $Q^{bf}$ is discharges to the surface as base flow, $ET^{gw}$ is water extracted by plant transpiration and $\Delta Q^{gw}$ is water that moves out of the accounting unit as groundwater flow.

For the artificial recharge project to be successful, requires regular significant run-off and good conduit lithology, preferable for recharge. One of the main stratigraphic units preferable for artificial recharge is Site 1 of the Omdel Aquifer, described as: an upper layer of loose coarse sand and gravel which cover the entire channel, with the thickness that varies from 10 m in the central parts to 40 m in the upstream parts (Tordiffe 2006). The groundwater table occurs near the bottom of the porous layer, which is a good conduit for recharge. Tordiffe further reported that a suitable downgrade hydraulic passage exists, from Site 1 to the secondary channel and the MC, which makes the site suitable for enhanced (artificial) recharge of at least 8 $Mm^3$/year.

Artificial recharge plays an important role in the groundwater balance of Omdel Aquifer and forms part of the groundwater management strategy. During the hydrological seasons of 1996/97/98 and 2010/11 the artificial recharge ranged between 52% and 89% of the total inflow to the Omdel Aquifer, representing significant rises in groundwater levels (recharge). As described in Chapter 3, the total annual recharge increased from 5.8 $Mm^3$/year (before the dam construction) to 7.87 $Mm^3$/year (after construction of the dam). The estimated sustainable yield of the Omdel Aquifer increased from 2.8 $Mm^3$/year (before the dam construction) to 4.6 $Mm^3$/year (after the dam construction).

## 5.4 Further research

The following are suggestions for further research that were identified during the study:

- There is a lack evaporation and evapotranspiration data, more data are required in order to improve the groundwater balance of the alluvial aquifers.
- A field investigation should be conducted on the delta or alluvial aquifers with potential in the Namib Desert, in order to collect hydrogeological information and field observations for better future recommendations.
- Identified potential sites should be investigated further for potential artificial recharge to enhance groundwater recharge, especially at existing groundwater schemes, which is part of the groundwater management strategy.
- Map that indicate major features such as the Namib Desert, Great Escarpment, Central Plateau and Kalahari from a local competent institution (Geological Survey of Namibia) or an expert.
- Run a transient groundwater flow model with different scenarios, SEAWAT module to be used to simulate sea water intrusion with different scenarios.

## 5.5 Conclusions

The conclusions of the study are:

- Accurate and comprehensive geological cross-sections are essential in order to obtain the bedrock geometry of the delta or alluvial aquifers in the Namib Desert.

- If the inflow components amount to less than the outflow components of the groundwater balance, the groundwater levels of the delta or alluvial aquifer will decline with time as a result of resource depletion or mining of the aquifer. Therefore, effective groundwater monitoring is required to monitor the groundwater levels, so that changes can be detected early by regular interpretation of the results.
- Run-off (ephemeral river flow), infiltration and groundwater flow are the main recharge mechanisms to the delta or alluvial aquifers in the Namib Desert.
- The run-off or flood water infiltration through beds of ephemeral rivers (transmission loss) plays an important role in the groundwater level rise (groundwater recharge) in the Namib alluvial aquifers, while direct rainfall contributes only a small or insignificant, portion to the groundwater level rise (groundwater recharge).
- Estimated groundwater recharge to the delta aquifer forms a major part of the sustainable groundwater management strategy. However, the estimated groundwater recharge upstream in the catchment plays a significant role; it contributes to groundwater flow upstream in the catchment, which in turn contribute to groundwater flow in the delta aquifer downstream.
- Artificial recharge plays a significant role in calculating the groundwater balance of the delta aquifers in the Namib Desert; about 52 to 89 % of the total inflow can infiltrate and give rise to the groundwater levels. The artificial recharge contributes to the total inflow and increases the sustainable yield of the delta or alluvial aquifer. Therefore, suitable infiltration sites should be established in ephemeral rivers for artificial recharge and groundwater storage.
- The simulated steady state model revealed high evapotranspiration rate at low abstraction rate and the simulated heads are much deeper at high abstraction rate. The calibrated steady state model also indicated that the change of abstraction rate affects the groundwater balance components and the simulated heads.

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# Appendix 1: Hydrochemical data of selected boreholes of the Omdel Aquifer (mg/l)

| BH NO | TDS | Na | K | Ca | Mg | $HCO_3$ | $CO_3$ | $SO_4$ | Cl | $NO_3$ | F |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 16953 | 1017 | 210 | 10 | 60 | 20.87 | 229.2096 | 112.8 | 67 | 315 | 9.73852 | 0.2 |
| 16953 | 701 | 147 | 8 | 44.8 | 16 | 180.4416 | 88.8 | 53 | 192 | 15.4931 | 0.6 |
| 16953 | 943.36 | 197 | 9 | 64 | 21.24 | 224.48 | 110.4 | 68 | 320 | 3.9 | 0.5 |
| 16953 | 935.32 | 189 | 9 | 50 | 15.17 | 219.6 | 108 | 73 | 245 | 3.9 | 0.8 |
| 21488 | 974 | 185 | 9 | 72 | 25 | 204.8256 | 100.8 | 56 | 305 | 13.2798 | 0.4 |
| 21488 | 1088 | 205 | 11 | 72.8 | 25.97 | 190.1952 | 99.6 | 62 | 385 | 9.29586 | 0.2 |
| 21488 | 1028.45 | 187 | 10 | 59 | 19.22 | 229.36 | 112.8 | 61 | 285 | 3.3 | 0.5 |
| 21488 | 979.54 | 187 | 10 | 63 | 21.24 | 202.52 | 99.6 | 65 | 285 | 3.7 | 0.6 |
| 22188 | 1035 | 189 | 14 | 94.8 | 25 | 199.9488 | 98.4 | 74 | 350 | 19.9197 | 0.1 |
| 22188 | 1151.73 | 220 | 12 | 100 | 26.29 | 202.52 | 99.6 | 90 | 380 | 4.47 | 0.5 |
| 22188 | 1561.1 | 595 | 6 | 6 | 6.07 | 1041.88 | 512.4 | 205 | 128 | 1.9 | 6 |
| 22188 | 1594.6 | 600 | 7 | 6 | 6.07 | 1078.48 | 530.4 | 178 | 120 | 1.6 | 5.3 |
| 100157 | 1346.7 | 205 | 13 | 121 | 24.27 | 229.36 | 112.8 | 104 | 395 | 2.9 | 0.5 |
| 100157 | 1264.29 | 215 | 13 | 101 | 21.24 | 234.24 | 115.2 | 100 | 385 | 2.7 | 0.5 |
| 100157 | 1327.94 | 235 | 13 | 117 | 25.28 | 231.8 | 114 | 141 | 375 | 3.3 | 0.5 |
| 22194 | 2157.4 | 535 | 16 | 103 | 35.4 | 236.68 | 116.4 | 240 | 840 | 7.8 | 0.8 |
| 22194 | 1809 | 420 | 17 | 112 | 37.42 | 219.6 | 108 | 260 | 620 | 7.3 | 0.6 |
| 22194 | 2251.2 | 460 | 17 | 106 | 35.4 | 222.04 | 109.2 | 190 | 730 | 6.7 | 0.9 |
| 22194 | 2278 | 500 | 16 | 99 | 34.39 | 222.04 | 109.2 | 210 | 700 | 8.5 | 0.9 |
| 29090 | 1494.1 | 260 | 15 | 106 | 38.42 | 124.44 | 61.2 | 131 | 520 | 4.1 | 0.6 |
| 29072 | 1353.4 | 245 | 13 | 104 | 22.25 | 231.8 | 114 | 128 | 385 | 2.9 | 0.6 |
| 28773 | 1688.4 | 340 | 15 | 112 | 35.4 | 143.96 | 70.8 | 142 | 600 | 4.2 | 0.6 |
| 27309 | 1324.59 | 210 | 14 | 98 | 33.37 | 158.6 | 78 | 109 | 400 | 3.3 | 0.5 |
| 27306 | 1634.8 | 320 | 15 | 106 | 37.43 | 151.28 | 74.4 | 132 | 570 | 4.1 | 0.6 |
| 27029 | 1675 | 370 | 13 | 61 | 30.34 | 78.08 | 38.4 | 49 | 660 | 1.8 | 0.8 |
| 26743 | 1842.5 | 320 | 12 | 139 | 35.39 | 34.16 | 16.8 | 47 | 760 | 4.4 | 0.9 |
| 27030 | 1960 | 355 | 17 | 142 | 53 | 154 | 75.6 | 170 | 720 | 24.3 | 0.2 |
| 27032 | 1894 | 380 | 16 | 124 | 52 | 102 | 50.4 | 145 | 775 | 26.6 | 0.2 |
| 16663 | 2599.6 | 710 | 45 | 80 | 40.45 | 322.08 | 158.4 | 180 | 980 | 0.5 | 1.2 |
| 29087 | 2190.9 | 930 | 17.9 | 27 | 14.67 | 112.73 | 55.4 | 200 | 1210 | 4.14 | 0.3 |
| 16485 | 6840.7 | 1660 | 45 | 500 | 179 | 165.92 | 81.6 | 420 | 3400 | 14.8 | 0.6 |
| 21926 | 4234 | 1440 | 24 | 56 | 23.25 | 183 | 90 | 580 | 1760 | 6.55 | 2.2 |
| 27032 | 1894 | 380 | 16 | 124.16 | 51.96 | 102.4 | 50.4 | 145 | 775 | 26.6 | 0.2 |
| 21499 | 672.68 | 144 | 7 | 45 | 14.16 | 180.56 | 88.8 | 50 | 199 | 3.7 | 0.7 |
| 16953 | 898.47 | 189 | 9 | 59 | 19.22 | 229.36 | 112.8 | 74 | 260 | 3.7 | 0.7 |
| 21643 | 634.49 | 136 | 7 | 40 | 13.15 | 185.44 | 91.2 | 51 | 178 | 3.8 | 0.8 |
| 21485 | 1061.28 | 190 | 10 | 71 | 26.29 | 180.56 | 88.8 | 67 | 345 | 4.3 | 0.7 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 100096 | 1160.44 | 205 | 10 | 72 | 25.28 | 173.24 | 85.2 | 69 | 345 | 5.3 | 0.7 |
| 21646 | 952.07 | 180 | 9 | 62 | 20.23 | 197.64 | 97.2 | 60 | 265 | 3.8 | 0.6 |
| 21488 | 938 | 185 | 10 | 66 | 21.24 | 214.72 | 105.6 | 62 | 270 | 3.5 | 0.6 |
| 100095 | 1135.65 | 197 | 11 | 80 | 30.34 | 153.72 | 75.6 | 57 | 370 | 5.5 | 0.6 |
| 21649 | 804.67 | 125 | 9 | 65 | 21.24 | 185.44 | 91.2 | 54 | 200 | 4.1 | 0.5 |
| 35339 | 1026.44 | 178 | 10 | 76 | 25.28 | 200.08 | 98.4 | 70 | 310 | 4.1 | 0.5 |
| 21491 | 946.71 | 190 | 9 | 60 | 19.22 | 224.48 | 110.4 | 69 | 290 | 4.4 | 0.7 |
| 21492 | 989.59 | 205 | 11 | 68 | 23.25 | 209.84 | 103.2 | 81 | 295 | 4.6 | 0.6 |
| 35338 | 1097.46 | 175 | 13 | 95 | 24.27 | 180.56 | 88.8 | 88 | 315 | 4.9 | 0.5 |
| 35337 | 1097.46 | 190 | 11 | 92 | 26.29 | 195.2 | 96 | 82 | 345 | 4.1 | 0.5 |
| 35336 | 798.64 | 142 | 9 | 68 | 19.22 | 197.64 | 97.2 | 56 | 246 | 4.1 | 0.5 |
| 22188 | 1151.73 | 220 | 12 | 100 | 26.29 | 202.52 | 99.6 | 90 | 380 | 4.5 | 0.5 |
| 21495 | 917.9 | 148 | 11 | 80 | 20.23 | 204.96 | 100.8 | 76 | 230 | 4.6 | 0.5 |
| 100140 | 1153.07 | 195 | 11 | 84 | 30.34 | 156.16 | 76.8 | 60 | 370 | 5.5 | 0.6 |
| 22187 | 1171.16 | 255 | 11 | 61 | 19.22 | 234.24 | 115.2 | 110 | 360 | 5.6 | 0.9 |
| 35341 | 1594.6 | 370 | 10 | 55 | 19.22 | 231.8 | 114 | 139 | 500 | 8.4 | 1.4 |
| 35342 | 1681.7 | 390 | 13 | 66 | 18.2 | 248.88 | 122.4 | 163 | 510 | 5 | 1.3 |
| 22195 | 1527.6 | 255 | 15 | 122 | 30.34 | 248.88 | 122.4 | 156 | 460 | 4.1 | 0.5 |
| 16484 | 5654.8 | 1080 | 36 | 680 | 168 | 170.8 | 84 | 320 | 2850 | 19.4 | 0.4 |
| 16485 | 6947.9 | 1520 | 46 | 520 | 177 | 104.92 | 51.6 | 500 | 3540 | 15.2 | 0.5 |
| 16493 | 1762.1 | 4300 | 109 | 1100 | 506 | 226.92 | 111.6 | 2200 | 8700 | 36.4 | 0.7 |
| 16493 | 1749 | 510 | 10.2 | 105 | 50.6 | 112.24 | 55.2 | 106 | 980 | 3.6 | 0.9 |
| 16497 | 1005.67 | 208 | 11 | 88 | 26.29 | 219.6 | 108 | 140 | 320 | 3.02 | 0.5 |
| 25579 | 9983 | 2860 | 66 | 580 | 205.29 | 224.48 | 110.4 | 540 | 5250 | 19.7 | 0.7 |
| 25992 | 6753.6 | 1060 | 26 | 729 | 343.93 | 21.96 | 10.8 | 23 | 3700 | 0.5 | 0.6 |
| 100039 | 1414 | 306 | 15 | 91.2 | 15.29 | 46.36 | 22.8 | 38 | 623 | 0.5 | 0.3 |
| 100041 | 1637 | 300 | 16 | 142 | 28.88 | 331.84 | 163.2 | 100 | 564 | 0.5 | 4.3 |
| 100044 | 2521 | 350 | 30 | 404.4 | 54.85 | 1318.82 | 648.6 | 265 | 546 | 0.5 | 3.8 |
| 100045 | 1954 | 375 | 17 | 384.4 | 43.93 | 268.4 | 132 | 180 | 1072 | 1.7 | 4 |
| 100046 | 2277 | 350 | 35 | 384.4 | 39.08 | 808.86 | 397.8 | 175 | 836 | 0.5 | 5.9 |
| 100047 | 5069 | 1180 | 36 | 339.6 | 95.87 | 400.16 | 196.8 | 320 | 2255 | 0.5 | 7.3 |
| 100048 | 2686 | 420 | 22 | 299.6 | 69.9 | 213.5 | 105 | 220 | 1126 | 5.6 | 4 |
| 100049 | 3082 | 540 | 20 | 309.6 | 71.84 | 185.44 | 91.2 | 220 | 1230 | 12 | 0.4 |
| 100050 | 4330 | 660 | 25 | 487.91 | 82.04 | 346.48 | 170.4 | 220 | 1660 | 0.5 | 0.6 |
| 100051 | 4250 | 680 | 25 | 379.6 | 89.08 | 217.16 | 106.8 | 220 | 1680 | 9.5 | 0.5 |
| 100053 | 5115 | 820 | 24 | 459.6 | 99.03 | 224.48 | 110.4 | 200 | 2080 | 15.5 | 0.6 |
| 100054 | 1927 | 390 | 30 | 144.8 | 23.06 | 392.84 | 193.2 | 45 | 640 | 1 | 0.6 |
| 100055 | 4204 | 690 | 25 | 369.6 | 83.01 | 295.24 | 145.2 | 240 | 1590 | 10 | 0.5 |
| 100056 | 9233 | 2750 | 46 | 549.2 | 195.87 | 790.56 | 388.8 | 200 | 5500 | 0.5 | 0.8 |
| 100057 | 4508 | 550 | 35 | 649.2 | 94.9 | 1300.52 | 639.6 | 200 | 1300 | 0.5 | 0.4 |
| 100058 | 8052 | 1500 | 45 | 599.2 | 185.92 | 339.16 | 166.8 | 240 | 3550 | 0.5 | 0.5 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 100059 | 5696 | 940 | 22 | 519.2 | 116.99 | 190.32 | 93.6 | 220 | 2380 | 18 | 0.3 |
| 100060 | 6646 | 920 | 29 | 699.2 | 163.83 | 134.2 | 66 | 200 | 2780 | 24 | 0.4 |
| 100061 | 3043 | 570 | 34 | 289.6 | 69.9 | 761.28 | 374.4 | 520 | 720 | 0.5 | 0.5 |
| 100062 | 9121 | 2500 | 65 | 829.2 | 151.94 | 2366.8 | 470.87 | 460 | 3800 | 0.5 | 0.8 |

# Appendix 2: Cation and Anion balance of selected boreholes of the Omdel Aquifer (meq/l)

| BH NO | Na | K | Ca | Mg | $HCO_3$ | $NO_3$ | $SO_4$ | Cl | F | CATION | ANIONS | Balance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16953 | 9.135 | 0.2558 | 2.994 | 1.716349 | 3.756745 | 0.695341 | 1.39494 | 8.883 | 0.01052 | 14.10115 | 14.74055 | -0.02217 |
| 16953 | 6.3945 | 0.20464 | 2.23552 | 1.31584 | 2.957438 | 1.106224 | 1.10346 | 5.4144 | 0.03156 | 10.1505 | 10.61308 | -0.02228 |
| 16953 | 8.5695 | 0.23022 | 3.1936 | 1.746778 | 3.679227 | 0.278464 | 1.41576 | 9.024 | 0.0263 | 13.7401 | 14.42375 | -0.02427 |
| 16953 | 8.2215 | 0.23022 | 2.495 | 1.247581 | 3.599244 | 0.278464 | 1.51986 | 6.909 | 0.04208 | 12.1943 | 12.34865 | -0.00629 |
| 21488 | 8.0475 | 0.23022 | 3.5928 | 2.056 | 3.357092 | 0.948192 | 1.16592 | 8.601 | 0.02104 | 13.92652 | 14.09324 | -0.00595 |
| 21488 | 8.9175 | 0.28138 | 3.63272 | 2.135773 | 3.117299 | 0.663734 | 1.29084 | 10.857 | 0.01052 | 14.96737 | 15.93939 | -0.03145 |
| 21488 | 8.1345 | 0.2558 | 2.9441 | 1.580653 | 3.75921 | 0.235623 | 1.27002 | 8.037 | 0.0263 | 12.91505 | 13.32815 | -0.01574 |
| 21488 | 8.1345 | 0.2558 | 3.1437 | 1.746778 | 3.319303 | 0.264184 | 1.3533 | 8.037 | 0.03156 | 13.28078 | 13.00535 | 0.010478 |
| 22188 | 8.2215 | 0.35812 | 4.73052 | 2.056 | 3.277161 | 1.422288 | 1.54068 | 9.87 | 0.00526 | 15.36614 | 16.11539 | -0.0238 |
| 22188 | 9.57 | 0.30696 | 4.99 | 2.16209 | 3.319303 | 0.319163 | 1.8738 | 10.716 | 0.0263 | 17.02905 | 16.25457 | 0.023269 |
| 22188 | 25.8825 | 0.15348 | 0.2994 | 0.499197 | 17.07641 | 0.135662 | 4.2681 | 3.6096 | 0.3156 | 26.83458 | 25.40538 | 0.027358 |
| 22188 | 26.1 | 0.17906 | 0.2994 | 0.499197 | 17.67629 | 0.114242 | 3.70596 | 3.384 | 0.27878 | 27.07766 | 25.15927 | 0.036725 |
| 100157 | 8.9175 | 0.33254 | 6.0379 | 1.995965 | 3.75921 | 0.207063 | 2.16528 | 11.139 | 0.0263 | 17.2839 | 17.29685 | -0.00037 |
| 100157 | 9.3525 | 0.33254 | 5.0399 | 1.746778 | 3.839194 | 0.192783 | 2.082 | 10.857 | 0.0263 | 16.47172 | 16.99728 | -0.0157 |
| 100157 | 10.2225 | 0.33254 | 5.8383 | 2.079027 | 3.799202 | 0.235623 | 2.93562 | 10.575 | 0.0263 | 18.47237 | 17.57175 | 0.024987 |
| 22194 | 23.2725 | 0.40928 | 5.1397 | 2.911296 | 3.879185 | 0.556928 | 4.9968 | 23.688 | 0.04208 | 31.73278 | 33.16299 | -0.02204 |
| 22194 | 18.27 | 0.43486 | 5.5888 | 3.077421 | 3.599244 | 0.521228 | 5.4132 | 17.484 | 0.03156 | 27.37108 | 27.04923 | 0.005914 |
| 22194 | 20.01 | 0.43486 | 5.2894 | 2.911296 | 3.639236 | 0.478387 | 3.9558 | 20.586 | 0.04734 | 28.64556 | 28.70676 | -0.00107 |
| 22194 | 21.75 | 0.40928 | 4.9401 | 2.828234 | 3.639236 | 0.606909 | 4.3722 | 19.74 | 0.04734 | 29.92761 | 28.40568 | 0.02609 |
| 29090 | 11.31 | 0.3837 | 5.2894 | 3.159661 | 2.039572 | 0.292744 | 2.72742 | 14.664 | 0.03156 | 20.14276 | 19.7553 | 0.009711 |
| 29072 | 10.6575 | 0.33254 | 5.1896 | 1.82984 | 3.799202 | 0.207063 | 2.66496 | 10.857 | 0.03156 | 18.00948 | 17.55979 | 0.012643 |
| 28773 | 14.79 | 0.3837 | 5.5888 | 2.911296 | 2.359504 | 0.299884 | 2.95644 | 16.92 | 0.03156 | 23.6738 | 22.56739 | 0.023927 |
| 27309 | 9.135 | 0.35812 | 4.8902 | 2.744349 | 2.599454 | 0.235623 | 2.26938 | 11.28 | 0.0263 | 17.12767 | 16.41076 | 0.021376 |
| 27306 | 13.92 | 0.3837 | 5.2894 | 3.078243 | 2.479479 | 0.292744 | 2.74824 | 16.074 | 0.03156 | 22.67134 | 21.62602 | 0.023598 |
| 27029 | 16.095 | 0.33254 | 3.0439 | 2.495162 | 1.279731 | 0.128522 | 1.02018 | 18.612 | 0.04208 | 21.9666 | 21.08251 | 0.020537 |
| 26743 | 13.92 | 0.30696 | 6.9361 | 2.910474 | 0.559882 | 0.314165 | 0.97854 | 21.432 | 0.04734 | 24.07353 | 23.33193 | 0.015644 |
| 27030 | 15.4425 | 0.43486 | 7.0858 | 4.35872 | 2.52406 | 1.735046 | 3.5394 | 20.304 | 0.01052 | 27.32188 | 28.11303 | -0.01427 |
| 27032 | 16.53 | 0.40928 | 6.1876 | 4.27648 | 1.67178 | 1.899268 | 3.0189 | 21.855 | 0.01052 | 27.40336 | 28.45547 | -0.01884 |
| 16663 | 30.885 | 1.1511 | 3.992 | 3.326608 | 5.278891 | 0.035701 | 3.7476 | 27.636 | 0.06312 | 39.35471 | 36.76131 | 0.034072 |
| 29087 | 40.455 | 0.457882 | 1.3473 | 1.206461 | 1.847645 | 0.2956 | 4.164 | 34.122 | 0.01578 | 43.46664 | 40.44503 | 0.03601 |
| 16485 | 72.21 | 1.1511 | 24.95 | 14.72096 | 2.719429 | 1.056736 | 8.7444 | 95.88 | 0.03156 | 113.0321 | 108.4321 | 0.020771 |
| 21926 | 62.64 | 0.61392 | 2.7944 | 1.91208 | 2.99937 | 0.467677 | 12.0756 | 49.632 | 0.11572 | 67.9604 | 65.29037 | 0.020038 |
| 27032 | 16.53 | 0.40928 | 6.195584 | 4.27319 | 1.678336 | 1.899268 | 3.0189 | 21.855 | 0.01052 | 27.40805 | 28.46202 | -0.01886 |
| 21499 | 6.264 | 0.17906 | 2.2455 | 1.164518 | 2.959378 | 0.264184 | 1.041 | 5.6118 | 0.03682 | 9.853078 | 9.913182 | -0.00304 |
| 16953 | 8.2215 | 0.23022 | 2.9441 | 1.580653 | 3.75921 | 0.264184 | 1.54068 | 7.332 | 0.03682 | 12.97647 | 12.93289 | 0.001682 |
| 21643 | 5.916 | 0.17906 | 1.996 | 1.081456 | 3.039362 | 0.271324 | 1.06182 | 5.0196 | 0.04208 | 9.172516 | 9.434186 | -0.01406 |
| 21485 | 8.265 | 0.2558 | 3.5429 | 2.16209 | 2.959378 | 0.307025 | 1.39494 | 9.729 | 0.03682 | 14.22579 | 14.42716 | -0.00703 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100096 | 8.9175 | 0.2558 | 3.5928 | 2.079027 | 2.839404 | 0.378426 | 1.43658 | 9.729 | 0.03682 | 14.84513 | 14.42023 | 0.014519 |
| 21646 | 7.83 | 0.23022 | 3.0938 | 1.663715 | 3.23932 | 0.271324 | 1.2492 | 7.473 | 0.03156 | 12.81774 | 12.2644 | 0.022061 |
| 21488 | 8.0475 | 0.2558 | 3.2934 | 1.746778 | 3.519261 | 0.249904 | 1.29084 | 7.614 | 0.03156 | 13.34348 | 12.70556 | 0.024489 |
| 100095 | 8.5695 | 0.28138 | 3.992 | 2.495162 | 2.519471 | 0.392706 | 1.18674 | 10.434 | 0.03156 | 15.33804 | 14.56448 | 0.02587 |
| 21649 | 5.4375 | 0.23022 | 3.2435 | 1.746778 | 3.039362 | 0.292744 | 1.12428 | 5.64 | 0.0263 | 10.658 | 10.12269 | 0.02576 |
| 35339 | 7.743 | 0.2558 | 3.7924 | 2.079027 | 3.279311 | 0.292744 | 1.4574 | 8.742 | 0.0263 | 13.87023 | 13.79776 | 0.002619 |
| 21491 | 8.265 | 0.23022 | 2.994 | 1.580653 | 3.679227 | 0.314165 | 1.43658 | 8.178 | 0.03682 | 13.06987 | 13.64479 | -0.02152 |
| 21492 | 8.9175 | 0.28138 | 3.3932 | 1.91208 | 3.439278 | 0.328445 | 1.68642 | 8.319 | 0.03156 | 14.50416 | 13.8047 | 0.024708 |
| 35338 | 7.6125 | 0.33254 | 4.7405 | 1.995965 | 2.959378 | 0.349865 | 1.83216 | 8.883 | 0.0263 | 14.6815 | 14.0507 | 0.021954 |
| 35337 | 8.265 | 0.28138 | 4.5908 | 2.16209 | 3.199328 | 0.292744 | 1.70724 | 9.729 | 0.0263 | 15.29927 | 14.95461 | 0.011392 |
| 35336 | 6.177 | 0.23022 | 3.3932 | 1.580653 | 3.23932 | 0.292744 | 1.16592 | 6.9372 | 0.0263 | 11.38107 | 11.66148 | -0.01217 |
| 22188 | 9.57 | 0.30696 | 4.99 | 2.16209 | 3.319303 | 0.321305 | 1.8738 | 10.716 | 0.0263 | 17.02905 | 16.25671 | 0.023203 |
| 21495 | 6.438 | 0.28138 | 3.992 | 1.663715 | 3.359294 | 0.328445 | 1.58232 | 6.486 | 0.0263 | 12.3751 | 11.78236 | 0.024536 |
| 100140 | 8.4825 | 0.28138 | 4.1916 | 2.495162 | 2.559462 | 0.392706 | 1.2492 | 10.434 | 0.03156 | 15.45064 | 14.66693 | 0.026022 |
| 22187 | 11.0925 | 0.28138 | 3.0439 | 1.580653 | 3.839194 | 0.399846 | 2.2902 | 10.152 | 0.04734 | 15.99843 | 16.72858 | -0.02231 |
| 35341 | 16.095 | 0.2558 | 2.7445 | 1.580653 | 3.799202 | 0.599769 | 2.89398 | 14.1 | 0.07364 | 20.67595 | 21.46659 | -0.01876 |
| 35342 | 16.965 | 0.33254 | 3.2934 | 1.496768 | 4.079143 | 0.357005 | 3.39366 | 14.382 | 0.06838 | 22.08771 | 22.28019 | -0.00434 |
| 22195 | 11.0925 | 0.3837 | 6.0878 | 2.495162 | 4.079143 | 0.292744 | 3.24792 | 12.972 | 0.0263 | 20.05916 | 20.61811 | -0.01374 |
| 16484 | 46.98 | 0.92088 | 33.932 | 13.81632 | 2.799412 | 1.385181 | 6.6624 | 80.37 | 0.02104 | 95.6492 | 91.23803 | 0.023603 |
| 16485 | 66.12 | 1.17668 | 25.948 | 14.55648 | 1.719639 | 1.085296 | 10.41 | 99.828 | 0.0263 | 107.8012 | 113.0692 | -0.02385 |
| 16493 | 187.05 | 2.78822 | 54.89 | 41.61344 | 3.719219 | 2.598999 | 45.804 | 245.34 | 0.03682 | 286.3417 | 297.499 | -0.01911 |
| 16493 | 22.185 | 0.260916 | 5.2395 | 4.161344 | 1.839614 | 0.257044 | 2.20692 | 27.636 | 0.04734 | 31.84676 | 31.98692 | -0.0022 |
| 16497 | 9.048 | 0.28138 | 4.3912 | 2.16209 | 3.599244 | 0.215631 | 2.9148 | 9.024 | 0.0263 | 15.88267 | 15.77998 | 0.003243 |
| 25579 | 124.41 | 1.68828 | 28.942 | 16.88305 | 3.679227 | 1.406601 | 11.2428 | 148.05 | 0.03682 | 171.9233 | 164.4154 | 0.022322 |
| 25992 | 46.11 | 0.66508 | 36.3771 | 28.2848 | 0.359924 | 0.035701 | 0.47886 | 104.34 | 0.03156 | 111.437 | 105.246 | 0.028571 |
| 100039 | 13.311 | 0.3837 | 4.55088 | 1.25745 | 0.75984 | 0.035701 | 0.79116 | 17.5686 | 0.01578 | 19.50303 | 19.17108 | 0.008583 |
| 100041 | 13.05 | 0.40928 | 7.0858 | 2.375091 | 5.438858 | 0.035701 | 2.082 | 15.9048 | 0.22618 | 22.92017 | 23.68754 | -0.01646 |
| 100044 | 15.225 | 0.7674 | 20.17956 | 4.510864 | 21.61546 | 0.035701 | 5.5173 | 15.3972 | 0.19988 | 40.68282 | 42.76554 | -0.02496 |
| 100045 | 16.3125 | 0.43486 | 19.18156 | 3.612803 | 4.399076 | 0.121382 | 3.7476 | 30.2304 | 0.2104 | 39.54172 | 38.70886 | 0.010644 |
| 100046 | 15.225 | 0.8953 | 19.18156 | 3.213939 | 13.25722 | 0.035701 | 3.6435 | 23.5752 | 0.31034 | 38.5158 | 40.82196 | -0.02907 |
| 100047 | 51.33 | 0.92088 | 16.94604 | 7.884349 | 6.558622 | 0.035701 | 6.6624 | 63.591 | 0.38398 | 77.08127 | 77.2317 | -0.00097 |
| 100048 | 18.27 | 0.56276 | 14.95004 | 5.748576 | 3.499265 | 0.399846 | 4.5804 | 31.7532 | 0.2104 | 39.53138 | 40.44311 | -0.0114 |
| 100049 | 23.49 | 0.5116 | 15.44904 | 5.908122 | 3.039362 | 0.856813 | 4.5804 | 34.686 | 0.02104 | 45.35876 | 43.18361 | 0.024566 |
| 100050 | 28.71 | 0.6395 | 24.34671 | 6.74697 | 5.678807 | 0.035701 | 4.5804 | 46.812 | 0.03156 | 60.44318 | 57.13847 | 0.028106 |
| 100051 | 29.58 | 0.6395 | 18.94204 | 7.325939 | 3.559252 | 0.67831 | 4.5804 | 47.376 | 0.0263 | 56.48748 | 56.22026 | 0.002371 |
| 100053 | 35.67 | 0.61392 | 22.93404 | 8.144227 | 3.679227 | 1.106716 | 4.164 | 58.656 | 0.03156 | 67.36219 | 67.6375 | -0.00204 |
| 100054 | 16.965 | 0.7674 | 7.22552 | 1.896454 | 6.438648 | 0.071401 | 0.9369 | 18.048 | 0.03156 | 26.85437 | 25.52651 | 0.02535 |
| 100055 | 30.015 | 0.6395 | 18.44304 | 6.826742 | 4.838984 | 0.714011 | 4.9968 | 44.838 | 0.0263 | 55.92428 | 55.41409 | 0.004582 |
| 100056 | 119.625 | 1.17668 | 27.40508 | 16.10835 | 12.95728 | 0.035701 | 4.164 | 155.1 | 0.04208 | 164.3151 | 172.2991 | -0.02372 |
| 100057 | 23.925 | 0.8953 | 32.39508 | 7.804576 | 21.31552 | 0.035701 | 4.164 | 36.66 | 0.02104 | 65.01996 | 62.19626 | 0.022196 |
| 100058 | 65.25 | 1.1511 | 29.90008 | 15.29006 | 5.558832 | 0.035701 | 4.9968 | 100.11 | 0.0263 | 111.5912 | 110.7276 | 0.003885 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100059 | 40.89 | 0.56276 | 25.90808 | 9.621258 | 3.119345 | 1.285219 | 4.5804 | 67.116 | 0.01578 | 76.9821 | 76.11674 | 0.005652 |
| 100060 | 40.02 | 0.74182 | 34.89008 | 13.47338 | 2.199538 | 1.713625 | 4.164 | 78.396 | 0.02104 | 89.12528 | 86.4942 | 0.014982 |
| 100061 | 24.795 | 0.86972 | 14.45104 | 5.748576 | 12.47738 | 0.035701 | 10.8264 | 20.304 | 0.0263 | 45.86434 | 43.66978 | 0.024511 |
| 100062 | 108.75 | 1.6627 | 41.37708 | 12.49555 | 38.79185 | 0.035701 | 9.5772 | 107.16 | 0.04208 | 164.2853 | 155.6068 | 0.027129 |

# Appendix 3: Production boreholes

| Borehole No. | Latitude | Longitude | Abstraction rate ($m^3/h$) |
|---|---|---|---|
| 16953 | -22.0831 | 14.25330 | 9.1 |
| 21500 | -22.06047 | 14.2914 | 36.7 |
| 21499 | -22.0748 | 14.2597 | 12 |
| 21492 | -22.00006 | 14.35199 | 20.1 |
| 21491 | -22.01098 | 14.3423 | 42.6 |
| 21489 | -22.02925 | 14.32242 | 42 |
| 21488 | -22.04126 | 14.31117 | 49.1 |
| 21487 | -22.04448 | 14.30084 | 12.1 |
| 21486 | -22.05889 | 14.28092 | 32.8 |
| 21485 | -22.06378 | 14.27373 | 45.1 |
| 21642 | -22.07898 | 14.269 | 39.7 |
| 21643 | -22.06271 | 14.26641 | 43.7 |
| 21646 | -22.05421 | 14.29877 | 28.4 |
| 21647 | -22.03985 | 14.29511 | 9.9 |
| 21648 | -22.04667 | 14.31074 | 50.1 |
| 21649 | -22.02991 | 14.33318 | 17.3 |
| 22187 | -21.95097 | 14.41036 | 44.8 |
| 22188 | -21.96349 | 14.38171 | 43.8 |
| 22186 | -21.93594 | 14.42195 | 23.8 |
| 22192 | -21.93555 | 14.43991 | 4.8 |
| 22194 | -21.91525 | 14.45983 | 21.6 |
| 22188 | -21.96349 | 14.38171 | 43.8 |
| 22567 | -21.95488 | 14.41641 | 24.2 |
| 21501 | -22.0296 | 14.31372 | 20.5 |

# Appendix 4: Monitoring boreholes

| Borehole No. | Latitude | Longitude | Elevation (mamsl) |
|---|---|---|---|
| 16479 | -22.0116 | 14.19067 | 0.88 |
| 16480 | -22.0566 | 14.2291 | 1.26 |
| 16484 | -22.1388 | 14.31772 | 12.21 |
| 16485 | -22.1164 | 14.341 | 33 |
| 16486 | -22.0677 | 14.2716 | 11.54 |
| 16489 | -22.0159 | 14.2582 | 32.07 |
| 16490 | -21.9921 | 14.23747 | 16.34 |
| 16492 | -22.0017 | 14.3311 | 67.8 |
| 16493 | -22.0712 | 14.38789 | 67.68 |
| 16495 | -21.9551 | 14.365 | 115.4 |
| 16496 | -21.9886 | 14.39109 | 114.15 |
| 16498 | -21.9606 | 14.44292 | 142.56 |
| 16499 | -21.8889 | 14.45683 | 170.38 |
| 16500 | -21.8902 | 14.4986 | 181.3 |
| 16501 | -21.8994 | 14.4929 | 188.1 |
| 16576 | -21.9163 | 14.40619 | 147.37 |
| 16657 | -21.8953 | 14.511 | 211.53 |
| 16658 | -21.8959 | 14.50415 | 202.55 |
| 16661 | -22.0322 | 14.2126 | 3.44 |
| 16662 | -21.9207 | 14.46821 | 170.2 |
| 16663 | -22.0915 | 14.32028 | 30.88 |
| 16925 | -21.8872 | 14.4747 | 176.26 |
| 16947 | -22.0514 | 14.2883 | 24.36 |
| 21498 | -21.9492 | 14.43342 | 144.46 |
| 21641 | -22.0716 | 14.24962 | -1.5 |
| 21650 | -22.0169 | 14.3489 | 68.45 |
| 21651 | -21.9847 | 14.3808 | 83.24 |
| 22194 | -21.9153 | 14.45983 | 166.83 |
| 21709 | -21.9614 | 14.3936 | 120.42 |
| 21924 | -21.8875 | 14.4711 | 175.39 |
| 21926 | -21.8763 | 14.49034 | 175.8 |
| 21927 | -21.9258 | 14.4528 | 161.44 |

| | | | |
|---|---|---|---|
| 21928 | -21.9254 | 14.45185 | 158.8 |
| 22165 | -22.0901 | 14.2618 | 2.05 |
| 22166 | -22.0877 | 14.2599 | 2.23 |
| 25408 | -21.8985 | 14.50779 | 208.27 |
| 25578 | -22.084 | 14.2496 | 1.02 |
| 25579 | -22.0911 | 14.37832 | 56.67 |
| 25990 | -22.0795 | 14.2503 | 1.83 |
| 25992 | -22.067 | 14.23795 | 1.11 |
| 25994 | -22.0915 | 14.2611 | 1.9 |
| 25996 | -22.0864 | 14.25592 | 2.03 |
| 26743 | -22.0251 | 14.21667 | 7.36 |
| 27312 | -21.9747 | 14.3567 | 103.58 |
| 28768 | -22.013 | 14.37646 | 97.4 |
| 28769 | -22.0214 | 14.34626 | 68.8 |
| 28773 | -21.9781 | 14.31063 | 75.69 |
| 28778 | -21.9281 | 14.26908 | 66.79 |
| 29066 | -22.0748 | 14.3073 | 26.6 |
| 29072 | -21.9606 | 14.36962 | 115.47 |
| 29084 | -22.0084 | 14.29513 | 56.3 |
| 29087 | -21.9503 | 14.24483 | 41.59 |
| 29089 | -22.0314 | 14.2711 | 29.25 |
| 29090 | -22.0244 | 14.26426 | 31.41 |
| 29092 | -22.0389 | 14.2772 | 28.96 |
| 29093 | -22.0031 | 14.2478 | 21.36 |
| 29095 | -21.9803 | 14.2286 | 16.31 |
| 29098 | -21.9978 | 14.1808 | 0.62 |
| 29102 | -22.0247 | 14.2006 | 1.65 |
| 29104 | -22.1319 | 14.3003 | 7.15 |
| 29106 | -22.0622 | 14.267 | 10.46 |
| 30683 | -22.0622 | 14.2672 | 10.42 |
| 30852 | -22.0844 | 14.2883 | 18.46 |
| 31241 | -21.9011 | 14.49271 | 187.33 |
| 31242 | -21.9004 | 14.4937 | 187.52 |
| 31243 | -21.9002 | 14.4942 | 187.71 |
| 31244 | -21.9002 | 14.495 | 186.26 |
| 31246 | -21.8995 | 14.4909 | 185.1 |

| | | | |
|---|---|---|---|
| 31365 | -21.8967 | 14.4923 | 184.11 |
| 31368 | -21.8994 | 14.4967 | 189.63 |
| 31369 | -21.8939 | 14.4996 | 183.64 |
| 31370 | -21.8982 | 14.4997 | 187.94 |
| 33066 | -21.8969 | 14.4885 | 180.64 |
| 33068 | -21.9004 | 14.4947 | 187.92 |
| 33069 | -21.9007 | 14.4939 | 187.8 |
| 33073 | -21.9007 | 14.4953 | 188.74 |
| 33074 | -21.9009 | 14.4937 | 187.64 |
| 33077 | -21.9002 | 14.4961 | 188.6 |
| 100051 | -22.0449 | 14.41877 | 97.56 |
| 100055 | -22.0677 | 14.40416 | 78.59 |
| 100056 | -22.1039 | 14.35706 | 41.57 |
| 16953 | -22.0831 | 14.2533 | 1.88 |
| 21500 | -22.0605 | 14.2914 | 22.73 |
| 21492 | -22.0001 | 14.35199 | 75.8 |
| 21491 | -22.011 | 14.3423 | 66.52 |
| 21489 | -22.0293 | 14.32242 | 47.32 |
| 21488 | -22.0413 | 14.31117 | 37.73 |
| 21487 | -22.0445 | 14.30084 | 32.98 |
| 21486 | -22.0589 | 14.28092 | 18.85 |
| 21485 | -22.0638 | 14.27373 | 13.62 |
| 21642 | -22.079 | 14.269 | 7.85 |
| 21643 | -22.0627 | 14.26641 | 10.6 |
| 21646 | -22.0542 | 14.29877 | 28.1 |
| 21647 | -22.0399 | 14.29511 | 31.64 |
| 21648 | -22.0467 | 14.31074 | 35.32 |
| 21649 | -22.0299 | 14.33318 | 51.98 |
| 22188 | -21.9635 | 14.38171 | 117.74 |
| 22186 | -21.9359 | 14.42195 | 145.05 |
| 22192 | -21.9356 | 14.43991 | 150.69 |
| 21708 | -21.9687 | 14.37802 | 111.97 |
| 100059 | -22.0903 | 14.38839 | 63.46 |

# Appendix 5: Transmissivity, hydraulic conductivity and storativity (S) of the Omdel Aquifer

| Borehole number | Latitude | Longtude | Transmissivity ($m^2/d$) | Storativity (S) | Saturated thickness (m) | K(m/d) |
|---|---|---|---|---|---|---|
| 22567 | -21.95488 | 14.41641 | 259 | 0.00036 | 42.7 | 6.065574 |
| 100094 | -21.9542 | 14.4169 | 74 | 0.0001 | 26.65 | 2.776735 |
| 100096 | -22.057 | 14.2814 | 54 | 0.0001 | 23.4 | 2.307692 |
| 100135 | -21.91811 | 14.45247 | 402 | 0.0001 | 77.4 | 5.193798 |
| 100137 | -21.90678 | 14.46211 | 70 | 0.0001 | 70.66 | 0.990659 |
| 100114 | -22.0543 | 14.29882 | 525 | 0.0001 | 38.7 | 13.56589 |
| 100113 | -22.03972 | 14.2848 | 159 | 0.0001 | 24.7 | 6.437247 |
| 100111 | -21.96323 | 14.38171 | 208 | 0.0001 | 56 | 3.714286 |
| 21501 | -22.0296 | 14.31372 | 624 | 0.01 | 17.37 | 35.92401 |
| 16494 | -21.97983 | 14.36881 | 218 | 0.0001 | 66.9 | 3.258595 |
| 16671 | -21.9776 | 14.3708 | 582 | 0.0001 | 68.9 | 8.447025 |
| 21486 | -22.05889 | 14.28092 | 29 | 0.0001 | 32.5 | 0.892308 |
| 21490 | -22.01994 | 14.33206 | 1174 | 0.01 | 68.3 | 17.18887 |
| 21491 | -22.01098 | 14.3423 | 830 | 0.0001 | 45.22 | 18.35471 |
| 21493 | -21.98976 | 14.35991 | 201 | 0.000268 | 51.7 | 3.887814 |
| 21494 | -21.97429 | 14.38242 | 115 | 0.0001 | 59.45 | 1.934399 |
| 21917 | -21.953 | 14.417 | 236 | 0.000788 | 44.2 | 5.339367 |
| 22188 | -21.96349 | 14.38171 | 451 | 0.0001 | 72 | 6.263889 |
| 22191 | -21.96286 | 14.42859 | 74 | 0.000116 | 69.2 | 1.069364 |
| 22193 | -21.92169 | 14.44637 | 450 | 0.0001 | 96.9 | 4.643963 |
| 22195 | -21.90026 | 14.46611 | 306 | 0.0001 | 72 | 4.25 |
| 33068 | -21.9004 | 14.4947 | 1389 | 0.0001 | 9.39 | 147.9233 |
| 33069 | -21.9007 | 14.4939 | 2307 | 0.0001 | 7.64 | 301.9634 |
| 33077 | -21.9002 | 14.4961 | 339 | 0.0001 | 10.86 | 31.21547 |
| 35336 | -21.97429 | 14.38242 | 65 | 0.0001 | 30.5 | 2.131148 |
| 35337 | -21.97983 | 14.36881 | 53 | 0.0001 | 31.2 | 1.698718 |
| 35338 | -21.98976 | 14.35991 | 17 | 0.0001 | 27.17 | 0.62569 |
| 35339 | -22.01994 | 14.33206 | 203 | 0.0001 | 9 | 22.55556 |
| 35340 | -21.94995 | 14.39366 | 138 | 0.000188 | 50.1 | 2.754491 |
| 35341 | -21.96286 | 14.42859 | 35 | 0.0001 | 37 | 0.945946 |
| 35342 | -21.92169 | 14.44637 | 208 | 0.0001 | 79.7 | 2.609787 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 35344 | -21.89118 | 14.47431 | 3916 | 0.0001 | 57.05 | 68.64154 |
| 100039 | -21.91692 | 14.53682 | 441 | 0.0001 | 20.56 | 21.44942 |
| 100041 | -21.92331 | 14.52169 | 727 | 0.0001 | 41.64 | 17.45917 |
| 100049 | -22.0347 | 14.43991 | 2505 | 0.0001 | 32.96 | 76.00121 |
| 100137 | -21.90678 | 14.46211 | 70 | 0.0001 | 70.66 | 0.990659 |
| 100138 | -21.89577 | 14.46929 | 228 | 0.0001 | 64.91 | 3.512556 |
| 100139 | -21.92813 | 14.44019 | 71 | 0.0001 | 35.07 | 2.024522 |
| 100140 | -21.95038 | 14.40246 | 363 | 0.0001 | 73.91 | 4.911379 |
| 100141 | -21.95687 | 14.38907 | 96 | 0.0001 | 40.84 | 2.350637 |
| 100142 | -21.94073 | 14.41072 | 1266 | 0.0001 | 12 | 105.5 |
| 100143 | -21.94516 | 14.42818 | 90 | 0.0001 | 47 | 1.914894 |
| 100144 | -21.95903 | 14.4068 | 129 | 0.0001 | 23.59 | 5.468419 |
| 100145 | -21.92656 | 14.43252 | 89 | 0.0001 | 64.52 | 1.379417 |
| 100146 | -21.94443 | 14.41901 | 157 | 0.0001 | 44.61 | 3.51939 |
| 100151 | -21.93007 | 14.44145 | 163 | 0.0001 | 40.62 | 4.012802 |
| 100152 | -21.9616 | 14.37522 | 37 | 0.0001 | 33.17 | 1.115466 |
| 100153 | -21.96178 | 14.37517 | 358 | 0.0001 | 56 | 6.392857 |
| 100154 | -21.95203 | 14.38655 | 62 | 0.0001 | - | - |
| 100155 | -21.94951 | 14.38552 | 1658 | 0.0001 | - | - |
| 100156 | -21.95444 | 14.38777 | 126 | 0.0001 | - | - |
| 100157 | -21.9497 | 14.38531 | 1232 | 0.0001 | 49.25 | 25.01523 |
| 100158 | -21.94938 | 14.38146 | 352 | 0.0001 | - | - |
| 100159 | -21.96477 | 14.37311 | 225 | 0.0001 | 8.15 | 27.60736 |

# Appendix 6: Observed vs simulated values

| Observation Name | Residual | Observed Value | Simulated Value | X | Y | Time | Object Name |
|---|---|---|---|---|---|---|---|
| WW16479 | 0.419682 | 0.88 | 0.460318 | 416465 | 7565672 | 1 | Waterelev_1 |
| WW16480 | -0.6849 | 1.26 | 1.944904 | 420456.9 | 7560707 | 1 | Waterelev_2 |
| WW16484 | 1.874685 | 12.21 | 10.33531 | 429642 | 7551657 | 1 | Waterelev_3 |
| WW16485 | 6.917042 | 33 | 26.08296 | 432032 | 7554145 | 1 | Waterelev_4 |
| WW16486 | 2.062148 | 11.54 | 9.477852 | 424848.2 | 7559500 | 1 | Waterelev_5 |
| WW16489 | -2.59058 | 32.07 | 34.66058 | 423437.8 | 7565227 | 1 | Waterelev_6 |
| WW16490 | -5.67329 | 16.34 | 22.01329 | 421285 | 7567851 | 1 | Waterelev_7 |
| WW16492 | -4.28581 | 67.8 | 72.08582 | 430955.3 | 7566834 | 1 | Waterelev_8 |
| WW16493 | -0.20052 | 67.68 | 67.88052 | 436848.2 | 7559168 | 1 | Waterelev_9 |
| WW16495 | -0.63885 | 115.4 | 116.0388 | 436436.1 | 7570351 | 1 | Waterelev_10 |
| WW16496 | 1.133774 | 114.15 | 113.0162 | 437141.9 | 7568315 | 1 | Waterelev_11 |
| WW16498 | -5.18904 | 142.56 | 147.749 | 442481.2 | 7571427 | 1 | Waterelev_12 |
| WW16499 | 2.265381 | 170.38 | 168.1146 | 443889.4 | 7579370 | 1 | Waterelev_13 |
| WW16500 | -5.93636 | 181.3 | 187.2364 | 448204.8 | 7579242 | 1 | Waterelev_14 |
| WW16501 | 1.87709 | 188.1 | 186.2229 | 447619.4 | 7578222 | 1 | Waterelev_15 |
| WW16576 | 1.666946 | 147.37 | 145.703 | 438669.7 | 7576319 | 1 | Waterelev_16 |
| WW16657 | 6.055908 | 211.53 | 205.4741 | 449487.6 | 7578681 | 1 | Waterelev_17 |
| WW16658 | 7.109436 | 202.55 | 195.4406 | 448780.2 | 7578613 | 1 | Waterelev_18 |
| WW16661 | 0.674129 | 3.44 | 2.765871 | 418740.4 | 7563399 | 1 | Waterelev_19 |
| WW16662 | 6.157776 | 170.2 | 164.0422 | 445077.2 | 7575854 | 1 | Waterelev_20 |
| WW16663 | 1.339865 | 30.88 | 29.54013 | 429882.6 | 7556892 | 1 | Waterelev_21 |
| WW16925 | 3.660461 | 176.26 | 172.5995 | 445734.8 | 7579566 | 1 | Waterelev_22 |
| WW16947 | -0.59389 | 24.36 | 24.95389 | 426562.9 | 7561313 | 1 | Waterelev_23 |
| WW16953 | 1.88 | 1.88 | 0 | 422968.4 | 7557786 | 1 | Waterelev_24 |
| WW21500 | 0.163984 | 22.73 | 22.56602 | 426887.4 | 7560310 | 1 | Waterelev_25 |
| WW21498 | -3.91994 | 144.73 | 148.6499 | 441495.6 | 7572693 | 1 | Waterelev_34 |
| WW21492 | -6.33953 | 75.8 | 82.13953 | 433110.9 | 7567025 | 1 | Waterelev_27 |
| WW21491 | -4.60323 | 66.52 | 71.12322 | 432115.8 | 7565812 | 1 | Waterelev_28 |
| WW21489 | -5.06381 | 47.32 | 52.38381 | 430072.8 | 7563780 | 1 | Waterelev_29 |
| WW21488 | -2.69709 | 37.73 | 40.42709 | 428917.7 | 7562446 | 1 | Waterelev_30 |
| WW21487 | 0.002979 | 32.98 | 32.97702 | 427853.3 | 7562084 | 1 | Waterelev_31 |
| WW21486 | 0.858557 | 18.85 | 17.99144 | 425805.2 | 7560480 | 1 | Waterelev_32 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| WW21485 | 1.646608 | 13.62 | 11.97339 | 425065.9 | 7559935 | 1 | Waterelev_33 |
| WW21498 | -3.91994 | 144.73 | 148.6499 | 441495.6 | 7572693 | 1 | Waterelev_34 |
| WW21642 | 1.493829 | 7.85 | 6.356171 | 424585.9 | 7558250 | 1 | Waterelev_35 |
| WW21643 | 1.447233 | 10.6 | 9.152767 | 424310.1 | 7560050 | 1 | Waterelev_36 |
| WW21641 | -2.96378 | -1.5 | 1.463782 | 422582.5 | 7559058 | 1 | Waterelev_37 |
| WW21646 | 0.158081 | 28.1 | 27.94192 | 427644.7 | 7561006 | 1 | Waterelev_38 |
| WW21647 | -1.3416 | 31.64 | 32.9816 | 427259.7 | 7562594 | 1 | Waterelev_39 |
| WW21648 | -1.76312 | 35.32 | 37.08312 | 428876.1 | 7561847 | 1 | Waterelev_40 |
| WW21649 | -5.23087 | 51.98 | 57.21087 | 431183.6 | 7563712 | 1 | Waterelev_41 |
| WW21650 | -2.98393 | 68.45 | 71.43393 | 432799.8 | 7565159 | 1 | Waterelev_42 |
| WW21651 | -25.9658 | 83.24 | 109.2058 | 436077.9 | 7568737 | 1 | Waterelev_43 |
| WW22188 | 0.436745 | 117.74 | 117.3033 | 436162.4 | 7571085 | 1 | Waterelev_44 |
| WW22186 | -4.11543 | 145.05 | 149.1654 | 440305.7 | 7574151 | 1 | Waterelev_45 |
| WW22192 | -2.64729 | 150.69 | 153.3373 | 442160.3 | 7574201 | 1 | Waterelev_46 |
| WW22194 | 4.523163 | 166.83 | 162.3068 | 444209.5 | 7576455 | 1 | Waterelev_47 |
| WW21708 | -1.81072 | 111.97 | 113.7807 | 435783.7 | 7570503 | 1 | Waterelev_50 |
| WW21709 | -3.79876 | 120.42 | 124.2188 | 437389.1 | 7571322 | 1 | Waterelev_51 |
| WW21924 | 3.807953 | 175.39 | 171.582 | 445363 | 7579531 | 1 | Waterelev_52 |
| WW21926 | -0.60117 | 175.8 | 176.4012 | 447346.4 | 7580782 | 1 | Waterelev_53 |
| WW21927 | 2.68782 | 161.44 | 158.7522 | 443487.6 | 7575285 | 1 | Waterelev_54 |
| WW21928 | 0.154022 | 158.8 | 158.646 | 443389.3 | 7575331 | 1 | Waterelev_55 |
| WW22165 | 1.080815 | 2.05 | 0.969185 | 423849.1 | 7557016 | 1 | Waterelev_56 |
| WW22166 | 1.363624 | 2.23 | 0.866376 | 423651.8 | 7557280 | 1 | Waterelev_57 |
| WW25408 | 7.65271 | 208.27 | 200.6173 | 449157.1 | 7578324 | 1 | Waterelev_58 |
| WW25578 | 1.02 | 1.02 | 0 | 422587.2 | 7557685 | 1 | Waterelev_59 |
| WW25579 | 4.189301 | 56.67 | 52.4807 | 435869.8 | 7556958 | 1 | Waterelev_60 |
| WW25990 | 1.83 | 1.83 | 0 | 422656.9 | 7558183 | 1 | Waterelev_61 |
| WW25992 | 1.11 | 1.11 | 0 | 421375.9 | 7559566 | 1 | Waterelev_62 |
| WW25994 | 1.68691 | 1.9 | 0.21309 | 423777.6 | 7556860 | 1 | Waterelev_63 |
| WW25996 | 2.03 | 2.03 | 0 | 423240.5 | 7557428 | 1 | Waterelev_64 |
| WW26743 | 1.218896 | 7.36 | 6.141104 | 419156.4 | 7564185 | 1 | Waterelev_65 |
| WW27312 | 1.700623 | 103.58 | 101.8794 | 433585.2 | 7569834 | 1 | Waterelev_69 |
| WW28768 | 5.971657 | 97.4 | 91.42834 | 435642.6 | 7565604 | 1 | Waterelev_70 |
| WW28769 | 1.024399 | 68.8 | 67.7756 | 432529.5 | 7564657 | 1 | Waterelev_71 |
| WW28773 | 3.046165 | 75.69 | 72.64384 | 428830.5 | 7569437 | 1 | Waterelev_72 |
| WW28778 | 12.48499 | 66.79 | 54.30501 | 424514.4 | 7574947 | 1 | Waterelev_73 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| WW29066 | -2.3604 | 26.6 | 28.9604 | 428535.2 | 7558731 | 1 | Waterelev_74 |
| WW29072 | 1.105835 | 115.47 | 114.3642 | 434912.7 | 7571397 | 1 | Waterelev_75 |
| WW29087 | 5.360371 | 41.59 | 36.22963 | 422022 | 7572481 | 1 | Waterelev_77 |
| WW29089 | 2.128946 | 29.25 | 27.12105 | 424777.4 | 7563518 | 1 | Waterelev_78 |
| WW29090 | 4.586128 | 31.41 | 26.82387 | 424067.8 | 7564287 | 1 | Waterelev_79 |
| WW29092 | 2.094677 | 28.96 | 26.86532 | 425410.9 | 7562691 | 1 | Waterelev_80 |
| WW29093 | -2.45391 | 21.36 | 23.81391 | 422357.4 | 7566639 | 1 | Waterelev_81 |
| WW29095 | -5.26287 | 16.31 | 21.57287 | 420362.7 | 7569153 | 1 | Waterelev_82 |
| WW29098 | -0.07904 | 0.62 | 0.699039 | 415438.1 | 7567188 | 1 | Waterelev_83 |
| WW29102 | 1.078626 | 1.65 | 0.571374 | 417497.6 | 7564223 | 1 | Waterelev_84 |
| WW29104 | 2.527268 | 7.15 | 4.622732 | 427842.1 | 7552407 | 1 | Waterelev_85 |
| WW29106 | 0.790813 | 10.46 | 9.669187 | 424370.7 | 7560107 | 1 | Waterelev_86 |
| WW30683 | 0.687053 | 10.42 | 9.732947 | 424391.3 | 7560107 | 1 | Waterelev_87 |
| WW30852 | 1.404366 | 18.46 | 17.05563 | 426579.9 | 7557660 | 1 | Waterelev_88 |
| WW31241 | 1.740829 | 187.33 | 185.5892 | 447600.4 | 7578032 | 1 | Waterelev_89 |
| WW31242 | 0.882401 | 187.52 | 186.6376 | 447702.4 | 7578111 | 1 | Waterelev_90 |
| WW31243 | 0.586472 | 187.71 | 187.1235 | 447754 | 7578133 | 1 | Waterelev_91 |
| WW31244 | -1.5528 | 186.26 | 187.8128 | 447836.6 | 7578134 | 1 | Waterelev_92 |
| WW31246 | 0.630341 | 185.1 | 184.4697 | 447412.8 | 7578210 | 1 | Waterelev_93 |
| WW31365 | -1.3271 | 184.11 | 185.4371 | 447556.4 | 7578520 | 1 | Waterelev_94 |
| WW31368 | 0.422836 | 189.63 | 189.2072 | 448011.9 | 7578223 | 1 | Waterelev_95 |
| WW31369 | -7.282 | 183.64 | 190.922 | 448309.5 | 7578833 | 1 | Waterelev_96 |
| WW31370 | -3.67043 | 187.94 | 191.6104 | 448321.4 | 7578357 | 1 | Waterelev_97 |
| WW33066 | -0.52599 | 180.64 | 181.166 | 447163.9 | 7578497 | 1 | Waterelev_98 |
| WW33068 | 0.42067 | 187.92 | 187.4993 | 447805.7 | 7578111 | 1 | Waterelev_99 |
| WW33069 | 1.072464 | 187.8 | 186.7275 | 447723.1 | 7578078 | 1 | Waterelev_100 |
| WW33073 | 0.806381 | 188.74 | 187.9336 | 447867.8 | 7578078 | 1 | Waterelev_101 |
| WW33074 | 1.139786 | 187.64 | 186.5002 | 447702.6 | 7578056 | 1 | Waterelev_102 |
| WW33077 | -0.08002 | 188.6 | 188.68 | 447950.2 | 7578134 | 1 | Waterelev_104 |
| WW100051 | 2.22345 | 97.56 | 95.33655 | 440023.1 | 7562089 | 1 | Waterelev_105 |
| WW100055 | 3.583992 | 78.59 | 75.006 | 438525.3 | 7559565 | 1 | Waterelev_107 |
| WW100056 | 4.470718 | 41.57 | 37.09928 | 433682.6 | 7555536 | 1 | Waterelev_108 |
| WW100059 | 8.529049 | 63.46 | 54.93095 | 436908.3 | 7557048 | 1 | Waterelev_109 |