TOWARDS SUSTAINABLE EXPLOITATION OF GROUNDWATER RESOURCES ALONG THE WEST COAST OF SOUTH AFRICA

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

Recent droughts that occurred in the Southern African region (2015-2017) exacerbated issues of water scarcity and equitable water allocation. Intervention measures aimed at mitigating the impact of the drought included the implementation of water conservation and demand management measures (water use restrictions) and triggered the consideration of alternative water supply options, e.g. groundwater and Managed Aquifer Recharge and Storage (MARS).

The Western Cape is one of the provinces which had been declared a disaster area during the 2015-2017 drought. The Western Cape Water Supply System (WCWSS) is currently stretched past its limit. Besides Cape Town and surroundings, the WCWSS provides water to the West Coast District Municipality (WCDM), i.e. Saldanha, Vredenburg and Hopefield. Records indicated that the WCDM has already exceeded its annual allocation from the WCWSS by > 2 Mm^3 for 2016. The Saldanha area has been earmarked for industrial development as a result of the natural harbor, with the Saldanha Industrial Development Zone and other developments in the pipeline. The need for water will consequently increase as developments take place, with water required for both industrial and domestic use, due to population expansion as a result of increased job opportunities. The logical source to increase water supply to the West Coast area is deemed to be groundwater.

The West Coast area has been the subject of periodic hydrogeological studies since the 1960s, resulting in the identification of the so-called “Lower Berg River Super-Unit” and the sub-division into four smaller aquifers, namely Langebaan Road, Elandsfontein, Grootwater and Adamboerskraal. In the late 1990s, a wellfield was developed in the Langebaan Road aquifer (LRA), with 4 production boreholes. The most recent research entailed a pre-feasibility hydraulic response study to evaluate and assess the practical implementation of MARS in the LRA and wellfield (Tredoux and Engelbrecht, 2009). This MARS pilot study produced significant and valuable insight that substantially advanced the understanding of the behaviour and response of the confined aquifer resulting from MARS. The study also raised pertinent questions and identified significant knowledge gaps and recommendations, such as identifying a suitable area for MARS, conducting MARS feasibility tests in a phased manner, and monitoring.

The overarching aim of this project was therefore to investigate the sustainable exploitation of groundwater resources on the West Coast of South Africa, with the specific objectives:

1. To investigate the hydrogeological characteristics and dynamics of the Langebaan Road Aquifer (LRA) and the Elandsfontein Aquifer (EA)
2. To determine the natural recharge areas of the aquifer units
3. To investigate the potential for implementation of a MARS scheme for additional storage of water, as well as the best possible MARS method to be used in the area
4. To develop a management plan for the LRA and EA, which considers the implementation of a MARS scheme
5. To design an optimized monitoring network for the aquifer system.

Although all four aquifers were investigated (Langebaan Road, Elandsfontein, Grootwater and Adamboerskraal), particular focus was given to Langebaan Road and Elandsfontein aquifers where major abstraction is taking place and the possible implementation of MARS may materialise.

The study area on the West Coast north of Cape Town included quaternary catchments G10K, G10L, G10M, G21A and half of G30A. The area is approximately 5,800 km^2 in size. The climate of the area is Mediterranean with hot, dry summers with moderate to strong southerly winds blowing in the afternoons, and cool, wet winters. Average rainfall ranges from 280 mm a^{-1} (central

area) to 350 mm a^{-1} (at the foot of the Table Mountain Group TMG). The topography is flat and undulating, with small urban centres and agricultural, mining and industrial activities taking place. The study area is predominantly covered with Tertiary and Quaternary mostly unconsolidated and semi-consolidated dune sands and calcrete. The basement topography (palaeochannels), faults, fissures, contact zones and the stratigraphy of the Cenozoic deposits all contribute to the complexity of the groundwater recharge, flow and discharge of the Lower Berg River Aquifer System. The basement is formed by Malmesbury Group shales and granites from the Cape Granite Suite. The Berg River is the only permanent water course found in the region and is tidal over part of its length. The Berg River has its limitations as well, since the water quality in the lower part of the river is variable as a result of tidal influences and upstream activities.

The project consolidated the historic data with new measurements of groundwater levels, quality and isotope analyses. The most exploited aquifer is the Langebaan Road, which is a heterogeneous anisotropic primary aquifer system that can be divided into the upper, unconfined aquifer unit (UAU) overlying the semi-confined to confined lower aquifer unit (LAU). A clay layer serves as aquitard between the two aquifer units. The layers of the Elandsfontein aquifer are similar to the Langebaan Road aquifer but the sediments have greater thickness. The Adamboerskraal aquifer seems to be connected to the Langebaan Road aquifer through a palaeochannel underneath the Berg River. The Grootwater aquifer is along the coast. The main groundwater recharge area seems to be the higher dune sands of the Hopefield area as well as the higher-lying areas around Elandsfontein. Groundwater recharge was estimated to be between 3% (LRA) and 31% (TMG). Groundwater quality in the LAU is considered to be good with electrical conductivity (EC) values of <120 mS/m, and values of ~80 mS/m in the LRA wellfield. The UAU, by comparison, produces groundwater with an EC >250 mS/m and even >500 mS/m, especially in the north eastern and northern portions of the LRA. The UAU is primarily exploited by local farmers, while the LAU serves a municipal water supply function.

Isotope sampling and analysis was conducted to study groundwater flow processes and recharge mechanisms, and to investigate the connectivity between the Langebaan Road and the Elandsfontein aquifers. Stable isotope analysis indicated that rainfall, topography and geomorphology conditions of the landscape control the recharge mechanism. The spatial distribution of $\delta^{18}O$ of the unconfined aquifer illustrates that recharge occurs from the south-east and flows from the south-east towards the Berg River, Saldanha Bay and the Langebaan Lagoon. Isotopic signatures suggested that upper and lower aquifer units were recharged during the same climatic event and precipitation is the dominant source of recharge for both the unconfined and confined aquifers. This would be possible through focused recharge mechanism or if the unconfined aquifer is directly superimposed over the basement aquifer where the clay and LAU are locally absent at the topographic high. The isotopic composition of bedrock aquifer suggests that it is recharged by piston flow and groundwater flows laterally. The spatial distribution of groundwater H-3 of the unconfined aquifer illustrated that there is a mixture of sub-modern with modern groundwater, which evidences the complexity of the stratigraphy. Low tritium content in the confined aquifer indicates that the groundwater is the same age as the unconfined aquifer, which indicates the source of recharge is similar. From the stable isotope and tritium trends, the results show that a hydraulic inter-connection exists between the unconfined, confined aquifer and the bedrock. The C-14 content in the unconfined aquifer indicates that that groundwater is of modern age and that residence times is short. The C-14 content of groundwater in the deeper confined aquifer of the EA and LRA is generally lower than the unconfined aquifer. Moreover, the groundwater of the EA has a longer residence time and is considered older than the LRA. From C-14 trends, the results suggest that there is negligible hydraulic inter-connection between the LRA and EA due to the significant difference in C-14 content. There seems to be a lateral and vertical hydraulic connection between the Langebaan Road and Elandsfontein aquifers, depending mostly on geological features and preferential pathways such as paleochannels. Poor construction of boreholes was also identified as possible reason for leakage between units.

The hydrogeological characterisation, groundwater sampling for hydrochemistry and isotope analyses resulted in the development of a conceptual model of the West Coast aquifer system, and served to generate input data for numerical groundwater flow modelling with MODLFOW. The main purpose of numerical modelling was to simulate the natural seepage conditions and identify suitable sites for implementing MARS. The finite-difference model was set-up as a three-dimensional 5-layer, steady-state groundwater model with the mesh size of 250 m for the LRA and EA. The numerical model was calibrated by comparison between observed and simulated groundwater levels, yielding an RMSE of 5.4 m, with a normalized RMSE (NRMSE) of 5.3%, and a mean error of 1.04 m, which was generally considered acceptable for the purpose of analyzing artificial recharge sites in study area. Scenarios were modelled in steady-state, and they predicted a future state of implementing MARS through infiltration pools and injection wells. The simulations indicated that recharging at the natural recharge area (south-west of Hopefield) can make groundwater level rise in a larger area, with associated benefits compared to recharging in the discharge region such as the Berg River and coastline. Tracing flow time shows that the time needed for the recharged water to flow from the infiltration ponds to the discharge area varies from dozens of years to thousands of years. Implementing MARS in the UAU is feasible according to the modelling, with an estimated storage capacity for MARS in the UAU in the region of 336.2 Mm^3.

A well-attended stakeholder workshop was organised in August 2019 to brief the stakeholders' community on the progress and findings of the project, and to get inputs for further development and implementation of the MARS scheme at Langebaan Road. The main conclusions and outcomes of the stakeholder engagement workshop were:

- There are still large uncertainties regarding groundwater flow and natural recharge due to lack of data. The project team attempted to fill these gaps through targeted sampling and isotope analyses in key areas.
- The effects of MARS practice on the broader area should be considered if the Berg River water is to be used for artificial recharge, e.g. the impact on the estuary of the Berg River, the effects on water availability for farmers upstream, etc.
- MARS should be explored as one of the most cost-effective options for augmenting the water supply to the West Coast District. A MARS pilot trial should be conducted before full implementation in order to provide more information and knowledge on the feasibility, the mode of operation, etc.

During the course of the project, new production/injection boreholes were drilled through development projects funded by Saldanha Bay Municipality, as part of the emergency water supply measures due to the 2016-17 drought. The establishment of boreholes took place in an area devoid of the clay aquitard (Hopefield Reserve to the west of the town of Hopefield) and based on a geophysical survey with resistivity tomography (resistivity values <33.2 ohm m associated with higher groundwater yields). Given the development of the new boreholes equipped both for abstraction and injection, a new monitoring network was proposed to serve the new wellfield with the use of six dataloggers to monitor hourly groundwater levels and temperature, monthly manual reading at both new and old boreholes (Department of Water and Sanitation), and bi-annual groundwater chemistry sampling and analyses.

Based on the information collected in the project, a new implementation plan was developed for MARS, based on the 10 "success criteria" of the Department of Water Affairs. The need for groundwater utilization and MARS was recognised by the The Western Cape Water Supply

System Reconciliation Strategy due to the projected increase in water demand by industry and urbanization. The excess winter flows of the Berg River and water treated in the Withoogte treatment plant is the most feasible option for a secure source of water for MARS. The amount of water that could be supplied by Withoogte WTW is estimated to be 2.84 million m^3/a (full capacity minus the water demand of local municipalities). Numerical modelling indicated that the available groundwater storage space for MARS in LRA is 366.2 Mm^3 of water. The groundwater in the UAU appears to be suitable for MARS, however this should be monitored through the newly developed monitoring program. For the engineering aspects of the project, a pilot phase is recommended. The small-scale pilot phase is also aligned with identification of potential environmental, legal and regulatory issues (no water licensing may be required because no water will be used above the authorised allocation). A dedicated economic study is required to quantify capital and operational costs of different options, including the "do nothing" scenario. The economic analysis should result in the estimated cost per m^3 of water as well as the projected price of water to the users. The main implementation agent of the MARS scheme at Langebaan Road aquifer is envisaged to be Saldanha Bay Municipality under the regulatory framework of the DWS, and with the strong participation and guidance from stakeholder groups. A framework for groundwater management was also established based on 12 principles: i) groundwater protection and ii) regulation; iii) groundwater users; iv) planning of future development of groundwater resources; v) groundwater monitoring; vi) groundwater conservation; vii) groundwater abstraction operations and viii) infrastructure; ix) groundwater resource assessment; x) institutional arrangements; xi) capacity and skills; and xii) awareness, communication and stakeholder engagement.

The main outcomes of the project were an improved understanding of the inter-relationships of the Langebaan Road Aquifer and Elandsfontein Aquifer, the implementation plan for a sustainable MARS scheme that should secure a continued, sustainable water resource within the WCWSS to meet increased water requirements. It is recommended that a piloting phase for MARS should commence. More work is required to quantify the interactions between the Berg River and the West Coast aquifer system, the impacts of groundwater depletion on ecosystems, and the role and dynamics of groundwater in the Adamboerskraal and Grootwater aquifers, where historic data are scarce.

TABLE OF CONTENTS

ACKNOWLEDGMENTS iii
EXECUTIVE SUMMARY v
LIST OF FIGURES xi
1. INTRODUCTION 1
1.1 Background 1
1.2 Objectives 4
2. STUDY AREA 5
2.1 Location 5
2.2 Climate 6
2.3 Topography 7
2.4 Vegetation 8
2.5 Land use 8
2.6 Geology 9
2.6.1 Basement 12
2.6.2 Cenozoic deposits 13
2.6.3 Palaeochannels and fault systems 20
2.7 Water resources 21
2.7.1 Surface water 21
2.7.2 Groundwater 22
2.7.3 Other water resources 29
2.8 Legislative framework 29
3. GEOHYDROLOGICAL CHARACTERISTICS 31
3.1 Rainfall 31
3.2 Groundwater recharge 34
3.2.1 Mechanisms of groundwater recharge 35
3.2.2 Groundwater recharge areas 35
3.2.3 Groundwater recharge estimations 36
3.2.4 Natural groundwater recharge 38
3.3 Groundwater levels 38
3.3.1 Langebaan Road aquifer unit 39
3.3.2 Elandsfontein aquifer unit 41
3.3.3 Adamboerskraal aquifer unit 43
3.3.4 Grootwater aquifer unit 45
3.3.5 Interpretation of CDM curves 46

3.3.6 Correlations between surface water and groundwater levels 48
3.4 Aquifer characteristics....51
3.5 Hydrochemistry....54
3.5.1 Rain water quality 54
3.5.2 Surface water quality 56
3.5.3 Groundwater quality....57
3.5.4 Isotope sampling....65
3.5.5 Connectivity between the confined units of Langebaan Road and Elandsfontein aquifers....70
3.6 Groundwater dependent ecosystems....73
4 ZONCEPTUAL MODEL 75
5 NUMERICAL MODELLING....79
5.1 Software introduction 79
5.2 Methodology 80
5.2.1 Numerical model set-up 80
5.2.2 Boundary conditions 82
5.2.3 Groundwater abstraction....83
5.2.4 Aquifer characteristics....84
5.2.5 Model calibration....85
5.3 Modelling results....87
5.3.1 Numerical model calibration....87
5.3.2 Scenario simulations....90
5.4 Discussion 96
5.4.1 MARS in UAU....96
5.4.2 MARS in LAU....98
6. STAKEHOLDER ENGAGEMENT 99
7. MONITORING NETWORK....101
7.1 Development of new wellfields....101
7.2 Development of new monitoring network 103
8. IMPLEMENTATION PLAN....105
8.1 Groundwater management plan....105
8.2 Implementation of MARS 110
9. CONCLUSIONS AND RECOMMENDATIONS....121
9.1 Conclusions 121
9.2 Recommendations....122
REFERENCES 123

LIST OF FIGURES

Figure 2.1: Google Earth image of the West Coast study area 5
Figure 2.2: Mean annual rainfall in the study area (Woodford and Fortuin, 2003)...................... 6
Figure 2.3: The topography of the study area (Woodford and Fortuin, 2003) 8
Figure 2.4: Simplified surface geology of the study area (Woodford and Fortuin, 2003)............. 9
Figure 2.5: Isopachs of Cenozoic strata in the Saldanha, Vredenburg and Velddrif environs. The geocentres record the locations of ancient channels of the Berg River and possibly the Groen River in the east (Roberts and Siegfried, 2014) 13
Figure 2.6: Subsurface distribution of the Elandsfontyn Formation in the Saldanha, Vredenburg and Velddrif environs (modified after Timmerman, 1988 and Cole and Roberts, 1996; Roberts & Siegfried, 2014)...15
Figure 2.7: Subsurface distribution of the Varswater Formation (Roberts, 2006b; Roberts and Siegfried, 2014) 17
Figure 2.8: Dune field morphology along the lower West Coast (modified from Geological Survey of South Africa, 1990). The exclusive development of dune plumes, whose orientation reflects the south-southwesterly dune building wind is clearly apparent (Roberts et al., 2009) 19
Figure 2.9: Palaeochannel map of the Lower Berg River Valley aquifer system, showing basement contours (Roberts and Siegfried, 2014)..20
Figure 2.10: Groundwater contours for the upper unconfined layer with flow directions (Woodford and Fortuin, 2003)...24
Figure 2.11: Natural discharge (L/s) from the Langebaan Road and Elandsfontein aquifer units to the rivers, wetlands, pans, springs and the sea, and estimates of mean annual recharge (Woodford and Fortuin, 2003)...26
Figure 2.12: Cone of depression associated with the Langebaan Road wellfield after a number of years in operation (Woodford and Fortuin, 2003)..27
Figure 2.13: Electrical conductivity in mS/m as an indication of the water quality of the Langebaan Road and Elandsfontein aquifer units (Woodford 2004) 28

Figure 3.1: Satellite image showing the location of the rainfall stations on a Google Earth map (Google Earth, 2017) 32
Figure 3.2: Time series of rainfall (bars) and Cumulative Departure from Mean (CDM, lines) in the study area...34
Figure 3.3: Google Earth image showing the distribution of monitoring points in the Langebaan Road aquifer..39
Figure 3.4: Time series graph of water levels for borehole G33323 with cumulative deviation from mean (CDM)...40
Figure 3.5: Time series graph of water levels for borehole G33327 with cumulative deviation from mean (CDM)...41
Figure 3.6: Google Earth image showing the distribution of monitoring points in the Elandsfontein aquifer 42

Figure 3.7: Time series graph of water levels for borehole G33317 with cumulative deviation from mean (CDM).....43
Figure 3.8: Google Earth image showing the distribution or monitoring points in the Adamboerskraal aquifer.....44
Figure 3 9: Time series graph of water levels for borehole G33255 with cumulative deviation from mean (CDM).....45
Figure 3.10: Google Earth image showing the distribution or monitoring points in the Grootwater aquifer.....46
Figure 3.11: Time series graph of water levels for borehole G33304 with cumulative deviation from mean CDM.....46
Figure 3.12: Time series of streamflow generated for flow gauge station G1H013.....49
Figure 3.13: Time series of streamflow generated for flow gauge station G1H013 on the Berg River and groundwater levels at G33323.....50
Figure 3.14: Piper diagram for the chemistry analysis of cumulative rainfall samples collected in rain gauges in the studied area (diagram generated with the WISH software).....55
Figure 3.15: Stiff plots for the chemistry results for cumulative rainfall collected with rain gauges (diagram generated with the WISH software).....55
Figure 3.16: Piper diagram for surface water samples taken from the Berg River at the Kersefontein bridge (diagram generated with the WISH software).....56
Figure 3.17: Stiff diagram for surface water samples taken from the Berg River at the Kersefontein bridge (diagram generated with the WISH software).....57
Figure 3.18: Distribution of monitoring points in the Langebaan Road aquifer unit (42 of the 47 sampling points sampled regularly until 2010).....58
Figure 3.19: Piper diagram for the representative points in the Langebaan Road area (generated with the WISH software).....60
Figure 3.20: Stiff plots for representative boreholes in the Langebaan Road aquifer unit (generated with the WISH software).....60
Figure 3.21: Piper diagram with representative points for the Elandsfontein aquifer unit (generated with the WISH software).....61
Figure 3.22: Stiff plots for representative geosites for Elandsfontein aquifer unit (generated with the WISH software).....62
Figure 3.23: Piper diagram for the monitoring points in the Adamboerskraal monitoring route (generated with the WISH software).....63
Figure 3.24: Stiff plots for the water quality of the geosites in the Adamboerskraal area (generated with the WISH software).....63
Figure 3.25: Piper diagram for representative points in the Grootwater aquifer unit (generated with the WISH software).....64
Figure 3.26: Stiff plots for representative boreholes in the Grootwater aquifer unit (generated with the WISH software).....65
Figure 3.27: Groundwater, surface water and rainwater isotope sampling locations throughout the West Coast Aquifer System.....66
Figure 3.28: Stable isotope analyses of all rain, surface and groundwater samples collected on the West Coast.....68

Figure 3.29: Plot of 3H and δ18O‰ illustrating tritium activity for the WCAS. (A) Illustrates most recently recharged groundwater 69
Figure 3.30: Plot of C-14 (pMC) and δ18O‰ illustrating groundwater age 70
Figure 3.31: Satellite image showing some of the wetland, non-perennial rivers and pans in the study area....74

Figure 4.1: Groundwater flow conceptual model of the study area (see Fig. 4.2 and 4.3 for cross-sections A and B)....75
Figure 4.2: Conceptual cross-section (A) of groundwater flow mechanisms of LRA (after DWA, 2010) 76
Figure 4.3: Conceptual cross-section (B) of groundwater flow mechanisms of EA (after DWA, 2010) 76

Figure 5.1: Finite-difference grid of the groundwater model....81
Figure 5.2: Examples of vertical cross-sections of the model domain (colours indicate numerical model layers)....82
Figure 5.3: Groundwater recharge distribution (from GRAII, DWAF, 2006) 83
Figure 5.4: Calibration boreholes used in the groundwater model....86
Figure 5.5: Modelled vs observed groundwater levels of the steady-state model calibration 88
Figure 5.6: Simulated groundwater table contours of UAU....89
Figure 5.7: Simulated groundwater piezometric head contours of LAU 90
Figure 5.8: Simulated groundwater piezometric head contours of LAU for scenario 1....92
Figure 5.9: Simulated piezometric head in LAU and pathlines of recharged water in step 1 for scenario 2. The clay layer-missing window is outlined in pink 94
Figure 5.10: Simulated piezometric head in LAU and pathlines of recharged water in step 2 for scenario 2. The clay layer-missing window is outlined in pink 95
Figure 5.11: Groundwater depth in the study area 97

Figure 7.1: Map of Langebaan Road Aquifer wellfields 1A and 1B and monitoring boreholes (Nel, 2018)....102
Figure 7.2: Map of Hopefield wellfield and monitoring boreholes (Nel, 2019) 103
Figure 7.3: New production/injection borehole (left) and landscape of the Municipal Nature Reserve to the west of Hopefield (right), which is deemed to be the main groundwater recharge area for the Langebaan Road aquifer 104

Figure 8.1: Groundwater use and availability as a function of time with timeous planning and development of groundwater resources (Fourie, 2020)....106

LIST OF TABLES

Table 2.1: Correlation of the lithostratigraphic layers of the different aquifer units, using information from K.M.G. Timmerman (Timmerman, 1985a; Timmerman, 1985b and Timmerman, 1988) 9
Table 2.2: Generalized geological formations of the study area (Theron *et al.*, 1992; Roberts and Siegfried, 2014) 11
Table 2.3: Summary of the yield and storage potential for the Lower Berg River Aquifer System. 25

Table 3.1 :Summary of rainfall records in the study area........33
Table 3.2: Summary of recent recharge estimations 37
Table 3.3: Comparison of CDM values between boreholes and the different aquifer units. .**Error! Bookmark not defined.**
Table 3.4: Aquifers, formations and their hydraulic properties (Timmerman, 1985b) 51
Table 3.5: Summarized hydraulic parameters of the West Coast aquifer system (Timmerman, 1985d) 52
Table 3.6: Estimated groundwater storage (Timmerman, 1985b) 54

Table 4.1: Description of model boundaries and numerical translation 78

Table 5.1: Layer arrangement for the groundwater model 80
Table 5.2: Calibrated hydraulic conductivities of the aquifer. 85
Table 5.3: Water budget of the calibrated model (inflows to the aquifer are positive, outflows are negative). 88
Table 5.4: Details of predictive scenarios in steady-state model 91
Table 5.5: Simulated infiltration recharge results 93
Table 5.6: Available space of MARS in UAU for the four aquifers in the study area. 98

Table 8.1: Summary template of the groundwater management plan for the West Coast District Municipality (Fourie, 2020). 109
Table 8.2: Engineering components of the MARS system (DWAF, 2007) and current status at Langebaan Road aquifer proposed site. 114
Table 8.3: Consolidated feasibility assessment for Langebaan Road aquifer MARS implementation based on the checklist by DWA (2009) 118

ABBREVIATIONS AND ACRONYMS

AMC – Aquifer Management Committees

CDM – Cumulative Deviation from Mean

CMA – Catchment Management Agencies

CMB – Chlorine Mass Balance

CMF – Catchment Management Forums

CRD – Cumulative Rainfall Departure

CSIR – Council for Scientific and Industrial Research

DWA – Department of Water Affairs

DWAF – Department of Water Affairs and Forestry

DWS – Department of Water and Sanitation

EA – Elandsfontein Aquifer

EC – Electric Conductivity

EMPs – Environmental Management Plans

GMWL – Global Meteoric Water Line

GUI – Graphical User Interface

LAU – Lower Aquifer Unit

LMWL – Local Meteoric Water Line

LRA – Langebaan Road Aquifer

MAP – Mean Annual Precipitation

MARS – Managed Aquifer Recharge and Storage

NEMA – National Environmental Management Act

NGA – National Groundwater Archives

NWA – National Water Act

NWRS2 – National Water Resource Strategy 2

PCG – Preconditioned Conjugate Gradient

RIB – Rainfall Infiltration Breakthrough

SAWS – South African Weather Services

SSGWCA – Saldanha Subterranean Government Water Control Area

TMG – Table Mountain Group

UAU – Unconfined Aquifer Unit

UGEP – Utilisable Groundwater Exploitation Potential

USGS – U. S. Geological Survey

WAAS – Water Availability Assessment Study

WCAS – West Coast Aquifer System

WCDM – West Coast District Municipality

WCWSS – Western Cape Water Supply System

WCWSSRS – Western Cape Water Supply System Reconciliation Strategy

WRC – Water Research Commission

WSA – Water Service Authority

WSA – Water Services Act

WSDP – Water Services Development Plan

WTW – Wastewater Treatment Works

WUA – Water User Association

1. INTRODUCTION

1.1 Background

South Africa is generally a semi-arid to arid country which experiences a highly variable climate and limited freshwater resources. The already limited water resources are vulnerable to the occurrence of extreme weather conditions, often caused by climate variability and change. Droughts are an example of such extreme weather conditions, which have the potential to result in significant adverse socio-economic impacts. Recent droughts that occurred in the southern African region (2015-2017) exacerbated issues of water scarcity and equitable water allocation. The drought, which started in 2015, was a result of the combined effects of a severe drought and a strong El Niño event (Baudoin *et al.,* 2017). This has resulted in some South African Provinces being declared disaster areas, declines in agricultural harvest being experienced which resulted in the necessity to import crops, heavy water restrictions being put in place to cope with dwindling water resources and the need to adapt to the "new normal" of water scarcity. Intervention measures aimed at mitigating the impact of the drought included the implementation of water conservation and demand management measures (e.g. water use restrictions). Awareness was triggered to consider alternative water supply options (e.g. groundwater, rainwater harvesting, seawater desalination, water recycling, etc.), as well as the implementation of alternative technologies, e.g. Managed Aquifer Recharge and Storage (MARS).

The Western Cape is one of the provinces which had been declared a disaster area during the 2015-2017 drought. Dam levels in the province were alarmingly low and the effects of the unusual low rainfall reflected on groundwater levels. The Western Cape Water Supply System (WCWSS) is currently stretched past its limit. Revisions of water use volumes in the system for both municipal supply and agricultural use showed that water use volumes are greater than the volume of water that can be supplied from the system at the current assurance of supply. Problems associated with water security in the region are further exacerbated by population growth, urbanization and development. The WCWSS provides water to Cape Town and the surrounding towns. This also includes the towns which form part of the West Coast District Municipality (WCDM), i.e. Saldanha, Vredenburg and Hopefield. Records indicated that the WCDM has already exceeded its annual allocation from the WCWSS by > 2 Mm^3 for 2016. According to GreenCape (2015), industrial development in Saldanha is likely to further increase the water demand in the already stressed Berg River catchment. The Saldanha area has been earmarked for industrial development as a result of the natural harbor, with the Saldanha Industrial Development Zone and other developments in the pipeline. The need for water will thus increase as developments take place, with water required for both industrial and domestic use, due to population expansion as a result of increased job opportunities. The logical source to increase water supply to the West Coast area is deemed to be the Langebaan Road Aquifer System (LRA). However, monitoring of the aquifer's response to current abstraction and lack of information on the dependence of wetlands in the Langebaan Lagoon and estuary of the Berg River on outflows from the aquifer have resulted in this option being viewed with extreme caution.

The LRA and the adjacent coastal aquifers on the West Coast have been the subject of periodic hydrogeological studies since the 1960s. The Geological Survey (which would later become the Council of Geoscience) began with a prospecting program in the coastal aquifers along the West Coast of the Western Cape in the 1960s, which was done for the exploration of economic minerals. Around 1974, this program was taken over by the Department of Water Affairs (DWA) that conducted a number of hydrogeological investigations, such as the one in the area between Velddrif, Hopefield, Darling and Langebaan, to assess the potential of the groundwater resources in the area (hydrogeological resource characterization and quantification of the groundwater supply potential as a supplementary source of potable water). The development potential of these primary aquifers was recognized from the outset as a result of the drilling of a number of artesian wells with a high yield and good water quality. The Saldanha Subterranean Government Water Control Area (SSGWCA) was declared in September 1976 to protect this strategic resource for future urban and industrial use. This resulted in the identification of the so-called "Lower Berg River Super-Unit" and the sub-division into four smaller aquifers (Timmerman 1985a, Timmerman, 1985b and Vandoolaeghe, 1982), namely:

- Langebaan Road,
- Elandsfontein,
- Grootwater, and
- Adamboerskraal.

Further work included geo-electrical soundings (Smith, 1982), cable tool percussion and mud rotary drilling, geophysical borehole logging, pumping tests, slug tests, hydrochemical sampling and water level monitoring (Timmerman, 1988).

In the late 1990s, the increased water needs of Saldanha Bay municipality, due to industrial developments such as Saldanha Steel (now Arcelor Mittal), prompted the need for the WCDM to secure additional sources of water. This led to the development of the Langebaan Road wellfield, with 4 production boreholes. The wellfield became operational in December 1999 when the WCDM was authorized to exploit groundwater to the amount of 1.46 Mm^3/a (4,000 m^3/d), drawn from the Langebaan Road Aquifer (LRA), to augment seasonal (summer) shortages in surface water supply. The Department of Water Affairs and Forestry (DWAF) commissioned a study to determine the current situation of water demand versus supply and to determine the various potential water resources that can be utilized in the near future for the area at a pre-feasibility level (Woodford *et al.,* 2003).

A later study assessed the water supply potential of the Langebaan Road and Elandsfontein aquifers (Seyler *et al.,* 2008) as part of the Berg River catchment Water Availability Assessment Study (WAAS) (DWAF, 1998). This study employed numerical modelling to establish the viability of MARS. The most recent research entailed a pre-feasibility hydraulic response study (Tredoux and Engelbrecht, 2009) to evaluate and assess the practical implementation of MARS in the LRA and wellfield. The results of these studies indicated the technical viability of MARS and the value in further pursuing this option in the basket of suitable and appropriate water supply augmentation schemes for the sub-region. The Department of Water and Sanitation (DWS, 2010) also recognized the exploitation potential of the LRA and the potential for implementation of a MARS scheme. The Western Cape Water Supply System Reconciliation Strategy (WCWSSRS) (DWS, 2016) envisaged the provision of 14 Mm^3/a to the water supply system from the LRA, operated conjunctively with MARS and with development of a wellfield in the untapped Elandsfontyn Aquifer System (EA; Seyler *et al.,* 2008). The WCWSSRS proposed that excess winter runoff from the Berg River be stored in the winter months in the aquifer and then be used in the summer months when the water demand is higher. The WCWSSRS incorporated the LRA MARS strategy as an intervention to supply the water by 2021. The successful implementation of the LRA water supply and MARS scheme has the potential to provide relief to the WCWSS, through the provision of water to the WCDM.

The LRA wellfield comprises two super-imposed units described on the basis of lithostratigraphic nomenclature after Roberts *et al.* (2006) as follows:

- Semi-consolidated to consolidated calcareous sediments comprising fluvial sands and gravels associated with the Elandsfontyn Formation at the base of the Sandveld Group and forming the semiconfined to confined Lower Aquifer Unit (LAU); and
- Weakly consolidated to unconsolidated sediments comprising phosphatic sand (Varswater Formation) overlain in turn by shelly and pebbly sand (Velddrif Formation), fine- to medium grained calcareous sandstone (Langebaan Formation) and fine- to medium-grained sand (Springfontyn and Witzand formations), collectively forming the semi-confined to unconfined Upper Aquifer Unit (UAU). As the UAU is confined in some areas and unconfined in others, a distinction is made throughout the report case by case.
- The Elandsfontyn Clay layer at the base of the Varswater Formation forms the confining aquitard/aquiclude that separates the UAU from the LAU.

Groundwater quality in the LAU is considered to be good with electrical conductivity (EC) values of <120 mS/m, and values of ~80 mS/m in the LRA wellfield. The UAU, by comparison, produces groundwater with an EC >250 mS/m and even >500 mS/m, especially in the north eastern and northern portions of the LRA. The UAU is primarily exploited by local farmers, while the LAU serves a municipal water supply function. However, some farmers do have access rights to the LAU. Woodford (2005) reported an observed reduction in potentiometric heads in the LAU of ~5 to 10 m in the five years since commissioning of the LRA wellfield in late 1990s. Further, an asymmetrical cone of dewatering extending ~4 to 11 km from the wellfield had developed, resulting in the dissipation of the artesian conditions that had characterised the discharge portion of this aquifer. Woodford (2005) also reported that the water table response in the UAU did not indicate a direct hydraulic connection with the LAU. Seyler *et al.* (2008) reported stable potentiometric heads in the LAU since 2003, and water table trends in the UAU ranging spatially (i.e. locality-dependent) between declining, stable and rising. According to Tredoux and Engelbrecht (2009), the confined nature of the LAU, however, significantly reduces the efficacy of MARS in developing additional water storage. The pre-feasibility pilot MARS study (Tredoux and Engelbrecht, 2009) confirmed that injection into the LAU only increases the potentiometric head and re-establishes artesian conditions resulting in wasteful discharge from the aquifer at inconvenient and unacceptable locations. This finding indicated that full-scale MARS needs to be carried out elsewhere in the aquifer, and that additional production wellfields need to be established in suitable areas (e.g. the EA) in order to increase the production capacity of the hydrosystem.

The pilot MARS study (Tredoux and Engelbrecht, 2009) produced significant and valuable insight that substantially advanced the understanding of the behaviour and response of the confined aquifer resulting from MARS. The possibility of implementing MARS at the wellfield using excess winter water from the Berg River to augment the groundwater in the Langebaan Road aquifer was tested. According to Tredoux and Engelbrecht (2009), the application of MARS by injection was feasible but storage in the confined aquifer was not possible due to the proximity of the injection point to the discharge area of the confined lower aquifer unit (LAU), i.e. the MARS technique was applied at the incorrect location. The study also raised pertinent questions and identified significant knowledge gaps, recommending that a study be carried out with the following objectives:

- Delineate the recharge area(s) of the confined LAU;
- Identify a suitable area in or close to the recharge area for the purpose of MARS;
- Research the hypothesis that an increase in hydrostatic head and the associated interaction between water in the aquifer and water in the borehole results in modification of the bacterial community;

- Ensure the proper functioning of all data logging devices in the study area;
- Conduct MARS feasibility tests in a phased manner starting with a single injection borehole established in the suitable area previously identified.

1.2 Objectives

The current project proposed to directly fill knowledge gaps related to the sustainable exploitation of the LRA, which have been identified by Tredoux and Engelbrecht (2009). The overarching aim was to investigate the sustainable exploitation of groundwater resources on the West Coast of South Africa. In particular, the specific objectives of the project were:

1. To confirm the hydrogeological characteristics and dynamics of the Langebaan Road Aquifer System (LRA) and the Elandsfontein Aquifer System (EA)
2. To determine the natural recharge areas of the aquifer units
3. To investigate the potential for implementation of a MARS scheme for additional storage of water, as well as the best possible MARS method to be used in the area
4. To develop a management plan for the LRA and EA, which considers the implementation of a MARS scheme
5. To design an optimized monitoring network for the aquifer system

The main envisaged outcomes of the project were an improved understanding of the inter-relationships of the Langebaan Road Aquifer and Elandsfontein Aquifer, and the development of a sustainable MARS scheme that should secure a continued, sustainable water resource within the WCWSS to meet increased water requirements. Although all four aquifers were investigated (Langebaan Road, Elandsfontein, Grootwater and Adamboerskraal), particular focus was given to Langebaan Road and Elandsfontein aquifers where major abstraction is taking place and the possible implementation of MARS may materialize.

2. STUDY AREA

2.1 Location

The study area is about 100 km north of Cape Town, along the West Coast of South Africa. Figure 2.1 shows the extent of the study area. It includes the quaternary drainage areas of G10K, G10L, G10M, G21A and half of G30A. The area is approximately 5,800 km^2. Most of the area is covered with unconsolidated sediments, with granite outcrops, Malmesbury shale and Table Mountain Group sandstones making up the rest of the surface geology. The Berg River is the major river in the area, with its tributaries, the Sout, Groen, Brak and Kuilders Rivers. Other areas include the Papkuils River, the Modder River and its tributary, the Kransduinen River, as well as a number of smaller coastal rivers that are mostly unnamed.

The study area falls almost exclusively within the West Coast District Municipality, with the major towns being Vredenburg, Hopefield, Malmesbury, Darling, Langebaan, Langebaan Road, Yzerfontein and Aurora. The area is mainly farming with tourism, fishing and a growing industry. The expansion of the harbor in Saldanha Bay allows for the anchoring of heavy bulk carriers that are carrying iron ore that comes from the mines in Sishen. Langebaan Road is the training centre for the South African Air Force.

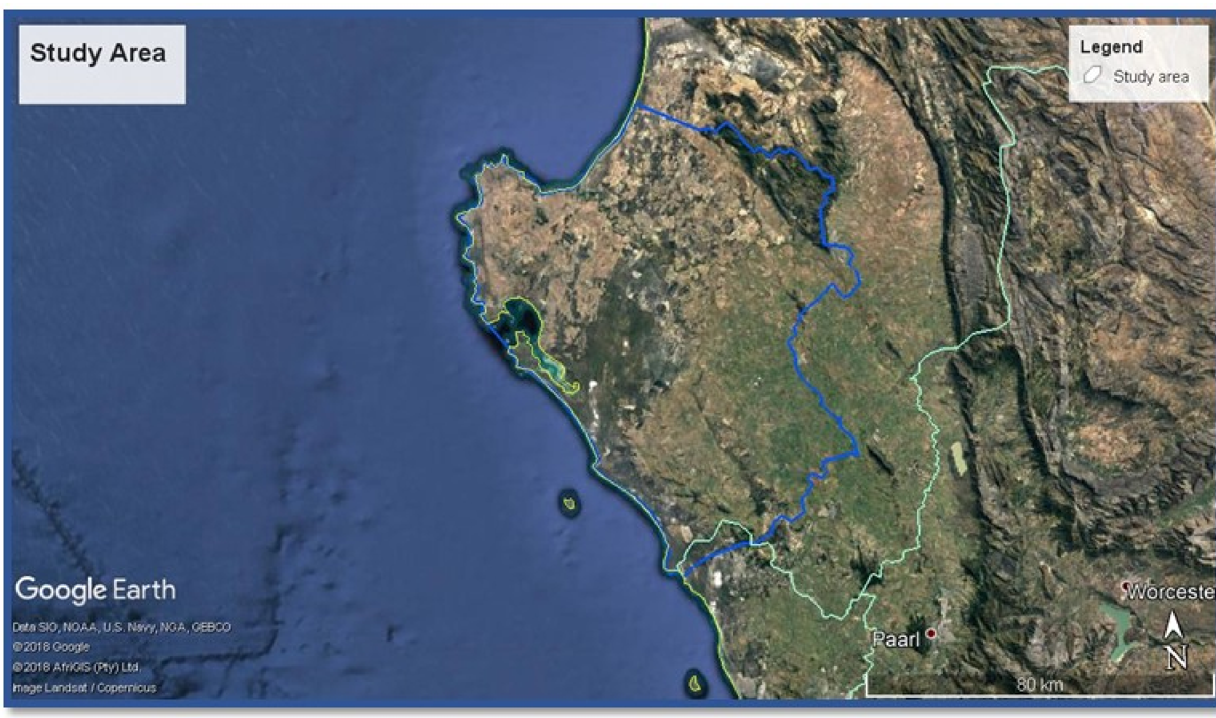


Figure 2.1: Google Earth image of the West Coast study area

2.2 Climate

The climate of the area is Mediterranean with hot, dry summers with moderate to strong southerly winds blowing in the afternoons, and cool, wet winters. It is to a great extent the product of the major pressure and wind systems in the Southern Hemisphere (Heydorn and Tinley, 1980). The temperatures of the study area are usually moderate with very little extremes because of its proximity to the Atlantic Ocean and the cold Benguela current. The average daily maximum is around 18°C near the coast and 21°C inland. Average daily temperatures vary between 12°C at the coast and 10°C inland. Prevailing winds in summer are moderately strong southerly winds in the afternoons, while the dominant wind direction during the rainy winter season is north-westerly or south-westerly. The potential evapotranspiration is high during the dry, hot summer months. It is influenced by high temperatures and wind. Potential evapotranspiration is lower in winter as a result of the lower temperatures and the higher cloud cover. The humidity of the study area is affected by the proximity to the coast and mist banks form along the coast. These banks seem to be more prevalent during the summer months. Most of the rain falls during winter months, with the rainy season beginning in April lasting through to October. Rain can occur in the summer months but is not a general occurrence. Storms that contribute significantly to the groundwater body are rare, with most rainfall being lost almost immediately through interception, direct evaporation and plant consumption (Noble, 1976). Precipitation decreases from south to north and from east to west (Figure 2.2). Orographic conditions are a dominant factor in the precipitation pattern. The average rainfall in the south is around 320 mm/a, decreasing to 280 mm/a in the central area. The rainfall average at the foot of the Table Mountain Sandstone escarpment north of the Berg River is about 350 mm/a (Timmerman, 1988). Mist adds to the precipitation along the coast.

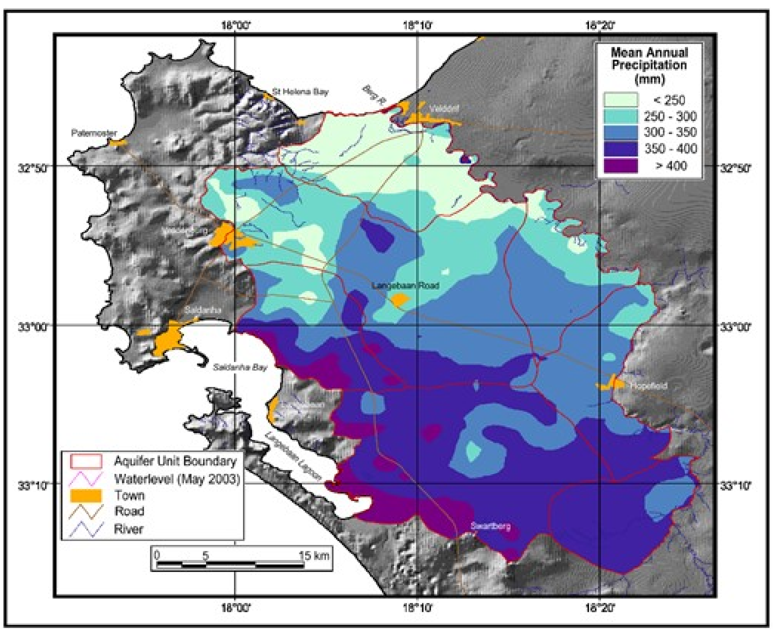


Figure 2.2: Mean annual rainfall in the study area (Woodford and Fortuin, 2003)

2.3 Topography

Narrow, steep, sandy beaches give way to a continental terrace which extends up to 40 km inland, with a landscape that is not greatly variable (Figure 2.3). Sand-covered plains, fixed dunes, surface limestone ridges and some unvegetated dunes characterize the area. Granite and related intrusives are found in the Vredenburg headland, the Darling hills and some isolated koppies, and can reach heights of up to 450 m. The topography is otherwise generally flat to slightly undulating. The area is covered by unconsolidated dune sands, which are completely vegetated. The highest parts of the area are in the east around Hopefield with a height of about 100 m, with a levelling off towards the Berg River in the north and the coast in the west. A topographical watershed is found in the west with passages through it (Vegter et. al, 1976). The Langebaan Road landscape is characterised by a lack of relief features and has an average elevation of 35 mamsl.

Timmerman (1988) described six different landscapes for the area. The first of these is the young dunes, that are strips of unvegetated to partially vegetated dunes that vary in height and can be found behind the beachfront. The second landscape type is the Sandveld that forms a hummocky landscape north of the Berg River behind the coastal dunes. These sandy dunes are old dunes that have been stabilized with vegetation and are associated with small salt pans. The Sandveld covers the entire southern and eastern parts of the area south of the Berg River, reaching an altitude of 95 mamsl west of Hopefield. These old dunes are arranged along a north-south axis between the Berg River and Yzerfontein and are a function of the dominant wind direction at the time of deposition (Visser and Schoch, 1973). The next landform type is the old calcretized dunes that can be found to the south and east of Langebaan Lagoon. These dunes are more prominent than the Sandveld dunes as they are higher reaching an altitude of 150 mamsl. The younger dunes that are not stabilised migrate across the older surfaces (Visser and Schoch, 1973). The fourth landscape type is the Langebaan Road Plain that can be found to the north and west of Langebaan Road. The landscape is a calcrete surface that lacks relief features and it has an elevation of 35 mamsl. The Berg River Valley that crosses the area from east to west forms the next landform. The river meanders in a broad valley with a floodplain that reaches a width of 2 to 3 km at the river mouth. Tidal action is visible up to 25 km inland. Isolated granite hills (“koppies”) form the last of the identified landforms and reach elevations of up to 300 mamsl. These hills are scattered between Langebaan and Darling, formed in part by the Langebaan and Darling plutons. The Vredenburg headlands are also formed by granite intrusions. The Table Mountain sandstone forms an escarpment to the north-east of the study area and forms the highest point above sea level.

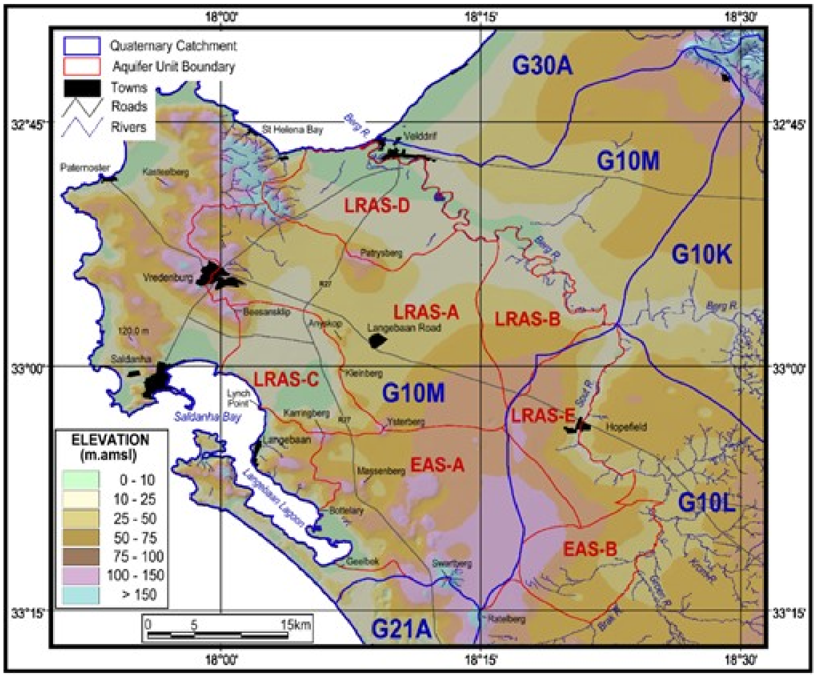


Figure 2.3: The topography of the study area (Woodford and Fortuin, 2003)

2.4 Vegetation

Timmerman (1988) used the vegetation classification of Acocks (1975) to describe the vegetation and found only two vegetation types, namely the Strandveld fynbos and Coastal Macchia that can be found along the entire beach front and in the floodplain, and renosterveld in the central and eastern portions of the study area. This classification excludes the vegetation that occurs on the Table Mountain Sandstone escarpment. The Sandveld and the old dune areas kept their original shrubby character, as Port Jackson willows (*Acacia cyanophylum*) and Rooikrans trees (*Acacia cyclops*) have replaced large parts of the natural flora. Large portions of the land are under cultivation.

2.5 Land use

In the 1980s, about 40% of the Sandveld vegetation have been cleared in strips for growing wheat in winter and the cultivation of vegetables in summer. Most of the agricultural activities had been limited to dryland farming, with a lack of large-scale irrigation. The reason for this was in part the prohibition of abstraction of large volumes of water under the Saldanha Subterranean Government Water Control Area. Groundwater abstraction in the Langebaan Road Aquifer Unit was limited to domestic use and stock watering purposes. Potato farming has led to the clearance of larger stretches of land with pivot point irrigation taking the place of dryland farming to the north of the Berg River. Large parts of the Langebaan Road plain had been used for dairy farming, but this has changed in recent years. The economic potential of the area lies in mining (minerals such as limestone, kaolin, phosphate, gypsum, glass sand and construction materials) (Noble, 1976), industrial development, agriculture and tourism. Water availability is a constraining factor.

2.6 Geology

The geology of the study area is the driver of the groundwater system, more importantly than surface topography. The study area is predominantly covered with Tertiary and Quaternary mostly unconsolidated with semi-consolidated dune sands (Noble, 1976) and calcrete. The basement topography (palaeochannels), faults, fissures, contact zones and the stratigraphy of the Cenozoic deposits all contribute to the complexity of the groundwater recharge, flow and discharge of the Lower Berg River Aquifer System. The basement is formed by Malmesbury Group shales and granites from the Cape Granite Suite. Granite outcrops occur in a number of places, with granite underlying the tertiary layers in the west. Malmesbury shale is mostly the underlying formation found towards the east. Fine to very fine-grained sand forms the tertiary layers, with silt and peat layers in places. Layers of calcrete, clay and poorly sorted gravel are also found (Vegter, et. al, 1976). The calcrete layers occur mostly near the surface, but they are not persistent (Noble, 1976). The inferred contact between the granites in the western part and the Malmesbury formation in the eastern part of the study area coincides with a major fault zone, known as the Colenso Fault, as can be seen in Figure 2.4.

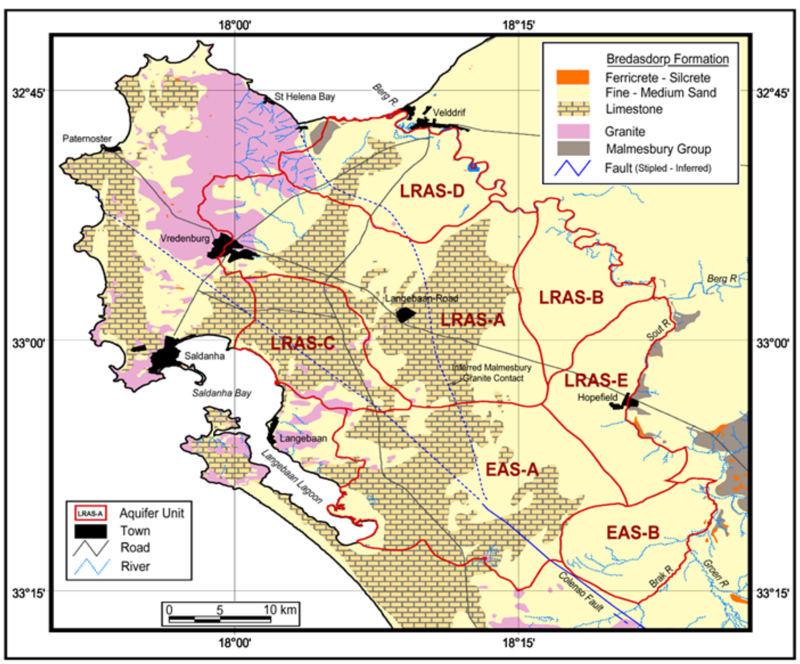


Figure 2.4: Simplified surface geology of the study area (Woodford and Fortuin, 2003)

Table 2.1 shows the correlation between the different lithostratigraphic layers and the different aquifer units, while Table 2.2 summarizes the generalized geology of the study area. The names used in the original reports (Timmerman, 1985a,b; Timmerman, 1988) were used and, where possible, they were linked with the latest designation.

Table 2.1: Correlation of the lithostratigraphic layers of the different aquifer units, using information from K.M.G. Timmerman (Timmerman, 1985a; Timmerman, 1985b and Timmerman, 1988)

TABLE 2.1 Correlation of the lithostratigraphic layers of the different aquifer units, using information from (K.M.G. Timmerman; Timmerman, 1985a; Timmerman, 1985b and Timmerman, 1988)			
Grootwater Aquifer Unit	**Elandsfontein Aquifer Unit**	**Langebaan Road Aquifer Unit**	**Adamboerskraal Aquifer Unit**
Yzerfontein Member	Witzand Formation (Witzand Member)	Witzand Formation (Witzand Member)	Yzerfontein Member
	Langebaan Formation (Langebaan Limestone Member)	Langebaan Formation (Langebaan Limestone Member)	
	Velddrift Formation (Velddrift Member)	Velddrift Formation (Velddrift Member)	Velddrift Formation (Velddrift Member)
Noordhoek Member	Springfontyn Formation (Springfontyn Member)	Springfontyn Formation (Springfontyn Member)	
	Calcareous Sand Member	Calcareous Sand Member	
Duynefontyn Member	Pelletal Phosphorite Member	Pelletal Phosphorite Member	
	Quartzose Sand Member	Quartzose Sand Member	
Silwerstroom Member	Shelly Gravel Member	Shelly Gravel Member	Bookram Member
	Saldanha Formation	Saldanha Formation	
Elandsfontyn Formation	Elandsfontyn Formation	Elandsfontyn Formation	Elandsfontyn Formation
Cape Granite Suite	Cape Granite Suite	Cape Granite Suite	Table Mountain Group
Malmesbury Group	Malmesbury Group	Malmesbury Group	Malmesbury Group

Table 2.2: Generalized geological formations of the study area (Theron *et al.*, 1992; Roberts and Siegfried, 2014)

TABLE 2.2
Generalized geological formations of the study area (Theron *et al.*, 1992; Roberts and Siegfried, 2014)

	Age	Lithology & Genesis	Member	Formation	Group
Quaternary	Holocene	Biocalcareous-siliclastic sand (Aeolian)		Witzand	Sandveld
	Middle to Late Pleistocene	Biocalcareous-siliclastic sand (Aeolian)	Kraal Bay	Langebaan	
	Late Pleistocene	Biocalcareous-siliclastic sand (Aeolian)	Diazville		
	Middle Pleistocene to Holocene	Biocalcareous-siliclastic sand with intermittent peaty layers (Aeolian)		Springfontyn*	
	Middle to late Pleistocene	Shallow-marine coquina, sand and gravel, cemented to uncemented		Velddrif	
Neogene	Mio-Pliocene	Quartzose sand (Fluvial/estuarine) Phosphatic sands, calcareous in part (Estuarine/tidal flat)	Langeberg quartz sand Muishond Fontein pelletal phosphorite	Varswater	
	Late Miocene	Lightly cemented phosphorite gravel and boulders (marine)	Konings Vlei		
	Middle to Late Miocene	Greenish to reddish brown clayey sands (Estuarine)	Langeenheid		
	Middle to Late Miocene	Reddish biocalcareous sand (Aeolian) (Conglomeratic sandy phosphorite)		Prospect Hill (Saldanha)	
	Early to Middle Miocene	Gravel, sand, clay and peat (Fluvial)		Elandsfontyn	
	Namibian / Cambrian	Granite, ignimbrites (Intrusive / Extrusive)		Cape Granite Suite	
	Namibian	Quartzitic greywacke, mudrock and phyllite (Metaturbidites)		Tygerberg Moorreesburg	Malmesbury

2.6.1 Basement

The basement of the primary aquifer in the Lower Berg River region is formed by the following stratigraphic units:

- Malmesbury Group (late Cambrium);
- Cape Granite Suite (late Precambrium to early Cambrium);
- Cape Super Group (Ordivicium to Carboniferous).

The last group is only represented by the escarpment above Aurora, of which a small portion is included in the study area.

Malmesbury Group

The Malmesbury Group could be described as a geosynclinals succession of sedimentary and low-grade metamorphic rocks of marine origin, but knowledge of the group is limited. The reason for this is the generally poor exposure of the group, lithological discontinuity, intense deformation of some contact zones and metamorphism. It is thus not possible to determine whether certain boundaries are stratigraphic or tectonic. No correlation exists across the major faults within the Malmesbury Group and it is difficult to establish the thickness of the Malmesbury Group or any of its components with any certainty. It is assumed that the total thickness of the Group would be more that 6 km (SACS, 1980; Timmerman, 1988).

Only the Tygerberg and Moorreesburg Formations occur in the study area. The two formations are very similar, except for some basal lavas and tuffs in the Tygerberg Formation. Younger formations cover the Malmesbury Group, which means that the Tygerberg Formation in the west and the Moorreesburg Formation in the east are not visible at surface. It would seem that the Malmesbury metasediments were deeply weathered during the early Cenozoic, which resulted in a sericitic clay. The clay may form a layer that can be 50 m thick and is considered to be impermeable where it is present (Timmerman, 1988). This weathering also formed palaeochannels, in which the Cenozoic sediments were deposited.

Cape Granite Suite

The Malmesbury Group sediments were intruded by a series of late Precambrium to early Cambrium age granitic plutons. There are two major batholiths in the study area, the first being the Darling batholith from the hills around Darling, while the second is the Saldanha-Langebaan batholith in the vicinity of Saldanha Bay (Timmerman, 1988).

The granites are widespread in the western part of the study area where the outcrops often form hills that dominate the dune landscape. Cenozoic sediments cover the granite in several places. In these situations, the granite forms a weathered zone that may be several meters thick, consisting of a kaolinitic clay. The clay layer is considered to be the base of the primary aquifer system, and seen to be impermeable (Timmerman, 1988).

2.6.2 Cenozoic deposits

Sediments in the area reach a maximum thickness of more than 100 m at Anyskop and at Elandsfontein (Figure 2.5), with an average thickness of around 70 m (Woodford *et al.,* 2003; DWAF, 2008; Roberts and Siegfried, 2014). The greatest thickness is found in the palaeochannels that were cut into the Palaeogene landscape by rivers like the Berg River. It is believed that sea-levels were much lower than the present levels when the palaeochannels were formed. The palaeochannels will be discussed later, as they are pertinent to the understanding of the groundwater flow in this groundwater system.

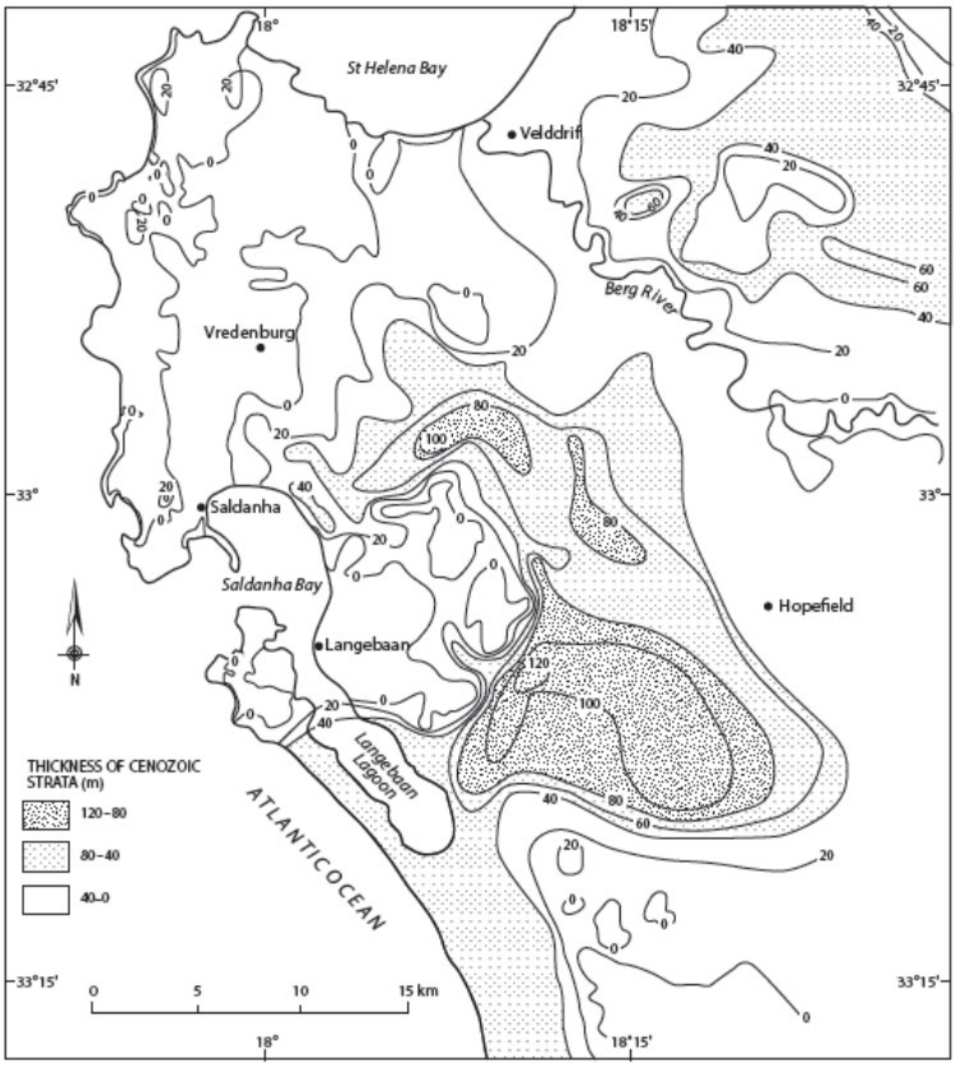


Figure 2.5: Isopachs of Cenozoic strata in the Saldanha, Vredenburg and Velddrif environs. The geocentres record the locations of ancient channels of the Berg River and possibly the Groen River in the east (Roberts and Siegfried, 2014)

Elandsfontyn Formation

The deep river channels were filled with a variety of sediments, mostly in fluviatile circumstances, with coarse sands and gravels alternating with peat and clay layers. This means that the distribution of the Elandsfontyn Formation is largely determined by the palaeochannels that often occur below sea level, reaching a maximum stratigraphical height of 5 mamsl. The maximum depth of the Elandsfontyn Formation is 50 m below present sea level. The coarse materials are normally at the bottom of the sequence, while the peat and clay layers deposited near the top. This provides an indication that there were higher energy levels at the early stages of the fluviatile deposits, with the river forming channel deposits and point bars. The later deposits most probably took place in flood plain and marshy conditions (Timmerman, 1988). These deposits are not well known, because of a lack of natural or artificial outcrops. They have only been described from a number of boreholes (Rogers, 1980; De la Cruz and Du Plessis, 1981; Rogers, 1982; Smith, 1982; Woodborne, 1982; Woodborne, 1983; Timmerman, 1988; Grindley *et al.,* 1989; Theron *et al.,* 1992; DWAF, 2008). Rogers (1980) proposed the name “Elandsfontyn Formation” for this layer. It should not be confused with Elandsfontein, which is used to describe the Elandsfontein aquifer unit.

The formation is characterized by cycles of angular, quartzose, gravelly sand fining upwards to cohesive, often peaty clays. The environment in which the clays were deposited, when deduced from lithological evidence and vegetation represented by pollen taxa, were that of a tropical meandering river (Coetzee and Rogers, 1982; Theron *et al.*, 1992). The Elandsfontyn Formation is continuous between the Berg River and links the two palaeochannels as can be seen from the subsurface distribution (Figure 2.6). Borehole logs seem to indicate that the link between the two palaeochannels may be formed by the clay layer of the Elandsfontyn Formation, and that the sand unit may be absent (Timmerman, 1988; DWAF, 2008).

Saldanha Formation

The Saldanha Formation is a controversial phosphatic quartzose sandstone layer that is poorly exposed and not well documented (Timmerman, 1988). It was described by Tankard (1975a) as a consolidated conglomeratic phosphorite from occurrences on Hoedjiespunt Peninsula at Saldanha and the Varswater Quarry on Langeberg 188. The correlation of phosphatic exposures on Hoedjiespunt with the occurrence at the Varswater Quarry has since been rejected, due to lithologically dissimilarities (Birch, 1977; Dingle *et al.,* 1979; Rogers, 1980). It can probably correlate with the Varswater Formation. Timmerman (1988) could not find this layer in boreholes drilled during his investigation of the study area.

Figure 2.6: Subsurface distribution of the Elandsfontyn Formation in the Saldanha, Vredenburg and Velddrif environs (modified after Timmerman, 1988 and Cole and Roberts, 1996; Roberts & Siegfried, 2014)

Varswater Formation

The typical section of the Varswater Formation is in Varswater Quarry at Langebaanweg. Rogers (1982) had provisionally subdivided the formation into four members. The lithostratigraphy of the formation has since then been reviewed extensively (Dingle *et al.,* 1979, 1983; Hendey, 1983; Rogers, 1983). The formation consists of deposits of phosphatic sand, which was exploited by Samancor, later Chemfos (now owned by BHP Billiton). It became known internationally for its rich Pliocene assemblage of vertebrate fossils (Hendey, 1981a and b).

Timmerman (1988) mapped the distribution of Varswater Formation in the northern part of the map area and found that the marine deposit was restricted to western, i.e. seaward parts of a major bedrock depression east of Langebaan Lagoon and Saldanha Bay (Theron *et al.,* 1992). In boreholes, the Varswater Formation can be distinguished from underlying deposits by rounded quartz grains. This is in sharp contrast with very angular grains in the Elandsfontyn Formation. The presence of phosphate is an additional characteristic of Varswater Formation that is absent from the Elandsfontyn Formation. There is, however, an upper boundary level above which the phosphate is absent (Theron *et al.,* 1992). Figure 2.7 shows the distribution of the Varswater Formation (Roberts and Siegfried, 2014). The Varswater Formation is absent from the south-eastern part of the Grootwater aquifer unit, but it can reach a thickness of more than 30 m on the farms Grootwater, Tijgerfontein and Rondeberg (Timmerman, 1985a).

The Langeenheid (Shelly Gravel) Member (Table 2.2) consists basically of gravels with phosphatized shell fragments, rolled phosphatic sandstones, pellets and rolled pebbles of bedrock material. It is only found locally, with its components often embedded in muddy, sandy material. It is possible that the shelly gravel deposits are the result of the first erosion phase of the Varswater transgression and subsequent sedimentation in a high energy beach and inner shelf environment (Rogers, 1980, and 1982; Timmerman, 1988).

The Konings Vlei (Quartzose Sand) Member is characterized by large vertebrate fossils of early Pliocene age (Hendey, 1981) found in the quartzose sand that is interbedded with lenses of intertidal clay, peat and even river channel sediments (Dingle *et al.*, 1979). Rogers (1982) described these sediments as being deposited in an estuarine environment where Pliocene rivers, possibly the proto-Berg River, meandered through the floodplain.

The Muishond Fontein pelletal phosphorite (Pelletal Phosphorite) Member is the main component of the Varswater Formation, consisting of fine to very fine sand that is often silty or even clayey. The member is rich in phosphorite pellets and phosphatized shell fragments with levels high enough in areas to make it economically viable to mine. This formation has been deposited in an intertidal lagoonal to inner-shelf setting (Rogers, 1982). It is possible that the Pliocene transgression had reached its highest point with a number of lagoons and embayments forming along the Cape Coast. Guano that was deposited on nearby granitic islands is the possible source of the phosphate deposits (Rogers, 1980; Timmerman, 1988).

The Langeberg quartz sand (Calcareous Sand) Member consists of calcareous sand poor in phosphate with intercalated calcretes (Hendy, 1981). According to Rogers (1982) these calcareous sands were Pliocene mid-shelf deposits (Timmerman, 1988).

Figure 2.7: Subsurface distribution of the Varswater Formation (Roberts, 2006b; Roberts and Siegfried, 2014)

Silwerstroom Formation

The Silwerstroom sediments emit a similar gamma count as the Elandsfontyn sediments but can be differentiated based on the roundness of the particles and the shell content (Timmerman, 1982a).

Springfontyn Formation

The Springfontyn Member consists of cohesionless bodies of medium quartzose sands with a granulometric size distribution that is identical to that of the overlying dune sands. Rogers (1980) concluded that these sands were aeolian in origin and could be dated as late to middle Pleistocene. The original calcareous shelly sands have been leached, leaving layers of pure silica sands (Timmerman, 1988). At Grootwater the Springfontyn Formation is separated from the Varswater Formation by an intermittent muddy sand horizon, called the Duynefontein Member (Timmerman, 1985a).

Varying amounts of organic fines are found inland in the Springfontyn Formation, while shallow (1-2 m) unconsolidated sand that is regarded as part of the formation occurs still further inland. This covers large areas west of the Berg River and is largely derived from nearby granite masses.

The sediments also contain quartz and some feldspar. Where the sand changes color to a reddish-brown, it gives an indication of a fair percentage of iron (Theron *et al.,* 1992).

Noordhoek Formation

The Noordhoek Member consists of fine peaty quartzose sands that probably originate from backshore dune landscape. The Papkuils Member was probably deposited in a backshore lagoon consisting of muddy fine sands. Both these sediments are of a similar age as the Springfontyn Member but occur further inland (Timmerman, 1988).

Velddrif Formation

The Velddrif Formation was the result of the Eemian transgression that reached a level of 7 m above the present sea-levels, that resulted in shelly and gravelly deposits locally along the coast and in the Berg River estuary (Rogers, 1980 and 1982; Timmerman, 1988). The type section of this formation was found close to Berg River mouth (Tankard, 1979), and it is also found south of the 33º latitude where the Velddrif Formation is exposed below Malgaskop, south of Saldanha, and at various localities along Postberg Peninsula. There are other occurrences to the south such as south of Modder River on diorite outcrops, but they are too small to be shown on a map (Rogers, 1980, 1982). The Velddrif Formation includes consolidated lime-rich beds of shell, comminuted shell-coquina to clay and sand with shell layers. It can be found along the western shore of the Langebaan Lagoon, where it underlies the Langebaan Formation (Timmerman, 1988).

Langebaan Formation

This deposit of calcrete and limestone is mainly of aeolian origin and it locally extends below sea-level where it covers large areas of the coastal plain. One of the markers for this layer is the shells of *Trigonephrus globulus*. It is believed that the extensive dune fields were formed during the Weichselian regression and were calcretized afterwards (Rogers, 1980; Rogers, 1982; Timmerman, 1988). The limestones (calcarenites) of the Langebaan formation overlie a variety of older units and are found from sea level to altitudes greater than 200 m. There are two distinct generations of dunes in that area superimposed upon one another, with the older dunes heavily calcretized. The younger dunes can be found along the western shore of Langebaan Lagoon. Here, the calcrete-capped, consolidated barrier dunes are exposed. The same kind of calcretized parabolic dunes extend from Yzerfontein in the south to the farm Elandsfontein. These dunes occur parallel to the younger dunes of the Witzand Formation to the west (Roberts and Siegfried, 2014). This was originally called the Langebaan Limestone Member (Visser and Schoch, 1973).

Langebaan limestones are usually medium grained and slightly greyish to cream in color. Comminuted shell and quartz grains can be clearly seen. There is a degree of cementation and hardness that varies in the formation (Roberts and Siegfried, 2014). The formation varies in thickness up to 88 m (Visser and Schoch, 1973; Rogers, 1980; Rogers, 1982).

Witzand and Yzerfontein Formations

The Witzand Formation is the youngest of the Cenozoic deposits that can be found on the coastal plain and is formed by unconsolidated calcareous dune sands (Figure 2.8). Timmerman (1988, based on Rogers, 1982) classifies it into two geomorphological dune types:

1. Active masses of Barchanoic dunes that moved inland from the beaches that were unsheltered from the prevailing south to south-easterly winds. Inland, these sands become rapidly vegetated and may become partially cemented. They form parabolic dune ridges that run parallel with the prevailing wind and are more abundant inland. Rogers (1982) named it the Witzand Member, now known as the Witzand Formation (Theron *et al.*, 1992).
2. Dunes are found along the coast barrier. These are quite distinct from the Witzand dunes and they were named the Yzerfontein Member. The barrier dunes are at their greatest height north of Yzerfontein, attaining a height of 30 m (Rogers, 1982; Timmerman, 1988).

Figure 2.8: Dune field morphology along the lower West Coast (modified from Geological Survey of South Africa, 1990). The exclusive development of dune plumes, whose orientation reflects the south-southwesterly dune building wind is clearly apparent (Roberts et al., 2009)

Other Cenozoic deposits

Silcrete and Ferricrete occur widely in the area, but it is difficult to map them due to their small footprint. They are formed near the surface by groundwater concentrating iron oxide and/or silica that is derived from the underlying weathered rocks (Theron *et al.,* 1992). These layers can ultimately have an effect on the recharge of the aquifers.

2.6.3 Palaeochannels and fault systems

The palaeochannels and the fault systems are important drivers of the groundwater flow of the Lower Berg River Aquifer System. Efforts to accurately map the basement contours of the palaeochannels of the Lower Berg River Aquifer System have met various levels of success. Figure 2.9 shows the latest version of the palaeochannel map (Roberts and Siegfried, 2014), with the colored section indicating the section of the palaeochannels that is below sea level. One of the big challenges is that most geophysical methods do not work very well in these thick sedimentary deposits, and it is difficult to differentiate between weathered bedrock and the Cenozoic deposits. Timmerman (1988) has also assumed that there would be a thick layer of sericitic or kaolinitic clay covering the base of the palaeochannel, which adds to the difficulties. Recent drilling has already indicated that this latest version of the basement topography may have a number of flaws (Nel, 2019). The fact that it indicates the links between the Adamboerskraal, Langebaan Road and Elandsfontein aquifer units, and hints at a link with the Grootwater aquifer unit (which is to the south outside of the map) is already providing a model that correlates with observations in the field, as well as monitoring data.

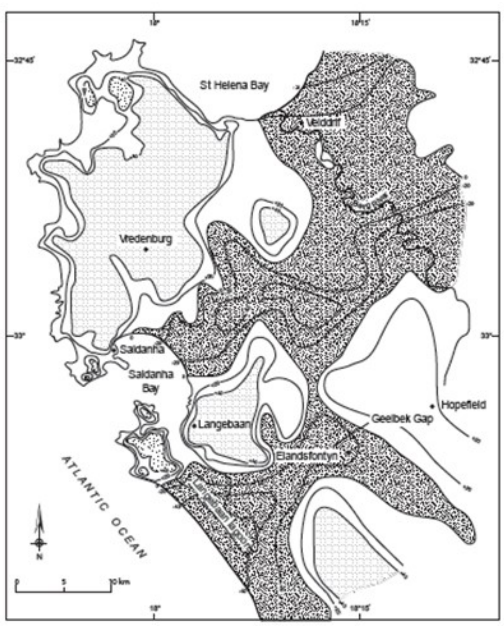


Figure 2.9: Palaeochannel map of the Lower Berg River Valley aquifer system, showing basement contours (Roberts and Siegfried, 2014)

The thick sedimentary deposits also made it difficult to accurately map the location of the Colenso Fault System (Figure 2.4). It was first described in literature by Schoch (1970), but very little is known about it. It is only visible above ground in a number of places. This includes the area in Franschhoek, on the farm Wintervogel, on the farm Colenso just north of Darling and also just south of Paternoster on the West Coast. The largest part of this fault system (De Beer, 2010) with interconnected parallel fault lines is buried under thick Cenozoic sediments and it is thus difficult to develop a basic geological understanding of the system (Vermaak *et al.,* 2019).

2.7 Water resources

2.7.1 Surface water

The lack of sufficient water was the main constraint to development in the area for almost three centuries. The Berg River is the only permanent water course found in the region and is tidal over part of its length (Noble, 1976). The peak runoff is the result of winter rainfall between May and September in the catchment of the Berg River, with most of it falling in the Franschhoek valley. The mean annual runoff before the completion of the Misverstand weir in 1978 was 1,033 x 10^6 m^3. The weir is about 60 km inland. Yearly runoff in the lower part of the Berg River was reduced to 267.7 x 10^6 m^3 after the weir became operational (Timmerman, 1985a; Timmerman, 1988). The runoff in the Berg River has been reduced further after the completion of the Berg River dam in 2007, and the river went dry in places during 2018 as a result of the drought.

The Berg River has its limitations as well, since the water quality in the lower part of the river is variable as a result of tidal influences and upstream activities. The tides can move up to 25 km inland (Timmerman, 1985a) and only releases from the Berg River dam makes it possible to abstract relatively fresh water. The river also receives treated effluent discharge from the wastewater treatment works from a number of municipalities along the way, as well as agricultural return flows. This adds to the nutrient and salt load in the water that reaches the Withoogte water treatment plant that provides potable water to the Saldanha Bay Local Municipality. The recent drought has also shown the vulnerability of the Berg River to droughts and the potential effects of climate change, as the river was in places reduced to puddles (“kuile”). It is a clear indication that the Berg River water is over-allocated and management of the resource is unsustainable. Alternative water resources are thus urgently needed, and groundwater is one of the best options under consideration for the area.

Ephemeral streams drain the rest of the region (Noble, 1976). These include the Kuilders River north of the Berg River and the Brak, Groen and Sout Rivers south of the Berg River. The Kuilders River is a tributary of the Berg River that runs from the TMG escarpment above Aurora, draining part of the Adamboerskraal aquifer unit area. The last three rivers drain the area north of Darling before flowing into the Berg River. The Modder River with the Kransduinen River as tributary, the Dwars River South and the Dwars River North with a number of smaller unnamed rivers flow from the Mamre or Darling hills towards the coast. Most of these rivers derive their flow from beyond the sand covered areas (Timmerman, 1988).

Vleis and pans are found in the flood plain of the Berg River, as well as along the Groen River. Natural springs can be found along the eastern boundary where the water table intersects the slopes of the Kuilders, Brak, Groen and Sout Rivers, as well as along the divide between the

Sandveld and the Langebaan Road Plain (Timmerman, 1988). Dune slack wetlands can also be found in the area, especially on the Elandsfontein and Grootwater Aquifer Units.

2.7.2 Groundwater

A request by the Cape Provincial Administration to the Department of Water Affairs was lodged in 1974 for groundwater exploration at Geelbek, at the southern end of the Langebaan Lagoon to provide water for the Saldanha harbor. Strong boreholes were located along the Misverstand-Saldanha pipeline, and thus the investigation focused on the Langebaan Road area rather than the Geelbek area. Gravimetric and seismic surveys were done during these early investigations, followed by the drilling of a number of boreholes. By early 1977, a total of 40 boreholes were drilled with 6 of them equipped with Johnson's screens and developed as production boreholes (Vegter and Kok, 1977). Additional work by Timmerman (1985a; 1985b; 1985c) and K.M.G. Timmerman (1985) lead to the identification of four aquifer units in the Lower Berg River Aquifer System.

The first and to date the most important of the aquifers was the LRA. The Langebaan Road Primary Aquifer Unit is bounded by the Berg River and the Sout River to the east and north-east, the Vredenburg headland in the north-west, Saldanha Bay in the west and an internal zero-flow boundary stretching roughly from Langebaan to Hopefield in the south (Timmerman, 1985a).

The Langebaan Road aquifer is a heterogeneous anisotropic primary aquifer system (Timmerman *et al.,* 1985) that can be divided into the upper, unconfined aquifer overlying the semi-confined to confined lower aquifer layer. A clay layer serves as aquitard between the two aquifer layers (Timmerman, 1985b). The base of the system is considered to be impervious and is formed by granite and Malmesbury metasediments. The inferred Colenso fault is the dividing line between the two basement domains which is presumed to be sealed (Timmerman et. al, 1985).

The confined to semi-confined aquifer has a matrix of unconsolidated coarse fluviatile Elandsfontyn sediments. These sediments are deposited in an east-west trending palaeo-channel of the Berg River. The sediments consist of poorly sorted angular gravels and sands which are interbedded with peat and clay lenses. The aquifer attains a thickness of up to 60 m north-east of Langebaan Road and pinches out towards Saldanha Bay, where finer Aeolian and marine sediments have replaced the Elandsfontyn deposits. Very little is known about the aquifer's extension towards the Berg River. This semi-confined to confined Elandsfontyn aquifer lies largely below sea level (Timmerman *et al.,* 1985).

The upper aquifer has a twofold hydraulic nature, since it is characterised by primary porosity and permeability in the unconsolidated Aeolian and marine sediments of the Bredasdorp and Varswater formations, and by secondary flow properties in the semi-consolidated deposits of the Bredasdorp formation (Timmerman *et al.,* 1985).

The aquitard is formed by discontinuous beds of clay and peat with sandy intercalations of Elandsfontyn age which gives it its leaky character (Timmerman *et al.,* 1985).

The layers of the Elandsfontein aquifer unit are similar to the Langebaan Road aquifer unit but the sediments have greater thickness. The Elandsfontein aquifer unit lies between the Groen and Brak Rivers to the east, the Darling hills to the south, the sea south of the Langebaan Lagoon and the Lagoon itself on the west and the no-flow boundary to the north (Timmerman, 1985b; Timmerman, 1988).

The Adamboerskraal aquifer unit also has similar layers to that of the Langebaan Road aquifer unit, and it seems to be connected to the Langebaan Road aquifer with the palaeochannel underneath the Berg River (K.M.G. Timmerman, 1985; Cole, 2012; Roberts and Siegfried, 2014). The aquifer unit is north of the Kuilders River, with the TMG escarpment and the Wellington-Piketberg Fault to the east, the Papkuils River and the sea to the north and the Berg River to the west (K.M.G. Timmerman, 1985; Timmerman, 1988).

The Grootwater aquifer unit is along the coast, between the Darling-Yzerfontein Road to the north, the Darling hills to the east, the Modder River to the south. The geology of this aquifer seems to be a combination of that of the three other aquifer units and that of the Atlantis aquifers.

Groundwater recharge

The main recharge area seems to be the higher dune sands of the Hopefield area (Noble, 1976; Tredoux and Engelbrecht, 2009), as well as the higher lying areas around Elandsfontein (Timmerman, 1988). The groundwater then flows from these high grounds, westwards and northwards towards Langebaan Road. A part of the water continues in a westerly direction towards Saldanha Bay and the rest flows in a northerly direction towards the Berg River (Timmerman, 1985a). Recharge to the semi-confined aquifer is thought to be mainly by downward leakage from the superficial deposits in the dune highlands on the south-eastern boundary of the unit (Timmerman, 1985a; Timmerman *et al.,* 1985).

No rivers occur in the investigation area and the rivers bordering the area gain water from the system under the piezometric and watertable conditions. Recharge to the aquifer system takes place from direct infiltration of precipitation (Timmerman, 1985a; Timmerman, et. al, 1985). Recharge is possible from the Berg River to the aquifer system under high flood conditions (Seyler *et al.*, 2016). Recharge to the aquifer has not yet been quantified when the original work was done (Timmerman, 1985a).

One option regarding recharge that has not been considered is that of recharge through faults and fissures in the basement from some of the high TMG mountains in the catchment. The recharge to the Sandveld aquifers (the area north of Dwarskersbos) is considered to come from the mountains, with recharge taking place from the basement upwards (Nel, 2004). This could possibly provide additional recharge to the Lower Berg River Aquifer System. Timmerman (1988), however, discarded this as a possible source of recharge because of the thick clay layer from the weathered basement that would act as an impermeable layer.

Groundwater flow directions

The upper unconfined to semiconfined aquifer layer for the Langebaan Road and Elandsfontein aquifer units is essentially one. Flow directions (Figure 2.10) for this layer are from the higher lying areas towards the north, towards the Berg River and Saldanha Bay, as well as towards Geelbek and the coast south of Langebaan Lagoon. Some of the flow is also towards the Groen and Sout Rivers (Timmerman, 1988; Woodford and Fortuin, 2003; DWAF, 2008; Seyler *et al.,* 2016).

Flow in the lower aquifer layer is controlled by the palaeochannels in both the Langebaan Road and Elandsfontein aquifer units. In the Langebaan Road aquifer unit, the flow is from the Berg River towards Saldanha Bay. The lower semi-confined to confined aquifer layer of Langebaan Road aquifer unit is under considerable piezometric pressure, especially in the Langebaan Road area as a result of the overlying aquitard. The flow of groundwater takes place from Hopefield in the south towards Langebaan Road where it bifurcates into a westerly and a north-easterly direction. The granitic barriers with Kleinberg and De Kop as the major outcrops cause the piezometric surface to rise above the water table in an area of about 30 km^2 north-east of Langebaan Road and creates free flowing wells (Timmerman, et. al, 1985). The flow in the lower aquifer layer of the Elandsfontein aquifer unit is towards the north-west from the farm Sonquasfontein, till it reaches the farm Elandsfontein, where after it turns to flow in a westerly direction towards Geelbek (Timmerman, 1988; DWAF, 2008; Seyler *et al.,* 2016).

Flow in the Adamboerskraal aquifer unit for both the upper and lower aquifer layers is towards the Kuilders River (south), the Berg River (east), the Papkuils River and the sea in the north (K.M.G. Timmerman, 1985; Timmerman, 1988). In the Grootwater aquifer unit, the flow is mostly towards the coast from the Darling hills (Timmerman, 1985a).

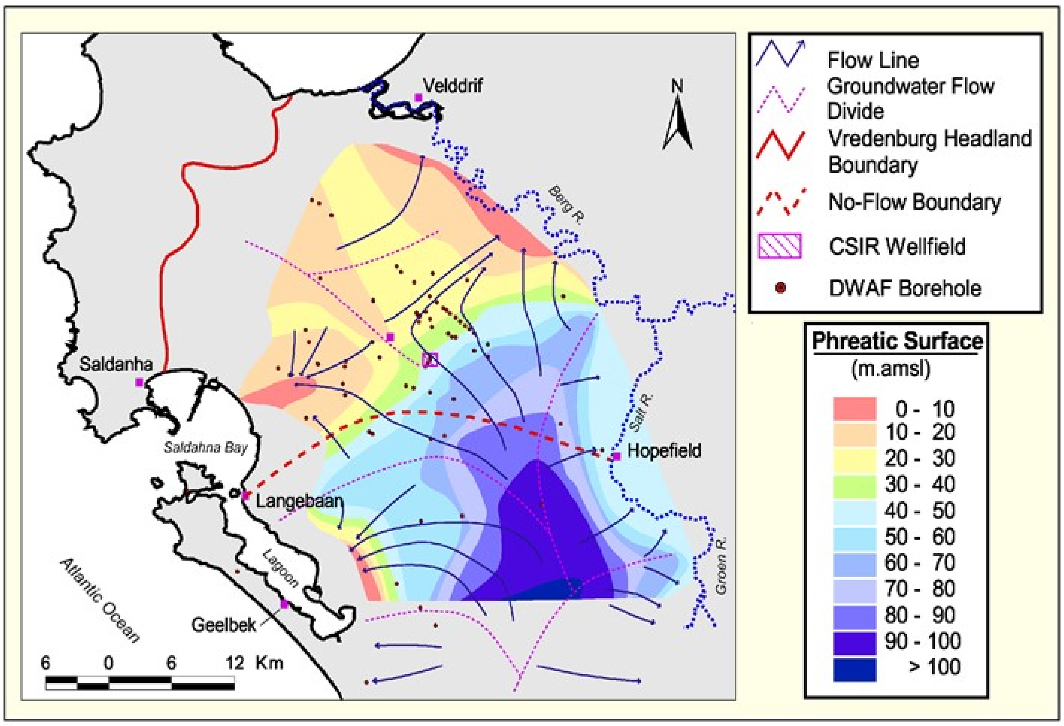


Figure 2.10: Groundwater contours for the upper unconfined layer with flow directions (Woodford and Fortuin, 2003)

Yield and water storage potential

Vegter and Kok (1977) made an initial assessment of the yield that can be expected from the first investigations in the Langebaan Road area. The estimations of Timmerman (1985; 1988) are higher and included the possibility of mining the aquifers. The findings of the initial exploration work are given in Table 2.3. The Lower Berg River Aquifer System has a large exploitation potential and a large storage capacity, but it is also linked to sensitive ecosystems. Mining of the semi-confined to confined layers could potentially cause the aquifer layer to become unconfined and then collapse. Seawater intrusion or brackish water intrusion also needs to be managed. It would thus be important to manage the abstraction from the system carefully to ensure that the system is not damaged.

Table 2.3: Summary of the yield and storage potential for the Lower Berg River Aquifer System

TABLE 2.3 Summary of the yield and storage potential for the Lower Berg River Aquifer System.						
Reference	Aquifer yield estimate [m^3/a]	Borehole yields [l/s]	Transmissivity [m^2/d]	Hydraulic conductivity [m/d]	Storage potential [m^3]	Area
Vegter and Kok, 1977	8-13 million	5-27.5*				Langebaan Road
Timmerman, 1985a	7-10 million	40	25-1000# 10-400	3-50#	200 x 10^6	Grootwater
K.M.G. Timmerman, 1985	15 x 10^6 2 200 x10^6 (mining)	30	500	25	200 x 10^{6} #	Adamboerskraal
Timmerman, 1985b	36 x10^6 55 x10^6 (mining)	50	Langebaan Rd: 10-4000 Elandsfontein: 5-250 QSM 100-1000 Springfontyn 50-500		Langebaan Rd: 21.9 x 10^6 200 x 10^{6} # Elandsfontein: 15.5 x106 2400 x 10^{6} #	Langebaan Road and Elandsfontein
Timmerman, 1988	15 x 10^6 (model area) 50 x10^6					Adamboerskraal, Elandsfontein and Langebaan Road

*artesian flow; #unconfined

Discharge and abstraction

Discharge takes place through gaining rivers, evapotranspiration, springflow, abstraction and the natural underflow towards Langebaan Lagoon, Saldanha Bay and the Atlantic Ocean (Timmerman, 1985a; Timmerman, et. al, 1985). Woodford and Fortuin (2003) provided some estimates of the values of the natural discharge (Figure 2.11).

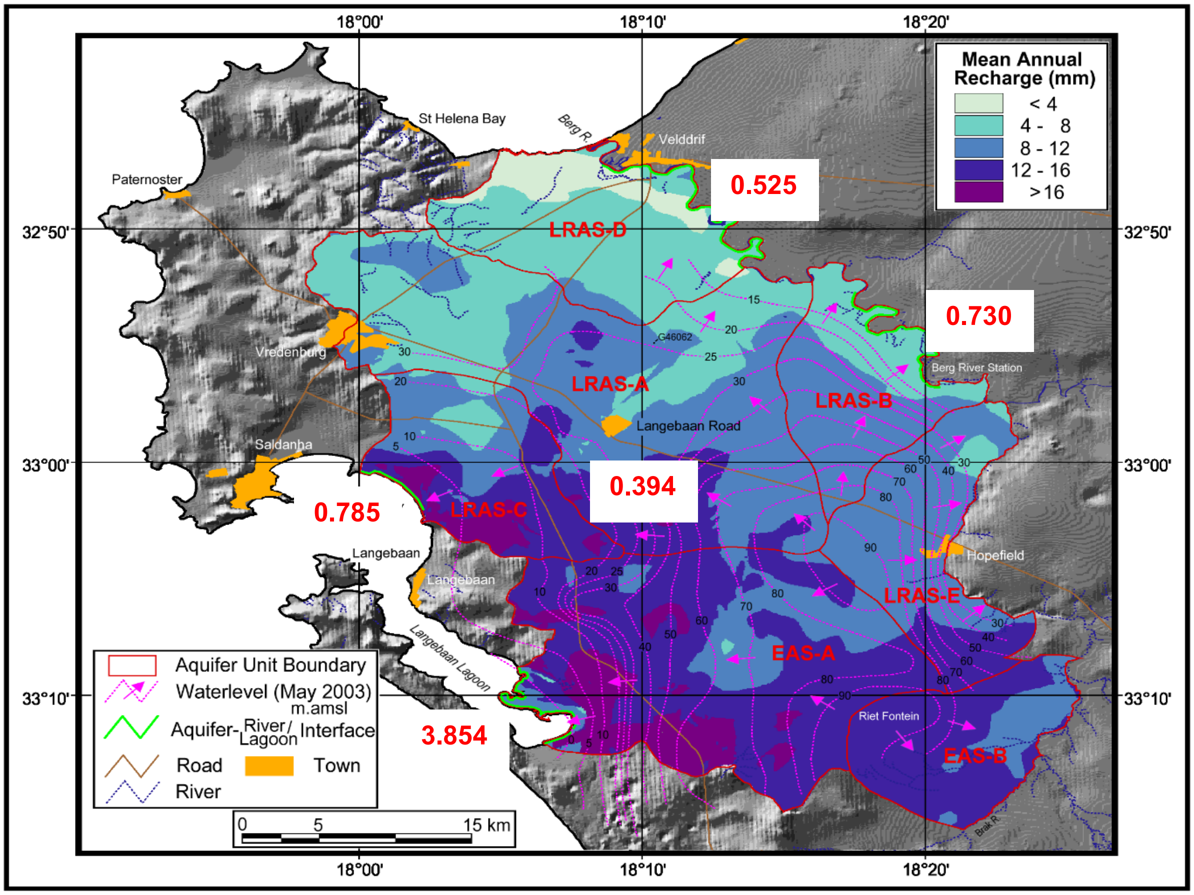


Figure 2.11: Natural discharge (L/s) from the Langebaan Road and Elandsfontein aquifer units to the rivers, wetlands, pans, springs and the sea, and estimates of mean annual recharge (Woodford and Fortuin, 2003)

The West Coast District Municipality is the largest single user of groundwater out of the Lower Berg River Aquifer System. The wellfield became operational in December 1999. Figure 2.12 shows the cone of depression after the wellfield had been operational for a number of years. The elongation of the cone of depression in an east-west line correlates with the direction of the palaeochannel. The loop towards the south was a bit unexpected, especially considering the no-flow boundary between the Langebaan Road and Elandsfontein aquifer units that was postulated by Timmerman (1985b; 1988). The impact that can be seen along the R45 towards Hopefield may be linked to the palaeochannnel mapped by Smith (1982), and also the fact that some of the recharge is coming from that direction (Timmerman, 1988; DWAF, 2008).

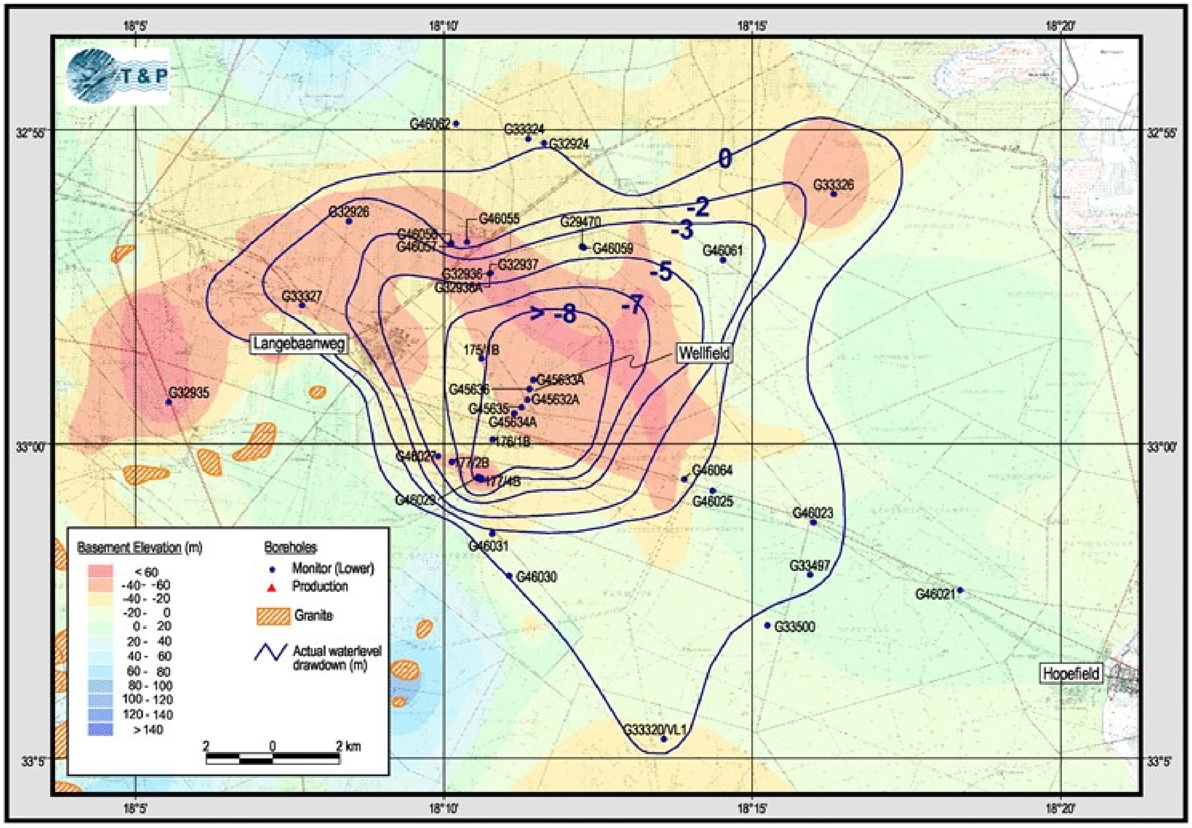


Figure 2.12: Cone of depression associated with the Langebaan Road wellfield after a number of years in operation (Woodford and Fortuin, 2003)

Groundwater quality

The water quality of the groundwater is generally good (EC below 300 mS/m), with the upper aquifer layers mostly of a poorer quality than the lower aquifer layers. Figure 2.13 provides an indication of the water quality using the EC for the Langebaan Road and Elandsfontein aquifer units. The southern and central part has good quality, that deteriorates towards the north and the west, where brackish water is found close to the Berg River and the sea (Timmerman, 1988; Woodford and Fortuin, 2003).

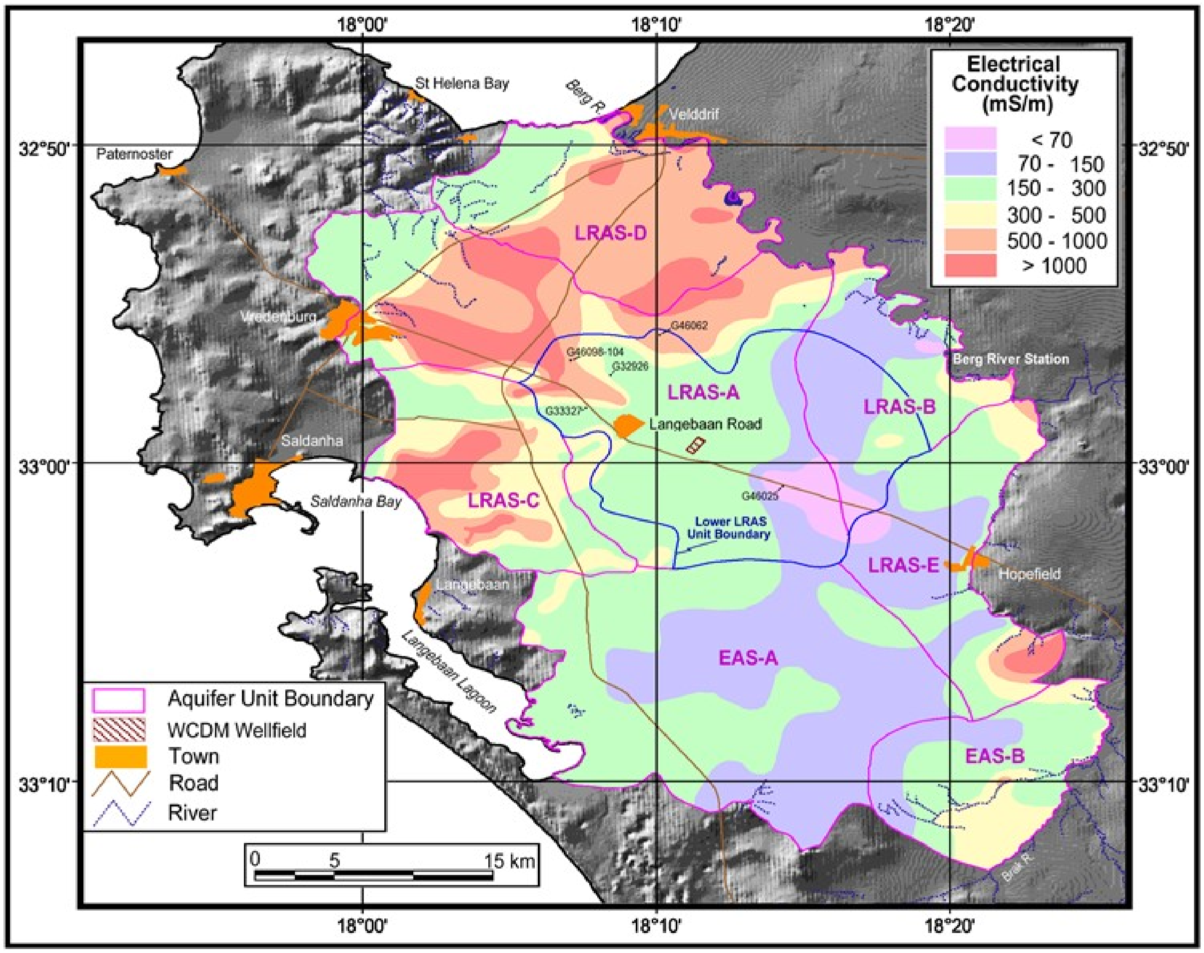


Figure 2.13: Electrical conductivity in mS/m as an indication of the water quality of the Langebaan Road and Elandsfontein aquifer units (Woodford 2004)

Groundwater protection

Groundwater was seen as a private entity under the Water Act of 1956 (Act 54 of 1956). The only way that groundwater could be protected was through the declaration of a Subterranean Government Water Control Area. The Saldanha Subterranean Government Water Control Area, which basically covered the Langebaan Road aquifer unit, was declared in September 1976. Timmerman (1985c) proposed the expansion of this control area to include the Adamboerskraal, Elandsfontein and Grootwater aquifer units. The proposal was to include the three northern aquifer units into one, under the name Lower Berg River Subterranean Government Water Control area. The Grootwater aquifer unit would be a separate area. Baron (1990) did further work on the Grootwater aquifer unit and the area was declared in 1990 under the name Yzerfontein Subterranean Government Water Control area. Water allocations for the landowners on the Grootwater aquifer unit was promulgated in 1992. The formal declaration of the Lower Berg River Subterranean Government Water Control Area with its boundaries apparently never happened.

The National Water Act of 1998 (Act 36 of 1998) replaced the Water Act of 1956. It included a number of tools for the protection of water resources, including groundwater. These tools and the legislation are referred to in section 2.8.

2.7.3 Other water resources

Other water resources include sea water through desalination. This option has been investigated, but put on the shelf for the time being due to the high cost (DWS, 2015; Smith, 2018). It is, however, an option that will become more important in the future. The possibility also exists for desalinization of brackish groundwater, which makes the use of groundwater from parts of the Adamboerskraal aquifer unit a more viable option.

Stormwater and wastewater are other options for additional water resources, but this would likely not make a big contribution to the water mix for a number of reasons. Stormwater is the result of rainfall, and in a semi-arid region where rainfall is limited, there will not be a lot of stormwater generated. It is, however, possible to make the most of the little that is available, even if it only reduces the use of potable use for gardening. Wastewater that is treated to potable standards is another option, but it is limited to the larger towns. It is currently being investigated for use by industries to reduce the reliance on the bulk system where potable water is being used for industrial processes (Smith, 2018). The capturing of mist may also provide some additional water.

2.8 Legislative framework

The overarching regulation for water management in South Africa is given through the National Water Act (NWA), Act No 36 of 1998 (RSA, 1998). According to the NWA, the management of water resources, whether surface water or groundwater as part of the integrated hydrological cycle, is the competency and responsibility of the National Department of Water and Sanitation, with the Minister of Water and Sanitation acting as custodian of the water resources. There is no competency for the management of water resources on a provincial or local level, in order to ensure that the management of the water resources in the country is to the benefit of all water users, not just those of a specific region. This becomes especially important in the light of the large amount of inter-catchment transfer schemes in the country.

The provision of water services is managed at a local level (municipalities, both local and district) under the Water Services Act (WSA), Act No 108 of 1997 and does not include the management of the resource as such (RSA, 1997). Groundwater management is especially challenging when it comes to its regulation at local level. There is no legal framework for municipalities to include it into their bylaws, aside from voluntary borehole registration, including operational and procedural requirements.

The challenge regarding groundwater management is increased by the fact that groundwater and surface water (to a great extent) are still managed as two different resources, that groundwater was seen as private property under the Water Act, Act No 54 of 1956 of 1956 (RSA, 1956), and that the concepts and language used in the NWA to explain the management and regulation of groundwater is that of surface water. In addition, groundwater does not conform to surface water boundaries. Groundwater units are often larger than the quaternary drainage areas that have been delineated as management units.

The *National Water Resources Strategy 2* (NWRS2) provides information on the implementation of the NWA. Strategies that have a direct link with groundwater management are the *Guideline for the Assessment, Planning and Management of the Groundwater Resources of South Africa,* the *Artificial Recharge Strategy* and the *National Groundwater Strategy*. Some of the tools available for the management of water resources are prescribed in Chapter 3 of the NWA. These are the *Water Resource Class* (Section 13) and the *Resource Quality Objectives* (Section 14). These tools are setting the benchmark or standards against which water resources are to be managed. The *Reserve* (Section 16) consists of two components, i.e. basic human needs and environmental water requirements. It is meant to ensure that the resource is never depleted, as it holds the necessity in trust. Principle 20 (on which the NWA is based) states that "The conditions upon which authorisation to water use is granted, shall take into consideration the investment made by the user in developing infrastructure to be able to use the water" (DWAF, 1997). This implies that those measures taken by the user at source to protect the water resource, must be taken into account to determine whether such use in sustainable. Moreover, where existing water uses are not at an optimum level, measures for adequate corrective action or remediation must be considered for implementation. These measures are referred to as *Source-directed Control Measures,* aimed to control actions that involve the use of water, as a means to achieve resource protection. The principle applied is that discharges must be controlled at their sources (Fuggle and Rabie, 1994).

Water use authorisations can also be used as a way to manage or protect water resources. Section 22 lists the permissible uses that do not require a water use licence. The first is *Schedule 1* use, which is the water needed for reasonable domestic use, watering of the garden, and stock watering. As soon as there is a commercial aspect linked to the water use, it is no longer a *Schedule 1* use. The second use is *Existing Lawful Use* meaning that the water use was lawful during a window period between 1996 and 1998. Conditions around existing lawful use are prescribed under Sections 32 to 35 of the NWA. The third permissible water use is the *General Authorisation*, as prescribed under Section 39. This water use is deemed to have a low enough impact so that it does not have to go through the whole authorisation process. There are some conditions linked to this water use authorisation, but it cannot be adjusted with site specific details and requirements. Water users that do not meet the requirements of the authorisations above (as a result of the volume needed or the severity of the impact of the proposed activity), have to go through the whole authorisation process in order to obtain a *Water Use Licence*. The requirements of the application procedure and other conditions connected to the water use licence is contained in Sections 40 to 42. *Compulsory Licensing* (Section 43) is the final option if the water use exceeds the available supply. The process of compulsory licensing entails a redistribution of the available supply, which can be interpreted as the reduction in the volume that an individual water user may abstract in order to allocate water equitably to other water users. It is possible to manage the water resource through the conditions set in individual water use licences. Some of the general conditions can be found in Sections 49 to 52. Site and case specific *Conditions of Authorisation* can be set by the case officer working on the licence application and the specialist scientists that provided comments on the licence.

3. GEOHYDROLOGICAL CHARACTERISTICS

Geohydrological investigations are conducted to get a better understanding of the groundwater system and develop a realistic and reliable conceptual groundwater model. The first geohydrological investigations for the study area were done in the early 1970s and almost five decades of monitoring data have been collected. More than 200 geosites formed part of the monitoring. The monitoring data and personal observations were used in the construction of a conceptual model. A summary of these data and analysis is presented and discussed in this Chapter.

The chapter starts by looking at rainfall, groundwater levels and the correlation between the two. It also discusses the effects of the abstraction at the wellfield and the MARS tests. Aquifer characteristics are summarized, and the groundwater quality is analyzed and how it correlates with the geology of the area. The Chapter ends with the estimations of discharge of groundwater from the aquifer system and a brief look at the groundwater dependent ecosystems associated with the Lower Berg River aquifer system.

3.1 Rainfall

Rainfall is an input in the hydrological cycle and it has traditionally been used as the basis of recharge calculations where the volume of recharge to groundwater has been calculated as percentage of rainfall. Rainfall in the study area was measured by DWS with cumulative rainfall collectors that are equipped with a Perspex measuring tube and OTT Thalimedes for continuous recording of data. The rain gauge was designed by van Wyk (Havenga, 2010) and the idea behind the design was to be able to collect rainfall samples that can be used for chemical and isotope analysis. The Thalimedes recorded hourly readings that were then processed using the HYDRAS3 software. The data then had to be recalculated to get monthly values, to be able to compare with data from the South African Weather Services (SAWS) and groundwater levels. Some rainfall data were also collected by farmers and other private citizens.

Figure 3.1 shows the location of a number of rainfall stations in the study area, with Table 3.1 giving a summary of data that were available for the analysis. BG00071-RF, BG00074-RF, G33323-RF, G46024-RF, G46059-RF, G46092-RF, G46105-RF and G10K1 are DWS cumulative rain gauges. Arnelia, Langrietvlei, Kleinklipfontein and Jakkalsfontein are private rainfall stations, while the rest are SAWS stations.

The Cumulative Deviation from Mean (CDM) is a simple arithmetic technique used in the evaluation of rainfall (Yesertner, 2008). Previous applications of this technique include an extensive analysis of rainfall variation in South Africa by Temperley (1980) and the work of Boehmer (1998) that showed that natural groundwater level fluctuations near Colesberg in the Karoo, South Africa, correlate with cumulative departure graphs of rainfall (Yesterner, 2008).

The CDMs were calculated for the rainfall station data, as follows:

- determine the average of the rainfall measurements over a defined period;
- determine the difference between the average and the actual measurement of the same defined period to find the deviation from the mean;
- the deviations are then plotted cumulatively in a graph;

- periods of above mean rainfall show an upward trending graph (wet cycle), while rainfall below the mean is downward trending (dry cycle).

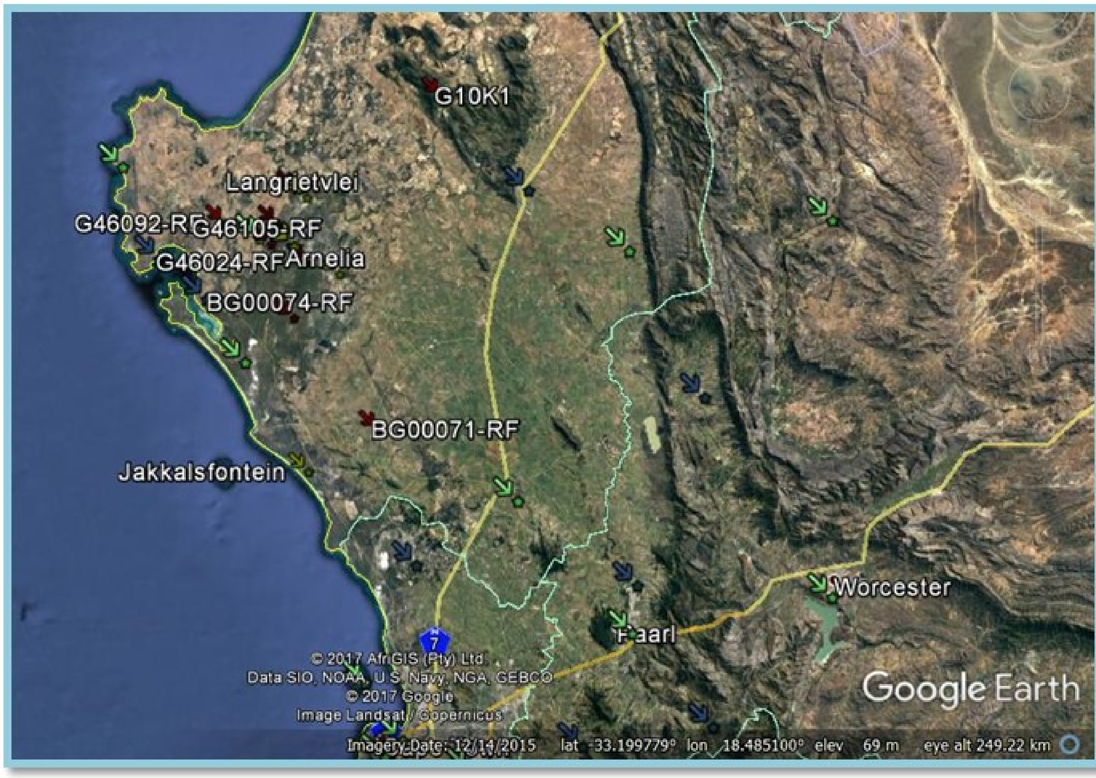


Figure 3.1: Satellite image showing the location of the rainfall stations on a Google Earth map (Google Earth, 2017)

Table 3.1: Summary of rainfall records in the study area

TABLE 3.1 Summary of rainfall records in the study area				
Rainfall station	Data Record	Years	Average annual rainfall	Maximum (year)
Arnelia	2000-2013	13	389	622 (2007)
Atlantis	1979-2013	34	428	573 (1987)
BG00071-RF	2016-2017	0.5	-	-
BG00074-RF	2007-2016	9	368	510 (2014)
Cape Columbine	1936-2016	80	247	546 (1951)
G10K1	2010-2016	6	534	960 (2014)
G33323-RF	2001-2016	15	186	323 (2013)
G46024-RF	2001-2016	15	275	511 (2007)
G46059-RF	2004-2016	12	213	434 (2007)
G46092-RF	2004-2016	12	203	303 (2009)
G46105-RF	2007-2016	9	265	348 (2009)
Geelbek	1992-2014	22	278	385 (2011)
Jakkalsfontein	1996-2016	20	377	560 (2007)
Kleinklipfontein	1992-2001	9	290	443 (1996)
Langebaan 1	1987-2001	14	315	533 (2001)
Langebaan 2	1920-2012	92	254	558 (2001)
Langrietvlei	1893-2000	107	265	479 (1996)
Malmesbury 1	1993-2013	20	352	516 (1996)
Malmesbury 2	1920-1999	79	456	810 (1977)
Malmesbury 3	1999-2013	14	369	518 (2007)
Piketberg	1920-2013	93	443	722 (1996)
Porterville	1920-2013	93	453	734 (1977)
Saldanha	1939-2008	69	316	877 (1954)

Figure 3.2 shows the data for the rain gauges with the CDM curves. The rainfall has a definite seasonal pattern, with the highest rainfall in the winter months (usually from April to October). It is also clear that the volume of rainfall recorded for each station is different. Rainfall is dependent on a number of characteristics, which include topography (orographic rainfall), distance from the coast, mountain ranges, wind direction and speed, and temperature (Vermaak and De Haast, 2013). Rainfall may vary over short distances. The CDM curves show similar cyclical patterns, especially for rainfall stations in the same area and topography. Most analyses of CDM patterns show a 10-year cycle that usually includes three to five wet years and five to seven drier years (Vermaak *et al.*, 2015), with some exceptions. Previous analyses gave an indication that the 7th year of a decade (or close to it) was usually linked to higher rainfall, that resulted in flooding. The maximum rainfall measurements in Table 3.1 seem to corroborate this, since the highest rainfall was measured on 1977, 1987, 1996, 2007 for some of the rainfall stations.

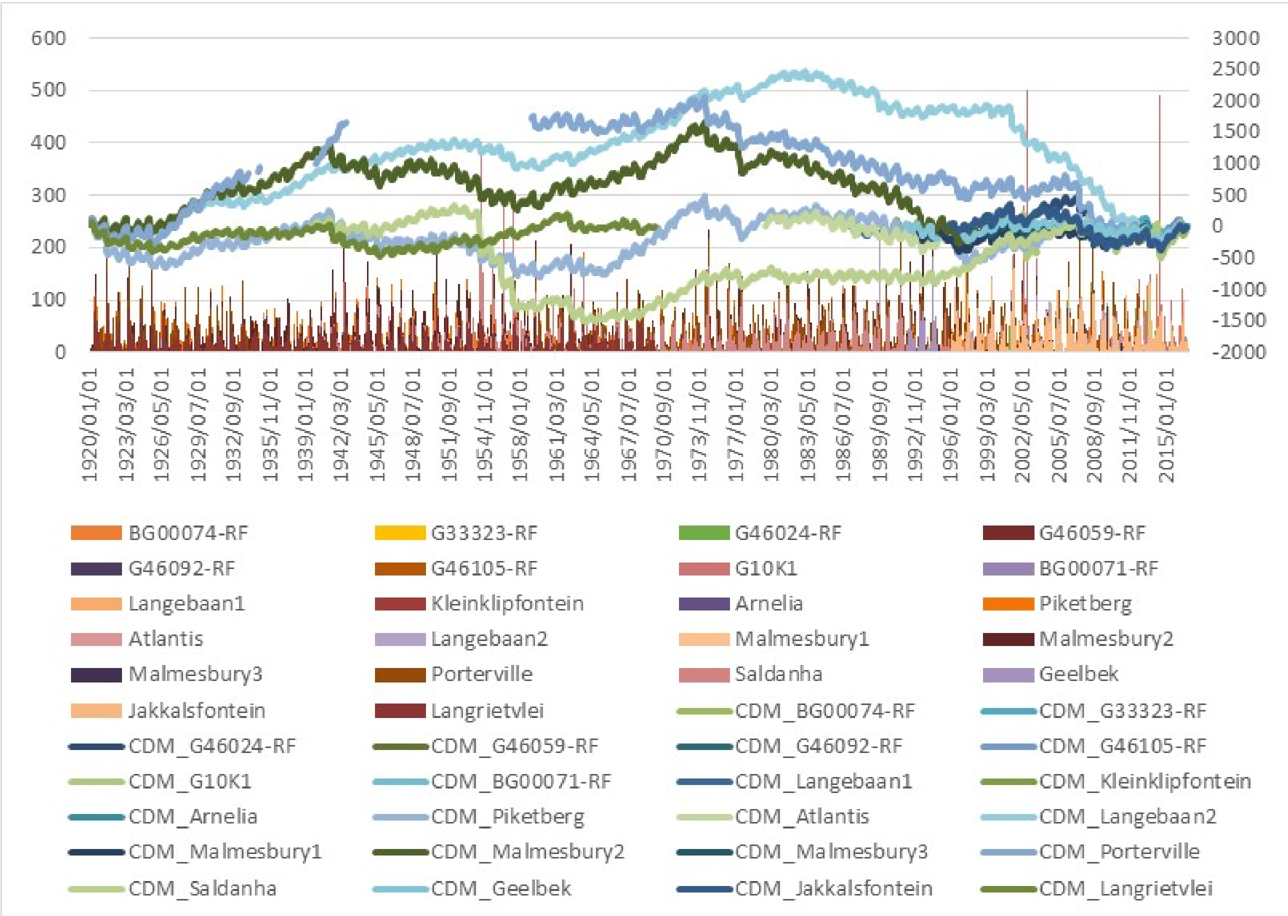


Figure 3.2: ***Time series of rainfall (bars) and Cumulative Departure from Mean (CDM, lines) in the study area***

3.2 Groundwater recharge

Groundwater recharge is defined as the flow of water reaching the water table subsequently adding to groundwater storage (Freeze and Cherry, 1979). Groundwater recharge depends on factors such as climate, geology, topography, hydrology, vegetation and land use (Healy, 2010; Scanlon *et al.*, 2002). Numerous studies on groundwater recharge have been carried out around the world. This was done in a wide variety of geological settings, using different factors and parameters (Hernández-Marin *et al.* 2018; Coelho *et al.*, 2017). Some consider it almost impossible to quantify recharge directly, as it is a multifaceted process that requires the inclusion of two or more concurrent estimation methods (Healy and Cook, 2002; Scanlon *et al.*, 2002; Yin *et al.* 2011; Hernández-Marin *et al.*, 2018). Arid and semi-arid environments are considered to be the most complicated areas in which to determine groundwater recharge, as the recharge tends to be lower and more variable on a spatial and temporal scale as the aridity increases (Sibanda *et al.,* 2009; Hernández-Marin *et al.*, 2018).

There is a number of factors that strongly affect the volume and distribution of recharge in arid and semi-arid environments. Precipitation is probably the most important, because of its scarcity. Rainfall changes over time and is highly seasonal/event-based (Adams, 2019); groundwater recharge is therefore dynamic in its response to rainfall. This can be coupled with high evapotranspiration rates and changes in land use. Some studies have shown that changing the land use from natural to agriculture had increased groundwater recharge (Allison *et al.,* 1990; Scanlon *et al.,* 2007; Hernández-Marin *et al.*, 2018). Another factor that has an influence on the recharge to groundwater is the vadose zone. This is especially true in areas of intense groundwater pumping, where the thickening of the vadose zone causes a decrease in the recharge volume (Han *et al.*, 2017; Hernández-Marin *et al.*, 2018). A thick vadose zone tends to store water instead of allowing it to percolate down to recharge the water table (Cao *et al.,* 2016).

3.2.1 Mechanisms of groundwater recharge

Four modes of recharge can occur, as generalized by Xu and Beekman (2003):

1. Downward flow of water through the unsaturated zone reaching the water table;
2. Lateral and/or vertical inter-aquifer flow;
3. Induced recharge from nearby surface water bodies resulting from groundwater abstraction; and
4. Artificial recharge such as from borehole injection or man-made infiltration ponds.

In the West Coast Aquifer System, there are different mechanisms of groundwater recharge. This includes *direct or focused recharge* which could be from recent rainfall or irrigation return flows. Very little irrigation is taking place in the study area, with the exception from the Adamboerskraal aquifer. Most farmers use dryland farming. There is a possibility that direct recharge may be limited as a result of the high soil water repellency, especially after dry periods. This seemed to be confirmed by recharge estimations by Smith (2019) using stable isotopes and the Cumulative Rainfall Departure (CRD) method of recharge estimation. The possibility exists that the recharge system may be similar to that found by Nel (2009) for the Langvlei Catchment, in the Sandveld area around Elands Bay and Lamberts Bay with recharge from the Cederberg Mountains through the fault systems. This would take the form of *preferential recharge* and may take place through the Colenso Fault System, sub-parallel faults, the inferred shale-granite contact, and other fractures and fissures in the bedrock. It is also possible for recharge to take place via *upward leakage* from the fractured bedrock aquifer. Recharge may also come in the form of *mountain block recharge* with the Malmesbury shale outcrops in Hopefield, the granite pluton forming the Darling hills, and the TMG Mountains above Aurora and potentially also Franschhoek or Stellenbosch. *Recharge by surface water* at the Berg River flood plain is another possibility which would recharge the aquifer through lateral flow. This can be seen in the groundwater level responses to the 2007 flood in the Berg River with a 2- to 3-year time lag in some instances.

3.2.2 Groundwater recharge areas

Recharge occurs naturally to the UAU from rainfall throughout the total area of the region. The sediments of the UAU have low permeabilities and large rainfall events recharge the UAU. Focused recharge is postulated to occur where contacts with granite koppies occur in Darling and Vredenburg due to enhanced runoff over these impermeable surfaces.

The recharge mechanism is more complex for the LRA, EA and basement aquifers due to lack of the Elandsfontyn and thick clay lenses that outcrop in the region. Timmerman (1985a) suggested that the LAU is recharged through downward percolation or leakage at topographically high areas where rainfall rate is highest, clay layer is thinnest, and the water level is higher in UAU than in the LAU. These conditions make it ideal for groundwater to move from the UAU towards the LAU and flow laterally under increasing pressure to the north and north-west via a piston flow mechanism (Seyler *et al.,* 2017). This hypothesis was supported by immediate response in groundwater levels in the LAU in 1977 and 1983 after high rainfall events. The recharge mechanism to the bedrock aquifer is still not clearly known. It has been hypothesised that the source of groundwater is derived from the Franschhoek Mountains via deep incised fracture network (Weaver and Talma, 2005). According to Weaver and Talma (2005), recharge to the bedrock aquifer is a local phenomenon.

The groundwater recharge areas have not been determined conclusively. Some local recharge to the Langebaan Road and Elandsfontein aquifer units most likely comes from the higher lying areas around Hopefield, and the absence of the clay layer in this area seems to increase the likelihood. The flood plain of the Berg River is another site for recharge, but it depends on the flood levels. The delays seen in groundwater level responses to the flood event of 2007 seem to fit this scenario. Smith (2019) found that local groundwater recharge seems to be small in comparison to the large volume of recharge that most probably comes from outside the study area, while Andries (2019) seemed to have found the exact opposite. The difference may be the result of the recharge estimation method used and the time period of the analysis.

3.2.3 Groundwater recharge estimations

Groundwater recharge has received a lot of attention in South Africa (Xu and Beekman, 2003). Methods for the estimation of groundwater recharge can be grouped into physical, modelling and chemical methods. Physical methods and models may be prone to large errors especially in arid and semi-arid areas due to the generally thick unsaturated zone and low rainfall (Scanlon *et al.*, 2002). The interest in adopting chemical methods (ions and isotope tracers) is increasing amongst practitioners. However, limited studies focused on groundwater recharge for the West Coast Aquifer System. Due to limited and fragmented geochemical (environmental isotope) data for the study area, it makes it difficult to accurately quantify and conceptualize groundwater recharge. While some studies have used secondary data to model recharge for hydrogeological units on the West Coast, there are limited studies that used primary hydrochemical data to quantify and conceptualize groundwater recharge.

Various recharge estimations have been done in recent years for the study area. Estimates generally agree that local recharge only contributes a small portion of recharge to the aquifer system (Smith, 2019). Spannenberg (2015) used the chloride mass balance (CMB) and rainfall infiltration breakthrough (RIB) methods to estimate the recharge for the unconfined layers of the Elandsfontein and Langebaan Road aquifer units, as well as for the TMG aquifer above Aurora. Spannenberg (2015) showed the impact of the proximity to the coast on the CMB method, which makes it less reliable for use in coastal areas. Ebrahim (2015) used the same methods, but for the lower aquifer layers. The low recharge value estimates are in most cases in line with the recharge estimates of Andries (2019) who used the CMB and isotopes. A summary of the results is reported in Table 3.2.

Table 3.2: Summary of recent recharge estimations

TABLE 3.2 Summary of recent recharge estimations				
	Aquifer	Chloride mass balance	Rainfall infiltration breakthrough	Other methods
Langebaan Road	Upper [1]	5.2 mm (3.25% of annual rainfall) on average	-	
Langebaan Road	Upper [2]	7.45% (G46024)	38.79% (G33323) 8.56% (BG00137)	
	Lower [3]	7.44% (G46023) 13.7% (BG00136)	0.12% (G46023) 5.72% (BG00136)	
Elandsfontein	Upper [2]	8.61% (BG00074)	10.53% (BG00074)	
	Lower [3]	7.88% (G33317) 13.26% (G33505B)	0.20% (G33317) 0.69% (G33505B)	
TMG		31.25% (37/1) [2]	32.84% (37/1) [2] 18.06% (37/2) [3]	
Langebaan Road			-	9.7% to 13.5% [4]
Langebaan Road	Upper [5]		-	5% to 8% [5]
Saldanha			-	8% to 12% [6]

[1]Andries (2019); [2]Spannenberg (2015); [3]Ebrahim (2015); [4]Weaver and Talma (2005); [5]DWS (2008) – water balance method and GIS techniques (GRA II); [6]du Toit and Weaver (1995) – water level data and reverse modeling techniques.

Limited studies applied a multiple environmental isotope approach to conceptualize groundwater recharge to the West Coast Aquifer System. Andries (2019) conducted an investigation to estimate groundwater recharge in the West Coast Aquifer System using chloride mass balance (CMB) and environmental isotopes (O-18, H-2, H-3 and C-14). Whereas environmental isotopes were analyzed to determine flow mechanisms and discussed in Section 3.5.4, chloride analyses were done to apply the CMB to quantify groundwater recharge of the unconfined aquifer at both regional and local scale. The unconfined aquifer is the most recently recharged and it would provide plausible recharge estimates with regard to shorter flow paths. For this purpose, rainfall and chloride concentrations in rain water as well as groundwater were measured during 2017.

Application of the Chloride Mass Balance (CMB) technique to the unconfined aquifer unit showed that groundwater recharge was estimated to be on average 5.2 mm which represented 3.25% of the total mean annual rainfall for the West Coast (Andries, 2019). These estimates were generally in the range of previous estimates yielded from physical and chemical methodologies, when the decreased rainfall of 2017 is considered (Table 3.2). Results revealed that the unconfined aquifer is recharged throughout the study area from rainfall, while the main recharge area was delineated in the topographically high-lying land close to Hopefield. Fluctuations in chloride concentrations indicated groundwater recharge occurs predominantly in winter. At localized scale, groundwater chloride concentration and recharge in the West Coast is controlled by position in the landscape, distance from the ocean, land use and seasonality.

3.2.4. Natural groundwater recharge

Discharge takes place towards a number of surface water bodies in the study area. This includes, but is not limited to the:

- Langebaan Lagoon;
- Saldanha Bay;
- Berg River and non-perennial rivers in area (base flow); and
- Pans, wetlands and springs.

The volumes of discharge have not been fully quantified yet, and the only estimates are the ones done by Woodford and Fortuin (2003). Isotope analysis by Andries (2019) has confirmed that the Elandsfontein aquifer unit is in hydraulic connection with the Langebaan Lagoon at Geelbek. The possibility exists that the interaction between the Elandsfontein aquifer unit and the Langebaan Lagoon could be a subterranean estuary. Information from game rangers in the West Coast National Park gives further credence to the idea of a subterranean estuary since the wells dug along the coast show fluctuating water levels and changes in the water quality in time with the tides.

The isotope analysis also shows a link with the Berg River, with the aquifer system contributing to the flow of the river as baseflow (Andries, 2019). The discharge to the Berg River depends on the water level in the aquifer system.

3.3 Groundwater levels

Historically, groundwater levels were measured as part of the DWS West Coast groundwater monitoring program (the area between Atlantis and Dwarskersbos vs. Sandveld monitoring program that comprises the region between Dwarskersbos and Strandfontein). Most of the groundwater levels were measured using a dip meter and the readings were recorded as meters below collar. At the beginning of the monitoring programme, there were almost 56 data loggers in the boreholes, but most of these had since been removed as a result of failure. The data loggers included Eikelkamp divers, Solinst Leveloggers, OTT Orphimedes and OTT Orpheus-Mini. The readings were taken at hourly intervals and the data analysed with HYDRAS3 before being exported and captured in the DWS database Hydstra.

The groundwater level readings were plotted as time series graphs, along with CDM and rainfall to determine the time lag between rainfall events and recharge to the aquifer. This is, however, complex since the recharge of a specific borehole does not necessarily come from the rain that fell on site. The soil characteristics in the study site seem to suggest that only minimal recharge came from direct infiltration. It is interesting to note that the CDM curves for the groundwater levels tend to have cyclical patterns, and groundwater abstraction can also present itself as a man-made dry cycle.

Some of the findings around the CDM curves are discussed below. Only a selection of representative graphs is discussed in this section. A complete record of the groundwater levels and other information can be found in Vermaak (2021). The results and discussion are done by aquifer unit for ease of reference.

3.3.1 Langebaan Road aquifer unit

Figure 3.3 gives and overview of the distribution of monitoring points in the Langebaan Road aquifer unit. The red oval shows the location of the wellfield.

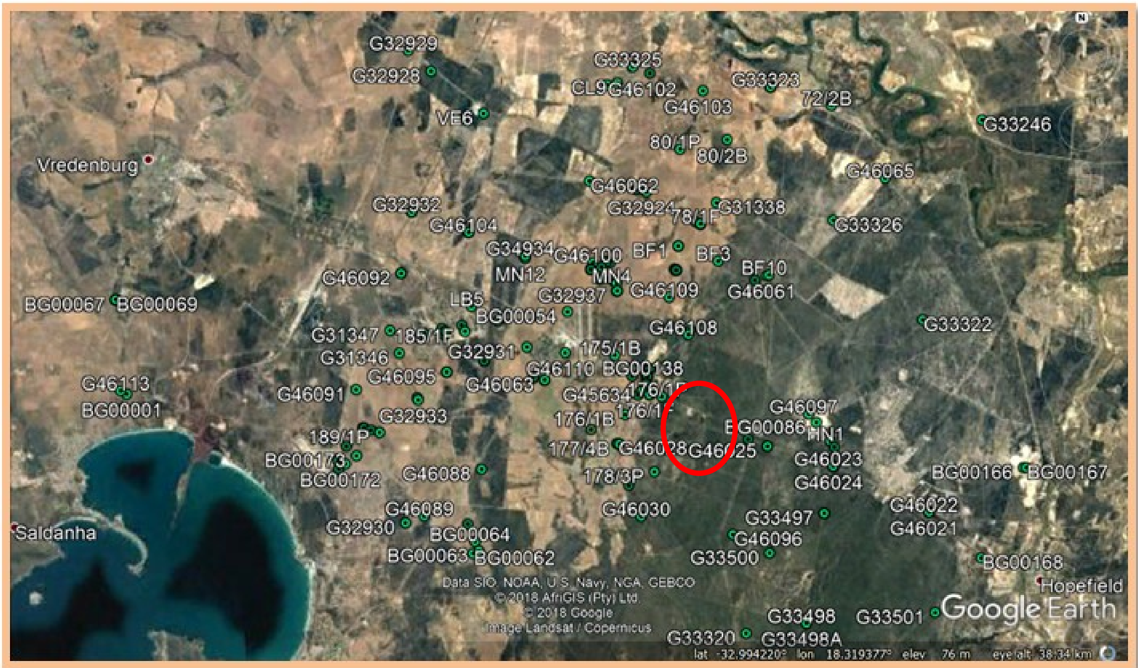


Figure 3.3: ***Google Earth image showing the distribution of monitoring points in the Langebaan Road aquifer***

Borehole G33323 was drilled in 1984 and is located close to the Berg River. It is in the unconfined aquifer layer of the Langebaan Road aquifer unit and seems to react fairly quickly to rainfall events (Figure 3.4). It is also possible that it is linked to flow in the Berg River. There is a clear seasonal trend in the water levels, with the highest water levels usually measured between August and November. The water levels have a downward trend from 2001 to 2007, when flooding in the Berg River recharged the aquifer. The peak of this rise was measured in October of 2007, where after the water levels began declining until May 2012. Good rains fell again late in 2013 and in 2014, after the low rainfall of 2011 and 2012. This led to a peak in water levels in August 2014. The recent drought began in 2015 and can be seen in the declining water levels since August 2014. The increase in rainfall in early 2019 should lead to an increase in the water levels in this part of the aquifer.

The CDM curve shows an initial steep increase for the historical data record from 1985/05/06 to 1991/01/10 (readings of -0.12 m and 10.07 m respectively; difference of 10.19 m). There is a steep drop in the CDM curve from 2003/02/08 (13.59 m) to 2007/02/03 (-1.18 m) with a difference of 13.59 m. The rest of the curve is fairly stable with fluctuation smaller than 2 m in this period.

Figure 3.4: ***Time series graph of water levels for borehole G33323 with cumulative deviation from mean (CDM)***

Borehole G33327 was also drilled in 1984 but it is in the lower semi-confined to confined layer of the Langebaan Road aquifer unit. It is about 12 km from the wellfield near the old phosphate mine, now the West Coast Fossil Park. It is responding to the abstraction at the wellfield, with an almost immediate response (see Figure 3.5). The wellfield became operational in December 1999, which can be seen in the steep drop in water levels. There was concern that the abstraction was having a permanent detrimental impact on the aquifer, and it was decided to test this in 2004 by resting the wellfield for 3 months while the pumps were serviced/repaired. This can be seen in the recovery of water levels. Based on the recommendation of the monitoring committee there was a voluntary 10% reduction in the volume abstracted from what was allowed on the water use licence.

The water levels dropped again after abstraction resumed in 2004. The next two peaks are the result of the artificial recharge / managed aquifer recharge test that was done in 2008 and 2009 by the CSIR for DWS (then DWAF). These peaks follow a smaller peak that was the result of the natural recharge to the system due to the flooding in the Berg River flood plain in 2007. The years 2007 to 2009 were all good rainfall years and they masked the effectiveness of the MAR test. The water levels dropped after the MAR test was completed and they reflect the poor rainfall of 2011 and 2012. It is interesting to note that this decline in water levels are not as steep as the decline in 1999 onwards when the wellfield become operational. The response to the higher rainfall in 2013 and 2014 were combined with the results of vandalism at the wellfield. The electrical wires were dug up and stripped on site in late March/early April of 2013, and shortly afterwards the pump houses were vandalized. This resulted in the wellfield not being used for a number of years, which can be seen in the recovery of the water levels. The repairs were completed in 2015 or

2016, but further security measures were needed after renewed vandalism (Faasen, 2016). The wellfield became operational again near the end of 2017, with the lowest peak in 2018 (June 2018 with the reading at 17.56 mbc) at the height of the Western Cape drought and Saldanha only days away from running out of water. The reading taken in June 2018 was the lowest recorded reading for this borehole.

The CDM curve for G33327 also has an initial rise, which continued after the monitoring resumed in 1998. In September 2000, as a result of the abstraction at the wellfield, there is a sharp decline in die CDM curve that lasted till around June 2008, when the curve stabilized for the next two years or so. This flattening out of the curve is most probably the result of the MARS test that was carried out. The curve is fairly steady after this with a dip that recovers slightly in 2013. Even though this curve is affected by the abstraction at the wellfield, the variation in CDM values – up to 100 m in one instance – is far greater than that of G33323 that is in an unconfined system.

Figure 3.5: ***Time series graph of water levels for borehole G33327 with cumulative deviation from mean (CDM)***

3.3.2 Elandsfontein aquifer unit

The Elandsfontein aquifer unit has similar layers as the Langebaan Road aquifer unit, with the difference that the layers tend to be thicker. There is also stronger dune formation in this area of the Lower Berg River. Figure 3.6 shows the distribution of monitoring points in the Elandsfontein aquifer unit.

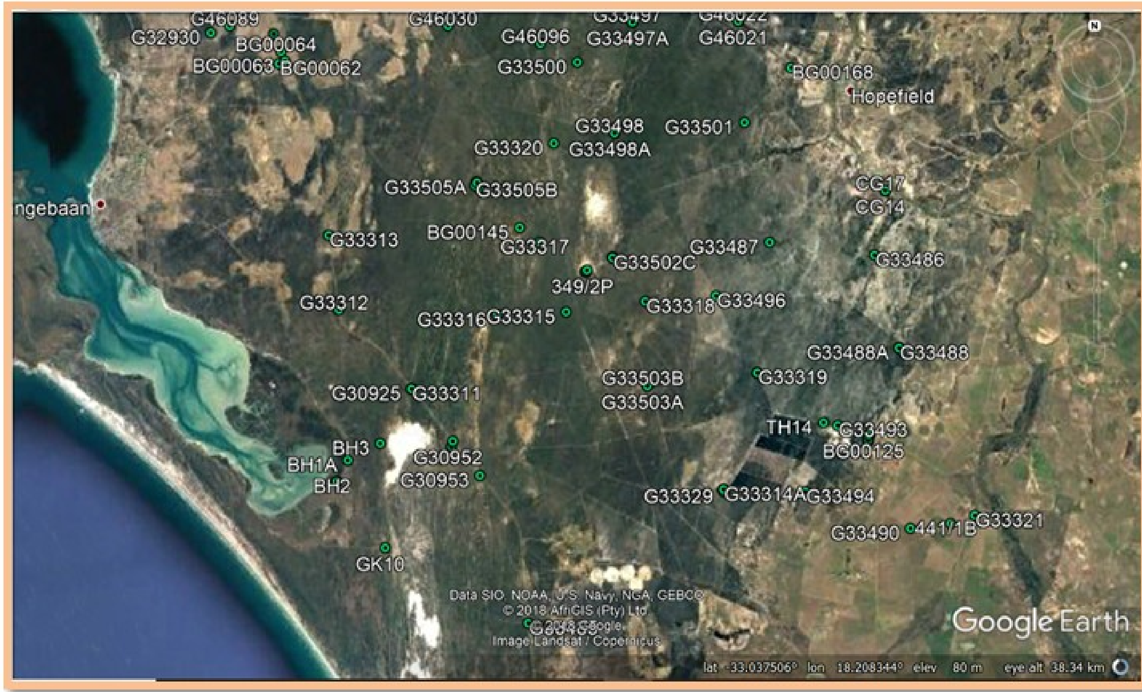


Figure 3.6: ***Google Earth image showing the distribution of monitoring points in the Elandsfontein aquifer***

G33317 was drilled in 1984 and is located in close proximity where the stratigraphic type borehole for the Elandsfontyn Formation (G30878) was drilled. It has screens in the upper and lower aquifer layers and was designated as a monitoring borehole. According to the bedrock contour map of Smith (1982), this borehole is located in the middle of the palaeochannel, where it changes direction. Figure 3.7 shows the changes in water levels for borehole G33317. The water levels were stable with very little fluctuation before 1991. A fairly steep drop occurred from September 2001 (13.13mbc) for the next five years, most probably as a result of the abstractions at the Langebaan Road wellfield where after the water level decline is less steep. In November 2016, it reaches a level of 15.17 mbc, which is only an approximate 2 m drop in water level. This is, however, a confined system, so it is of great significance. There is a sudden decline in water levels, reaching a value of 15.86 mbc in August 2017, before they recover to resume the normal trend. This dip in water levels is most likely linked to the activities of the Kropz Elandsfontein phosphate mine, but this cannot be confirmed, due to a lack of information from the mine. Another explanation can potentially be the higher abstraction at the Langebaan Road wellfield. This would mean a time lag of only a month or two compared to the one to two years when the wellfield became operational. This dip in the normal trend of the water levels can be seen in a number of boreholes in the Elandsfontein aquifer unit and was even observed in some of the Langebaan Road aquifer unit boreholes. The time period when it was measured differed between the boreholes. The ideal would be to compare this data with the monitoring data from the mine and their activities on site, as well as the abstraction at the wellfield.

The CDM curve for G33317 is relatively simple with a rising leg – with a 10-year gap – and a declining leg. The readings for the first section of the curve has a variation of about 23 m (0.92 for 1985/03/15 to 23,56 for 1990/01/12). The difference between the section starting in 2001 to the peak in 2005 is almost 25 m. The decline of the CDM curve goes slightly past zero at the end of the data record.

Figure 3.7: ***Time series graph of water levels for borehole G33317 with cumulative deviation from mean (CDM)***

3.3.3 Adamboerskraal aquifer unit

The Adamboerskraal aquifer unit is to the north of the Berg River and borders with the Piketberg mountains. Only one investigation was done on this aquifer unit in 1984 by K.M.G. Timmerman (1985). Only four boreholes form part of monitoring (Figure 3.8).

Figure 3.8: ***Google Earth image showing the distribution or monitoring points in the Adamboerskraal aquifer***

Borehole G33255 is on the farm Harde Valley, in the area identified by Timmerman (1985b) for possible wellfield development. The graph for borehole G33255 shows natural seasonal patterns till May 2010 (See Figure 3.9). After this, the impact of nearby abstraction can be seen on the water levels, with a variation in water levels of almost 9 m. The lowest water level was measured on 2016/02/23 with a reading of 13.56 mbc, with the reading of June 2018 coming close. The depth of this response to the nearby abstraction may be an indication of confining conditions and a higher conductivity of the sedimentary deposits. The impact of the drought could be clearly seen in the drop of water levels as a result of lower rainfall, higher temperatures and greater abstraction to compensate for this.

The CDM curve has a similar trend as G33317 with a rising limb and a falling limb, with a few differences linked to the different water level patterns.

Figure 3 9: ***Time series graph of water levels for borehole G33255 with cumulative deviation from mean (CDM)***

3.3.4 Grootwater aquifer unit

The Grootwater aquifer unit is along the coast with the R27 running through the middle. Figure 3.10 shows the distribution of the monitoring points. The points around Darling are not in the Grootwater aquifer unit, but they monitor the Colenso Fault system.

Borehole G33304 is next to the R27 and adjacent to the Modder River. The water levels show a seasonal cycle (Figure 3.11) with recharge events linked to periods of increased rainfall: 1987-1989, 2001, 2007-2009 and 2013-2014. The CDM curve tends to mimic these periods, with a two to three-year delay between the peak in the water levels and the peak in the CDM curve. The impact of the drought can be observed in the water levels of the last four years.

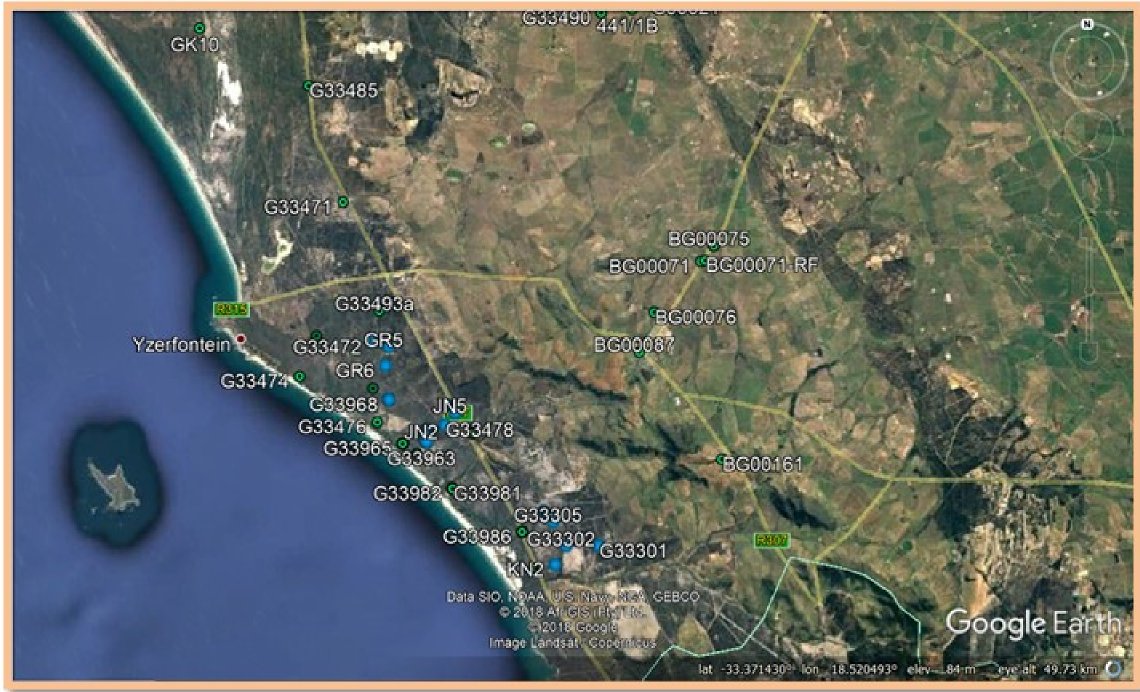


Figure 3.10: ***Google Earth image showing the distribution or monitoring points in the Grootwater aquifer***

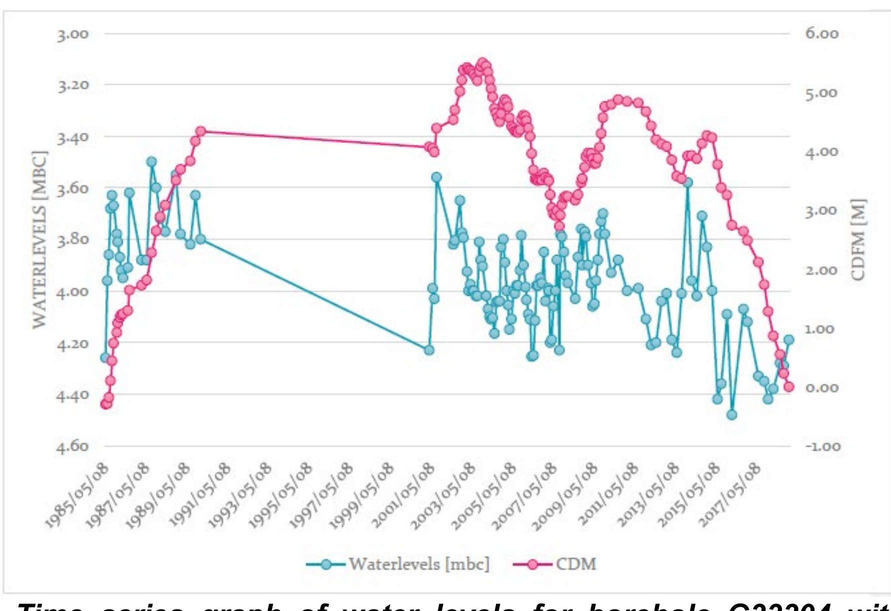


Figure 3.11: ***Time series graph of water levels for borehole G33304 with cumulative deviation from mean CDM***

3.3.5 Interpretation of CDM curves

The CDM method has previously been used mostly for the analysis of rainfall data. It has also been used for surface water by Vermaak *et al.* (2015). The section below shows its application to groundwater levels. The reasoning was that rainfall is part of the hydrological cycle, and if the CDM method can be used on one part, it may be possible to use it on other parts of the cycle, i.e. surface water and groundwater levels. The method was adopted as a way to determine the time lag between recharge events and the actual recharge to the aquifer that could be measured through rising water levels. The method was used in different sites in the Berg River catchment area and the patterns were observed. More than 200 data sets were analysed for the study area alone. It was noted that some patterns are repeated, independent of the length of the data record or whether new data was added to the data record. In boreholes of a similar geological setting and experiencing similar impacts, the trends showed the same patterns regardless of the length of the data record. When new data was added, the amplitude or size of the deviation of the CDM curve changed, but not the general pattern.

It was noticed that there is a difference in the values when plotting the CDM curves. Some of the boreholes show a slight difference in the upper and lower values, while other have a large variation. The amplitude and size of groundwater levels, within their aquifer units, whether they are in the unconfined upper layer or the semi-confined to confined lower layer, were noted in Table 3.3 and then compared with the variation in CDM values. There seems to be a correlation between boreholes in the upper aquifer layers with lower CDM variation and lower aquifer boreholes with a larger variation in CDM values. It could thus be possible to determine whether a borehole is in an unconfined or confined system. The cut-off value to differentiate between the two aquifers is difficult to point out, and it would probably entail further analysis of more water level time series data sets. However, the analysis seems to indicate 50 m as a potential cut-off value for the variation in CDM values.

There is another potential explanation for this variation, which may have to do with abstraction. The three boreholes with the largest variation in CDM values (marked with * in Table 3.3) are influenced by the abstraction at the wellfield or an adjacent borehole.

The aim of the MARS in the Langebaan Road aquifer unit was to store excess winter water from the Berg River in the aquifer to have it available during the summer months when the population in the towns of the Saldanha Bay local municipality grows as a result of the summer holidays. Initial analysis of the MARS test was that it was unsuccessful and that there were flaws/misconceptions in the conceptual model of the aquifer system. Analyzing the monitoring data using the CDM plot showed that the MARS test was not a complete failure. MARS managed to store enough water to boost the available supply for three to four months after the tests were completed at the end of 2008 and 2009. The CDM curve also seem to indicate that there was a cumulative response to the injection from one year to another. The possibility exists that it could have made a big difference to the water stored in the aquifer if it was continued. Another potential use of the CDM curve is to differentiate between natural recharge and MARS. The slope of the CDM curve just after MARS was observed to be almost twice as steep as for natural recharge.

Table 3.3: Comparison of CDM values between boreholes and the different aquifer units

Table 3.3 Comparison of CDM values between boreholes and the different aquifer units.					
Borehole number	**Aquifer unit**	**Upper/Lower layer**	**Highest value**	**Lowest value**	**Difference**
G33323	Langebaan Road	Upper	13.59 m (2003/03/08)	-0.12 m (1985/05/06)	13.71 m
G33327	Langebaan Road	Lower	113.87 m (2000/07/05)	-9.77 m (2018/12/12)	123.64 m*
G45635A	Langebaan Road	Lower	101.18 m (2000/04/18)	-72.05 m (2008/05/22)	173.23 m*
G33317	Elandsfontein	Upper & Lower	49.75 m (2005/12/13)	-1.25 m (2018/11/16)	49.75 m
BH1A	Elandsfontein	Upper	1.04 m (2016/09/01)	-0.22 m (2018/05/08)	1.26 m
37/2	TMG	Upper	12.53 m (2014/11/19)	-2.94 m (2018/06/13)	15.47 m
G33255	Adamboerskraal	Lower	54.45 m (2009/11/11)	4.05 m (2018/11/21)	54.45 m
G33246	Adamboerskraal	Lower	2.17 m (2015/11/17)	-17.99 m (2007/06/05)	20.16 m
G33333-VL1	Grootwater	Lower	72.48 m (2002/06/01)	2.52 m (1985/03/15)	69.96 m
G33333-VL3	Grootwater	Lower	129.05 m (2007/01/23)	3.35 m (1985/03/15)	125.70 m*
G33304	Grootwater	Upper	5.49 m (2003/11/06)	-0.29 m (1985/05/08)	5.78 m
G33310	Grootwater	Upper	6.77 m (2003/05/06)	-3.68 m (2007/07/24)	10.44 m

*Influenced by abstraction of the wellfield or adjacent boreholes.

3.3.6 Correlations between surface water and groundwater levels

The groundwater contribution to baseflow is considered negligible for the region. Piezometric maps show flows towards the Berg, Sout and Groen Rivers coupled with relatively shallow water levels. This indicates that there is a hydraulic connection between groundwater of the LAU and UAU and surface water in the region. Groundwater is expected to occur as coastal discharge as the main mechanism for discharge for the LAU. In the event when the Berg River is in flood and experiences high flows, the gradient is reversed and the Berg River experiences losing conditions and it recharges the LAU locally (Seyler *et al.*, 2017). The pressure effects of the fluctuations in the river stage are detectable in the water levels in the upper aquifer unit. The effects of these pressure waves are present in borehole G33323, situated 1.5 km away from the Berg River. G33323 displays a yearly cyclic fluctuation of 0.8 m as the result of fluctuating river stage.

The link between the water levels in the Berg River and the Lower Berg River aquifer system were investigated. Figure 3.12 shows the data record for flow gauge G1H013 at Drieheuvels from 1964 to 2018. It is clear from this record that 2007 was the year with the highest flow, with the highest peak measured on 2007/06/07 at 7:48 with a reading of 6.560 mamsl. The effects of the recent drought can also be seen from around 2015, with no peaks for 2018 and no flow for the last couple of weeks on the data record. This was probably the first time in the history of records that flow over the weir ceased.

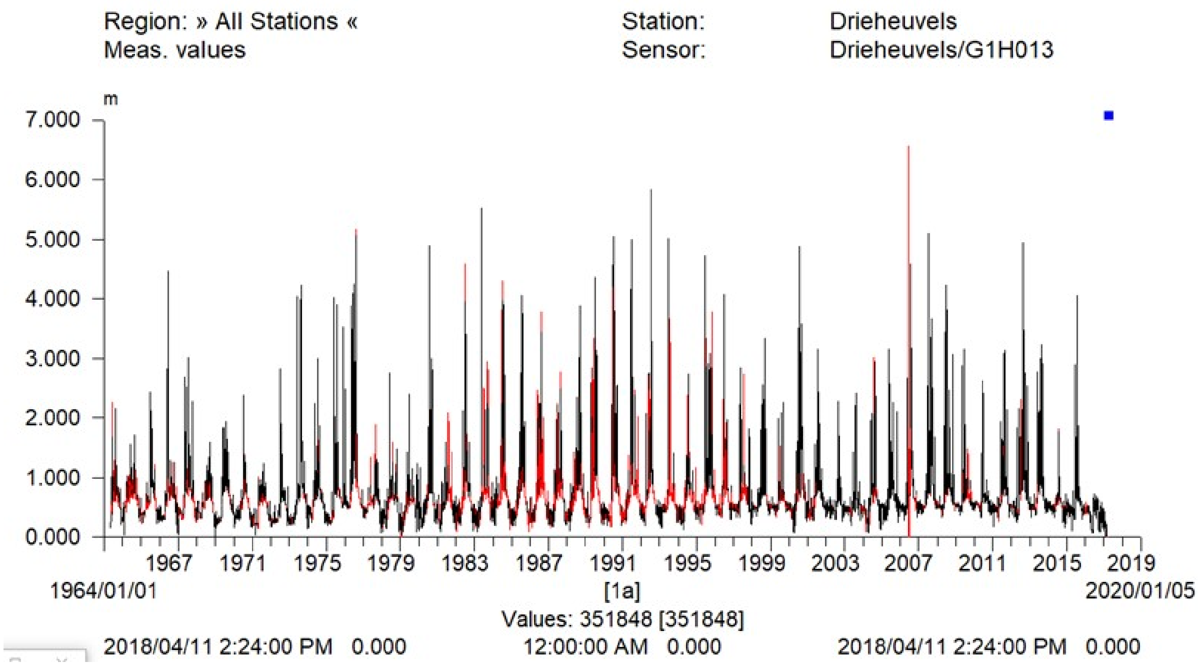


Figure 3.12: ***Time series of streamflow generated for flow gauge station G1H013***

Figure 3.13 shows that there is a high correlation of the water flow over the weir at Drieheuvels (G1H013) with water levels measured in borehole G33323, just upstream of G1H013. There is a time lag of about a month over 1.5 km between the highest peaks in streamflow compared to the groundwater level peaks in the borehole which would account for the time it takes for the water to flow from the weir and infiltrate into the aquifer system to impact the groundwater levels. The highest peak in groundwater levels was also measured in 2007, with another high peak in 2013. This agrees with the peaks in streamflow. The very low flow levels measured in 2018 correlate with the water levels in the borehole and corroborate the findings of Andries (2019) that the river did not contribute to recharge at the time.

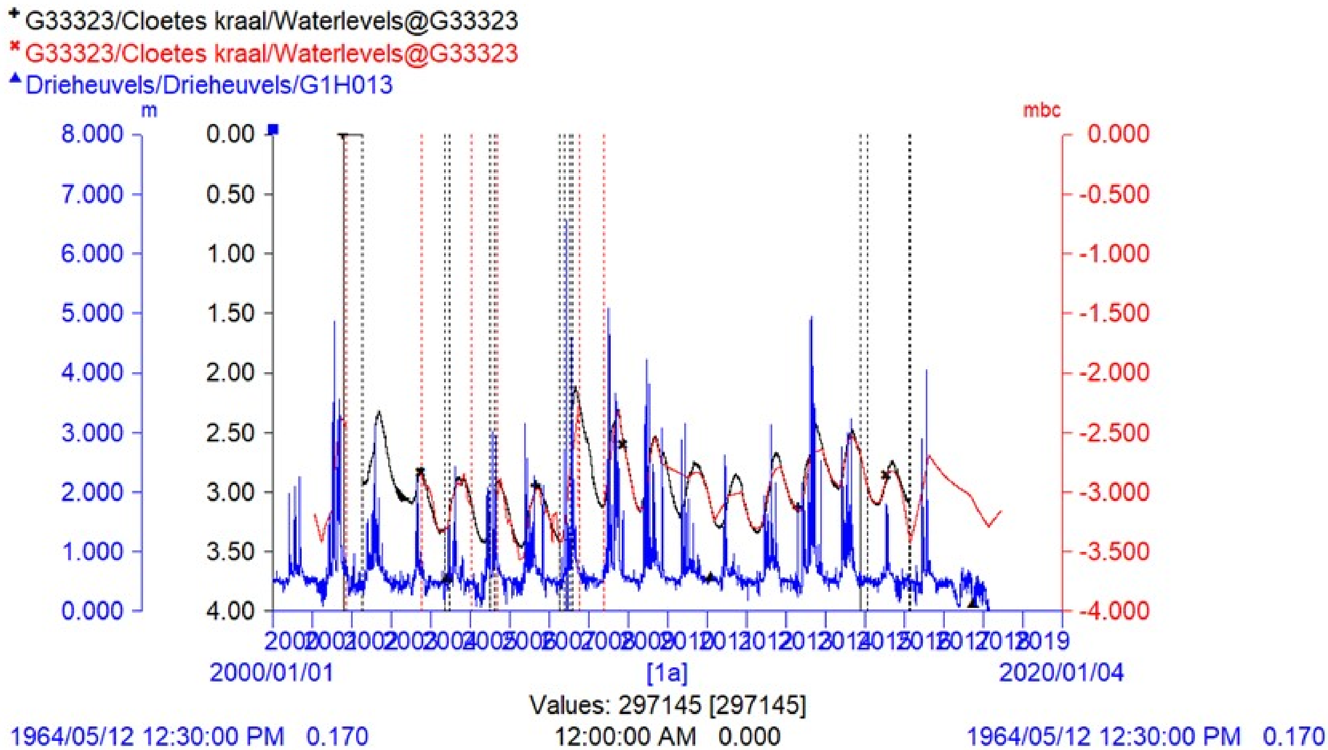


Figure 3.13: ***Time series of streamflow generated for flow gauge station G1H013 on the Berg River and groundwater levels at G33323***

Further analysis of the correlation between stream flow and groundwater levels may be necessary in order to have a better idea of the contribution of the river to recharge and the aquifer to baseflow in the river during low flow periods.

3.4 Aquifer characteristics

Aquifer hydraulic parameters are essential in assisting with the understanding groundwater flow and hydraulic connection between the aquifers. The various lithological layers have their very own aquifer characteristics. Aquifer characteristics data were sourced from a number of previous reports and consolidated in Table 3.4 (Timmerman, 1985b) and Table 3.5 (Timmerman, 1985d). Original raw data were very sparse and rare (e.g. Woodford, 2003), and they often need to be re-processed because they are in the form of pumping tests and hard copies of documents. In general, aquifer characteristics have very large variability and this represents a challenge in determining groundwater flows, hydraulic connectivities, conceptual modeling and numerical modeling. For example, aquifer yields and storage potential are key parameters in assessing the feasibility of groundwater development. The yield and storage potential are functions of the sedimentary deposits from which the abstraction takes place and where the groundwater is stored, and they will differ over short distances. It is thus difficult to determine a yield or storage potential that would be true for an aquifer, if not more so for the whole aquifer system.

Table 3.3: Aquifers, formations and their hydraulic properties (Timmerman, 1985b)

TABLE 3.4
Aquifers, formations and their hydraulic properties (Timmerman, 1985b)

Aquifer	Lithostratigraphic unit		Aquifer type	Approximate thickness (m)	Transmissivity (m^2/d)	Storativity
	Formation	Member				
Adamboerskraal	Bredasdorp	-	Unconfined	10-20	100	-
	Elandsfontyn	Clay	Aquitard	20-30	-	-
		Sand and gravel	Confined	20-40	500	10^{-3}
Langebaan Road	Bredasdorp	Langebaan limestone	Unconfined	10-20	100	-
	Elandsfontyn	Clay	Aquitard	10-20	-	-
		Sand and gravel	Confined	40-60	1000	3.1×10^{-3}
Elandsfontyn	Bredasdorp	Springfontyn	Unconfined	5-20	300	-
		Noordhoek	Aquitard	5-60	-	-
	Varswater	PPM	Aquitard	0-20	-	-
		QSM	Semi-confined	0-30	500	3.6×10^{-3}
	Elandsfontyn	Clay	Aquitard	10-30	-	-
		Sand and gravel	Confined	10-30	600	10^{-3}
Grootwater	Bredasdorp	Springfontyn	Unconfined	10-20	700	-
		Noordhoek	Aquitard	10-30	50	-
	Varswater	PPM	Aquitard	10-20	-	-
		QSM	Semi-confined	10-20	200	10^{-3}

Table 3.4: Summarized hydraulic parameters of the West Coast aquifer system (Timmerman, 1985d)

TABLE 3.5 Summarized hydraulic parameters of the West Coast aquifer system (Timmerman, 1985d)						
Tested lithological sequence	Borehole	Thickness (m)	Horizontal hydraulic conductivity (m d^{-1})	Transmissivity (m^2 d^{-1})	Vertical hydraulic conductivity (m d^{-1})	Storativity
Bredasdorp Witzand	30871	7.5	15.4	116	0	
	30872	8.2	17.9	147	16.5	
	30878	3.7	13.2	49	12.8	
	30879	10.9	11.9	130	0.04	
	30925	14	8.9	125	0.02	
	31341	7	14.5	101	13.6	
	S21	15	13.8	208	0.24	
Bredasdorp	15 boreholes	-	0	0	0	
Langebaan Limestone	30925	30.8	1.45	45	0	
	32928	12.0	1.51	18	0	
	32929	5.5	0.91	5	0	
Bredasdorp Springfontyn	30872	7	30.5	214	29.1	
	31339	12.8	19.8	254	12.5	
	32927	4.2	7.2	30.4	6.7	
	S21	19.5	23.1	451	20.2	
Bredasdorp Noordhoek	30871	11	19.8	217	0.03	
	30879	53.5	7.97	426	0.01	
	32926	12.8	1.4	17.9	0	
Varswater CSM	30878	16.3	10.9	179	7.3	
	30925	52.7	3.3	175	0	
Varswater PPM (Duynefontyn)	30878	20.9	3.1	65	0	
	31344	8.3	0.8	6.6	0	
	32927	15.4	0.9	13.7	0	
	32933	1.4	1.9	2.6	0	
	S21	12	15.6	188	0	
Varswater QSM	31344	6.7	52.2	350	7.1	
	31346	14.2	27.9	396	22.0	
	S22	40.2	23.2	932	2.1	
	S23	66	15.8	1046	5.6	
	33330	32	2.4	76.1	-	3.6×10^{-4}

Tested lithological sequence	Borehole	Thickness (m)	Horizontal hydraulic conductivity (m d^{-1})	Transmissivity (m^2 d^{-1})	Vertical hydraulic conductivity (m d^{-1})	Storativity
Varswater SGM (Silversroom)	30878	4.4	6.4	28.5	5.9	
	S22	18.2	23.5	428	0.01	
	S21	5.5	19.1	105	12.9	
Elandsfontyn clay	15 boreholes	-	0	0	0	
	29769	4.5	0.8	3.8	0	
	30878	31	1.8	55	0	
	31339	3.6	0.3	1.2	0	
	31343	22.2	1.1	24.9	0	
	32926	29.2	2.5	73	0	
	32935	4	-	-	$3x10^{-3}$	
	32938	5	-	-	$1.1x10^{-2}$	-
Elandsfontyn sands	39769	54	7.3	395	-	
	39820	46	1.5	70.2	-	
	30842	51	10.1	516	-	
	30872	6	8.7	52.0	0	
	30878	22	1.0	23	0	
	30925	20	0.18	3.6	0	
	31338	13.1	16.9	222	4.2	
	31339	8.3	4.7	39	0.03	
	31341	7	56.5	396	1.6	
	31346	30.6	13.5	412	0.01	
	31347	44.8	5.8	262	0	
	32924	16.4	14.2	232	0	
	32925	4.2	3.2	13.3	0	
	32928	9.6	13.0	125	0	
	32929	10	76.0	760	21.9	
	32930	1.4	10.5	14.8	1.6	
	32931	23.3	35.4	826	11.8	
	32932	3.5	133	464	74.9	
	32934	37	32.6	1208	-	$8x10^{-3}$
	32935	41	5.1	210	-	$1.3x10^{-3}$
	32938	20	5.1	103	-	$3.9x10^{-4}$
	32939	53	26.5	1405	-	$2.7x10^{-3}$
	S1	39.4	118	4664	40.5	
	S22	22.9	9.3	213	6.0	

Timmerman (1985b) also estimated the volumes of groundwater stored in different aquifers (Table 3.6). The total amount of groundwater stored in the system was therefore 5,800 x 10^6 m^3. The confined storage was estimated to be 109 x 10^6 m^3, this volume being available without mining groundwater.

Table 3.5: Estimated groundwater storage (Timmerman, 1985b)

TABLE 3.6 Estimated groundwater storage (Timmerman, 1985b)								
Aquifer	Adamboerskraal		Langebaan Road		Elandsfontyn		Grootwater	
	Confined storage (m^3)	Total storage (m^3)	Confined storage (m^3)	Total storage (m^3)	Confined storage (m^3)	Total storage (m^3)	Confined storage (m^3)	Total storage (m^3)
Elandsfontyn aquifer	$70.3x10^6$	$1,100x10^6$	$21.4x10^6$	$1,035x10^6$	$15.5x10^6$	$750x10^6$		
Post-Miocene aquifer		$100x10^6$		$200x10^6$		$2,400x10^6$	$1.8x10^6$	$218x10^6$
Total		$1,200x10^6$		$1,235x10^6$		$3,150x10^6$		$218x10^6$

3.5 Hydrochemistry

3.5.1 Rain water quality

The electrical conductivity (EC) of the rainfall samples were all low, mostly below 10 mS/m, and the concentrations of all inorganic constituents were usually very low. The results were plotted on a Piper diagram (Figure 3.14) and Stiff plots (Figure 3.15) in order to compare them to the groundwater chemistry results. There is not a clear pattern to the distribution of the points on the Piper diagram. This may be related to the season when the samples were taken. During low rainfall periods, it is possible that the chemical constituents were more concentrated. The proximity to the coast may also influence the salt content of the rainfall samples. One of the drawbacks of the cumulative rain gauges, is that birds like to perch on them with possible contamination of rainfall samples, increasing the ammonia content.

G10K1 is the furthest inland sampling site and at the highest elevation in the mountains north of Aurora. All the constituents on the Stiff plot are low, with sodium and chloride being the dominant ions. G33323-RF is in the floodplain of the Berg River and at a low altitude. Its highest ion concentrations are for sodium and chloride, followed by magnesium and sulfate. G46024-RF usually records the highest rainfall after G10K1. It is close to Hopefield in an area with a higher elevation than G33323-RF, and likely high groundwater recharge. The EC recorded at this site is the lowest of all the rain gauges, along with G46059-RF. The major contributing ions are calcium and bicarbonate. G46105-RF is at the Langebaan Road wellfield, in a small basin surrounded by higher lying dunes and granite outcrops. The major ions are sodium and chloride. G46059-RF is north of the wellfield, but it usually records higher rainfall. Its salt content is higher, with the major ions being sodium and chloride. BG00071-RF is the furthest south, just north of Darling. The highest ion concentrations are bicarbonate, chloride and sodium. BG00074-RF is between BG00071-RF and the Langebaan Road cluster. No Stiff plot was available for this rain gauge as a result of incomplete data sets. G46092-RF is the closest to the coast at low elevation. It has the highest salt content according to the Stiff plot. The highest ion concentration is for bicarbonate, followed by sodium and chloride.

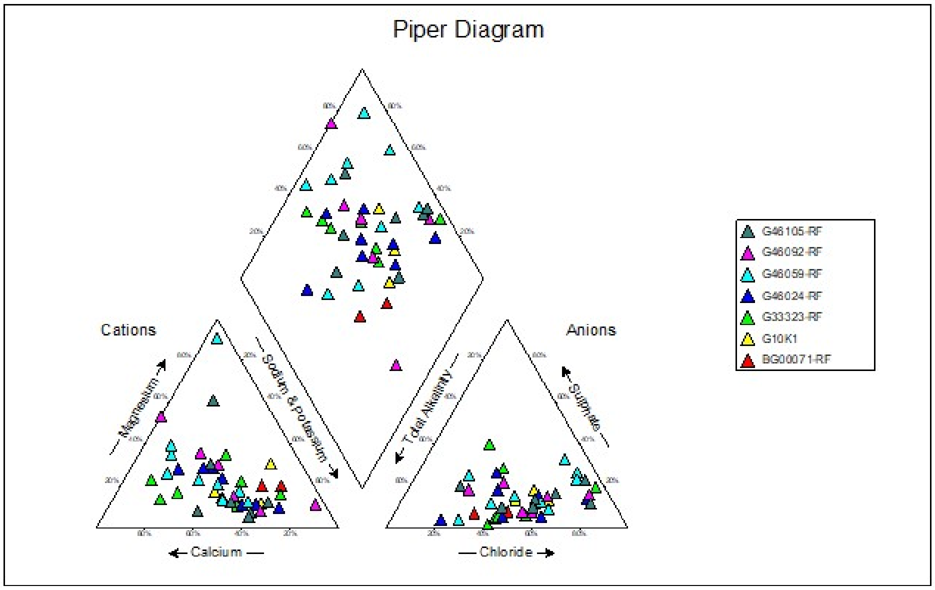


Figure 3.14: ***Piper diagram for the chemistry analysis of cumulative rainfall samples collected in rain gauges in the studied area (diagram generated with the WISH software)***

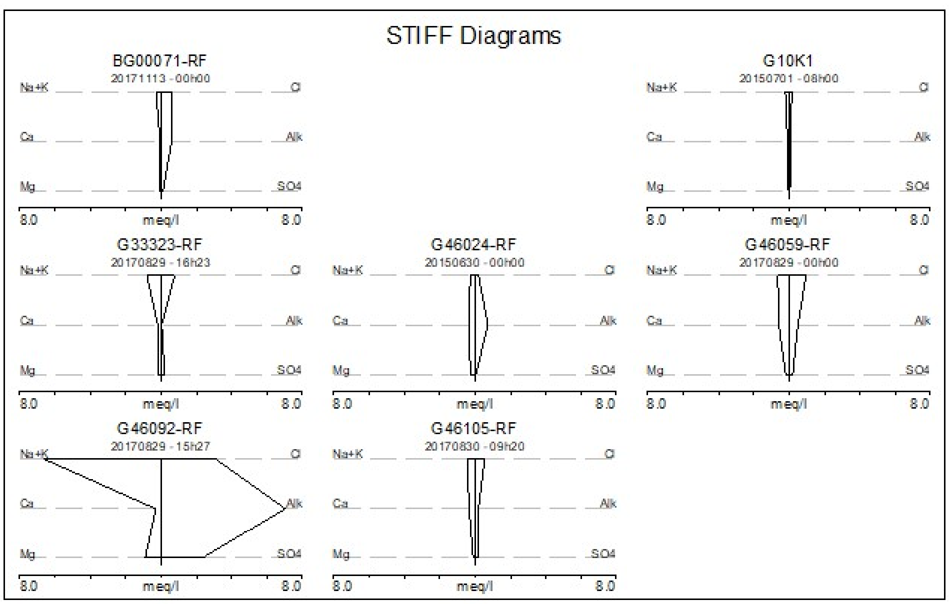


Figure 3.15: Stiff plots for the chemistry results for cumulative rainfall collected with rain gauges (diagram generated with the WISH software)

3.5.2 Surface water quality

The only surface water samples were taken from the Berg River at the bridge near the farm Kersefontein and three samples were sent in for chemical analysis. The EC field readings fluctuated during the year with a value of 3520 mS/m measured in February 2018 and 243 mS/m measured in August 2018. The dominant ions were sodium and chloride (See Figure 3.16 for the Piper diagram and Figure 3.17 for the Stiff plot), which correlates with the fact that the sampling point was within the tidal zone of the river.

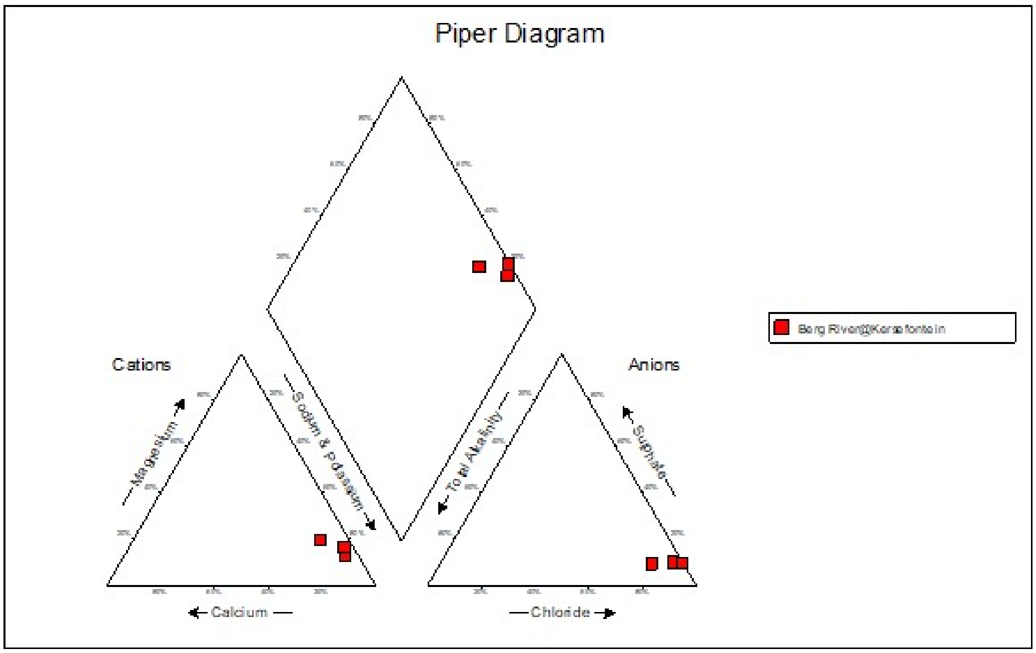


Figure 3.16: ***Piper diagram for surface water samples taken from the Berg River at the Kersefontein bridge (diagram generated with the WISH software)***

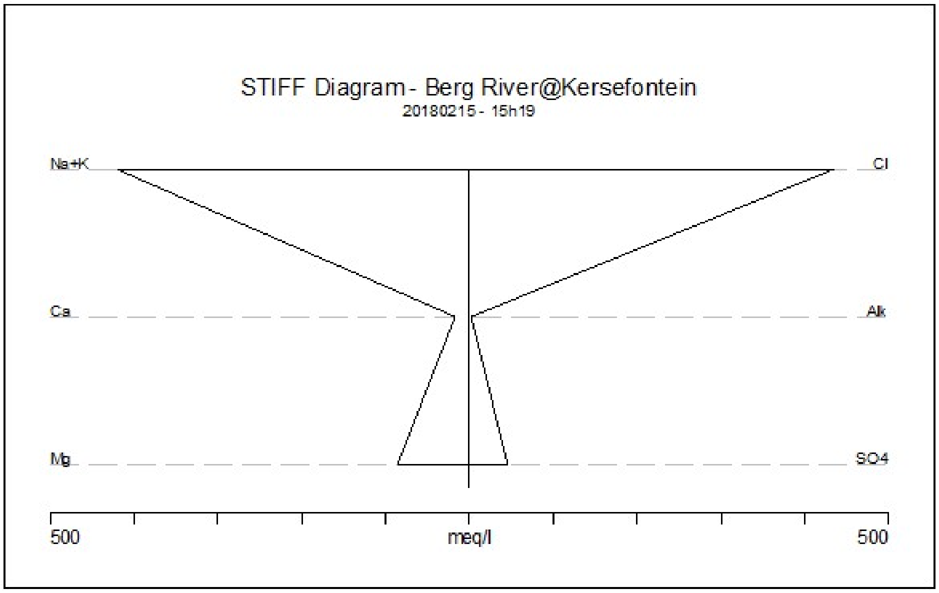


Figure 3.17: ***Stiff diagram for surface water samples taken from the Berg River at the Kersefontein bridge (diagram generated with the WISH software)***

3.5.3 Groundwater quality

A first rough analysis of the groundwater chemistry was done in 2009 when DWS still monitored the water quality in 42 boreholes (Vermaak, 2009). This number has been reduced to 25 in 2010, with the bulk of the monitoring for the Langebaan Road aquifer unit. Water quality monitoring points have since been added for the Grootwater, Elandsfontein and Adamboerskraal aquifer units. Figure 3.18 gives an indication where the monitoring points in the Langebaan Road aquifer unit are situated. These points have a long data record of water quality. The original water quality analyses were reported by Vermaak (2021).

The conductivity of the major part of the study area is less than 100 mS/m, with the best quality of water occurring in the central part. The water quality deteriorates towards the Berg River in the north and Saldanha Bay in the west (Timmerman, 1985a). The results from this study seem to agree with that done by Timmerman in 1985, where the major part of the study area has an EC below 100 mS/m.

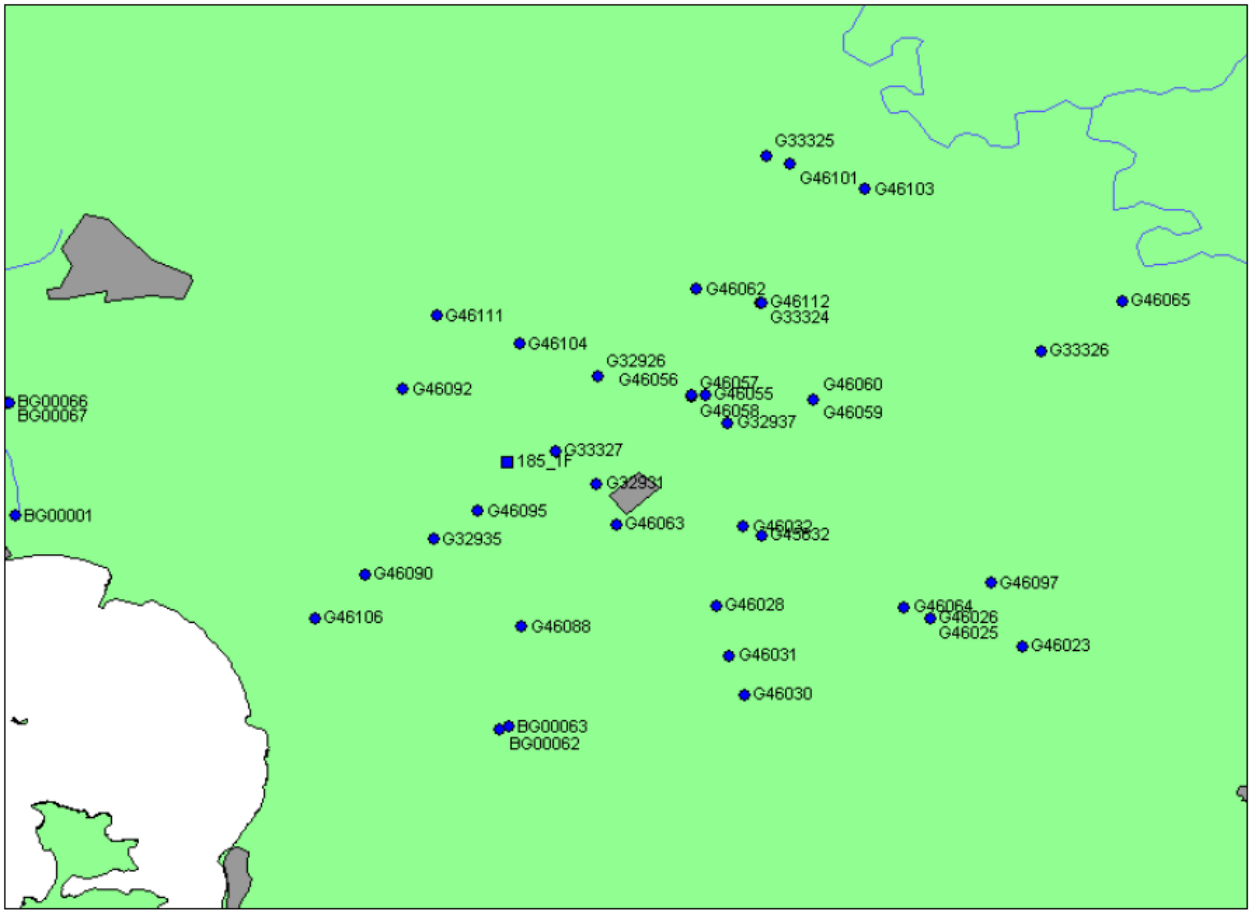


Figure 3.18: ***Distribution of monitoring points in the Langebaan Road aquifer unit (42 of the 47 sampling points sampled regularly until 2010)***

Langebaan Road aquifer unit

The Piper diagram (Figure 3.19) indicates that the most dominant groundwater type for the Langebaan Road aquifer unit is chloride-sodium water, with most of the data points forming a cluster. There is a number of samples that tends towards the bicarbonate-calcium water type, which could be as a result of the calcrete in the area. Magnesium and sulphate concentrations are generally low, with a few exceptions in some of the Stiff plots. There seems to be a bit of a progression with the boreholes upgradient in the palaeochannel plotting more towards the middle of the diamond and those closer to the coast plotting at the right-hand side. BG00058 seems to be the exception to this, as it is an artesian borehole in the middle of an old mining excavation at the West Coast Fossil Park. It is in its own cluster, lower that the main line of the other data points. G46105 is in the basement aquifer, which in this case is Malmesbury shale. It forms its own cluster below the main cluster. There is one outlier for BG00136 in the anion triangle that shows high levels of sulphate. This may be due to the presence of peat in the area and the fact that the borehole had not been in use since 2009. Sampling at the borehole only started again in 2015.

Figure 3.20 shows the Stiff plots for representative geosites in the Langebaan Road aquifer unit. G33323 is closest to the Berg River and shows direct recharge from either rainfall or the river. The water is of a sodium-chloride type with fairly high concentrations. It may potentially be affected by evapotranspiration, since it is in the unconfined layer of the aquifer unit. This point is about 13 km north-east of the wellfield. When comparing the Stiff plot of this borehole with the Stiff plots for the boreholes at or around the wellfield, there must have been some natural treatment taking place to reduce the salt content of the water. It may also be an indication that there may be recharge from another source that helped to dilute the salt content. BG00136 is the injection borehole for the MARS test that was done in 2008 and 2009, while G46105 is the basement aquifer borehole at the wellfield. Boreholes G32926 and G32937 are both towards the north-west of the wellfield, with G32937 having a tendency to become artesian. It shows that there is a slight decline in water quality further from the wellfield (G32926 is further away from the wellfield than G32937). G33327 is just before the West Coast Fossil Park, closer to the wellfield and BG00058 is in one of the old quarries that made up the old Samancor phosphate mine that is now the West Coast Fossil Park. The Stiff plots for these two boreholes are similar, and closely resemble those of BG00136, G32937 and G46105. There is thus little change in water quality over a large area of the lower aquifer layer of the Langebaan Road aquifer unit. The water quality of 185/1F (CAD185/1F on the plot) is different from the two boreholes close to it. It is a surface water body inside one of the old quarries at the mine site that is green in color and has an inflow of groundwater since it is below the water table. The EC that has been measured in this water body is around 5000 mS/m, which gives an indication of the effects of evaporation and possibly the salts that remained in the soil after the closure of the mine. The EC measured in the adjacent water body is in the vicinity of 17000 mS/m. It has a pink color and the soil surrounding the water is covered with a salt crust. There is potentially a lower groundwater inflow into this part of the quarries. BG00063 is a borehole that was drilled into the Colenso Fault System. Its water levels show a tidal pattern and it shows a higher magnesium concentration than most of the other boreholes in the Langebaan Road aquifer unit. The Stiff plot also has a different shape, indicating that this borehole is not linked to the main aquifer unit.

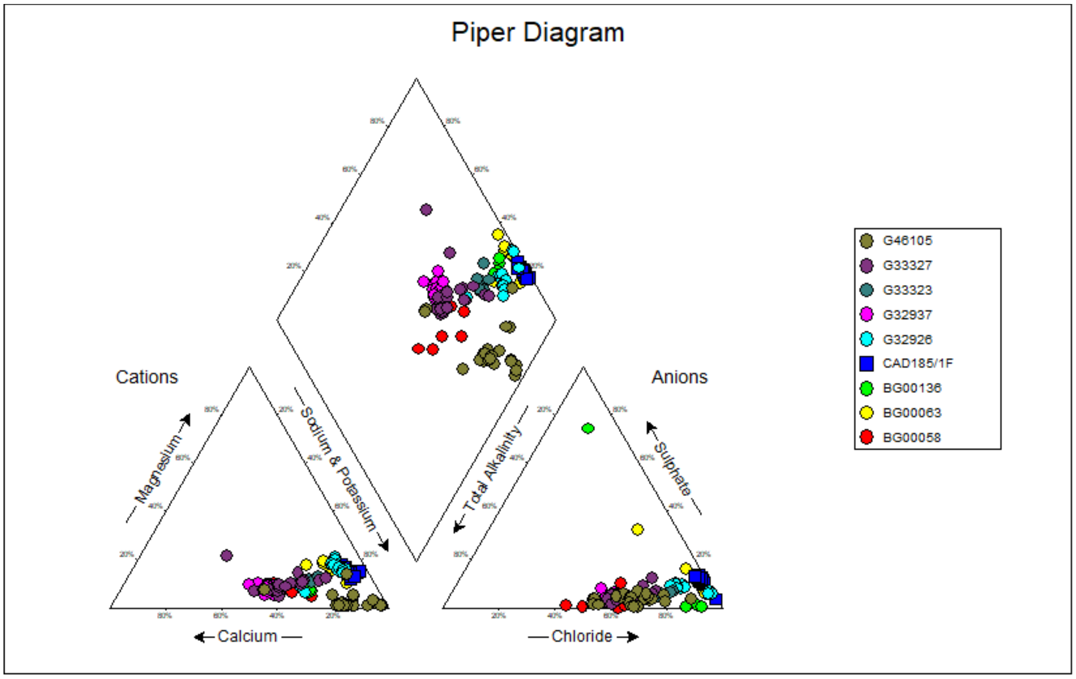


Figure 3.19: ***Piper diagram for the representative points in the Langebaan Road area (generated with the WISH software)***

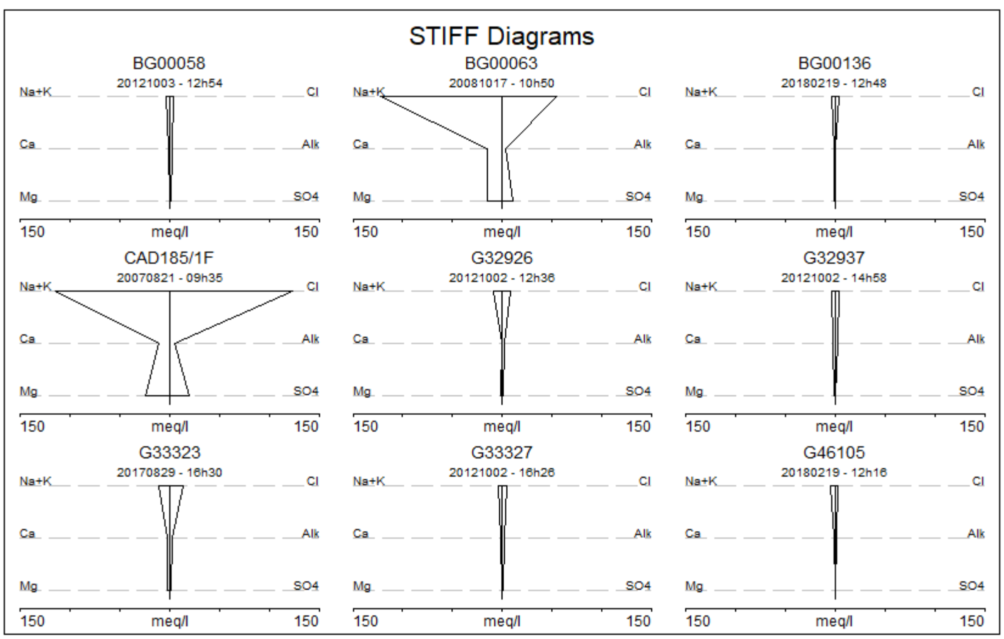


Figure 3.20: ***Stiff plots for representative boreholes in the Langebaan Road aquifer unit (generated with the WISH software)***

Elandsfontein aquifer unit

The water quality characteristics of the Elandsfontein aquifer unit is different to that of Langebaan Road. There is a very strong calcium-bicarbonate characteristic in most of the data points (Figure 3.21) and this is also reflected in the Stiff plots (Figure 3.22). This could be an indication that this aquifer unit is closer to the recharge source, but it could also reflect the geology of the area. There are very prominent calcrete banks in some of the dunes and this can be seen in the borehole logs. The data points mainly form a cluster in the middle of the diamond with a few scattered outliers. G33320 is the furthest north of the geosites on the border between the Langebaan Road and Elandsfontein aquifer units. G33505B, which is to the north of the aquifer unit, just south of G33320, forms its own cluster below the main cluster and G30925 its own cluster to the right. G30925 is closer to the coast than most of the boreholes (borehole BH1A and BH2A being the exceptions). BG00124 is on the farm Theefontein and is the one furthest inland. Most of these boreholes are in the confined layer of the aquifer unit, and show that there is very little variation in the water quality over a large area of the aquifer unit.

The Stiff plots of BG00074, BG00124, BH1A, G33316(1), G33317, G33320(1) and G33505B show similar shapes, providing an indication that these boreholes are all in the same groundwater system (Figure 3.22). There is a very high calcium-bicarbonate component to the sodium-chloride type water found in this aquifer unit. G30925 has a much smaller calcium-bicarbonate component, despite the fact that it is in a high dune with calcrete and sand layers. Its proximity to the coast and exposure to salt spray from the ocean may contribute to the high sodium-chloride signature. The Stiff plot of BH2A provides an indication that the borehole is in a different groundwater system or exposed to different conditions. It is to the south of the Langebaan Lagoon and potentially still hydraulically linked to the water of the lagoon.

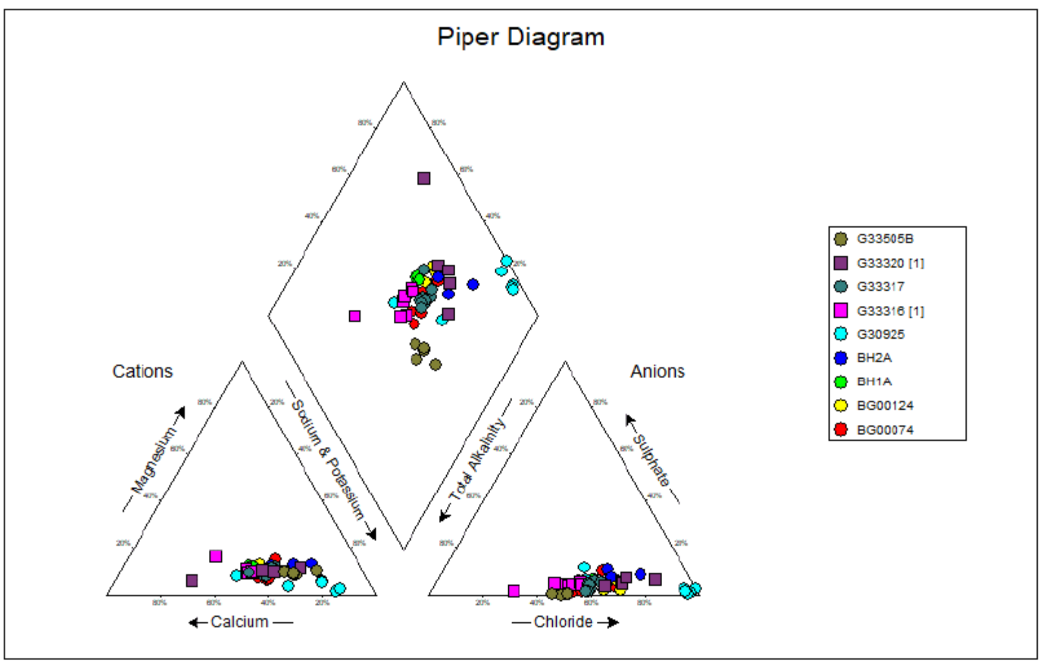


Figure 3.21: ***Piper diagram with representative points for the Elandsfontein aquifer unit (generated with the WISH software)***

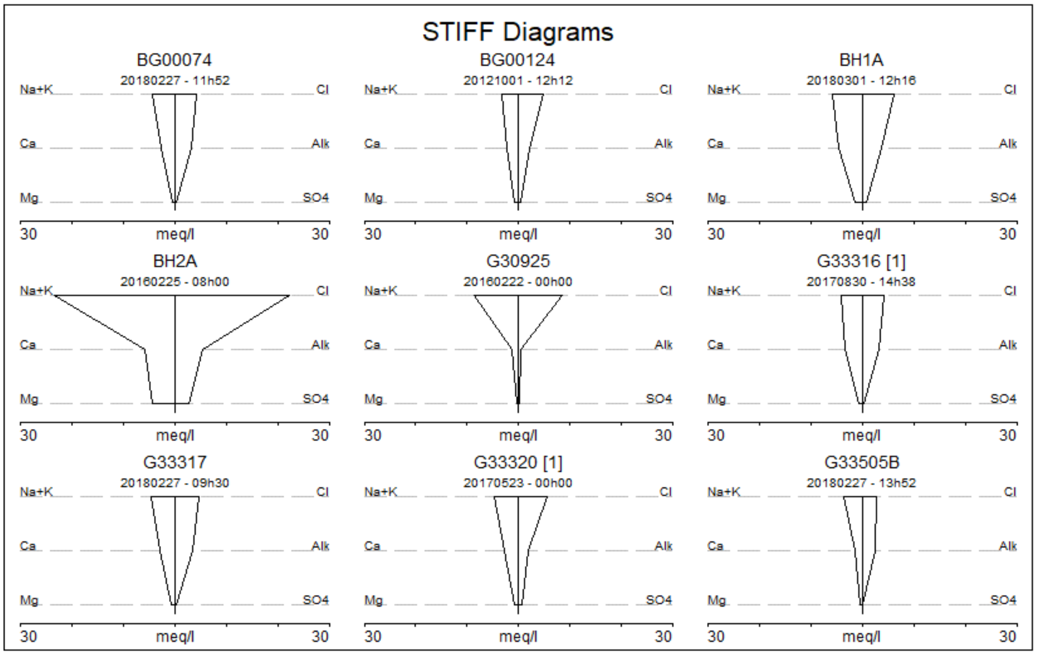


Figure 3.22: ***Stiff plots for representative geosites for Elandsfontein aquifer unit (generated with the WISH software)***

Adamboerskraal aquifer unit

The Piper diagram in Figure 3.23 shows the chemical composition of representative points in the Adamboerskraal aquifer. Borehole 37/1 (marked CAD37/1 on the plot) represents a borehole at the top of the mountain above Aurora. It is thus in the TMG aquifer. This borehole shows a similar chemical character as that of the rainfall collected from G10K1. The geosite 3218CB/CA1 is a spring just outside Aurora that originates at the foot of the mountain, and as such represents TMG aquifer water. The position of the data points for the spring water (3218CB/CA1) is in the same area as GEOSS-A7 and GEOSS-A12, which most probably also represents mostly TMG water. They are boreholes at the foot of the mountain. The data points for borehole G33249 lie to the bottom of the previous cluster, while those of G33255 almost form a cluster of their own lower down in the diamond, with high concentrations of sodium, chloride, magnesium and alkalinity.

There seems to be a gradual change in the shapes of the Stiff plots in the following sequence: 37/1 (TMG), GEOSS-A7 (TMG), 3218CB/CA1 (TMG), GEOSS-A12, G33255 and G33249 (Figure 3.24). This most probably shows the change from TMG type water – where very little interaction takes place between the rock formations and the water – to the coastal aquifer unit overlying Malmesbury shale. The Stiff plot for GEOSS-A7 shows the closest resemblance to that of 37/1. The Stiff plots of G33255 and GEOSS-A12 have a similar shape, with a slightly higher sodium and chloride dominance in G33255. This could be an indication that these boreholes are located in the same palaeochannel. G33249 seems to be in a different palaeochannel, as the pattern of the Stiff plot is very different from the other boreholes. It is possible that this site is in the same palaeochannel as G33248 and G33246. The dominant ions are sodium and chloride for all the geosites.

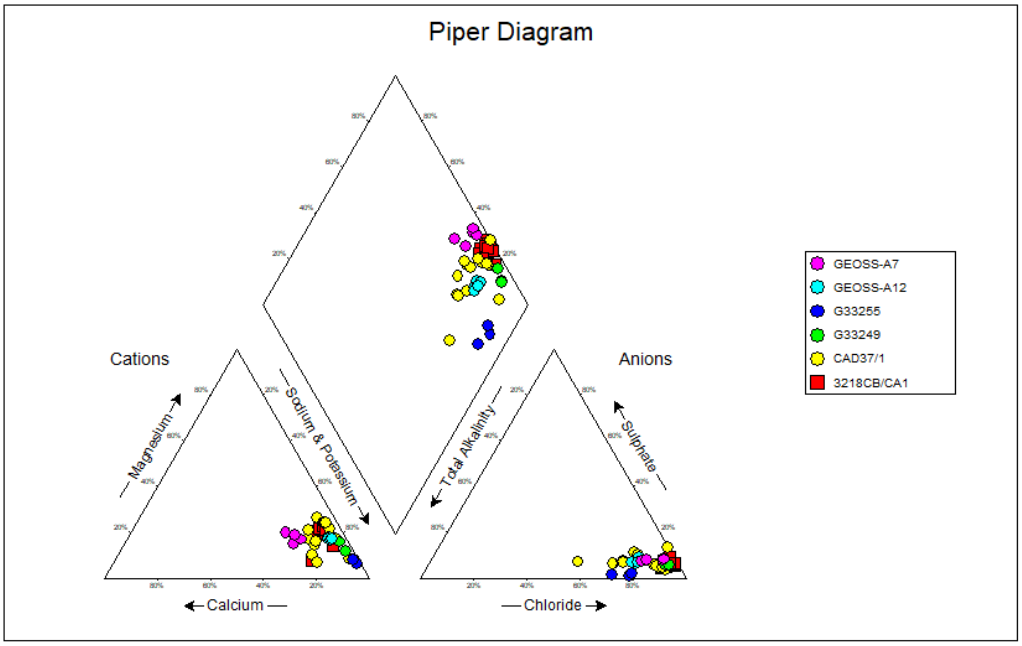


Figure 3.23: ***Piper diagram for the monitoring points in the Adamboerskraal monitoring route (generated with the WISH software)***

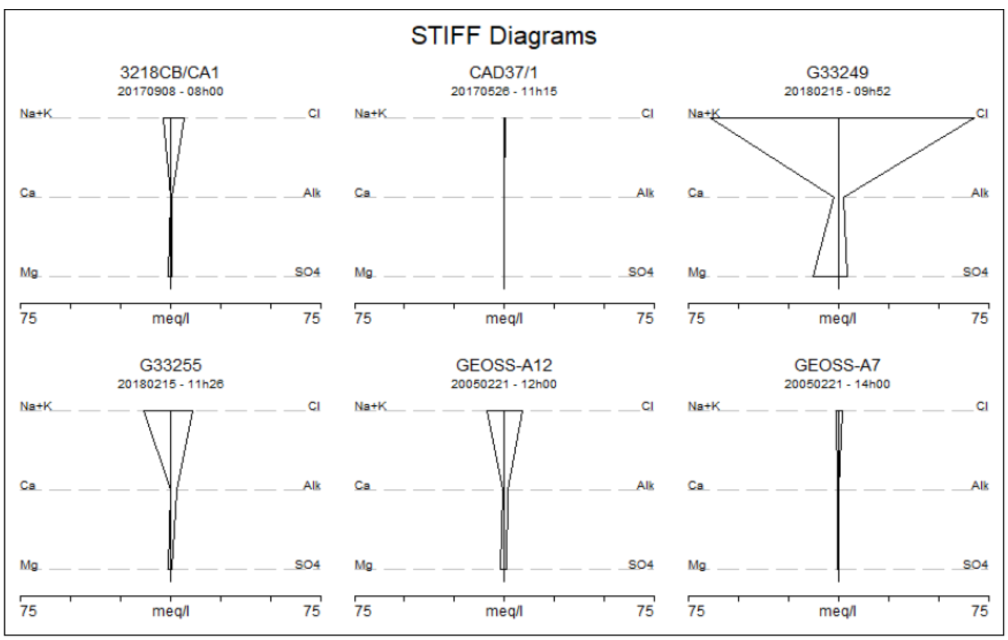


Figure 3.24: ***Stiff plots for the water quality of the geosites in the Adamboerskraal area (generated with the WISH software)***

Grootwater aquifer unit

The data points in the Piper diagram for the Grootwater aquifer unit plot where one would expect the water quality of a coastal aquifer to lie (Figure 3.25). The data points form a single cluster showing a sodium-chloride type water.

There is a bit more variation in the Stiff plots for the Grootwater aquifer unit (Figure 3.26). The water quality in this aquifer unit is good when considering its proximity to the coast, with EC measurements for most of the boreholes below 100 mS/m. G33301, which is the furthest inland, and some of the boreholes closest to the coast had EC values over 100 mS/m. All the boreholes have a sodium-chloride type water, with magnesium featuring strongly in some cases. There is no significant calcrete deposits in the area that can potentially affect the water chemistry.

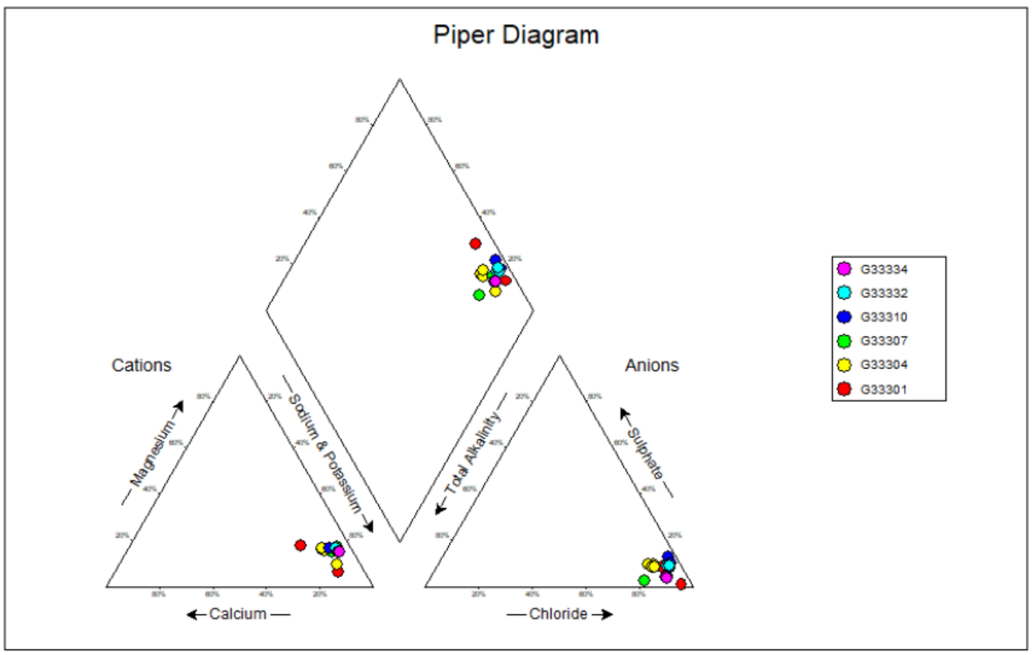


Figure 3.25: ***Piper diagram for representative points in the Grootwater aquifer unit (generated with the WISH software)***

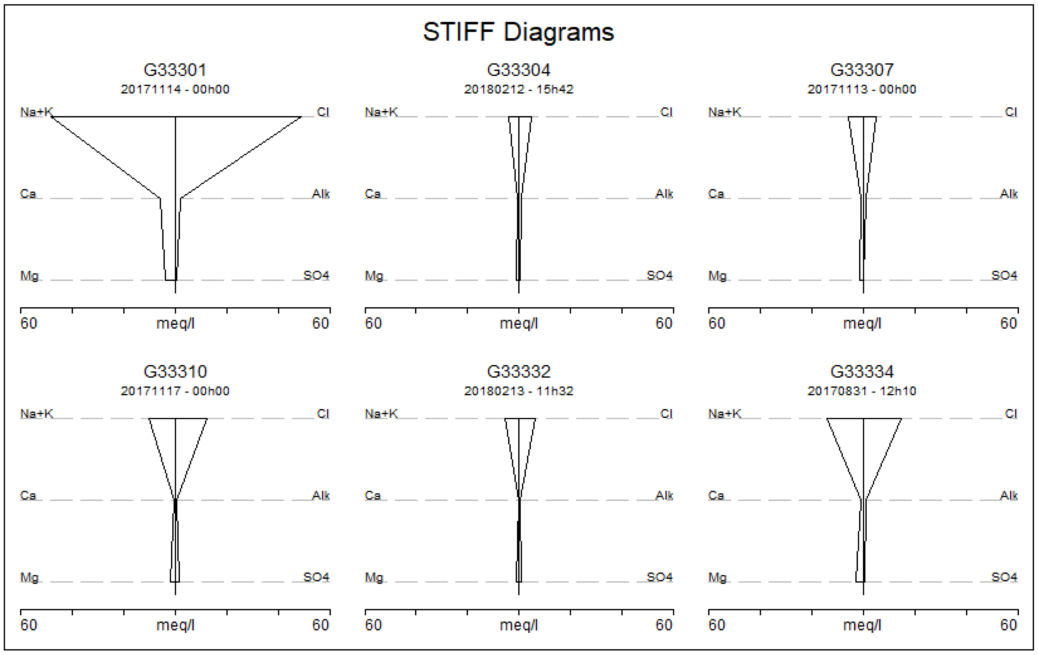


Figure 3.26: ***Stiff plots for representative boreholes in the Grootwater aquifer unit (generated with the WISH software)***

3.5.4 Isotope sampling

Isotope sampling and analysis was conducted during two MSc thesis of students at the University of the Western Cape (Andries, 2019; Van der Schyff, 2019). Andries (2019) used isotope analyses to study groundwater flow processes and recharge mechanisms, whilst van der Schyff (2019) investigated primarily the connectivity between the Langebaan Road and the Elandsfontein aquifers.

Groundwater flow and recharge mechanisms

The main purpose of the isotope sampling by Andries (2019) was to get insights into groundwater flow and recharge mechanisms. Sampling boreholes were selected to elucidate recharge mechanisms to the unconfined aquifer (Sandveld formation), to the confined aquifer (Elandsfontyn formation) and the bedrock aquifer (Malmesbury Shale). This was an important criterion to draw comparisons of dominant recharge processes. To conceptualize groundwater recharge, it was important to select experimental groundwater monitoring sites from the upper, middle and lower parts of the West Coast Aquifer System. Other criteria for sampling site selection were the continuity of groundwater level data, distance of boreholes from rain gauges, rain gauges which are in working condition with continuity in rain gauge data, as well as ease of access.

Figure 3.27 illustrates the sampling locations for this study. For the unconfined aquifer, the upper aquifer was sampled from the high elevation areas close to Hopefield (G46024, G33502C, G33315 and G33505), the middle part of the unconfined aquifer (G46060, BG00137, G46028, G33316VL2) and the lower part of the unconfined aquifer (G33323, G46106, G46092 and BH1). For the EA, samples were collected in the upper aquifer (BG00074, G33505B and G33317) and in the lower aquifer (BH2). For the LRA, samples were collected from the upper aquifer (G46023) and the middle aquifer (G46059, G46029 and BG00136). The bedrock aquifer was also sampled

(G46105, G46030 and G33502A). For the assessment of groundwater-surface water interaction, the Berg River and Geelbek Lagoon were sampled.

At each selected site groundwater, surface water and rainfall samples (n=239) were collected on a quarterly basis during the wet winter season (May and August 2017) and during the dry summer season (November 2017 and February 2018) for stable isotope analysis. Tritium and C-14 were sampled at each selected groundwater monitoring site (n=30) once during the data collection period during the wet winter month of August 2017. A tritium sample (n=1) was collected from a rain gauge located just outside the study area in the Aurora-Piketberg Hills in Aurora in August 2017. Groundwater samples were collected following the low flow/low stress purging method, following set protocols (EPA, 2017; Weaver et al, 2007). Stable isotope samples were measured at the Department of Earth Science at UWC, whilst other chemistry analyses were done at the CSIR Laboratory in Stellenbosch. The drum precipitation method was used for collection of water samples for radiocarbon analysis. H-3 and C-14 were measured at iThemba Laboratory in Johannesburg. Cumulative rainfall samples were collected via permanent rainfall collectors previously installed by DWS and located in close proximity (1-25 m) to groundwater monitoring sites. Rainfall was sampled in August, November 2017 and February 2018 for stable isotope analyses. Surface water samples were collected from the Berg River and the Geelbek Lagoon using the grab sample method on a quarterly basis from May 2017 to February 2018.

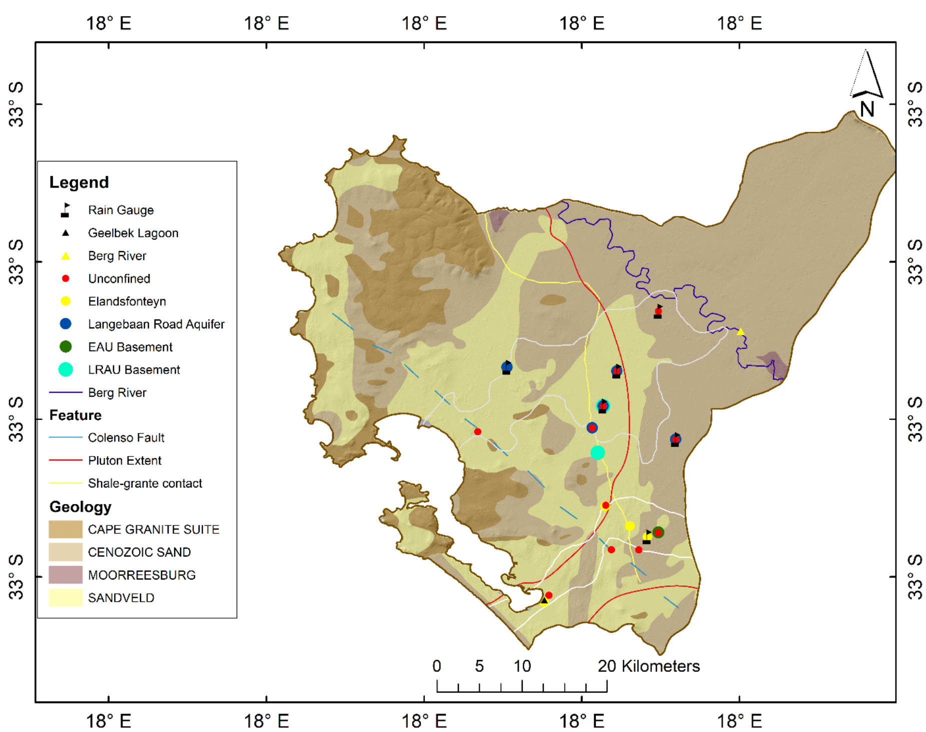


Figure 3.27: ***Groundwater, surface water and rainwater isotope sampling locations throughout the West Coast Aquifer System***

Figure 3.28 represents the stable isotope analyses for all rain, surface and groundwater samples collected on the West Coast. The Global Meteoric Water Line (GMWL; Craig, 1961) and the Local Meteoric Water Line for Cape Town (LMWL; Diamond and Harris, 2008) and an evaporation line, which represents the line of best-fit of all groundwater samples, are plotted on the graph. Data in Figure 3.28 can be interpreted compared to the GMWL, LMWL and evaporation line. For the unconfined and confined units, $\delta^{18}O$ was mostly depleted in the topographically higher areas in the south-east of the study region where no irrigation occurs compared to the flat topographically low-lying areas, which are located north-west and west in the study region, where irrigation practices prevail. This indicates that rainfall, topography and geomorphology conditions of the landscape control the recharge mechanism. The spatial distribution of $\delta^{18}O$ of the unconfined aquifer illustrates that recharge occurs from the south-east and flows from the south-east towards the Berg River, Saldanha Bay and the Langebaan Lagoon. The stable isotope composition agrees with postulated flow direction from previous researchers (Timmerman, 1985; Seyler *et al.*, 2016).

It was observed that there are four distinct groundwater signatures (Figure 3.28). Groundwater samples in group A plot between the GMWL and LMWL for all unconfined and confined aquifers. The lack of significant difference between isotopic composition of shallow and deep groundwater in group A suggests the aquifer units were recharged during the same climatic event and precipitation is the dominant source of recharge for both the unconfined and confined aquifers.

Group B is groundwater of the unconfined and bedrock aquifer that have experienced significant evaporation effects prior to infiltration. The range for groundwater in the confined aquifer is similar to that of the unconfined aquifer, which indicates that groundwater is recharged from a source that is exposed to evaporation effects prior to infiltration such as rainfall. This would be possible through focused recharge mechanism or if the unconfined aquifer is directly superimposed over the basement aquifer where the clay and LAU are locally absent at the topographic high. The isotopic composition of bedrock aquifer suggests that it is recharged by piston flow and groundwater flows laterally.

Group C is made up of all rainwater samples collected during the study period. Groundwater sampled from a shallow borehole close to the coast (G46106) exhibited similar isotopic composition suggesting the main recharge mechanism in this region. This borehole was drilled in close proximity to the Vredenburg pluton. This suggests that in winter months the runoff generated by the impermeable pluton is a source of recharge for the unconfined aquifer.

The surface water samples collected from the Langebaan Lagoon and the Berg River plotted the furthest to the right of the GMWL and they were the most enriched samples (Group D). This was expected due to the immediate evaporation of surface waters due to direct exposure to the atmosphere. Since the groundwater and lagoon had similar isotopic composition, it can be deduced that a hydraulic connection exists. The lagoon is sourced from seawater from the Atlantic Ocean and groundwater discharge from the unconfined aquifer, and it is exposed to the evaporation which is why the lagoon is slightly more enriched than deep groundwater. The significant difference in the isotopic composition of groundwater at the lagoon and the rest of the West Coast Aquifer System (WCAS) confirmed that a saline-freshwater interface exists in deep geological zones, which is controlled by deposition of the clay layer and calcrete lenses. The groundwater of the upper aquifer at the Geelbek Lagoon has similar isotopic composition to the rest of the WCAS. The water that was sampled from the Berg River had significantly different isotopic composition than groundwater of the WCAS. The results show that surface water is not a source of recharge for the unconfined and confined aquifer in the region.

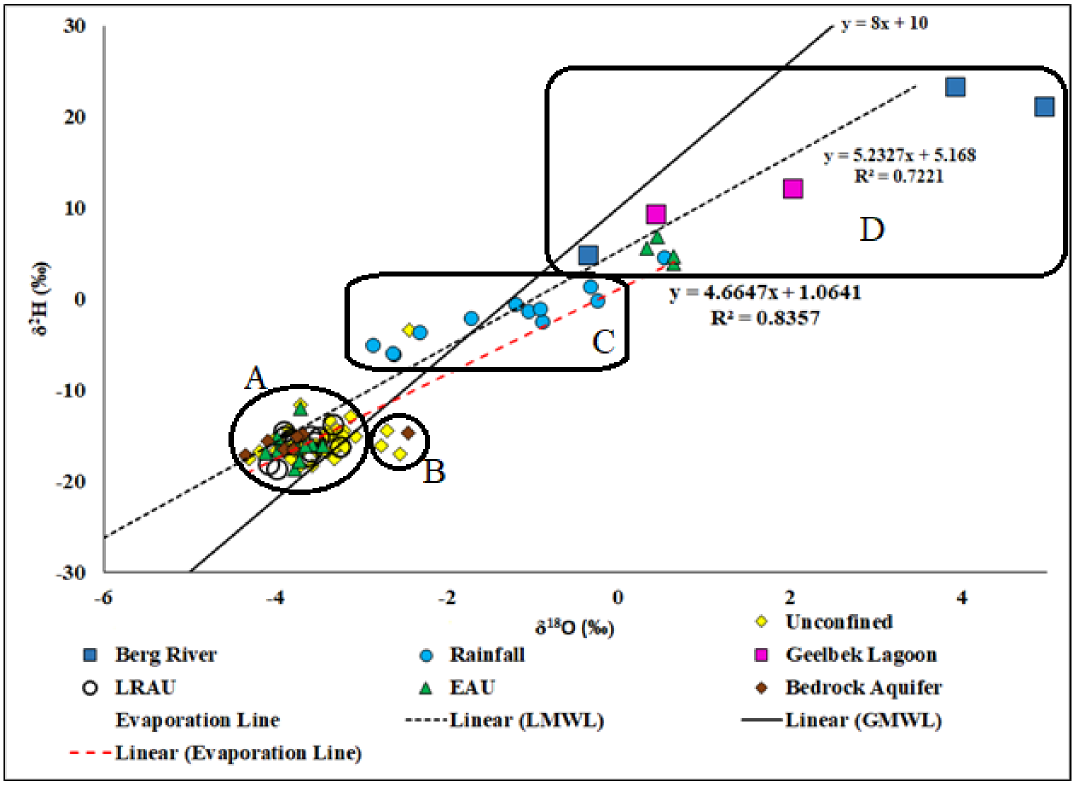


Figure 3.28: Stable isotope analyses of all rain, surface and groundwater samples collected on the West Coast

Figure 3.29 illustrates the results of groundwater tritium activities, which is shown as a function of δ18O‰ as these parameters were used as proxies for groundwater recharge. Groundwater tritium activities showed good positive correlation with stable isotope data, as deep groundwater, which experienced enriched isotopic signatures, had elevated H-3 activities. The spatial distribution illustrated that, for the unconfined aquifer, H-3 activity is the highest close to geological features (deformations in the basement) such as the shale-granite contact and Colenso Fault. The H-3 results for the LAU were generally below detection limit and there was no correlation with topography in the region. H-3 activity was generally the highest for the UAU in the north and decreased southwards. The LRA exhibited greater tritium activity than the EA. Tritium activity did not correlate well with water table elevation. H-3 activity was low in the region where the water table for the LAU and UAU was the highest close to topographically high areas in Hopefield. Comparatively, groundwater H-3 was higher in topographically lower regions towards the west.

The spatial distribution of groundwater H-3 of the unconfined aquifer illustrated that there is a mixture of sub-modern with modern groundwater, which evidences the complexity of the stratigraphy. Low tritium content in the confined aquifer indicates that the groundwater is the same age as the unconfined aquifer, which indicates the source of recharge is similar. Generally, the confined aquifer has longer residence time, which indicates that groundwater is older and that tritium has disintegrated due to its half-life. The high tritium content of the boreholes established in the confined aquifer are all located adjacent to the Malmesbury Shale-Granite Contact. The lineament could possibly act as a conduit for regional local groundwater flow and recharge the bedrock aquifer. From the stable isotope and tritium trends, the results show that a hydraulic inter-connection exists between the unconfined, confined aquifer and the bedrock.

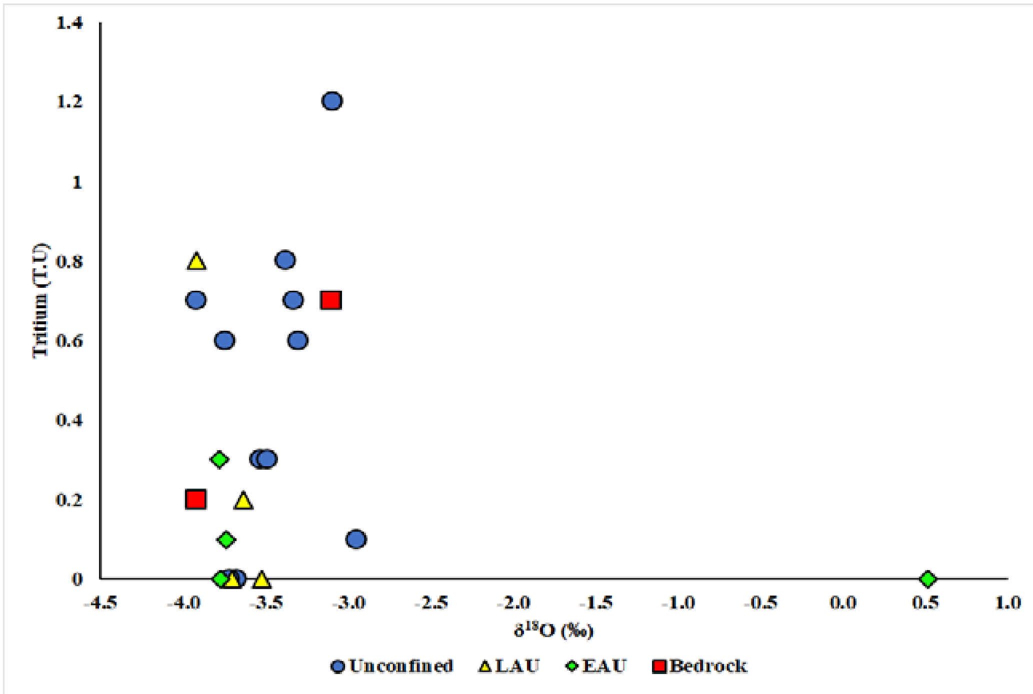


Figure 3.29: ***Plot of 3H and δ18O‰ illustrating tritium activity for the WCAS. (A) Illustrates most recently recharged groundwater***

Figure 3.30 illustrates results of groundwater radiocarbon activities as a function of δ18O‰. The highest groundwater C-14 content was sampled from boreholes that are in close proximity to the coast (G46106 and BH2). C-14 contents correlated better than other environmental isotopes with aquifer depth as the pMC (percent Modern Carbon) in the UAU was higher than the LRA, EA and bedrock aquifer respectively, which was expected. The southern paleochannel EA had a lower C-14 activity than the LRA, which had a C-14 activity that is in close range to the pMC content in the UAU. The high C-14 activity of groundwater at Geelbek corresponded to tritium activity that is below detection limits and highly enriched in heavy isotopes.

Groundwater radiocarbon contents correlated well with depth, better than stable isotope and tritium content as its long half-life discerns residence time that are more realistic groundwater age. The C-14 content of groundwater in WCAS is the highest in the unconfined aquifer and correlates well with tritium content in the same unit except for groundwater at the lagoon where the tritium activity and C-14 content are inversely proportional to each other. The C-14 content in the unconfined aquifer indicates that that groundwater is of modern age and that residence times is short. The C-14 content of groundwater in the deeper confined aquifer of the EA and LRA is generally lower than the unconfined aquifer. Moreover, the groundwater of the EA has a longer residence time and is considered older than the LRA. This result is in agreement with the geological conformation of the basal gravels of the Elandsfontyn formation which suggests that the LRA is thicker and larger in areal extent, so groundwater residence time is shorter as virtue of the geology (Timmerman, 1985; DWAF, 2008; Seyler et al, 2017). From C-14 trends, the results suggest that there is negligible hydraulic inter-connection between the LRA and EA due to the significant difference in C-14 content.

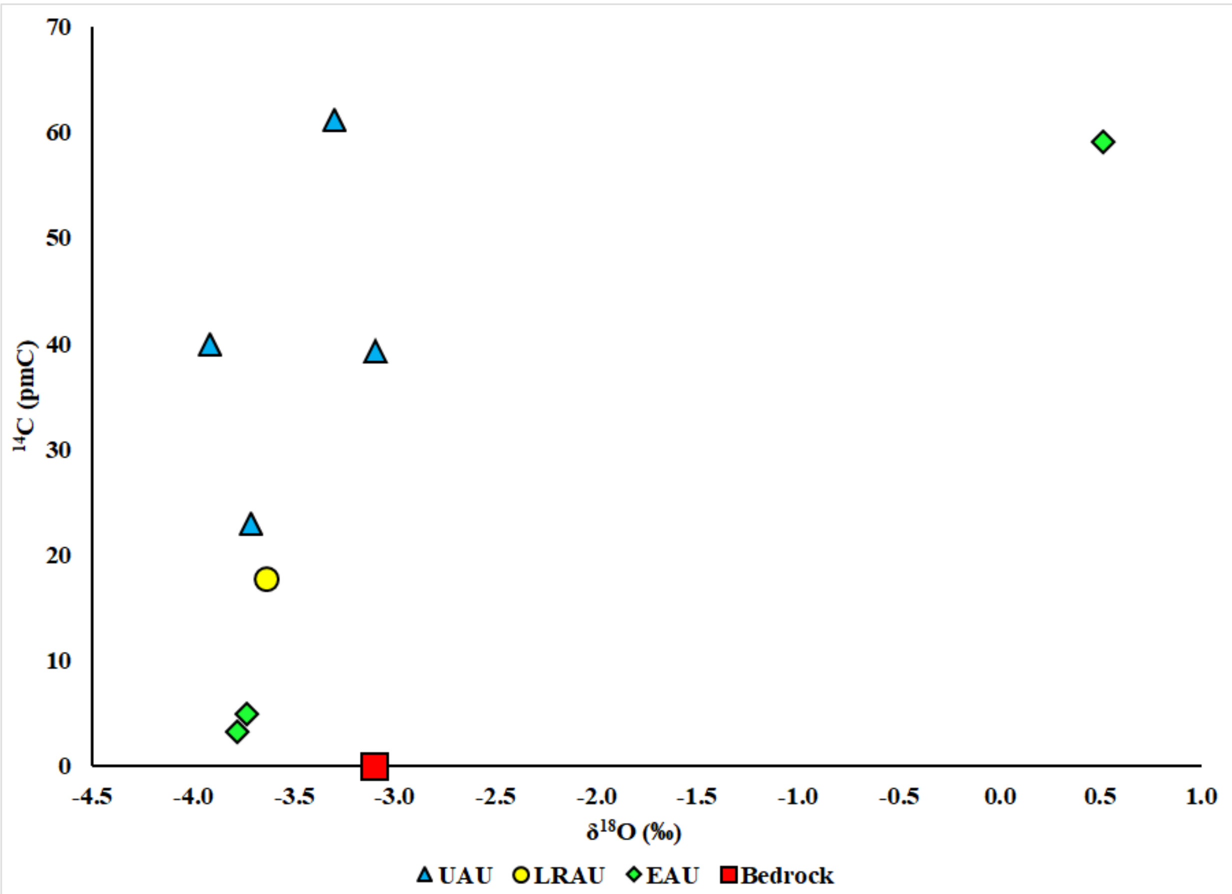


Figure 3.30: ***Plot of C-14 (pMC) and δ18O‰ illustrating groundwater age***

3.5.5 Connectivity between the confined units of Langebaan Road and Elandsfontein aquifers

The main scope of van der Schyff (2019) was to investigate the connectivity between the Langebaan Road aquifer and the Elandsfontein aquifer, specifically the confined units. The specific objectives were to i) determine the groundwater flow path and direction between the two aquifers; ii) establish the interaction between the two aquifers; and iii) develop a groundwater conceptual model to explain the interaction between aquifers. Van der Schyff (2019) made use of geological, hydrological and hydrochemical information. The new data on isotopes, general chemistry, geology and geophysics provided key insights on the extent of connectivity between the two aquifers.

Each aquifer has an upper and lower unit that is separated by an aquitard that can reach a thickness of up to 50 m but pinching out toward the western and eastern parts of the study area. The diffuse inter-unit leakage was estimated to be lower where the aquitard (clay layer) is thick and continuous. Leakage is higher where the aquitard is absent, such as in the south-western part of the study area.

Objective i) focussed on establishing the groundwater flow path and direction between aquifers. The preferential flow paths in the study area were caused by both natural features, i.e. fractures and palaeo-channels, and man-made features, i.e. boreholes. The Cl concentration was used as natural tracer and the lowest concentrations were observed in the regional recharge zone, where the highest effective infiltration occurred. Hydrogeochemical data and water level data were interpolated which gave a spatial distribution of the water level and tracers. The analysis from the groundwater contour maps showed that the general direction of groundwater flow for the unconfined aquifer system was from the south-east Hopefield area towards the Berg River and the Atlantic Ocean along the existing paleochannels thereby transporting water between the Langebaan Road and Elandsfontein aquifer units. This was expected as described by previous studies and the presented study confirmed such findings and interpretation. Laboratory chemical analyses on groundwater samples indicated that the geochemistry of the study area is homogenous. This could indicate mixing between the EA and LRA. A confined aquifer should have a distant hydrochemical signature compared to an unconfined aquifer. However, both aquifers show similar hydrochemical signatures which may indicate leakage between the two aquifers.

The second study objective aimed at establishing the interaction between the two aquifers, i.e. Langebaan Road and Elandsfontein aquifers. The study found that leakage existed between the two aquifers and the main two factors that contributed to leakage within the aquifers were due to leaking boreholes seals and fractures in the clay layer (aquitard). Multiple tracers were used to establish mixing between the aquifers. The $\delta^{18}O$ and $\delta^{2}H$ relationships suggested variations in groundwater recharge mechanisms. The stable isotopic signatures revealed three water groups: non-evaporated waters that indicate recharge by recent infiltration; evaporated waters that are characterized by relatively enriched $\delta^{18}O$ and $\delta^{2}H$ contents (this includes the Berg River and BH2); and groundwater characterized by their depleted isotopic composition. However, there was no distinct separation between confined and unconfined aquifer isotopic signature; this implies that there is possible mixing between aquifers. The radiogenic tritium (^{3}H) isotope data indicated significant evolution in the groundwater in terms of old versus recent recharge. The general trend of the tritium is that the unconfined aquifer has high tritium values compared to the lower values in the confined. However, when mixing of the water occurs, the confined unit had a higher tritium value which indicates that vertical leakage takes place at these locations. The evidence showed inter-unit leakage. At one site, where the lower aquitard was continuous, it was concluded that the leakage is due to poor borehole construction or deterioration of existing borehole casing. Considering the evidence from hydrochemical and geophysical data on existence of preferential flow at some locations, it can be concluded that such features enhanced inter-aquifer leakages.

Absence of tritium (0 to 1 TU) at many locations indicates long residence time. In these areas, ^{14}C analyses would be a better isotope to use to determine age of the groundwater as it would recognize older water. A selection of 14 sites from both confined and unconfined parts of the Langebaan and Elandsfontein aquifers were sampled. The results show distinct values for the unconfined and confined aquifers as expected; the younger water was found in the unconfined aquifer and confined aquifer has older water. Groundwater from wells in the study area (well depths ranging from 11 to 148 m), have ^{14}C values ranging from 3.2 to 59.1 pMC with the exception of a sample located in the basement of the LRA wellfield at a well depth of 148 m having a value of 0-1.4 pMC, which corresponds to very ancient water. Given the distinct values of ^{14}C throughout the study area, samples in the unconfined aquifer (G33317, G33505, BH2, BH1A, G46060 and G46106) with relatively high values are a likely result of ‘modern’ surface or precipitation water infiltration. Boreholes G33505B and G46059 have ^{14}C values (4.9 and 17.6 pMC); these wells are both found in the confined aquifer at depths of 80 m and 30 m, respectively. Borehole G46105, which was drilled into the basement of the LRA, was found to be the oldest water in the system. This indicates that there is no leakage from the basement aquifer upwards to the overlaying aquifer units. Geological logs and screen position (NGA database) of borehole G33317 found in the Elandsfontein aquifer indicate that this borehole penetrates the unconfined aquifer. The age values of this groundwater sample lean towards an older water which is characteristic of confined systems. This could be an indication of leakage between confined and unconfined aquifers giving the unconfined borehole an older water signature. BH2 and BH1A are both found in the Geelbek area which is situated at the discharge area of the Elandsfontein paleochannel. There is no Elandsfontein clay present in the geological logs of the two boreholes and the location of the boreholes coincides with probable pinching out of the clay layer (Woodford, 2002). For these unconfined boreholes (BH2 and BH1A), the older signature 22.9 pMC at BH1A is due to discharge of the confined system which indicates mixing that could be taking place at this site. BH2 displays young water as it could be fed by the Langebaan Lagoon which is less than 200 m away from the borehole.

Comparing tritium and ^{14}C results, two water groups were identified in the two aquifer units. Group 1 represents groundwater with high tritium (0.6-1.2 TU) and high corrected ^{14}C activity (40-62 pMC); this groundwater type is of short residence time (< 60 years), corresponding to recharge of post-bomb precipitation. This group occurs in both shallow and deep groundwater. Group 2 represents samples showing low tritium (0-0.5 TU) and low corrected ^{14}C activities (< 30 pMC). This groundwater originated from pre-bomb precipitation, and mainly occurs in the confined parts of the aquifer. The presence of any measurable tritium in these waters is presumably a result of mixing with small amounts of younger water.

The third objective of the study was to develop a groundwater conceptual model to explain the interaction between aquifers. Hydraulic connection between the LRA and EA has been discussed in previous studies done on the West Coast (DWAF, 2008; Tredoux *et al.,* 2009; Hay *et al.,* 2010; Seyler *et al.,* 2016). From the analysis of the current study, it was concluded that there is a dominant direction of the groundwater flow and a spatial representation of the leakage sites between the aquifers.

There seems to be a lateral and vertical hydraulic connection between the aquifers. The lateral hydraulic connection is found in the confined systems. According to Timmerman (1988), it was suspected to be a basement high that separates the two lower aquifer systems. The two lower aquifers could therefore be linked through the shale-granite contact. According to new knowledge and data that has been collected (DWAF, 2008), there could be a paleochannel hydraulically connecting the two aquifer systems additional to the shale-granite contact. Lateral hydraulic connection is therefore dependent mostly on geological features, which cause preferential pathways as the paleochannels in this case. The upper aquifers have no division between them. Elandsfontein upper aquifer has a far better quality than Langebaan Road upper aquifer (Du Plessis, 2012). Groundwater recharge occurs at the Elandsfontein aquifer side, the upper part of the Elandsfontein is at a higher level due to the dunes that formed and has more calcrete layers that are still intact. In the Langebaan Road area, most of the calcrete layers have been destroyed due to anthropogenic practices such as mining and ploughing. This allows the possibility of atmospheric salt making the Langebaan Road aquifer saltier because of precipitation. Calcrete acts as confining layer where it is found at the surface in some areas of the aquifers, which creates a barrier allowing the water in EA to be of a better quality. The Elandsfontein paleochannel is also much deeper than the Langebaan road paleochannel, hence infiltration depth is greater.

The Langebaan Road aquifer is a multi-layer aquifer unit with an unconfined portion, a confined portion and an aquitard separating the two portions of the unit. Vertical hydraulic connection within the LRA is postulated to occur at areas where the confining unit is absent, while no vertical hydraulic connectivity occurs where the aquitard is at its thickest (Cherry and Parker, 2004). The hypothesized hydraulic connection is likely to be prominent where the clay layer is less than 5 m thick. The confining layer affects the water level. Higher water levels have been recorded in areas where the clay layer is thin, i.e. <5 m, and in areas where the clay layer is thicker, i.e. >5 m lower water levels were recorded. This could indicate leakage of the confined aquifer unit feeding the unconfined. Water level declines in areas where the clay layer is thicker.

In this study, it was highlighted that over 200 boreholes penetrate through the clay layer creating the possibility of discontinuities within the clay lenses. Poor construction of boreholes is a scenario that promotes leakage between systems. Weaver and Fraser (1998) mentioned that bentonite plugs were not installed when putting in the production boreholes. It is necessary that all the old boreholes are located, and their condition checked to plug those that may be leaking for reducing head losses and for protecting the water quality in the confined aquifer. An example is borehole G33316 which penetrates the confined aquifer where the clay layer is thought to be thin. At this site, there could be vertical leakage between the upper and lower aquifer units. Geochemistry shows that the reading is within the same range and this is also as a result of the thin clay layer. The geophysics indicates geological features that present preferential flow paths for groundwater and that could indicate that vertical leakage is present. The artificial recharge in the confined aquifer can only be done where the confining layer is absent and enough storage space exists in the aquifer.

3.6 Groundwater dependent ecosystems

A proper assessment of groundwater dependent ecosystems has not been done for the area. The WRC study on aquifer dependent ecosystems for Geelbek (Colvin *et al.*, 2007) was the only study found in the literature. Figure 3.31 shows the wetlands, pans and non-perennial rivers that can easily be seen on the Google Earth satellite image. They are easier to find in unimpacted areas as they were not disturbed by agricultural activities. It is possible that some of the wetlands may be the remnants of oxbow lakes.

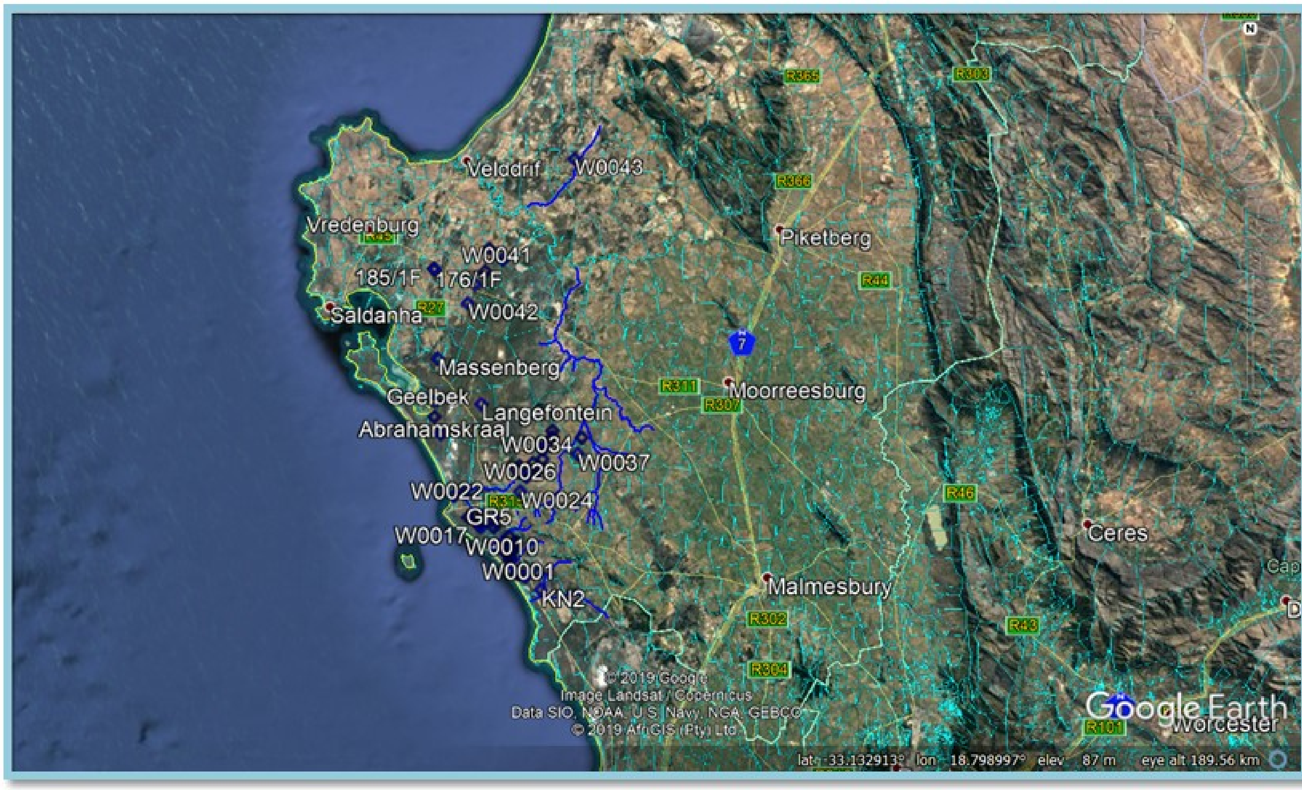


Figure 3.31: ***Satellite image showing some of the wetland, non-perennial rivers and pans in the study area***

4 ZONCEPTUAL MODEL

The groundwater flow conceptual model is shown in Figure 4.1, and it includes recharge and discharge areas and two cross-sections, A and B, corresponding to the LRA and EA (Figures 4.2 and 4.3). Due to the lack of outcrop of the Elandsfontyn Formation and its separation from the UAU by the clay layer across most of the interior, the recharge mechanism to the LAU is more complex and more open to interpretation. Timmerman (1985c) suggested that the low permeability UAU sediments around the recharge mound (south-west of Hopefield) would facilitate the downward percolation of the recharged water into the LAU, and then the lateral movement of this water, under increasing confining pressures to the north and north-west, in a north-westerly direction towards the LRA via a "piston-flow" mechanism. This suggestion is broadly supported by the mapped clay thickness, i.e. it is thin and even missing around the water level high in the south (at the junction of G10L, G10M, and G21A), and thicker to the north-west and south-west (Figure 2.3). For downward percolation to occur, the water levels in the UAU must be greater than those in the LAU, supported by the sparse data set. Thus, recharge to the LAU also occurs through leakage via the UAU in areas where the clay is thin and the head difference between upper and lower aquifer is large enough to drive vertical recharge downwards. The conceptual interpretation of recharge to the LAU, in areas where clay is thin or missing and there is a high head in the UAU, is captured in Figures 4.2 and 4.3 for the two cross-sections of LRA and EA.

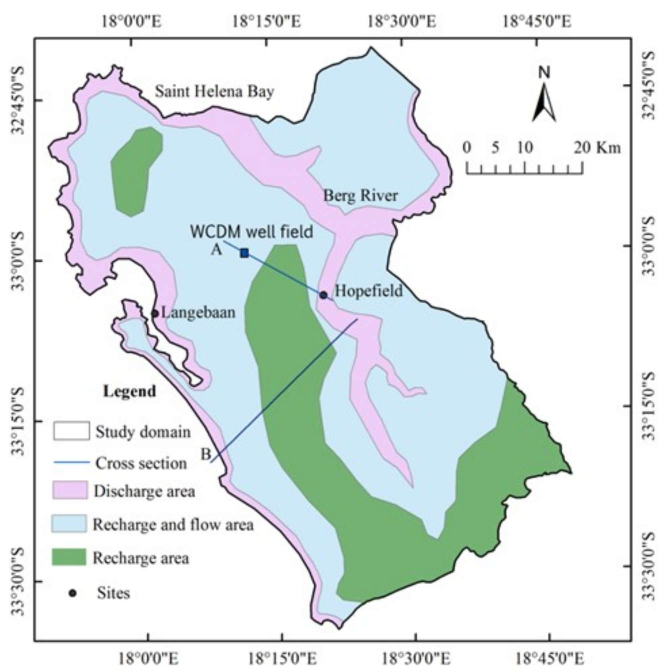


Figure 4.1: ***Groundwater flow conceptual model of the study area (see Fig. 4.2 and 4.3 for cross-sections A and B)***

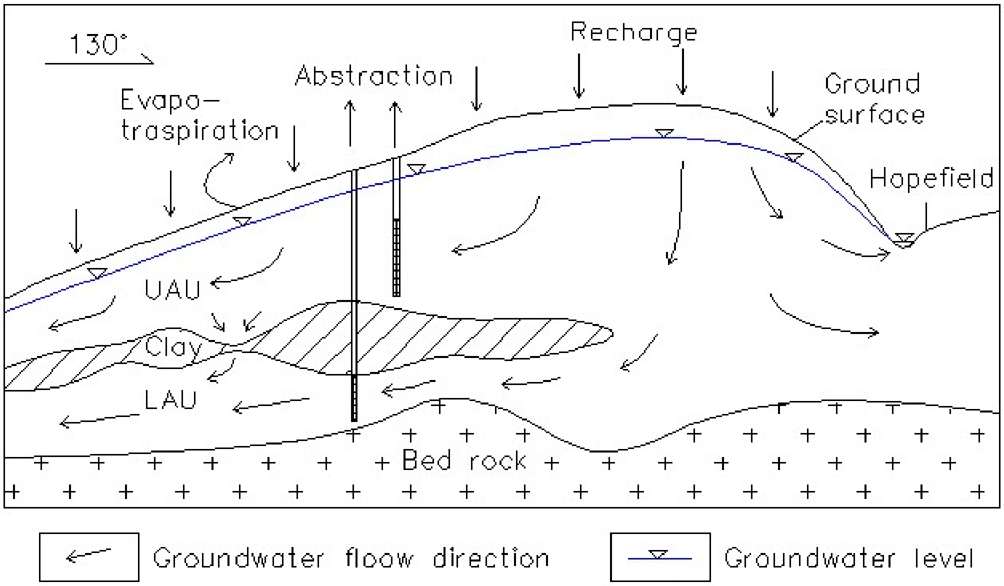


Figure 4.2: ***Conceptual cross-section (A) of groundwater flow mechanisms of LRA (after DWA, 2010)***

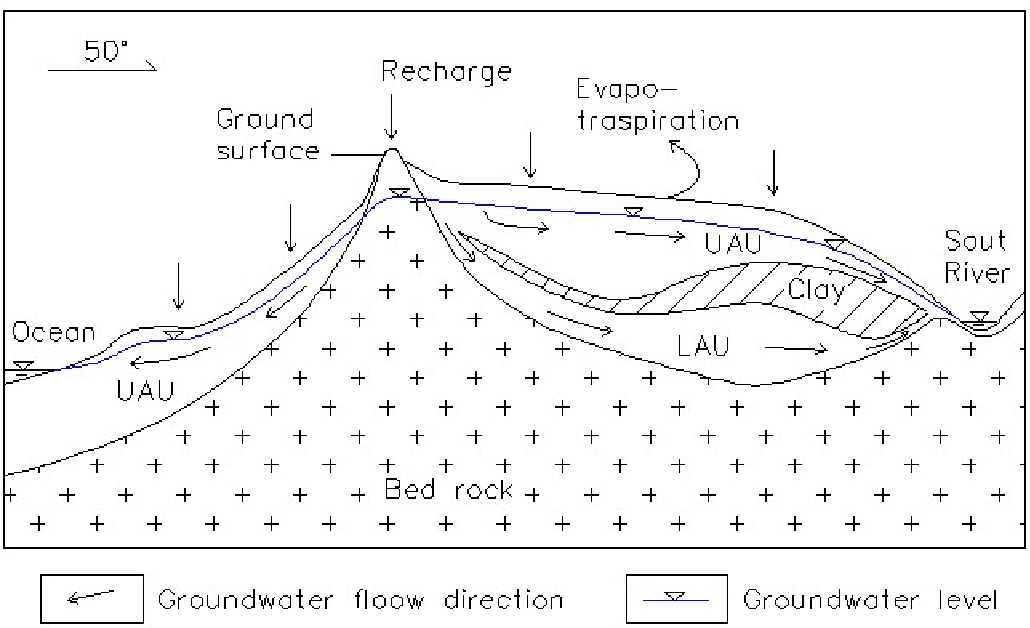


Figure 4.3: ***Conceptual cross-section (B) of groundwater flow mechanisms of EA (after DWA, 2010)***

The aim in setting up models is to represent processes as simply as possible, without losing detail of the physics (DWAF, 2008c). Physical features and processes that dictate the groundwater flow system form the basis of the conceptual model. The high variability of the composition and thickness of the various sedimentary layers forming the aquifer units and clay aquicludes or aquitards constrains the efficiency of simplification. The heterogeneity of the chemical composition of groundwater in the upper aquifer unit underlines a lack of continuity in the flow system in this unit. The existence of palaeochannels was confirmed but their exact extent is still in question.

The salient conclusions for the groundwater flow system, as detailed in Chapter 2, are summarized here. The natural boundaries of the conceptual model are described in Table 4.1. The conceptual model of the groundwater flow regime is established based on the following understanding of the study area:

1) It is assumed that the palaeotopography is representative of ancient fluvial systems and therefore a continuous palaeochannel is inferred. LAU of LRA and EA are in some degree of hydraulic connection. Figure 2.12, showing the cone of depression in the lower aquifer unit after several years of pumping, depicts a strong limb extending northwards and northeastwards from the Langebaan wellfield inferring inflow from the north-east, i.e. likely from the Adamboerskraal aquifer LAU passing underneath the Berg River.
2) The geology can be interpreted as four distinct hydrostratigraphical units:
   a) The upper unconfined aquifer unit comprising the Witzand, Springfontyn, Langebaan, Velddrif formation sediments and Varswater sediments if present.
   b) The confining layer (Upper Elandsfontyn clay)
   c) The lower (semi-) confined aquifer unit (Elandsfontyn sediments)
   d) Bedrock: Granites of Cape Granite Suite and shales of Malmesbury Group.
3) The geology data sourced from the National Groundwater Archives (NGA) is correct and dominate the distribution of the palaeochannel and the four distinct hydrostratigraphical units mentioned above.
4) Sources, sinks, flow direction:
   a) The UAU is recharged directly from rainfall. Flow in the UAU is topographically controlled and occurs away from the recharge mound or higher places to the lower places. Finally, the UAU discharges to the Berg River and the coastline in the north and west of the study area. On average, the Berg River and its tributaries gain from the aquifer as there is a strong hydraulic gradient towards it. However, it is possible that the Berg River recharges the UAU during winter.
   b) Recharge to the LAU occurs at the clay missing “window” area in the south-west of Hopefield based on the NGA borehole logs. Besides, flow in the LAU is basement controlled and occurs along the axes of the palaeochannels. The LAU mainly discharges to the coastline but also via free-flowing boreholes and springs when piezometric levels are higher.

Table 4.1: Description of model boundaries and numerical translation

TABLE 4.1 Description of model boundaries and numerical translation.		
Location	**Conceptual Description and assumptions**	**Numerical Translation**
North-west, west and south-west Atlantic coastline	Atlantic Ocean serves as a regional drainage datum plane and accepts the discharge from aquifers.	A constant head boundary condition is applied along the coastline.
Berg River and Sout river near Hopefield	The Berg River and Sout river are assumed to be in contact with the UAU, and not to be deeply incised. However, quantities of water from either of these rivers entering the upper aquifer units and vice versa are thought to be insignificant.	River boundary condition is applied.
Ephemeral Rivers of Sout and Groën together with their tributaries and other gullies	Work as the drainage boundary of the model.	Drain boundary condition is applied.
North-east, south and south-east mountain area	It is assumed that there is no flux across the boundary of the catchment. Recharge could however enter the aquifer from the north-east, which would mean that this should not be a no-flow boundary.	No-flow boundary is applied.

5 NUMERICAL MODELLING

5.1 Software introduction

The main purpose of modelling in this project was to simulate the natural seepage conditions and identify suitable sites for implementing MARS. For this purpose, the graphical user interface (GUI) Model Muse developed by the U.S. Geological Survey (USGS) was adopted. Model Muse provides a GUI for creating the flow and transport input files for MODFLOW-2005 using the finite-difference method to describe the movement of groundwater flow.

The three-dimensional movement of groundwater of constant density through porous earth material may be described by the partial-differential equation (Michael *et al.*, 1988):

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})-W=S_s\frac{\partial h}{\partial t} \qquad (1)$$

where:

- K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (Lt^{-1});
- h is the potentiometric head (L);
- W is a volumetric flux per unit volume and represents sources and/or sinks of water (t^{-1});
- S_s is the specific storage of the porous material (L^{-1});
- t is time (t).

In general, S_s, K_{xx}, K_{yy} and K_{zz} may be functions of space ($S=S_s(x,y,z)$, $K_{xx}=K_{xx}(x,y,z)$, etc.) and W may be a function of space and time ($W=W(x,y,z,t)$); equation (1) describes ground-water flow under non-equilibrium conditions in a heterogeneous and anisotropic medium, provided the principal axes of hydraulic conductivity are aligned with the coordinate directions.

Equation (1), together with specifications of flow and/or head conditions at the boundaries of an aquifer system and specifications of initial-head conditions, constitutes a mathematical representation of a ground-water flow system. A solution of equation (1), in an analytical sense, 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 (1), the equation and its initial and boundary conditions are satisfied. A time-varying head distribution of this nature characterizes the flow system, in that it measures both the energy of flow and the volume of water in storage, and it can be used to calculate directions and rates of movement.

The Modflow package in Model Muse is capable to derive quantitative results for groundwater flow problems of an aquifer, and the Modpath package was used to trace the path of specified water particles.

5.2 Methodology

5.2.1 Numerical model set-up

The model domain covers a surface area of 4674.7 km^2 including three entire catchments G10M, G10L and G21A. The north-west and south-west boundary is the Atlantic coastline. The south-east model boundary follows the quaternary catchment border of G21A and G10L. The model boundary in the north-east follows the Berg River and its tributaries to the geological contact with the Table Mountain Group Formation.

The finite-difference model was set-up as a three-dimensional 5 layer, steady-state groundwater model (Table 5.1). The mesh size of interest to LRA and EA is 250 m, while for other areas it was 500 m (Figure 5.1). DEM data at 30 m x 30 m scale is available for the area and it was used to construct the model surface topography in the GIS software. The other layers were defined through 341 NGA boreholes lithology data and 1:250000 geology map of study area. Figure 5.2 represents two examples of vertical cross-section of the model domain.

Modflow package in Model Muse uses layer property flow package and preconditioned conjugate gradient (PCG) solver for the iterative solution of the flow and transport equation. The closure criterion for the solver, i.e. the convergence limit of the iteration process was set at a residual below 0.01.

Table 5.1: Layer arrangement for the groundwater model

TABLE 5.1 Layer arrangement for the groundwater model			
Element Layer	**Layer description**	**Thickness (m)**	**Data source**
1	The top 2 m of the model area. Established for numerical stability.	2	Layer top: DEM Layer bottom: DEM – 2 m
2	Upper Aquifer Unit (UAU)	0.1~119	Layer top: DEM – 2 m Layer bottom: UAU bottom as defined through NGA lithology data.
3	Clay layer	0.1~84	Layer top: UAU bottom as defined through NGA lithology data. Layer bottom: clay bottom as defined through NGA lithology data.
4	Lower Aquifer Unit (LAU)	0.1~64.5	Layer top: clay bottom as defined through NGA lithology data. Layer bottom: basement elevation defined through NGA lithology data.
5	Bedrock	20	Layer top: basement elevation defined through NGA lithology data. Layer bottom: basement elevation – 20 m

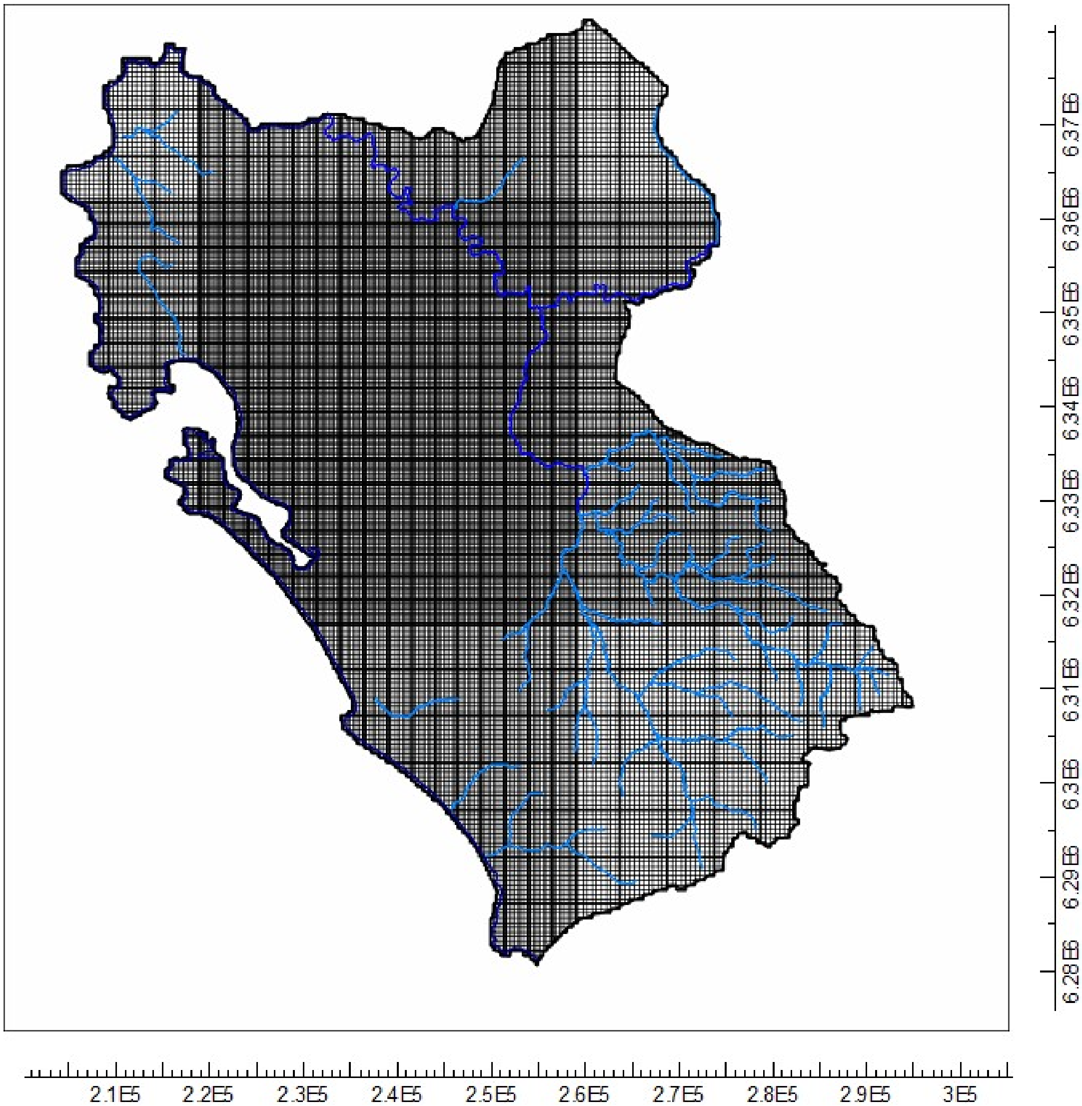
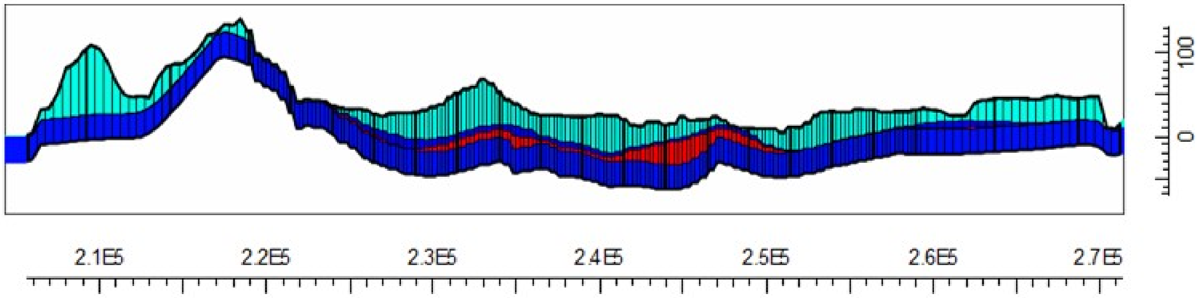
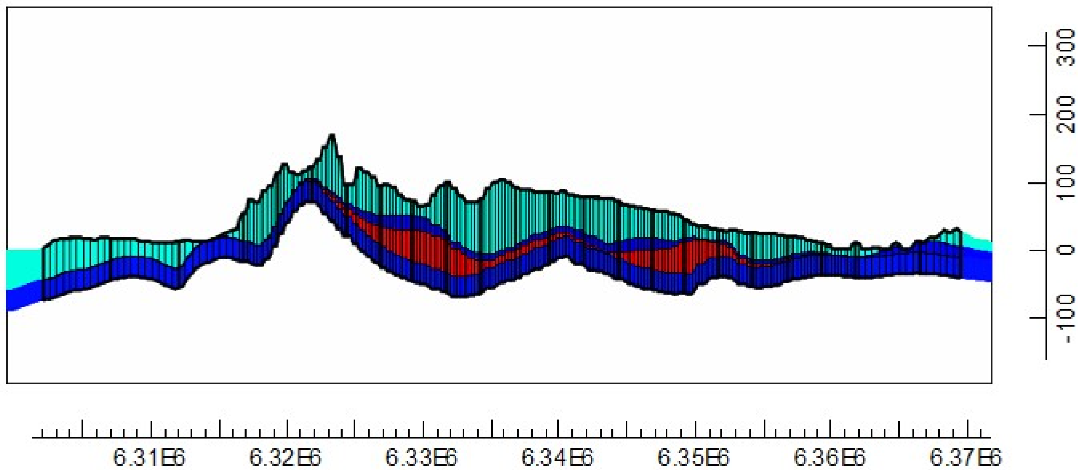


Figure 5.1: ***Finite-difference grid of the groundwater model***



(a) Section from west to east



(b) Section from south to north

Figure 5.2: ***Examples of vertical cross-sections of the model domain (colours indicate numerical model layers)***

5.2.2 Boundary conditions

Numerical model boundaries are required to be set at positions where a known piezometric head, known flux of groundwater, or known loss of groundwater from the system can be specified and input to the model. Positions of known fluxes within the model area are also specified as internal boundary conditions. The water level of the Atlantic Ocean was set to Time-Variant Specified-Head package with the value of 0 masml based on the assumption that the water level of the ocean does not change during modelling or the fluctuation has little impact on the groundwater flow system. The water level of the Berg River was assigned through River package by two segments, with its value interpolated from 0 masml at its estuary in the north to 10 masml in the south-east of the model domain. The water level of the perennial segment of Sout River was assigned through River package with the value “ground surface +1” masml. The water level of other ephemeral streams in the model domain were assigned through Drain package with their values being equal to the ground surface.

Recharge was set according to four zones as illustrated in the GRAII data for the region (DWAF, 2006; Figure 5.3). Over the model domain, the recharge rate varies from 5 to 35 mm/a. Comparing the recharge distribution to the mean annual precipitation (MAP) surface also developed by DWAF (2006), a recharge rate between 6 and 7% of rainfall was suggested.

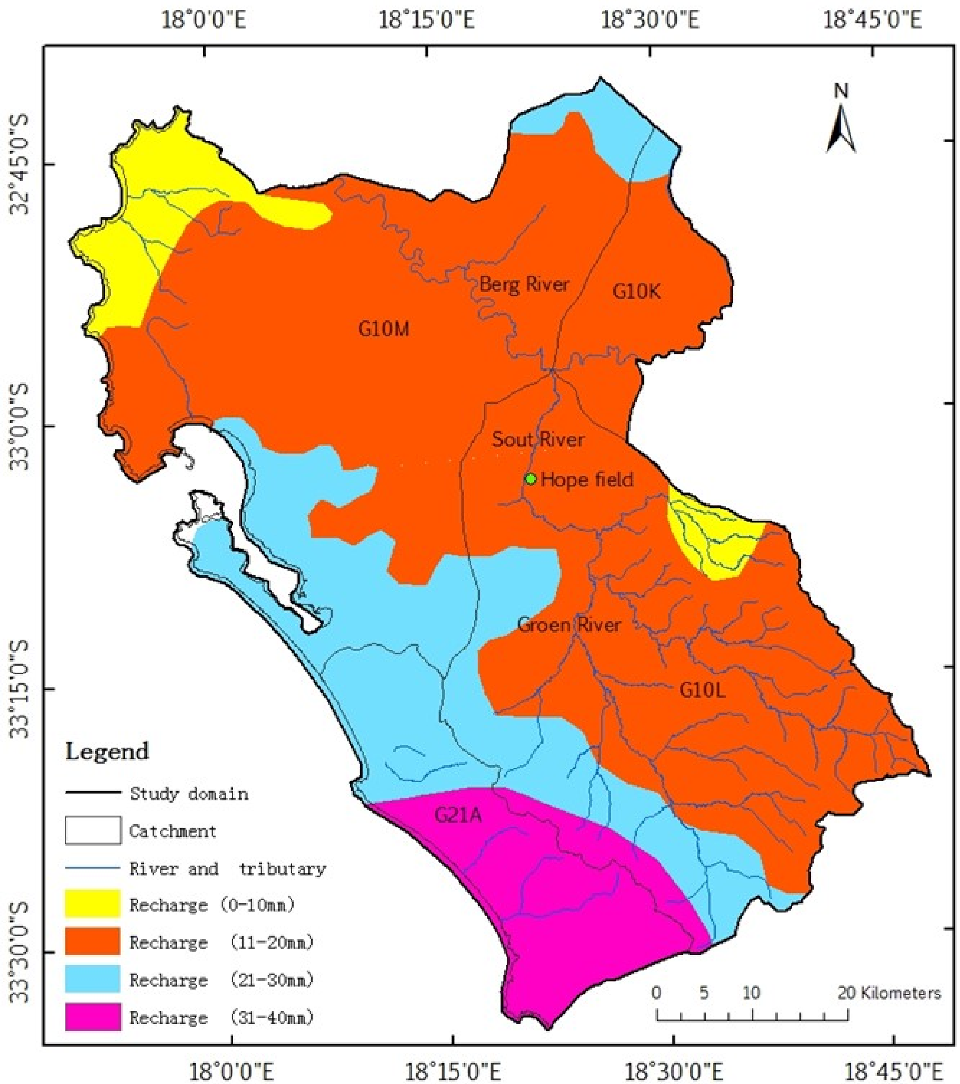


Figure 5.3: ***Groundwater recharge distribution (from GRAII, DWAF, 2006)***

5.2.3 Groundwater abstraction

The WCDM operates a wellfield abstracting from the LAU, within the LRA palaeochannel. The abstracted groundwater augments the surface water from the Withoogte Water Supply Scheme, supplying a broad region slightly beyond the boundaries of Langebaan Local Municipality. The wellfield is licensed to abstract 4000 m^3/d or 1.46 Mm^3/a, and between commissioning in December 1999 and January 2005, the WCDM utilized 80% of this allocation. Over this 5-year period of abstraction, the piezometric level in the LAU reduced by around 10 m, while the UAU water table remained stable (Seyler *et al.,* 2017). During 2005, concern was raised over the 10 m reduction in piezometric level in the LAU, leading to a reduction in the abstraction rates by 10%. With the reduction of 10 m, the LAU remained confined in the area of the wellfield. Abstraction during April 2006-March 2007 totaled just over 1 Mm^3/a (76% of revised allocation). From 2007 to 2012, annual abstraction values however remained around 1 Mm^3/a (WCDM, 2012). Abstraction significantly reduced in 2014-2015 due to wellfield pump and infrastructure vandalism. Groundwater is also abstracted from a wellfield at Hopefield and no detailed information could be obtained. The All Towns Strategy (DWS, 2016) states that the town has 7 boreholes which are in poor condition, with yield of 0.16 Mm^3/a, but these are not currently in use.

An earlier hydrocensus was extensively made by Woodford (2003) to calculate the estimated total volume of private groundwater abstraction. There are 78 registrations in the WARMS database for the study area, with a total registered abstraction of 6.9 million m^3/a. The sum of registered abstractions per water use sector was reported by Seyler (2016). The majority of groundwater use is for irrigation. However, comparing the distribution and sum total of WARMS registrations along with the distribution and sum total of abstractions from WCDM monitoring reports (WCDM, 2005, 2009, 2011, 2012), it is clear that a number of private abstractions are not captured in the WARMS database. An additional challenge with the WARMS database is that there is no information on which aquifer is targeted (LAU, UAU). The majority of private groundwater use is assumed to be from the UAU, however some private groundwater users do access the LAU (DWAF, 2010c).

The abstraction dataset available for modelling therefore contained the original hydrocensus data (DWAF, 2003) and the WARMS data used in the modelling of DWAF (2008c). Borehole abstraction from the model domain was simulated using the pumping well boundary condition. Outflow rates were assigned to single nodes (at the appropriate elevation) within the model mesh.

5.2.4 Aquifer characteristics

Hydraulic conductivities were set based on the existing estimates for the area (Table 5.2). Horizontal hydraulic conductivities were set to the same value in both X and Y direction, while vertical hydraulic conductivities were set at 10% of the horizontal conductivities, and not varied. The range of hydraulic conductivities in the calibrated model for each model layer is shown in Table 5.2.

Table 5.2: Calibrated hydraulic conductivities of the aquifer

TABLE 5.2 Calibrated hydraulic conductivities of the aquifer.				
Model layer	**Hydraulic conductivity (m/d)**			**Remarks**
	Kx	**Ky**	**Ky**	
1	0.05-9	Kx	Kx /10	The low values usually lie at the EA and the connected area of LRA and EA; High value at LRA area.
2	0.05-9	Kx	Kx /10	The low values usually lie at the EA and the connected area of LRA and EA; High value at LRA area.
3	0.001-0.008	Kx	Kx /10	
4	0.2-50	Kx	Kx /10	The low values usually lie at the EA and the connected area of LRA and EA; High value at LRA area.
5	0.02-0.2	Kx	Kx /10	

5.2.5 Model calibration

The procedure adopted for calibration is standard to modelling investigations: the simulated piezometric heads and flows ("modelled" data) are compared against field-measured values ("real" or "observed" data). This modelling study was conducted with steady-state simulations. Aquifer parameters were varied based on the geologic and hydrogeological condition until a reasonable fit was generated between modelled and observed data selected as calibration data.

The water level monitoring database of DWS contains a significant number of data observations. However, several boreholes are closer to each other than the model mesh (i.e. closer than 250 m). Furthermore, the monitoring boreholes show varied monitoring dates. Prior to modelling, the water level dataset was therefore manually amended to remove points that were very close together. Priority was given to DWS monitoring points that were continually measured until today. Sixty-one DWS water monitoring boreholes were utilized for calibration (Figure 5.4). Among these boreholes, 33 were assigned to the UAU and 28 to the LAU. However, the dataset was insufficient to draw conclusions over the degree of hydraulic separation (difference in piezometric head) between the UAU and LAU, and insufficient for a separate calibration of UAU and LAU. All water level calibration data were therefore grouped together.

Initial water heads for the model were interpolated from the DWS monitored water level dataset of 2010 using Kriging interpolation. When applied to the model, the elevation of water level was corrected if it was above the ground surface.

There is no known standard protocol for quantitative evaluation of a model calibration (Anderson and Woessner, 1992). Point data were used here so that a quantitative evaluation was possible, rather than a qualitative visual comparison between contoured maps (which also include any interpolation errors induced on contouring real data). Point data allowed scatter plots of the measured against simulated heads to be generated, which for a calibrated model would show a random distribution of points lying closely around the 1:1 line. The difference between the measured and simulated heads can be calculated, and the average of these absolute "errors" ("error" refers to the absolute difference between measured and modelled values) is a useful quantification of the goodness of the fit in the model run. However, normally the root mean square error (RMSE) was used as quantitative indicator for the adequacy of the fit between the observed (h_{obs}) and simulated (h_{sim}) water levels:

$$RMSE = \sqrt{\frac{\sum (h_{obs} - h_{sim})^2}{n}} \qquad (2)$$

$$NRMSE = \frac{RMSE}{h_{\max} - h_{\min}} \qquad (3)$$

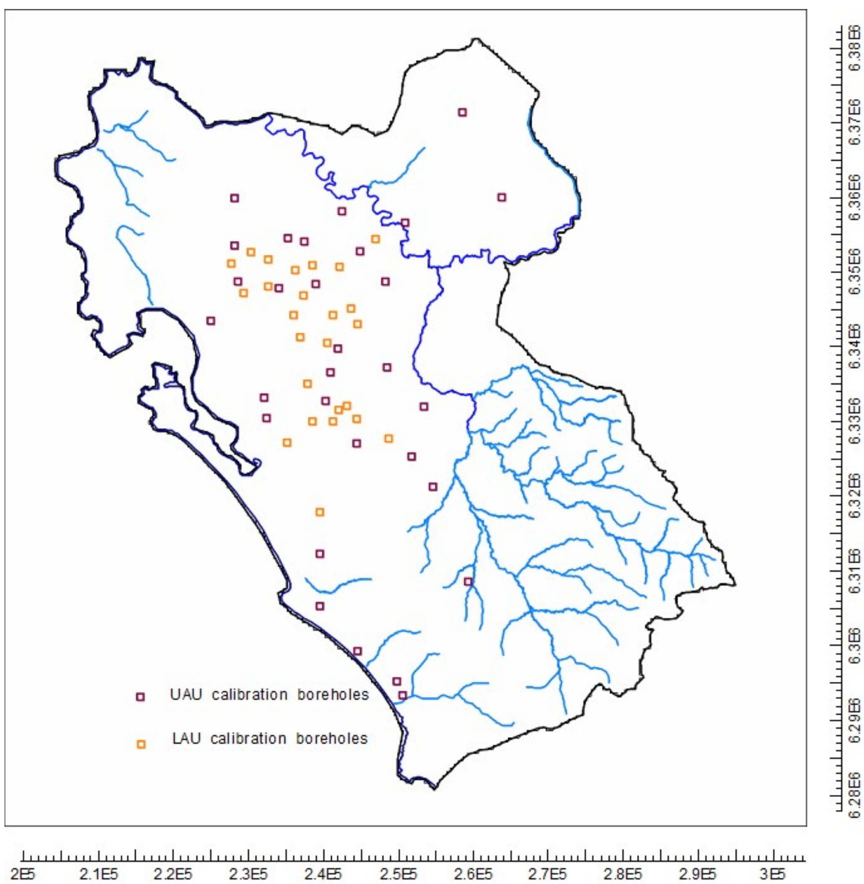


Figure 5.4: ***Calibration boreholes used in the groundwater model***

5.3 Modelling results

5.3.1 Numerical model calibration

The model was run with the initial conditions and the hydraulic conductivities were adjusted using sensible boundaries until a best fit between measured and computed heads was achieved. The following steps were taken during calibration:

(1) The model comprises a large area, across which there is significant topographical and geologic variability (and in many areas not a significant recharge variability), and yet depth to groundwater is fairly constant in the observation data. This leads to the need for a highly heterogeneous hydraulic conductivity in each layer to represent the water level variability. Once a set of hydraulic conductivities per layer was generated with generally acceptable calibration, large errors between simulated and observed data were investigated possibly related to irregular layer thicknesses from interpolation of borehole logs. Therefore, adjustment of the thickness of aquifer layers was needed, especially aiming at those boreholes with limited depth or unclear soil identification.

(2) The groundwater level is high in the south of EA and this was a challenging area in the calibration. Large differences in model errors occurred in close proximity to each other, suggesting a high heterogeneity that could not be replicated by the model. To replicate the observed water levels, the hydraulic conductivity of UAU was set lower in the EA than other regions, which corresponded with the description that up to four aquifer-aquitard layers may be present within the UAU in the EA (Timmerman, 1985c). In comparison to the EA, the UAU in the LRA region was set bigger than in other regions in order to replicate the observed water levels. Due to the complexity of the aquifer, the calibrated conductivities did not match the geology map.

(3) The lithology in G10L catchment is mainly composed of clay, shales and granite, thus there is no significant aquifer defined in this catchment, subsequently there are few observation points according to the monitoring database collected from DWS.

The water budget of the calibrated model is shown in Table 5.3. From the calculated water balance, the recharge in the modelling is 229897.27 m^3/d, which is close to the value of Seyler *et al.* (2016). The biggest contribution to discharge is drainage from tributaries, accounting for 40.82% of the total discharge amount, then drainage to the ocean and river leakage.

Figure 5.5 shows the correlation between observed and modelled groundwater levels. An RMSE of 5.4 m was achieved, with a normalized RMSE (NRMSE) of 5.3%, and a mean error of 1.04 m. An RMSE and NRMSE of less than 10% is generally considered acceptable (Seyler *et al.,* 2016), and with such a large model domain, the calibration was considered to be acceptable. The resulting modelled piezometric contours of UAU and LAU are shown in Figures 5.6 and 5.7. The comparison of the piezometric head contours for the UAU and LAU shows the separation of piezometric heads between the two layers. Although a formal calibration to point data has not been carried out for the LAU, comparison of the modelled contours to the monitored groundwater level suggests that the modelled piezometric heads are a bit lower around the EA. Further investigation would be required to improve the model calibration, but the result was considered acceptable for the purpose of analyzing artificial recharge sites in study area.

Table 5.3: Water budget of the calibrated model (inflows to the aquifer are positive, outflows are negative).

TABLE 5.3 Water budget of the calibrated model (inflows to the aquifer are positive, outflows are negative).		
Item	**Fluxes (m³/d)**	**Percentage**
Recharge	229897.27	100
Ocean net	-78463.32	-34.13
River leakage (Berg river and Sout river)	-39698.8	-17.27
Drains (Sout, Groën & Tributaries)	-93838.05	-40.82
Abstraction	-17232.47	-7.5
Difference	664.63	0.28

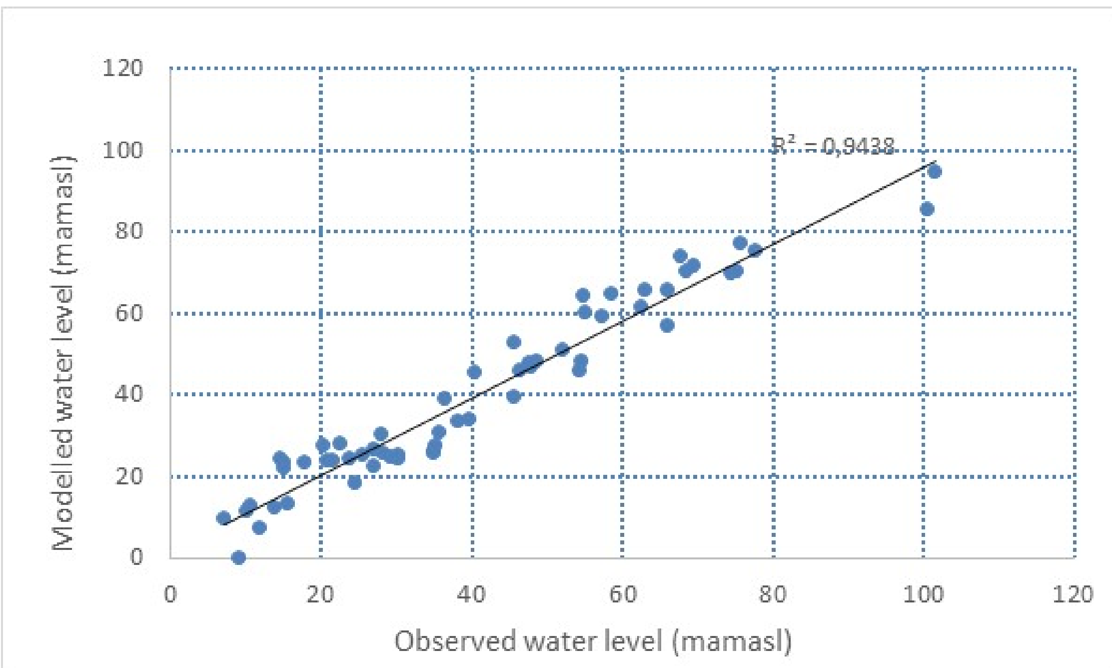


Figure 5.5: ***Modelled vs observed groundwater levels of the steady-state model calibration***

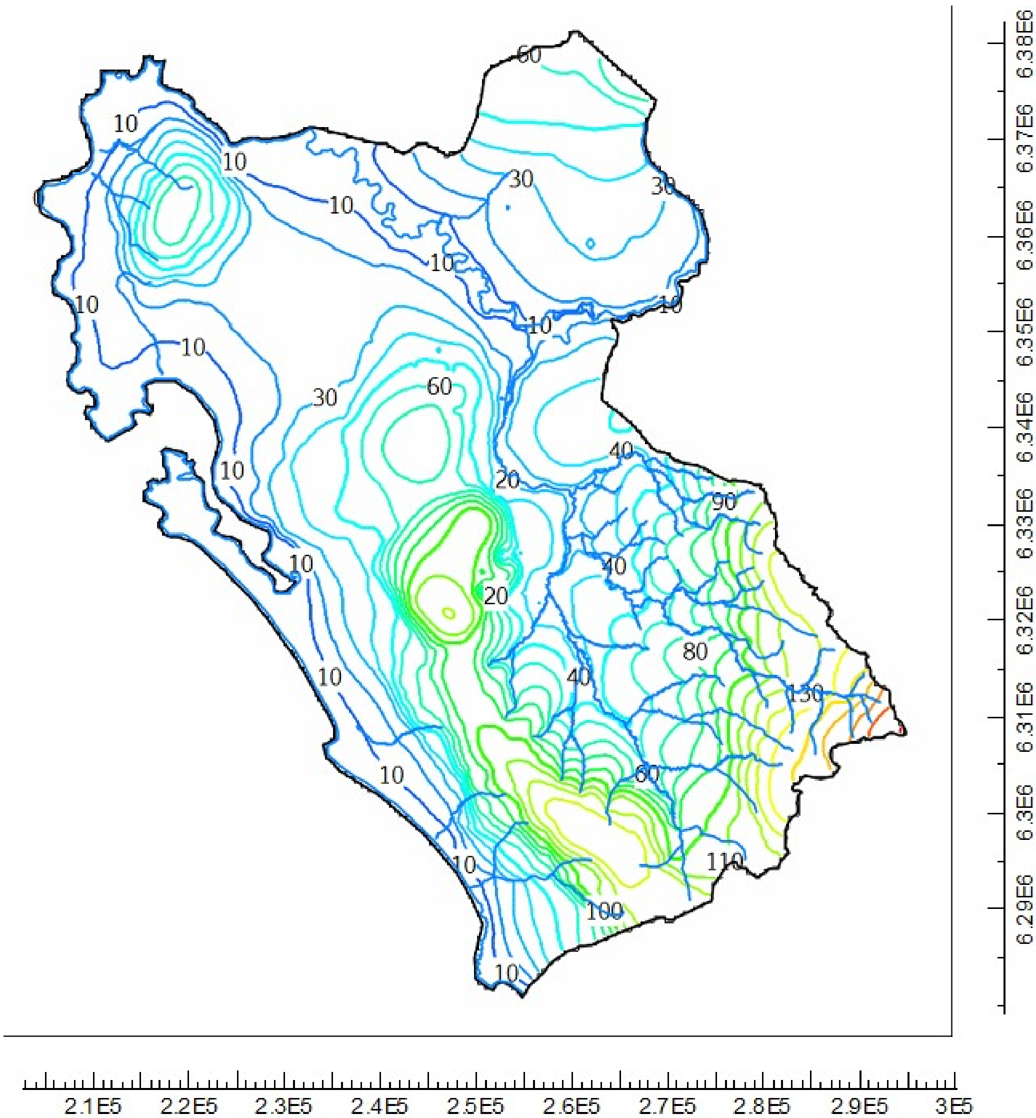


Figure 5.6: ***Simulated groundwater table contours of UAU***

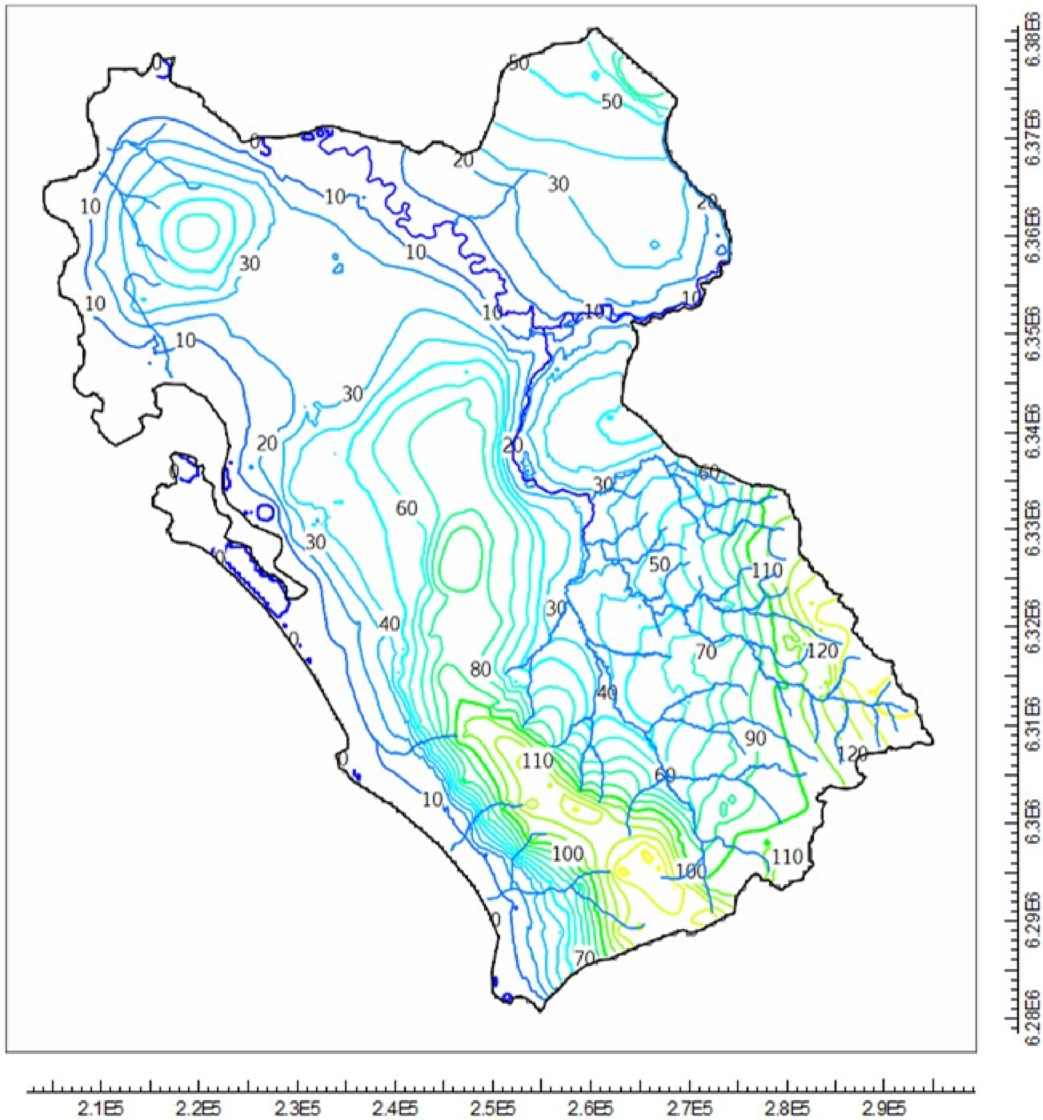


Figure 5.7: ***Simulated groundwater piezometric head contours of LAU***

5.3.2 Scenario simulations

The steady-state model was developed to support the selection of suitable sites for implementing MARS. Scenarios were modelled in steady-state, and they predicted a future state of implementing MARS. Examples of three scenarios were developed to model the impacts of implementing MARS in UAU and LAU, and presented here. The aim of scenario 1 was to model the implementation of MARS in UAU through infiltration pools, while scenario 2 simulated the implementation of MARS in LAU of LRA through injection wells. As it is described in Chapter 2, there is a clay-missing window to the west of Hopefield, which is regarded as the natural recharge area for LAU of LRA. Thus, the injection wells were assigned mainly in this clay-missing window in the modelling. Details of predictive scenarios are shown in Table 5.4. The results for each scenario are summarized below.

Table 5.4: Details of predictive scenarios in steady-state model

TABLE 5.4 Details of predictive scenarios in steady-state model			
No.	**Aim**	**Scenario description**	**Software Package**
Scenario 1	Simulating suitable sites for implementing MARS in UAU	Eight infiltration ponds (Length: 250 m, Width: 250 m, Depth: 3 m) with recharge rate of 200 m^3/d each are assigned to Langebaan Road, Elandsfontein, Grootwater and Adamboerskraal aquifers. There are two infiltration ponds in each aquifer, the one is placed close to the natural recharge area of the aquifer, the other is placed close to the discharge area. Modpath package is used to trace the recharged water.	Modflow, Modpath
Scenario 2	Simulating suitable sites for implementing MAR in LAU at clay-missing window	Step 1: Three injection wells with recharge rate of 200 m^3/d each, which depths are from model top to LAU bottom, are placed at three different sites in the clay layer-missing window area. Step 2: Same as step 1, three injection wells with recharge rate of 200 m^3/d each are placed at three different sites in the clay layer-missing window area. At the same time, four abstraction boreholes at the WCDM wellfield (46032, 46033, 46034, 46036) operate with the rate of 500 m^3/d each, and an abstraction borehole with the rate of 2000 m^3/d west of EA pumps groundwater from LAU.	Modflow, Modpath

Scenario 1

Simulated groundwater level contours of UAU and pathlines of recharged water are shown in Figure 5.8. Compared with Figure 5.6, local groundwater level near the infiltration ponds shows increase. The recharged water of the Adamboerskraal aquifer in the north of Berg River flows south to the Berg River, and the recharged water of the Grootwater aquifer in G21A catchment flows south-west into the ocean. The water recharged west of Hopefield in LRA flows north-west to the WCDM wellfield and then turns south-west to the Langebaan lagoon or north-east to the Berg River. Similarly, water injected south of Hopefield in EA flows north-west and it turns before it flows south-west to the Langebaan lagoon. The water injected at the natural recharge area has a longer path line in comparison with the water injected near the discharge area (Table 5.5). The simulated infiltration recharge results are shown in Table 5.5.

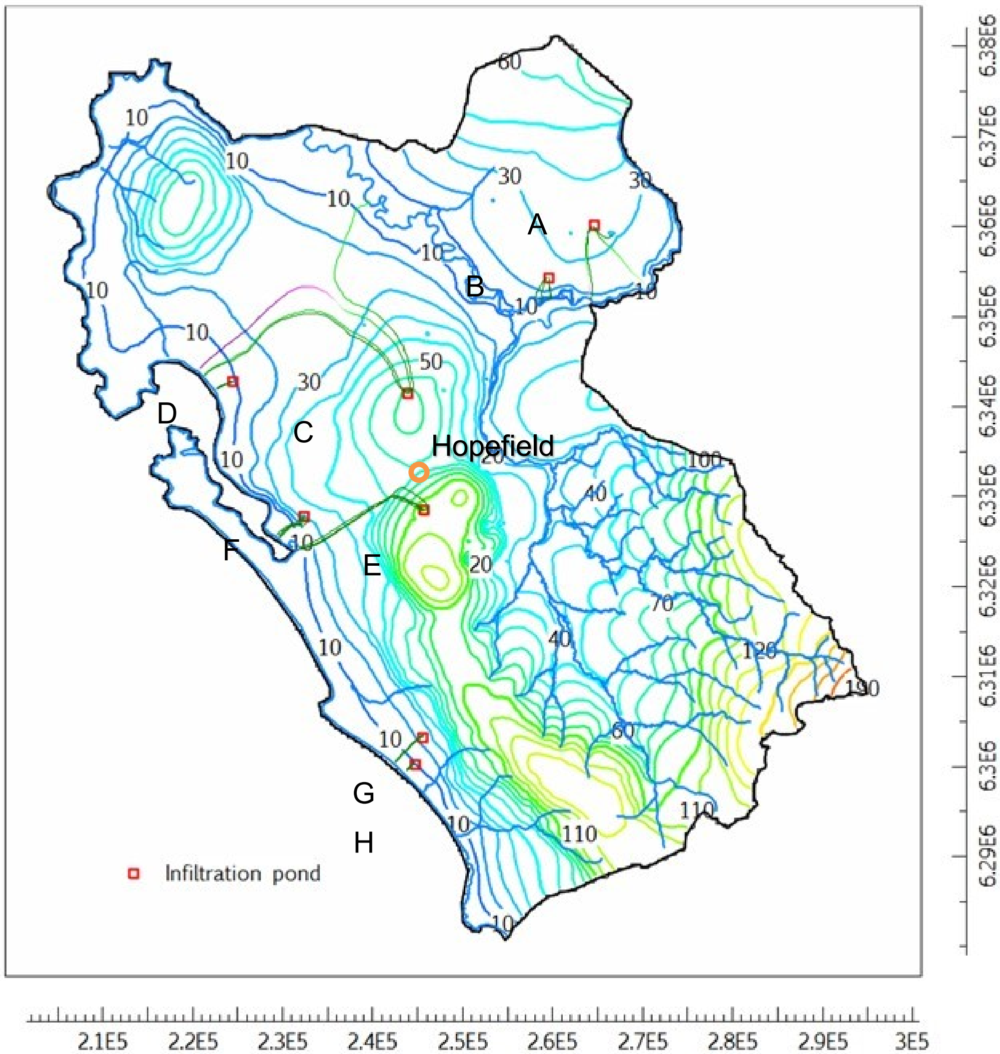


Figure 5.8: ***Simulated groundwater piezometric head contours of LAU for scenario 1***

Table 5.5: Simulated infiltration recharge results

TABLE 5.5 Simulated infiltration recharge results.					
No.	**Aquifer**	**Location**	**Discharge location**	**Trace distance (m)**	**Flow time (years)**
Infiltration pond A	AAS	Berg River north 7800 m	Berg River	9000-14000	6027-36986
Infiltration pond B	AAS	Berg River north 2100 m	Berg River	2500-2900	370-1296
Infiltration pond C	LRA	Hopefield west about 9000 m	Langebaan lagoon and Berg River	29000-30300	1178-3288
Infiltration pond D	LRA	Langebaan lagoon north-east 2000 m	Langebaan lagoon	2050-2100	41-67
Infiltration pond E	EA	Langebaan lagoon north-east 14500 m	Langebaan lagoon	15000-18500	849-35342
Infiltration pond F	EA	Langebaan lagoon north-east 1670 m	Langebaan lagoon	1700-1750	27-262
Infiltration pond G	GAS	Ocean north-east 4000 m	Ocean	4650-4700	107-110
Infiltration pond H	GAS	Ocean north-east 1600 m	Ocean	1650-1700	53-65

Scenario 2

As it is described in Chapter 2, there is a clay-missing window area lying west of Hopefield, which is recognized as the natural recharge area of LAU. Thus in scenario 2, three injection wells were placed north-east, north and south-west of this clay-missing window area in step 1. Simulated results of step 1 are shown in Figure 5.9.

Compared with Figure 5.7, the injected water increases local groundwater piezometric head of LAU by about twenty meters at the clay-missing window area. From the simulated pathlines of recharged water, the water injected at different sites in this clay-missing window has diverse flow directions. The water injected to the north-east well flows partly north into the Berg River, and partly east into the Sout River. The water injected to the north well flows north-west to the WCDM wellfield and it then turns south-west to the Langebaan lagoon. The water injected at the south-west well flows south-west directly into the Langebaan lagoon.

In the second step, three injection wells in the clay-missing window were kept working the same as step 1. Abstraction boreholes at WCDM wellfield (46032, 46033, 46034, 46036) with a pumping rate of 500 m^3/d each from LAU were added to simulate the impacts of MARS under abstraction. Simulated results are shown in Fig. 5.10. Similar to step 1, the injected water increases local groundwater head of LAU by about twenty meters at the clay-missing window area. The water injected at different sites kept a diversity of flow directions. However, the water injected at the north well flowed north-west to the WCDM wellfield, and then abstracted instead of turning south-west to the Langebaan lagoon. Most of the water recharged south of the clay-missing window flowed west to the Langebaan lagoon, and partly south-west to the abstraction borehole. In addition, the pumping decreased the local groundwater piezometric head of WCDM wellfield area and in the vicinity of abstraction borehole of EA.

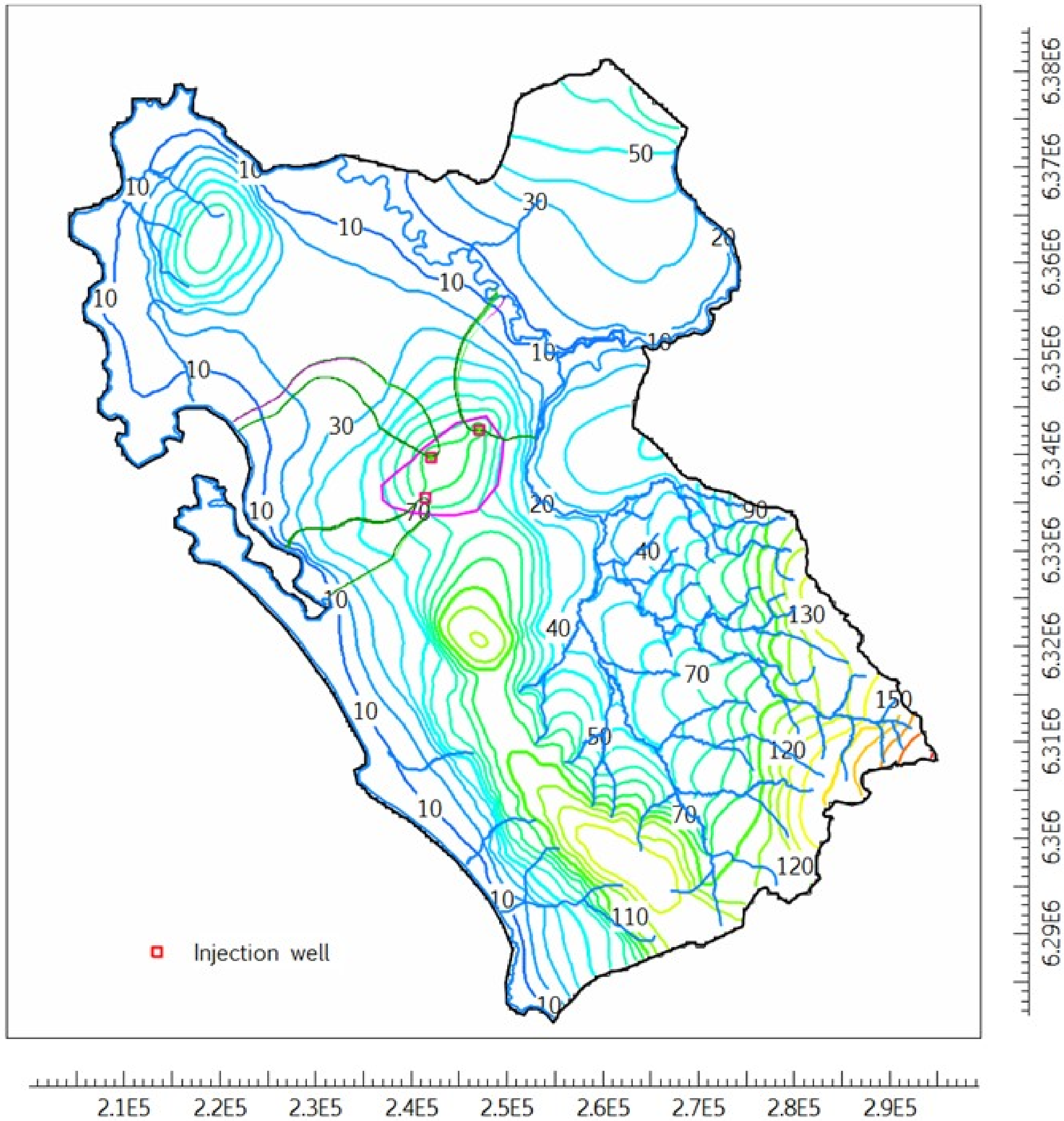


Figure 5.9: ***Simulated piezometric head in LAU and pathlines of recharged water in step 1 for scenario 2. The clay layer-missing window is outlined in pink***

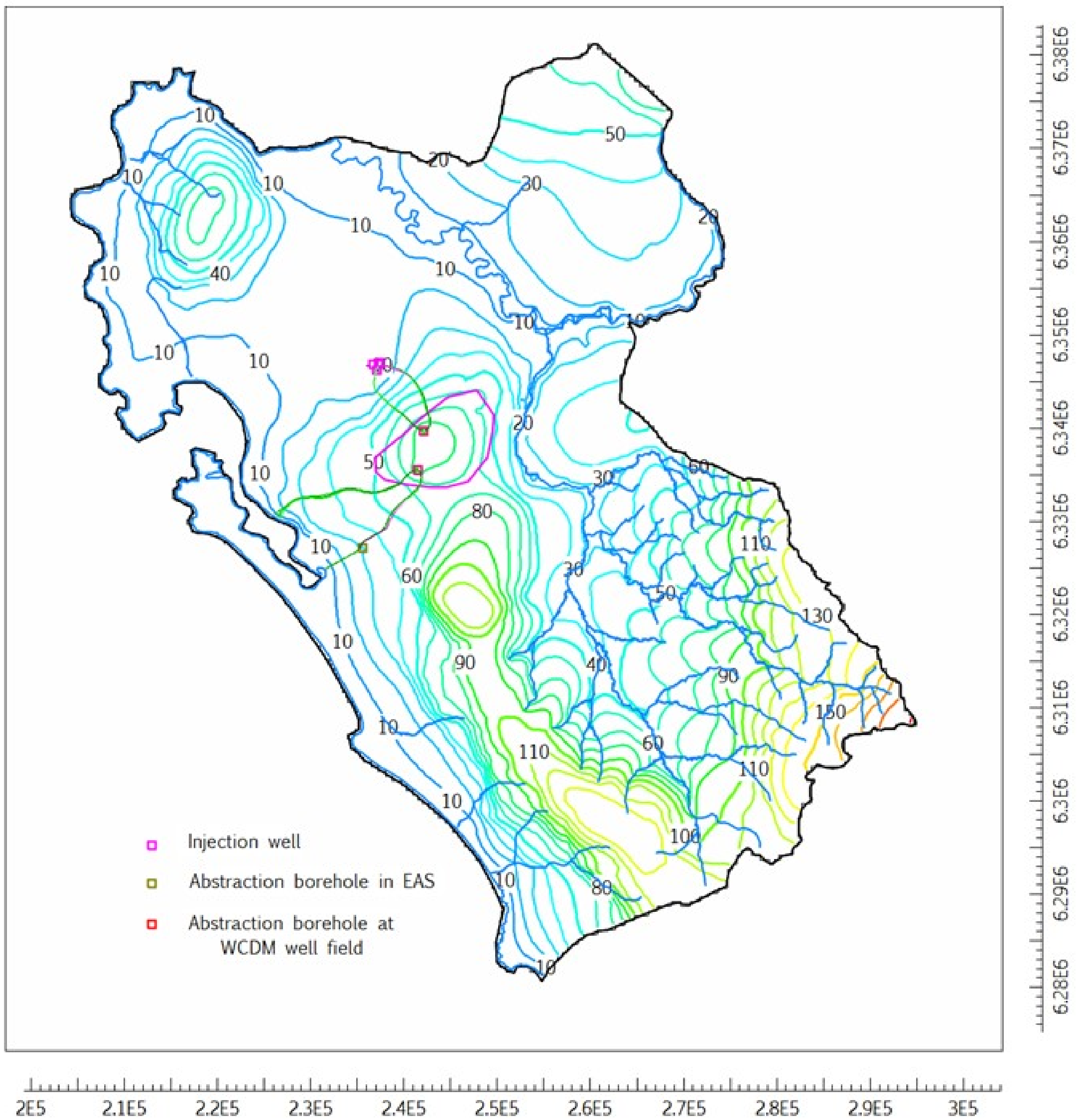


Figure 5.10: ***Simulated piezometric head in LAU and pathlines of recharged water in step 2 for scenario 2. The clay layer-missing window is outlined in pink***

5.4 Discussion

From the steady-state modelling of several scenarios, some preliminary understanding about the implementation of MARS on the West Coast was gained.

5.4.1 MARS in UAU

Based on the simulations, implementing MARS in UAU can lead to the rise in local groundwater levels. However, due to the difference in hydrogeological characteristics at different places, the rise in groundwater level shows divergent results. The rise in groundwater level depends mainly on the hydraulic conductivity of aquifer: the lower the hydraulic conductivity of the aquifer, the larger the rise in groundwater level. The simulations also indicate that recharging at the natural recharge area (south-west of Hopefield) can make groundwater level rise in a larger area, with associated benefits compared to recharging in the discharge region such as the Berg River and coastline. Without considering abstraction, the recharged water will flow and discharge into the Berg River or the ocean. Tracing flow time shows that the time needed for the recharged water to flow from the infiltration ponds to the discharge area varies from dozens of years to thousands of years. The isotope studies by Tredoux and Talma (2009) and WCDM (2009) indicated that mean groundwater residence time in the UAU is between 30 to 60 years from tritium analysis, and between recent to 9000 years from Carbon-14. The modelling results coincide with the isotope studies and prove the reliability of the numerical model, which also indicates that the water flow under natural condition is slow. Above all, implementing MARS in the UAU is feasible according to the modelling.

Storage space for recharged water and the availability of water for injection are two key factors that affect the implementation of MARS in UAU. The total groundwater storage capacity (Vs in m^3) can be calculated through equation (4):

$$Vs = A \times b \times Sy \quad (4)$$

where A refers to the areal extent of the aquifer (m^2), b refers to the average thickness of UAU, valued at 25 m (LRA), 50 m (EA), 15 m (AAS) and 50 m (GAS) according to the NGA borehole logs, Sy refers to storage parameter estimated to be 0.1.

The estimated total groundwater storage capacity of UAU is presented in Table 5.6. However, the storage space for implementing MARS in UAU includes only the unsaturated zone. The map of depth to groundwater level was drawn based on the groundwater level data of 138 boreholes which were observed in the rainy season of 2018 by DWS (Figure 5.11). The depth to groundwater varied from 0 to 41 meters, which was shallower near the discharge area such as the Berg River and Langebaan lagoon, while it was deeper to the south-west of Hopefield, which is regarded as the natural recharge area.

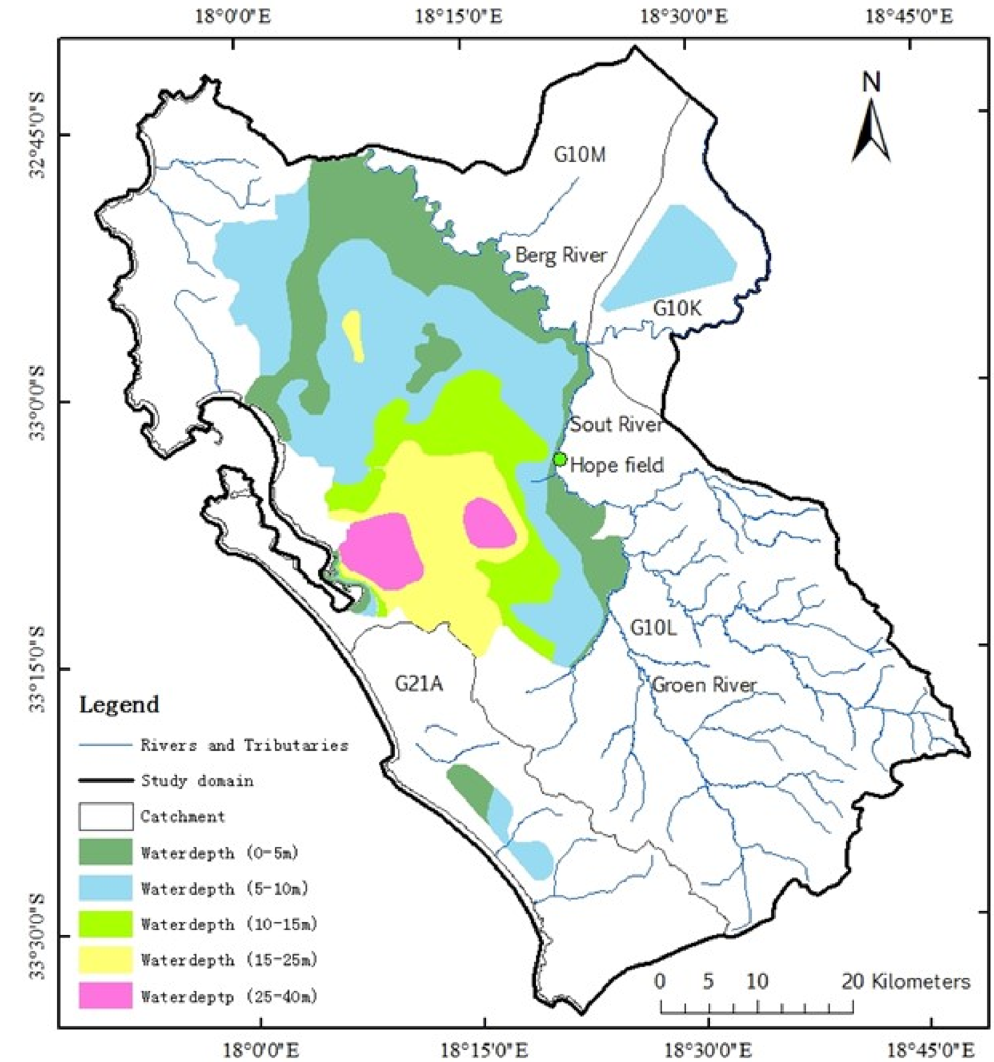


Figure 5.11: ***Groundwater depth in the study area***

Based on the map of depth to groundwater level and boreholes logs, the available space for MARS in UAU was calculated with equation (5).

$$Q = \sum_{i=1}^{m} A \times H \times n_i \tag{5}$$

where

Q is the available space for implementing MARS;

A is the area of the UAU aquifer;

H is the thickness of unsaturated aquifer in UAU;

n is the effective porosity of the UAU aquifer, estimated to be 0.1;

m is the number of aquifers with the same unsaturated thickness.

The available space for MARS in UAU is calculated and shown in Table 5.6.

Table 5.6: Available space of MARS in UAU for the four aquifers in the study area

TABLE 5.6 Available space of MARS in UAU for the four aquifers in the study area.				
No.	**Aquifers**	**Catchment**	**Estimated total groundwater storage capacity of UAU (Mm^3)**	**Available Space for MAR in UAU (Mm^3)**
1	LRA	G10M, G10L	2267.7	366.2
2	EA	G10M, G10L	2167.9	549.5
3	AAS	G10K	120.8	40.3
4	GAS	G21A	194.2	14.9

The depth to groundwater level at the natural recharge area is normally larger than in any other area, which means that there is more space to store a larger volume of recharged water. Therefore, the natural recharge area is a suggested site where to implement MARS in UAU. However, recharge in the aquifer of UAU would cause local groundwater level rising, which implies implementing MARS for local use.

Recharge rate is another key issue of MARS implementation. According to the simulations, the high groundwater level around the natural recharge area is due to low permeability of the soil of the Langebaan Formation. Thus, considering this limitation and the risk of flooding caused by MARS, the recharge rate is suggested to be controlled and tested in the field.

5.4.2 MARS in LAU

Implementing MARS in LAU is more complicated than in UAU because there is no storage space for recharged water. The previous pilot injection study (Tredoux and Engelbrecht, 2009) indicated that direct injection at the WCDM wellfields was not appropriate for MARS. The steady-state modelling indicates that the water recharged at the clay-missing window will flow to the LAU in LRA and the south-west part of EA. Thus the clay-missing window lying west of Hopefield is a suitable site for the implementation of MARS in LRA. However, the top of the clay layer around the “window” area is about 30 mamsl, while the groundwater level varied from 55 m to 80 mamsl and the groundwater level was very stable under varied rainfall. A comparison between the water level and the distribution of clay (confining layer) showed that the groundwater level is usually much higher than the top of the clay layer.

6. STAKEHOLDER ENGAGEMENT

Besides engagements with stakeholders during Reference Group meetings, conferences and other public events, a dedicated stakeholder workshop was organized at West Coast Fossil Park, near Vredenburg, on 29 August 2019. The detailed proceedings were reported in Deliverable 7 of this project.

The purpose of the workshop was primarily to brief the stakeholders' community on the progress and findings of the project, and to get inputs for further development and implementation of the Managed Aquifer Recharge and Storage (MARS) scheme at Langebaan Road. The workshop programme was structured into two parts: i) a morning session included technical presentations on the progress achieved; and ii) an afternoon session when feedback and inputs from the attendees were solicited.

More than 40 key stakeholders took part in the workshop. Discussion and feedback of stakeholders took place in particular in the afternoon session, during which the participants compiled a list of the main actors in Government, civil society and NGOs, Universities and research organizations, groups of water users and media. The participating stakeholders were then organized in groups that discussed the feasibility of MARS from the engineering and environmental perspectives, with both groups considering also the socio-economics.

The "environmental" group indicated that successful augmentation of the water supply may lead to more people moving to the West Coast, which could increase water demand from tourism, agriculture and industry perspectives. The project must fit into the Saldanha Bay Environmental Management Framework and specialist environmental and socio-economic studies must be undertaken. A number of knowledge gaps still exists, such as the water requirements for the 'biological' and 'ecological' users, namely the Berg River and estuary, the freshwater requirements and flow paths, whether there is enough recharge of the aquifer in the area, the considerable uncertainty and lack of information on pollutants and water quality problems. Other problems raised were the funding for the establishment, operation, monitoring and evaluation of the MARS scheme, the shortage of scientific and technical capacity to do monitoring and infrastructure maintenance and the resources required to conduct such monitoring. A balance of water use needs to be ensured between the different water users, e.g. landowners, the environment, etc. and the impact of all the users on the freshwater system needs to be known.

The "engineering" group indicated that aquifer recharge is a feasible option to augment water supplies because this was done in the past, and that aquifer storage capacity is a primary concern. It is important to determine the balance between recharge required and actual water usage. They suggested a three month trial period to investigate the physics of the high conductive zone and leakage between aquifers. The group also raised a number of issues regarding the capacity in managing the system, the governance and management of the MARS scheme in perpetuity, the ownership and tariffs of the scheme. If more water becomes available, this could lead to an increase in residential, commerce and mining water use, and more people depending on the resource. Short- and long-term planning is therefore crucial in view of potential immigration of people to the West Coast. If there is an increase in industrial water use, this could compromise the integrity of the aquifer. There is a risk related to the quality of the water injected and artificial recharge may lead to a rise in water level and chemical changes. Water quality monitoring is therefore a huge priority as well as the requirement for transparent and available data. Additional issues are costs of the scheme, including the financial repercussions of operation and maintenance, prevention of clogging of boreholes, etc. The group also discussed alternatives such as desalination and its costs. From the municipality's point of view, desalination is not feasible at large scale; groundwater exploitation on a small scale is more feasible. Inter-aquifer recharge might be an opportunity and residence time is a concern.

Following the groups' feedback, a discussion ensued about whether infiltration ponds or borehole injection should be used as a mechanism to recharge the aquifer. Infiltration would only replenish the upper aquifer and storage space is a limitation for infiltration ponds. However, they may be a more affordable and less technical method of recharge than borehole injection, but they would require a considerable amount of land (e.g. Municipal land). On the other hand, infiltration ponds depend on surface connectivity and they can be characterised by massive evaporation and a salinization effect, with the latter not being ideal for a system that is already borderline saline. However, borehole injection tests in the area had not been successful in previous years as water had started seeping back to the surface a few hundred metres away, although more data are available now than in previous years. It was suggested that a pre-feasibility study would need to be conducted followed by a feasibility study to evaluate advantages and disadvantages of both MARS methods. A pilot study rather than a desktop approach would be crucial to answering a number of important issues, e.g. duration of pumping into one point, the amount of space required per pond, the storage capacity of the aquifer, the issue of salinity and others.

The need to understand the natural recharge pathway was emphasized in order to follow the same route when recharging artificially. Artificial recharge should be implemented where there is no impediment (i.e. clay layer) and this project aided in identifying the specific locations where to conduct aquifer recharge. Alternatives to artificial recharge in the Saldanha Bay municipal area were also discussed, e.g. more efficient use of water, reuse of water for domestic purpose (including community perceptions and attitudes) and industrial use.

Additional points of discussion included the lack of information on the Adamboerskraal Aquifer, the implications of the MARS scheme for areas that are quite far away (e.g. on water users in those areas), alternatives to MARS and their cost-effectiveness, the legal perspective to determine the responsibilities of different government actors regarding the implementation of the MARS scheme to ensure that it is implemented in an effective manner.

The main conclusions and outcomes of the stakeholder engagement workshop were:

- There are still large uncertainties regarding groundwater flow and natural recharge due to lack of data. The project team attempted to fill these gaps through targeted sampling and isotope analyses in key areas.
- The effects of MARS practice on the broader area should be considered if the Berg River water is to be used for artificial recharge, e.g. the impact on the estuary of the Berg River, the effects on water availability for farmers upstream, etc.
- MARS should be explored as one of the most cost-effective options for augmenting the water supply to the West Coast District. A MARS pilot trial should be conducted before full implementation in order to provide more information and knowledge on the feasibility, the mode of operation, etc.

7. MONITORING NETWORK

7.1 Development of new wellfields

As a result of the groundwater modelling, a broad area for implementation of MARS was identified. However, it was necessary to determine specific sites for MARS, targeting the following conditions:

- Location within the main groundwater recharge area
- Clay sediment layer does not occur
- Aquifer storage capacity is particularly large
- Accessibility of land (e.g. Municipal land)
- Topography that determines the feasibility of artificial recharge through infiltration basins or borehole injection

During the course of the project, new production/injection boreholes were drilled through development projects funded by Saldanha Bay Municipality, as part of the emergency water supply measures due to the 2016-17 drought. A study was first conducted by Nel (2018) to investigate upgrading of the existing Langebaan Road wellfield 1A and the expansion of the Langebaan Road wellfield 1B with new boreholes. The additional water available from the Langebaan Road 1B wellfield was supplied to the WCDM pipeline. The main purpose of the study was to support the application of the water use license to the Department of Water and Sanitation by Saldanha Bay Municipality for groundwater supply of 15120 m^3/d (5.53 x 10^6 m^3/a) mainly to domestic and industrial users. Groundwater abstraction rates of 15120 m^3/d were determined based on historical sustainable yield assessments, available drawdown in the aquifer, and groundwater recharge values of between 13 and 14 mm/a estimated with the chloride mass balance method (Nel, 2018). The recommended condition was to establish a monitoring program for early warning to wellfield drawdown and sustainable use of the groundwater resource (abstraction, groundwater levels and chemistry). Water quality should be monitored to ensure that drinking water quality is maintained. In addition, the water level response to the abstraction should not reach the bottom of the clay layer. The map in Figure 7.1 indicates Langebaan Road Aquifer wellfields 1A, 1B and monitoring boreholes (Nel, 2018).

The establishment of Langebaan Road Aquifer wellfield 1B was followed by another investigation on siting of boreholes in the new Hopefield wellfield as part of the emergency water supply, but also as longer term water supply to Saldanha Bay Municipality (Nel, 2019). The additional water available from the Hopefield wellfield would be supplied to the WCDM pipeline. The primary scope of the investigation was to establish boreholes in an area devoid of the clay aquitard (Hopefield Reserve to the west of the town of Hopefield) and based on a geophysical survey with resistivity tomography. Resistivity profiles were examined and boreholes were drilled in accessible locations targeting areas with resistivity values of 33.2 ohm m or less that would be associated with higher groundwater yields. The resistivity profiles and borehole logs can be found in the report by Nel *et al.* (2019), along with groundwater quality analyses and aquifer tests (step drawdown, 72 h constant discharge rate and recovery tests).

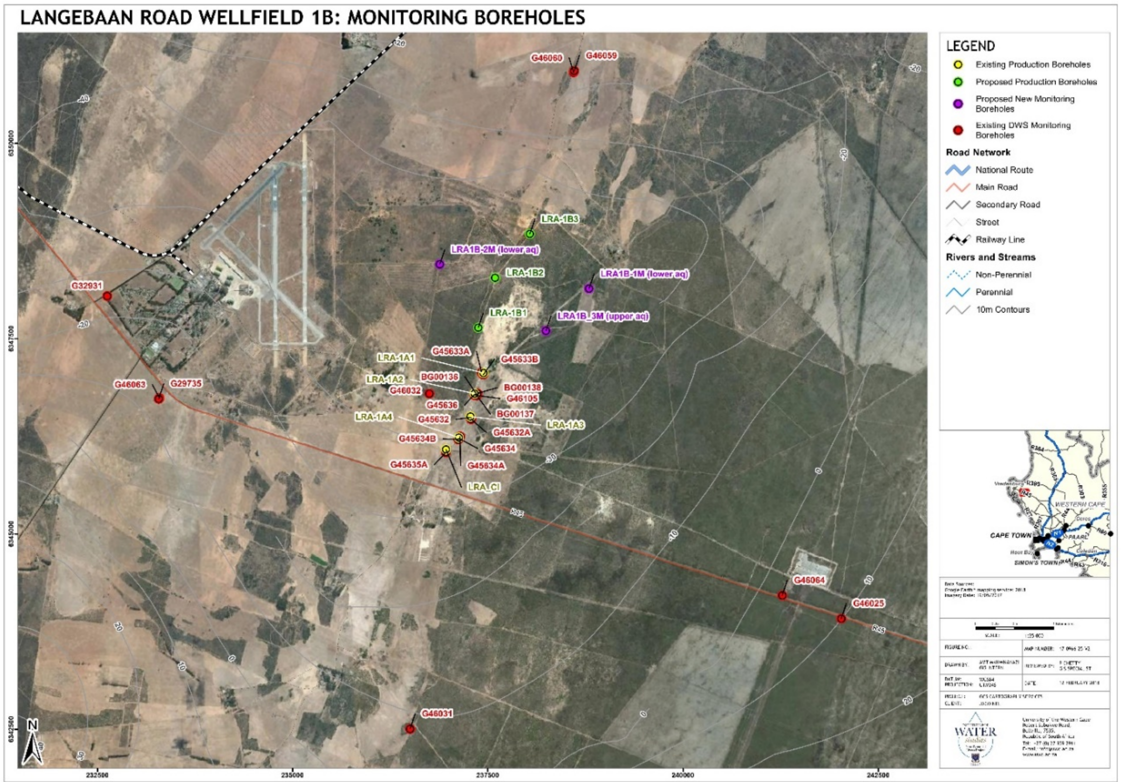


Figure 7.1: ***Map of Langebaan Road Aquifer wellfields 1A and 1B and monitoring boreholes (Nel, 2018)***

Fifteen boreholes were established in the Hopefield wellfield, namely ten production boreholes (HPF 2-2; HPF 2-4; HPF 2-5; HPF2-6; HPF 2-7; T2-540; T2-1190; T4-2240; TB-2150; T3W-1510) and five monitoring boreholes (HPF 2-3M; HPF2-4M; HPF 2-5M; HPF 2-6M; HPF 2-7M). The groundwater quality is generally good with EC ranging between 54 and 63 mS/m. The Hopefield wellfield can provide a sustainable long term yield of 50 L/s (4.4 M L/d). The new boreholes were mapped and displayed in Figure 7.2. Figure 7.3 represents photos of one of the new boreholes and the landscape of the Municipal Nature Reserve to the west of Hopefield, which is deemed to be the main groundwater recharge area for the Langebaan Road aquifer and a suitable site for MARS (infiltration ponds or injection). Additional monitoring data were collected to fill information gaps for the siting, management and monitoring plans of MARS, specifically down-the-hole logging, estimation of groundwater age through ^{14}C dating, borehole logs to ascertain the extent and thickness of the clay layer, the presence of calcrete and other geological impediments, as well as infiltration rates and blow yields.

7.2 Development of new monitoring network

Given the development of the new boreholes equipped both for abstraction and injection, a new monitoring network was proposed to serve the purpose of the new wellfield (Figure 7.2) with the use of six dataloggers to monitor hourly groundwater levels and temperature, monthly manual reading at both new and old DWS boreholes and bi-annual groundwater chemistry sampling and analyses.

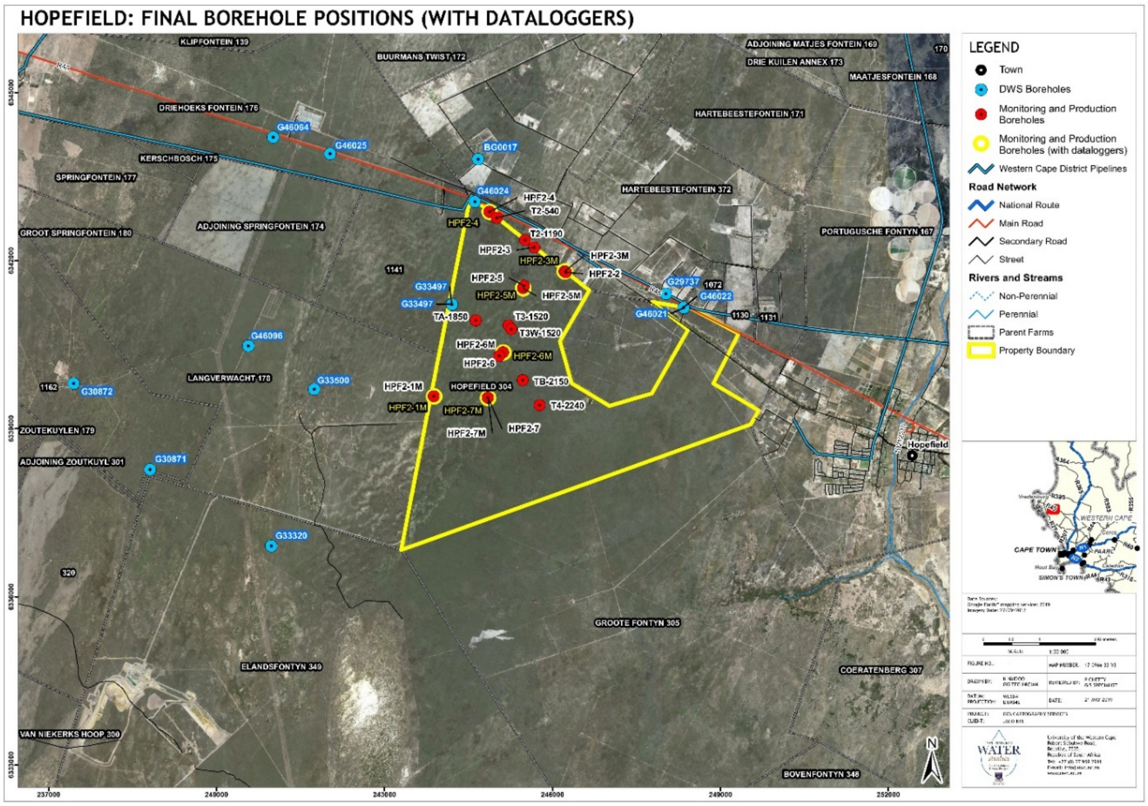


Figure 7.2: ***Map of Hopefield wellfield and monitoring boreholes (Nel, 2019)***

Figure 7.3: ***New production/injection borehole (left) and landscape of the Municipal Nature Reserve to the west of Hopefield (right), which is deemed to be the main groundwater recharge area for the Langebaan Road aquifer***

8. IMPLEMENTATION PLAN

8.1 Groundwater management plan

A groundwater management plan can be developed based on a sound understanding of the physics and hydrogeological settings of the system, as well as the collection of data. It has to take into consideration not only the technical aspects, but also the socio-economic, financial, institutional and environmental issues. It needs to integrate government processes (usually high-level) with groundwater management activities (usually at local governance level). Riemann *et al.* (2010) established a groundwater management framework based on two elements: i) aquifer protection and aquifer utilization with the regulatory tools in between and ii) monitoring and evaluation linked to the assessment of the groundwater resource.

Fourie (2020) established 12 principles for groundwater management. These are summarized below:

Protection: Groundwater needs to be protected both in terms of quantity (over-abstraction) and quality (pollution sources and contamination). Preventative measures include protection zones around the aquifer, wellfield or borehole.

Regulation: The overarching regulatory framework is the National Water Act (1998) that divides the regulations into authorization for use (Schedule 1, General Authorization and Water Use Licenses) and measures for the management and protection of groundwater (Water Resource Classification, Resource Quality Objectives, Reserve Determination).

Use: Groundwater needs to be managed with consideration of other users of the resource (aquifer) and their requirements in terms of quantity, quality and over time (periods of the day or year). It is especially relevant to consider different users when groundwater assessment and allocations are done: Irrigation abstraction by farmers; Industrial use, Mining use and dewatering; and Communal abstraction from small holdings area and residences in town areas (built-up area). Groundwater use is likely to increase during dry periods when other sources have been depleted. Groundwater yields will follow seasonal and inter-annual trends until a threshold level of groundwater availability is reached after several dry seasons of low rainfall. Fourie (2020) represented these trends schematically, after Robins *et al.* (1997) in Figure 8.1.

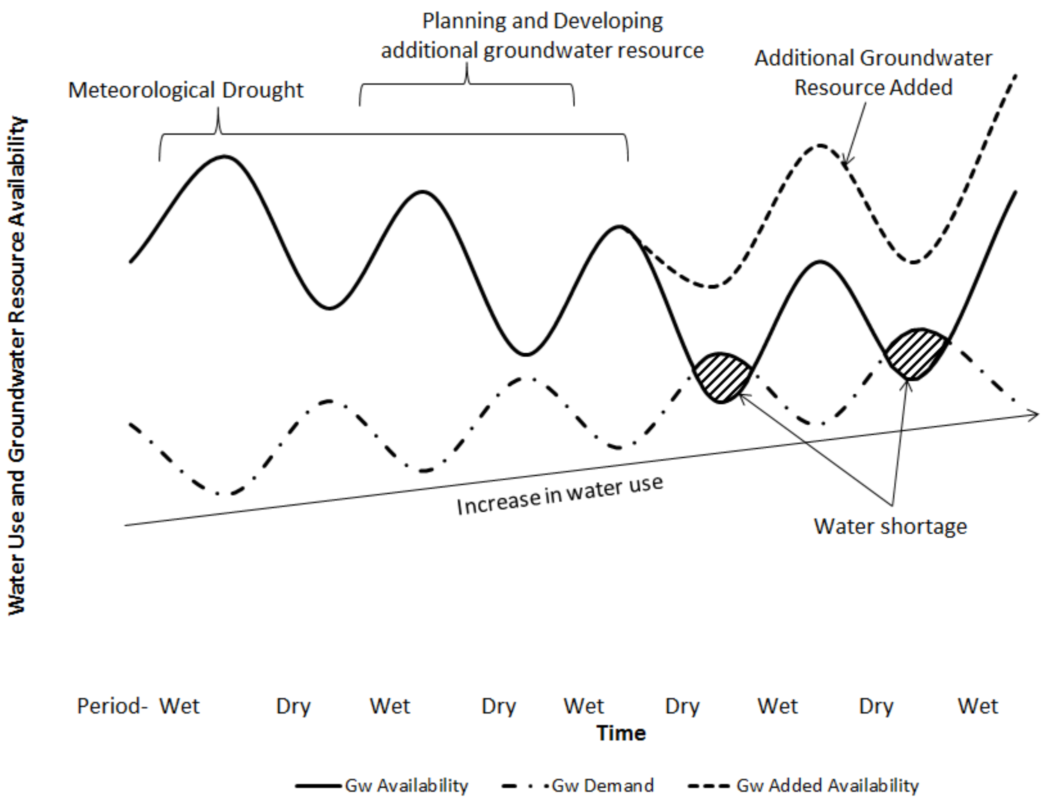


Figure 8.1: ***Groundwater use and availability as a function of time with timeous planning and development of groundwater resources (Fourie, 2020)***

Planning: The future development of a groundwater resource requires detailed planning and insight into the water requirements of the users to determine sustainable groundwater abstraction, infrastructure and finances, through a sequence of detailed phases by scale and level of detail and by increasing the confidence in the yield estimations. Planning consists of three phases, namely i) resources investigation (through means such as conceptualization, reconciliation, pre-feasibility study, feasibility study and option analysis), ii) implementation/development (where, when and how to develop a resource) and iii) operations (training, maintenance, evaluation and monitoring). This is done typically at the Municipal level, where the Water Service Authority (WSA) need to develop a Water Services Development Plan (WSDP) focusing on the increasing access to water services that includes the water supply sustainability.

Monitoring: Groundwater monitoring is the basis for management of groundwater resources. Monitoring networks need to be designed and set up based on the purpose of monitoring and aquifer characteristics. Monitoring protocol and network design were discussed by Riemann *et al.* (2010): parameters to be observed; equipment requirements; methods for the analysis of the data collected; methods of data collection; timing and scheduling of data collection; requirements for trained personnel; frequency of measurements; data accessibility; locations to be monitored; data dissemination; and revision policy. Monitored data are captured, stored and processed in a database so that they can be easily extracted, analysed and reported.

Conservation: Conservation of groundwater consists in using groundwater at the right time and for the real purpose of use. Groundwater can be conserved when other water sources are available (conjunctive water use). Various techniques and methods exist to enhance the recharge through low maintenance infrastructure designs such as contour cultivation and dyking/bunding; infiltration columns with coarse filled material; stormwater collection ponds; land use management (grazing, vegetation type, erosion, run-off). Artificial recharge (or MARS) or enhancing the recharge is an approach to put water back into the aquifer. MARS is cross-cutting and impacting on other principles, such as Planning, Conservation and Operation.

Operation: The sustainability of groundwater is linked to the operation of abstraction volumes and activities. Groundwater operating rules can be divided into three groups based on scale, namely i) borehole, ii) wellfield and iii) aquifer. Conjunctive use with other water sources needs to be taken into consideration as the water sources may not always be available throughout the year (seasonal).

Infrastructure: The infrastructure is the link between the aquifer and the user, but if this 'link' is not monitored, operated and maintained, then no water will reach the users. Maintenance includes activities required to sustain the equipment, infrastructure and supply system (pump, power source, valves, pipes, borehole, etc.) in a proper working condition. A Maintenance Plan is required that would include Preventive maintenance, Corrective maintenance and Crisis maintenance (Davis and Brikké, 1995).

Assessment: Assessment of an aquifer represents the status quo of a geographic extent of an aquifer system. A groundwater resource can only be sustainable if the amount of water abstracted is equal or less than what enters the system. The main elements of aquifer assessment are (Margane, 2003): Determination of the groundwater system's extent, thicknesses and saturation limits of the aquifers; Determination of hydrogeological properties and characterisation of groundwater flow; Identification of the exploitation potential of the aquifer; Assessment of groundwater quality; Assessment of groundwater vulnerability to land use, hazards and pollution to groundwater; Surface water-groundwater interaction (baseflow and ecological requirements) and spring capture; Evaluation of risks to the groundwater system (such as pollution threats, depletion threats, risks to ecological habitats such as groundwater-dependent ecosystems); Evaluation of existing relevant monitoring networks which may include a risk-based, numerical or analytical model of the aquifer; Determination of the possibility of the artificial recharge and its possible impact on the quantity and quality of the environment and natural water resources; Determination of water requirements (current and future), needs of water users (all sectors); Assessment of existing or planned infrastructure that may be impacted; and Assessment of demographic and socio-economic impacts and changes on groundwater.

Institutional Arrangements: The institutions that manage groundwater resources can be divided into three government levels, namely national, regional and local. At the national level, the Department of Water and Sanitation (DWS) have the organisational function of centralised planning and policy-making as well as a supporting function to Regional Offices. At a regional level, the DWS Regional Offices, Catchment Management Agencies (CMA) and Aquifer Management Committees (AMC) (for cross/transboundary aquifer) are the institutions that manage groundwater resources (including monitoring); implementing policies and strategies; and allocating water for use. Local-level institutions include Catchment Management Forums (CMF), Water User Association (WUA), District and Local Municipalities and Water Boards. Local-level institutions have the responsibility of day-to-day management and administration; planning; developing water services and infrastructure; quality protection, monitoring, etc. However, in many cases, groundwater is managed by individual users (farmer, local municipality, mine, etc.)

on their property. Failures in groundwater resource management and protection are often attributed to institutional arrangements, and this can be analysed through gap analysis, problem-driven analysis or political-economic approaches.

Capacity and Skills: Capacity and skills relate to institutions and personnel managing groundwater, stakeholder participation as well as government leadership. Lack and turnover of personnel, slow appointment process or financial constraints to appoint qualified staff are common stumbling blocks. DWA (2010) proposed that "Municipal Hydrogeologists" be appointed at local municipalities or at district municipality level, to support and/or manage the groundwater supply.

***Awareness, Information, Communication and Stakeholder Participation*:** Awareness, information, communication and stakeholder participation are pre-requisites to ensure flow of information, participation in decision-making, management, accountability and success in securing safe water.

Some external drivers also exist that may influence the behaviour of the users and the managers of the groundwater, the use of the groundwater resource and the pollution pressure that will be placed on the groundwater resource (Fourie, 2020). This include the political boundaries, authorisation for mining and industrial development, climate change, the process of urbanisation, fluctuating electricity prices, increased crop prices in the agricultural sector, the financial income of the service provider (e.g. Municipality). This may influence investments in operations of wellfields, maintenance of the infrastructure and new source development.

Based on the 12 principles above, Fourie (2020) developed an adapted approach for groundwater management plans. The management objectives are central to the groundwater management and they were provided as a list of over 150 objectives in the 12 management principle categories. This approach was used to draft a groundwater management plan for the Langebaan Road aquifer, focusing on the implementation, operation, monitoring and institutional arrangements for the newly developed wellfields. Although in the past, the Langebaan Road aquifer was managed on its own, recent research indicated that the three aquifers react as an aquifer system and they need to be managed as one single aquifer system. The aquifer connectivity of the alluvium aquifer type system was only scientifically proven after detailed studies and comprehensive monitoring analysis. This new information brought forth the importance of the more comprehensive focus on the institutional arrangements with all stakeholders in the "new extended area of influence". The groundwater management plan for the Langebaan Road aquifer was therefore summarized in a suitably developed summary template for day-to-day use (Table 8.1).

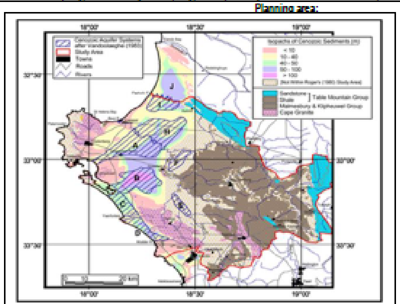
Table 8.1: Summary template of the groundwater management plan for the West Coast District Municipality (Fourie, 2020)

Groundwater Management Plan
West Coast District Municipality
2019 – 2024

Organisational management of the aquifer: West Coast District Municipality is responsible for the management of the water supply as WSP to Saldanha, Vredenburg, Velddrif, Langebaan and surrounding towns from surface water – Misverstand dam and groundwater – Langebaan Road (borehole-, wellfield-, pipeline- and electricity infrastructure; and aquifer management)[1]. Other users on the 3 aquifers include farmer –agriculture, Elandsfontein mine – mining. A large portion of the aquifers is covered with the Subterranean Water Control Areas namely Saldanha SWCA. The Lower Berg River Valley SWCA was never formally declared (in the Government Gazette) but were managed as a SWCA[2].

Institutional coordination: Agreements with private landowners, servitudes are in place. Meetings with other stakeholders (West Coast District Municipality,Saldanha Bay Municipality, NGOs, industry and domestic – water users) are held on an ad-hoc basis.

Planning area:



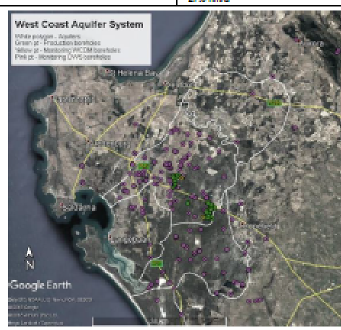
Hydrologeology[3]: Aquifer Units in the Elandsfontyn Formation: Langebaan Road, Elandsfortein and Adamsboerskraal Aquifers.
Unconfined aquifer: Bredasdorp and Varswater Formations. Aquiclude: Elandsfontyn Formation – clay. Confined aquifer: Elandsfontyn Formation – sand and gravel.

Water resources[1]: Groundwater = 1.35 hm and Surface water (Misverstand Dam/ Withoogte WTW) = 13.166 hm. Total = 14.516 hm
Additional developed groundwater resources: Langebaan Road 1A + 1B: 4.0 hm[4] and Hopefield B: 1.6 hm[5]
Total: 5.6hm/a

Water consumption[1]: Summer = 55.4 ML/d and Avg = 41.0 ML/d
Future Water requirements[1]: 2030 = 27.5 hm/a

Protection: Only borehole protection – sanitation seal, security gate fence alarm system and pump housing around borehole. Land use management agreement with farmer and servitude.

Groundwater dependent ecosystems: The only areas with shallow water table are location across the 3 aquifers. Various springs are associated with deep laying fault systems and depressions



Regulatory/licence/allocations Conditions:
Registered: Total: 0.148hm³/a; Wellfield: Hopefield A 147 000m³/a is registered with DWS WARMS under Saldanha Bay Municipality (WSA).
Not registered: wellfield: existing Langebaan Road 1A - 1.5hm³/a.
In the process of registration: Langebaan Road: Extension (1B)[6] – 2.416 hm³ and Existing (1A) existing abstraction[3] – 1.5 hm³ and the additional volume[6] – 1.614 hm³; Langebaan Road Total[6] – 5.53 hm³. Hopefield B[7] – 1.6 hm³.

HIGH PRIORITY Groundwater Management Objectives (detail list of Objectives in GwMP)

Management Objectives	Performance Standards / Milestones	Responsible person / Organisation	Time
Protection			
Id Recharge area; develop protection zones with allowed land use activity list (stormwater management practices, etc.)	Zones map and land use activity list	WCDM:Tech Man + CMA	'22
Id + develop a program for abandonment boreholes to prevent leaking through clay layer (program to seal, plug unused bh's)	Project to seal/plug unused bh's	WCDM: H&SafetyOff; Tech Man	'22
Ensure pump intake is above the clay layer (confined aquifer) to prevent unconfined conditions	Maintain gw level head above the clay layer	WCDM: WaterTech	'20
Develop Remediation/rehabilitation/mitigation (programs (aware-ness, Emergency Response Plan/Unit (spill or fire)) along R45	ERPlunit + program linked to the DM	SBM: EnviroOff + WCDM	'22
Regulation			
Finalise Water use rights (registration/authorisation) Register Langebaan Road 1A and 1B; and Hopefield B wellfields	Water Use Licences	SBM: TechMan + CMA	'20
Develop Bylaws, mitigations, plans and procedures to implement Drought restriction regulation (DRR)	DRR Bylaws, mitigations, plans and procedures	SBM: TechMan + DWS	'22
Review the SWCA and GA limits to ensure sustainable development	Sustainable development	WCDM: TechMan + CMA + DWS	'21
Report water use volumes/licences vs availability	Annual report + WUL conditions	SBM: TechMan + WCDM	'19

Management Objectives	Performance Standards / Milestones	Responsible person / Organisation	Time Frame
Use			
Investigate the increase in water reuse (agriculture, landscape irrigation, greywater)	Potential reclamation plant expansion, other sector use	SBM: TechMan	'23
Develop a program to promote the use of non-domestic quality standard water for other uses (brackish – Industrial, dual toilet)	Non-domestic quality water use program	SBM: TechMan + Comms	'24
Planning			
Develop a Climate Change Plan with interventions and implementation framework include Managed Aquifer Recharge	Climate Change Plan	WCDM: TechMan+ DWS + CMA	'23
Exploration drilling and testing of Langebaan Road 2 and 3 welf	New wellfields add to bulk syst	WCDM +SBM	'21
Drought management plan – operations, short-term sources	Drought management plan	SBM:TechMan+WCDM	'21
Monitoring			
Develop a comprehensive monitoring program which includes all water sources, infrastructure, land use, pollution sources, etc.	Monitoring programs	WCDM: TechMan	'20
Develop a monitoring network to include DWS mon. boreholes at Langebaan Road and Hopefield for quantity and quality	New routes	WCDM: Water Tech+ DWS	'19
Capture all monitoring data on a database	Updated monitoring database	WCDM: TechMan; Admin	'19
6 monthly analysis on monitoring data with adjustment actions	6 Monthly monitoring report	WCDM: TechMan	'19
Report and publish monitoring data public, DWS/CMA	Reporting and publish of data	WCDM+SBM:Counc	'19
Conservation			
Develop artificial recharge scheme in the LbR Aquifer	AR scheme in LbRA	WCDM: TechMan	'20
Conjunctive use schedule developed to use other water sources at the right time	Conjunctive use schedule	WCDM: TechMan	'19
Operation			
Develop Operational rules for each borehole, wellfield + aquifer	Operational rules	WCDM: TechMan	'19
Implement wellfields	Sustainable gw supply	WCDM	'19
Emergency procedures develop for infrastructure failure, spillage	Emergency procedures rules	WCDM:TechMan+SBM	'19
Infrastructure			
Equip all newly drilled boreholes (dipper tube, w sampling tap)	Monitoring infrastructure install	WCDM: Water Tech	'19
Develop an Asset register and update including photos	Asset Register	WCDM: SCM	'20
Assess bulk infrastructure capacity from Withoogte, the incorpor- ation of the new + future wellfield to meet future requirement	Infrastructure Assessment Report with augmentations	WCDM: Engineering Services	'20
Update infrastructure design plans/layout with new schemes	Updated infrastructure plan	WCDM: Eng Serv	'20
Develop Maintenance program/schedule which includes monitoring equipment, reticulation system	Maintenance program/schedule	WCDM: Water Tech	'20
Put the existing 5 boreholes of Hopefield A in operation	0.147hm extra water to system	WCDM	'20
Assessment			
Re-assess the Long-term safe yield of all the boreholes/ wellfields with climate variability influences	Long-term safe yield	WCDM: TechMan	'23
Update the numerical model with monitoring data of Langebaan Road Aquifer and West Coast Aquifer System	Updated model	WCDM + DWS	'22
Institutional Arrangements			
Re-establish an Aquifer Management Committee (AMC) with land-owners, NGOs around Langebaan Road and Hopefield Aq	Aquifer Management Committee	CMA + SBM+WCDM	'19
A subcommittee of the AMC: Collaboration with other users in LbRAS like Kropz mine, irrigation, SAAF	User agreements	WCDM	'19
A subcommittee of the AMC: Monitoring committee evaluating monitoring data, quantity, quality, environment	Independent representative monitoring structure/committee	CMA + WCDM	'19
Define WSA and WSP roles and responsibilities	WSA/WSP Agreement	WCDM and SBM	'19
Assess the total cost of water supply including maintenance, development, operations, rehabilitation, monitoring resources, tools and equipment, etc. to link the water use tariff	Water budget	WCDM:Finance+SCM + SBM:TechMan + Council	'20
Capacity and Skills			
Training of key personnel in data capturing software/database	Training	WCDM: TechMan	'20
Appoint Gw Technician	Gw Technician	WCDM: HR	'20
Awareness, Information, Communication and Stakeholder participation			
Develop news/information bits to info/educate users of the water status in aquifers (with monthly accounts + Saldanha Bay Water Quality Forum Trust + West Coast Biosphere)	Monthly news bits	WCDM : TechMan; SBM: Admin	'20
Monthly report back to WSA on Status of water infrastructure, water use, resources level	WSP water status report	WCDM: TechMan + CMA	'19
A research study to increase the knowledge of AR, recharge	More effective management	DWS+WCDM	'24

Operational Production Boreholes and Management Specifications

Aquifer / Groundwater Unit	Wellfield	Borehole name/ number	Borehole Depth (m)	Pump In take (m)	Pump Capacity (l/s)	Pump Duty cycle (h/d)	Max Abstraction Daily (ML/d)	Max Abstraction Monthly (ML/m)	Max Permissible Drawdown (mbgl)	No pump days / yr
Langebaan Road	1A[3]	G45632	87	35	25	24	2.160	65.70	21	365
		G45633	74	35	25	24	2.160	65.70	21	365
		G45634	82	35	25	24	2.160	65.70	23	365
		G45636	78	50	20	24	1.728	52.56	37	365
	1B[6]	LRA-1B1	78	46	25	23	2.070	62.96	40	365
		LRA-1B2	43	30	14	16	0.806	24.53	30	365
		LRA-1B3	72	55	6	23	0.496	15.11	43	365
		LRA-1B4	72	53	41	22	3.247	98.77	38	365

Aquifer/ Ground-water Unit	Wellfield	Borehole name/ number	Borehole Depth (m)	Pump In take (m)	Pump Capacity (l/s)	Pump Duty cycle (h/d)	Max Abstraction Daily (ML/d)	Max Abstraction Month ML/m	Max Permissible Drawdown (mbgl)	No pump days /yr
Langebaan Road	Hopefield B[5]	HPF2-2			3.4	24	0.30	9.13		365
		HPF2-5			6.5	24	0.56	17.03		365
		HPF2-6			5.8	24	0.50	15.21		365
		HPF2-7			5.5	24	0.47	14.30		365
		T2-540			3.7	24	0.32	9.73		365
		T2-1190			3.6	24	0.31	9.43		365
		T3W-1510			4.5	24	0.38	11.56		365
		T4-2240			10	24	0.86	26.16		365
		TB-2150			2.18	24	0.19	5.78		365
		TA-1850			5.75	24	0.50	15.21		365
Hopefield	Hopefield A						0.40	12.25		

Funding for objectives: Water sales. Council approval

Operational Tasks (more detail in the Operational and Maintenance Plan

Task	Who	Detail description of what the task entails	Existing Impediment	Who should remove impediment
DAILY				
Respond to telemetry alarms	Tech	Carry the telemetry cell phone at all times. Receive + respond to alarms	Automate system to send 2-hourly SMS	WCDM:TechM
Respond to leak report	Foreman	Carry out leak prepare to pipeline, pumps	No Report book	WCDM:TechM
WEEKLY				
Water team meeting	TechM	Meet water team: tasks, HR, feedback		
2-WEEKLY				
Physical check all bh	Foreman	Drive to all bhs, inspect, rectify, repair, report as necessary		
Read bulk meters	Tech	Physical reading of bulk meter + balance		
MONTHLY				
Water level monitoring	Tech + Office	Monitor each bh (prod +mon) water level, flowmeter, capture data and report	Dipmeter in poor condition	WCDM:TechM
Data to hydrogeologist	TechM	Captured data - email		WCDM:TechM
QUARTERLY				
Review data/balance	TechM	Review data, supply/demand- report to SBM	Budget	WCDM:MM
Report to council	TechM	Report: incidence, use, level, recommend		
ANNUALLY				
Sample of all prod bh	Tech	Sample, analysis and report	Field equipment	TechM
SBM: Report to DWS	TechM	Report to DWS as per WUL conditions		

List of tasks/actions (Time frame)	Y1 Q1		Y1 Q2		Y1 Q3	Y1 Q4	Y2 Q1-2	Y2 Q3-4	Y3	Y4
Immediate action (1 month)										
Expand monitoring network to include Langebaan Road 1B and Hopefield B wellfields										
Equip all newly drilled boreholes with dipper tube and water sampling tap										
Short term (3 - 6 months)										
Take over DWS monitoring bhs										
6 Monthly monitoring assessment report										
Re-establish an Aquifer Management Committee										
Medium-term (1-2 Years)										
Assess report on aquifer behaviour on full production –upd model										
Appoint Gw Technician										
Water use rights and conditions are received from DWS										
Long term (3-5years)										
Development of phases 3 and 4 wellfields										
Develop a Artificial Recharge Scheme in LangebaanRoad Aquifer										

Reporting: Monthly reporting by Technical Manager to Municipal Manager; Quarterly reporting to Council
Audit: Yearly evaluation and update of action; the Year 2024 review; develop/update GwMP

Signed-off:
Municipal Manager : ______________ Date: ______________
Director: Engineering Services : ______________ Date: ______________
Manager: WSA/WSP : ______________ Date: ______________

1) DWS, 2016; 2) Vermaak, 2015; 3) Weaver, 1998; 4) Nel, 2018a; 5) Nel, 2019; 6) Conrad, 2018; 7) Nel, 2018b

8.2 Implementation of MARS

The following action plan is recommended for the implementation of MARS at Langebaan Road aquifer:

1) Groundwater infrastructure development (drilling and testing)
2) Setting up the groundwater monitoring system (artificial recharge volumes, groundwater levels and water quality)
3) Ensuring that the required water use license and environmental authorisations are obtained
4) Developing detailed infrastructure design, carrying out the tendering process and constructing the scheme
5) Compiling the monitoring, operation and maintenance procedures.

The first three activities of implementation (borehole drilling and testing, setting up the monitoring system, and securing licenses) have been completed or they are in the process of being completed. Detailed infrastructure works are still to be designed and executed, in particular if the option of infiltration basins/trenches is considered. Monitoring, operation and maintenance procedures need to be developed.

During operation and maintenance (production stage), the following activities are envisaged:

1) Monitoring scheme performance and aquifer response during recharge and abstraction.
2) Updates of operation and maintenance procedures.
3) Phased increase in the scheme's capacity.
4) Reporting on information related to the water use licence and environmental authorisation.

The tasks and timelines of these actions depend largely on the investor and water supply scheme operator (Saldanha Bay Municipality) and the regulatory authority (DWS).

The implementation plan for a MARS system in the area of the Hopefield wellfield is being developed following the checklist developed by DWA (2007), and according to 10 "success criteria". Two important factors that are outlined are the fact that most MARS implementation cases are site specific, and that a significant period of testing is required prior to developing the design and implementation. In the case of the current West Coast study, preliminary testing was only done during 2008/2009 in the Langebaan Road wellfield. The checklist of DWA (2009) recommends incremental increases in capacity while monitoring of variables in the system to ensure that a better understanding of systems' behavior during MARS can be achieved. This also informs the likely success of implementing, running/managing of a MARS scheme. A consolidated assessment for MARS at the Langebaan Road aquifer (Hopefield wellfield) is summarized in Table 8.2 and discussed below.

The need for artificial recharge

The purpose of a MARS scheme in the Langebaan Road aquifer originated from the need to augment and secure water supply to the West Coast District Municipality and the farmers in the area. Groundwater seems to be the logical choice to augment water supply. Other augmentation options such as desalination of sea water are deemed to be too expensive.

The potential for groundwater use in the Saldanha Bay area was recognised for a long time as the DWS declared a Subterranean Government Water Control Area Groundwater in the 1970s, reserving groundwater for municipal use (Conrad and Naicker, 2019). Groundwater, therefore, plays a critical role in the Saldanha Bay area with the development of groundwater from the Langebaan Road aquifer.

The total Utilisable Groundwater Exploitation Potential (UGEP) which represents management restriction on the volumes that may be abstracted based on the “maximum allowable water level drawdown” on a sustainable basis and under drought conditions was estimated to be 9.0 million m^3/a. Currently, Hopefield wellfield was developed for groundwater supply to the Saldanha Bay Municipality to abstract 1.64 million m^3/a based on the water use licence provided by DWS.

Given the safe yield of the groundwater, there is potential for the development of the Langebaan Road aquifer, the Hopefield aquifer and the Elandsfontein aquifer, from which the Elandsfontein mining area is currently abstracting. This source will supplement the surface water resources of the Berg River system.

Committed augmentation options of the water reconciliation strategy of the Western Cape include groundwater development, in particular the Langebaan and Hopefield aquifers (DWS, 2019), and under the responsibility of Saldanha Bay Municipality.

The augmentation of water supply through groundwater development needs to be sustainable. This can potentially be achieved by storing excess water during winter periods in the aquifer. The option of MARS was contemplated given the vicinity of fairly secure sources of water (Berg River and wastewater stream) and the hydrogeological settings of the Langebaan Road alluvial aquifer. The necessity of MARS was confirmed by the seasonal, abstraction- and drought-induced fluctuations of groundwater level observed over many years as presented in Chapter 3 of this report.

The source water

According to the water reconciliation strategy of the Western Cape Water Supply System (WCWSS) (DWS, 2019), the average annual population growth rate in Saldanha Bay Municipality during the period between the 2001 and 2011 census was 3.5% (DWS, 2019). Thanks to industrial development (e.g. Saldanha Steel, marine traffic) and tourism, the population of the West Coast District Municipality supplied from the Western Cape Water Supply System (WCWSS) is envisaged to increase from 0.27 million persons in 2011 according to Stats SA to 0.60 million persons by 2050 for a median growth scenario (DWS, 2019).

Saldanha Bay Municipality has a surface water use authorisation from the WCWSS. In the lower sections of the Berg River, the Misverstand Dam diverts water to the West Coast District Municipality's pump station, which delivers water to the Withoogte Water Treatment Works (WTW) and onward to the Vredenburg/Saldanha area. The total authorised surface water use is 20.43 million m^3/a, of which 15.2 million m^3/a is allocated from the Voëlvlei Dam while 5.23 million m^3/a is allocated from the Berg River Dam. The authorised water use is released from the Voëlvlei Dam and Misverstand weir for operational reasons. Saldanha Bay Municipality also has a groundwater use licence for the Langebaan Road aquifer. The West Coast District Municipality exceeded their water use allocation prior to the issuing of the new water license in 2012. The current water allocation is projected to be exceeded by 2022-2025 based on the projected increase in water demand (DWS, 2019).

Total water allocations for irrigation in the Lower Berg River reach are 54.89 million m^3/a. The actual water use by irrigators was historically lower than the water allocation, especially during periods of drought. Water allocations will therefore not be increased in future as improved irrigation water management may somewhat offset the expansion of irrigated areas.

According to DWA (2012), the required streamflow into the Berg River Estuary during the summer months should vary between 0.6 and 0.9 m^3/s.

The source of water for MARS is generally surplus water that cannot be used directly and will be lost mainly as outflow to the sea. Several sources of water for MARS were contemplated. Wastewater could be a secure source of water, however this has been earmarked for industrial reuse due to the lower quality (less treatment required and less travel distance). The inferior quality wastewater may have implications to groundwater recharge via MARS and it may require expensive treatment facilities. In addition, the logistics of transporting water from WTWs to MARS sites may require unfeasible infrastructure and operational costs.

The excess winter flows of the Berg River and water treated in the Withoogte treatment plant appears to be the most feasible option for a secure source of water. The quantity is variable depending on seasonal streamflow. Reliability depends on climatic conditions. Assurance supply is therefore required from Withoogte treatment plant because of seasonality and inter-annual variability (e.g. drought periods). The water quality in the Berg River is variable, i.e. more saline during low flows. However, the water quality at Withoogte treatment plant is stable and according to drinking water quality standards (SANS 241).

According to DWS (2019), the local municipalities of Saldanha Bay, Bergrivier and Swartland have a total allocation of 23.44 million m^3/a from the Voëlvlei Dam and abstracted downstream of Misverstand weir. The water is treated at the Withoogte WTW. The current capacity of Withoogte WTW is 72 ML/d or 26.28 million m^3/a, although it was identified for an upgrade to expand the capacity to 92 ML/d (33.58 million m^3/a). At the current full capacity, Withoogte WTW could therefore provide 2.84 million m^3/a (full capacity minus the water demand of local municipalities) for managed aquifer recharge. The municipalities are served by a 63 km long, 1,200 mm diameter gravity main, from where water can be diverted to the MARS site.

Aquifer hydraulics

The hydraulic conductivity and the storage capacity are the two main hydraulic characteristics that determine whether artificial recharge water will flow into the aquifer, whether the aquifer has sufficient space for water storage and whether the water will be recoverable. Based on the geohydrological characteristics (Chapter 3) and conceptual model (Chapter 4), the Langebaan Road aquifer is characterized by high, but variable hydraulic conductivity and high storage capacity subject to the presence and thickness of the impeding clay layer. Secondary hydraulic characteristics are the hydraulic gradient and natural geological barriers to flow.

Hydraulic conductivity of the unconsolidated sediments are estimated to range between 0.1 and 86.4 m/d in the UAU and between 0.1 and 34.6 n/d in the LAU, with conductivities of aquitard and bedrock being very low. Borehole yields are also very variable, spanning from 5 to 27.5 L/s at Langebaan Road aquifer. The thickness of the aquifer storage area spans between none and >100 m. The hydraulic gradients and groundwater flow directions were discussed at large in the groundwater modelling Chapter 5, as well natural geological features such as granite outcrops, Colenso fault, etc.
Because of the variabilities in aquifer characteristics and the many unknown factors still to be investigated, aquifer storage potential for MARS (in addition to the natural storage capacity of the aquifer) could not be directly estimated. At this stage, the most reliable figures are those obtained from the modelling work presented in Chapter 5. For LRA, the available space for MARS was

calculated to be 366.2 Mm^3 of water. The available storage space was calculated to be 549.5 Mm^3 for EA, 40.3 Mm^3 for Adamboerskraal and 14.9 Mm^3 for Grootwater unit.

Water quality

The long-term sustainability of MARS depends greatly on groundwater quality, as MARS is intended to protect or improve groundwater quality. This also depends on the standards and fitness for specific uses. In the case of Langebaan Road aquifer, it is essential to maintain groundwater water quality at the highest standard for drinking water supply. The water quality of both groundwater and water used for recharge needs to be assessed and monitored. In addition, the blended groundwater quality resulting from mixing recharged water (usually rich in oxygen) and groundwater (usually poor in oxygen) needs to be assessed with associated chemical reactions that may occur as a result of blending as well as water-rock interactions. Resulting problems that may occur are aquifer clogging or borehole clogging due to a variety of physical, biological and chemical processes (DWAF, 2007). Depending on the water quality, pre-treatment or post-treatment processes may be required. Infiltration basins may be a safer method than direct injection in order to ensure *in situ* pre-treatment by filtering through the soil and vadose zone. Monitoring of the system for water quality should be done at key control points and a risk assessment for human and environmental impacts should be conducted.

In the case of Langebaan Road aquifer, the quality of source water and the different aquifer units in the WCAS were extensively discussed in Chapter 3.5. The effects of blending recharged water and groundwater as well as water-rock interaction should be monitored through a proper programme and modelled with available software, e.g. PHREEQC.

Engineering aspects

The primary engineering aspects concern the design of the system. The document published by DWAF (2007) listed the components in Table 8.2 along with their current status at the Langebaan Road aquifer proposed MARS site. The cost of infrastructure plays a particularly important role as well as the cooperative planning between engineers, hydrogeologists and geochemists. Both options of water source from the Withoogte treatment plant (Berg River water) and wastewater plants along the West Coast were considered. Both water volumes reliability and water quality needed to be considered. For the latter, Berg River water is more advantageous than wastewater, except during periods of low flow (during summer and droughts) when the Berg River records higher salinities. The need for pre-treatment and post-treatment needs to be assessed for both waters. The infrastructure for the Berg River water source is in place. The infrastructure for the use of wastewater as water source needs to be established. For this option to be implemented, wastewater would need to be pumped from the wastewater treatment plants on the West Coast to the MARS site. This was retained an unfeasible option and the wastewater was earmarked for industrial reuse. Both borehole injection and infiltration basins/trenches can be considered as method for artificial recharge. It is not unusual to implement the system in incremental phases that allow to test the performance of the system at smaller capacities first. A wider area for MARS should be investigated besides the Hopefield wellfield, e.g. the Berg River excess flow could also be used for MARS in the vicinity of the Berg River at the point of intersection with the paleochannel. Modelling and geophysical work could aid in identified more sites with absence of impeding layers.

Table 8.2: Engineering components of the MARS system (DWAF, 2007) and current status at Langebaan Road aquifer proposed site

TABLE 8.2 Engineering components of the MARS system (DWAF, 2007) and current status at Langebaan Road aquifer proposed site.	
Component	**Current status**
Source abstraction works	Berg River treated water (Withoogte): Existing Wastewater: Existing
Pump stations and pipelines	Withoogte Berg River water: Existing Wastewater: Pumping required from coastal area inland
Pre-injection treatment works	Need to be assessed for both Berg River treated water and wastewater
Injection supply pumps and pipelines	Existing
Injection boreholes and well head works	Existing (newly drilled boreholes at Hopefield wellfield)
Infiltration basins/trenches	Not existing
Abstraction boreholes, pumps and pipelines	Existing
Post-injection treatment works	Need to be assessed for both Berg River treated water and wastewater
Storage and distribution	Existing

The phased approach for MARS with the borehole injection method should include:

1) Engineering infrastructure (in place)
2) Pilot tests
    a. Injection volumes and rates
    b. Groundwater flow and seepage tests
    c. Borehole clogging
    d. Groundwater quality modelling
3) Assessment of need for water treatment
4) Monitoring programme

The phased approach for MARS with the infiltration basins/trenches method should include:

1) Engineering conveyance infrastructure (in place, except delivery to basin)
2) Pilot tests
    a. Infiltration tests
    b. Siting and construction of basins in low-lying area
    c. Basin volume and capacity
    d. Clogging and maintenance
    e. Groundwater quality modelling
3) Assessment of need for water treatment
4) Monitoring programme

Environmental issues

Both negative and positive impacts of MARS may occur and need to be assessed. These are particularly linked to changes in groundwater table and water quality changes within aquifers.

The negative effects of increased groundwater levels were evident during the borehole injection pilot tests conducted in a previous project (Engelbrecht *et al.*, 2009). This manifested through groundwater seepage and flooding of a portion of farms. Any effects of pollution due to recharged water and groundwater blending will have to be tested at pilot phase and through modelling. The is a potential risk of groundwater salinization due to repeated cycles of artificial recharge and intensified abstraction for farming activities and in areas prone to seawater intrusion. However, if sited properly, there is no indication that increased groundwater levels may cause other negative effects (e.g. vegetation dieback, proliferation of invasive alien species, damage to infrastructure, discharge of foreign waters into wetlands and rivers) as the area is predominantly under natural vegetation and farming.

If properly designed and operated, MARS at Langebaan Road aquifer is meant to recharge the aquifer and no effects of lowering groundwater levels are envisaged, except during periods of drought and over-abstraction. No major impacts on wetlands, rivers, woodlands and wildlife is expected as the site is located under protected vegetation area and farms. Land subsidence is unlikely to be a problem in the sedimentary aquifer. Drying-up of boreholes may occur under extreme circumstances.

Water quality issues include borehole clogging (implication to maintenance and rehabilitation of boreholes), mobilization of unwanted constituents (oxidation-reduction conditions may decrease fitness for some uses) and aquifer organisms (particularly critical if wastewater is used for recharge).

In terms of quantifying environmental impacts, there is more than sufficient data on groundwater levels and quality to define baseline conditions. Decision-making to reduce any potential risks as well as reverse any negative impacts can be based on a well-implemented monitoring program and precautionary principle. The extent, magnitude and significance of environmental risks can be quantified and weighted against the benefits in the environmental impact assessment conducted for the purpose of water licensing.

Legal and regulatory issues

The legal requirements regarding the assessment and operation of artificial recharge schemes include:

- Water use licensing for artificial recharge schemes (National Water Act, NWA)
- Environmental authorisation requirements for both testing and implementing the scheme (i.e. Basic Assessment or Environmental Impact Assessment according to National Environmental Management Act, NEMA)
- Environmental Management Plans (EMPs)
- Compliance with regulations (e.g. relating to water reuse)
- Rights associated with the use of artificially recharged water.
- Compliance with the conditions and reporting requirements of the water use licence and environmental authorisation.

Although MARS is not defined explicitly according to NWA, licensing is required for a number of water uses (Section 21 of the Act). Two of these uses are clearly linked to artificial groundwater recharge, namely ""storing water" (s21(b)), which is the main purpose of MARS, and "the intentional recharging of an aquifer with any waste or water containing waste" (s21(e)) should wastewater be used to recharge the aquifer.

Similarly to NWA, the environmental regulations under NEMA don't mention explicitly MARS. However, a number of activities required to implement MARS may fall under the activities listed that require environmental authorization (Basic Assessment), namely:

1) "The construction of facilities or infrastructure for the bulk transportation of water in pipelines with an internal diameter of 0.36 m or more, or with a peak throughput of 120 L/s or more"
2) "The off-stream storage of water, including dams and reservoirs, with a capacity of 50000 m^3 or more"
3) The transformation of an area zoned for use as public open space or for a conservation purpose to another use" in the instance where infiltration ponds may be considered in the Hopefield conservation area.

The water license was granted by the Department of Water and Sanitation to Saldanha Bay Municipality for taking 5.52 $Mm^3\ a^{-1}$ water from the Langebaan Road wellfields with the provision of drilling alternative water supply boreholes should the existing production boreholes show a reduction of pumping rates. In addition, this is conditional to a monitoring program that entails recording monthly groundwater abstractions, groundwater levels and quarterly groundwater sampling and laboratory analyses for variables specified in SANS 241:2011 (drinking water quality specifications).

No authorization was, however, granted yet by DWS for artificial groundwater recharge and this may also be subject to environmental authorization based on the listed activities that require the Basic Assessment. The piloting phase, however, may not require such authorization as no water will be used above the authorized allocation. Environmental flows required through release from the Voëlvlei dam into the Lower Berg reaches (including flows supporting the estuary) could represent, however, an environmental legislative requirement.

Economics

A dedicated economic study is required to quantify capital and operational costs of different options, including the "do nothing" scenario. Such study should take into consideration water saving (e.g. through reduced evaporation), the strategic value of the practice, costs of transferring water from remote areas, etc. The economic analysis should result in the estimated cost per m^3 of water as well as the projected price of water to the users.

Institutional arrangements, management and technical capacity

Institutional arrangements, management and technical capacity are fundamental pre-requisites for the success of a MARS scheme. Previous experiences reported that the main cause for failure of MARS schemes was related to institutional issues.

It is envisaged that the scheme operator would be Saldanha Bay Municipality reporting to the Department of Water Affairs as principal regulatory authority and water resource management institution.

It is envisaged that the bulk of the infrastructural funding will be provided by local government (Saldanha Bay Municipality), which is envisaged to be the scheme operator. The role of the scheme operator would be bulk water supply, performance monitoring, water quality control and reporting. These are very important tasks in order to identify possible losses of efficiency (e.g. borehole clogging, poor maintenance, etc.) that could result in performance below the design capacity. Given the strategic importance, size and technical complexity of the scheme, it would be beneficial to appoint a dedicated manager with relatively high technical knowledge and skills in hydrogeology, water supply sources and engineering, recharge and recovery methods, water treatment and quality management. Operation and maintenance manuals need to be produced in order to transfer knowledge and in case of loss of skills due to turnover of staff.

In summary, the main implementation agent of the MARS scheme at Langebaan Road aquifer is envisaged to be Saldanha Bay Municipality under the regulatory framework of the DWS, and with the strong participation and guidance from stakeholder groups. The general consensus amongst the interested parties, as elaborated in Chapter 6 on stakeholder engagement, is the phased implementation of the MARS scheme, as outlined under the engineering and regulatory aspects. A pre-requisite of the licence condition of DWS is the phasing-in of new wellfields and MARS, with the Hopefield wellfield being the first step and subsequent sites to be identified based on suitable hydrological settings, in particular the absence of the clay layer.

Table 8.3 provides a summary of the implementation steps.

Table 8.3: Consolidated feasibility assessment for Langebaan Road aquifer MARS implementation based on the checklist by DWA (2009)*

TABLE 8.3 Consolidated feasibility assessment for Langebaan Road aquifer MARS implementation based on the checklist by DWA (2009)*		
Success Criteria	**Check list that addresses the success criteria**	**Progress with respect to implementation plan/success criteria**
The need for artificial recharge	1. Listing of primary and secondary objectives of MARS. 2. Discuss working of scheme to meet requirements, describe recharge and abstraction regimes. 3. Define the minimum injection volume per annum to make the project worthwhile. 4. Quantify the additional assured yield of the aquifer with artificial recharge.	Objectives for the West Coast have been defined. Main objective is to augment supplies during times of drought or peak use during summer seasons. Abstraction from boreholes will occur as required, i.e. when surface water supply becomes insufficient. Injection/infiltration to occur when abstraction levels reduce groundwater levels to below what natural recharge can replenish, based on groundwater levels discussed in Chapter 3. Volumes for injection and additional assured yield to be quantified.
The source water	Source water availability and volumes	Source water options include the Berg River. Volumes of water availability need to be established as these can be variable. This should be calculated as the treatment capacity of Withoogte treatment plant minus the water demand from WCDM during periods of excess flow in the Berg River. In addition, the discharge capacity of the pipeline network represents an upper limit for the availability of source water.
Aquifer hydraulics	1. Quantify the volume of water the aquifer is able to receive (groundwater levels and abstraction data). 2. Quantify artificial recharge rate. This depends on the method used. Infiltration basins require infiltration tests, while injection requires injection pressure tests. 3. Groundwater flow regime needs to be defined, and potential downstream losses need to be quantified.	Modelling has indicated areas where storage may be available in the unconfined part of the aquifer. For LRA, the available space for MARS was calculated to be 366.2 Mm^3 of water. Artificial recharge rate needs to be determined by doing field tests in the study area. Based on modelling and field observations, boreholes forming part of the extension of the Langebaan wellfield and Hopefield wellfields have been constructed to be used for both abstraction and injection. The Hopefield wellfield, a new wellfield, is only equipped with abstraction boreholes. Infiltration and injection pressure tests have to take place in the Hopefield area to assess the suitability of the two methods for artificial recharge. Groundwater flow direction has been determined for the area. Downstream losses need to be quantified, but they depend on abstraction/injection/infiltration rates as well as the amount of users from this point and along the flow path (including ecosystem services). Modelling can aid in quantifying losses for different scenarios.
Water quality	All aspects of water quality need to be addressed for the source water and groundwater as well as the mixed composition.	The groundwater chemical characteristics have been defined for various parts of the West Coast. Potential sources for artificial recharge need to be tested in terms of suitability for artificial recharge. Modelling or testing of mixing/blending of water compositions is required to determine whether any mineral precipitates are likely to form and to establish the mixed water composition needs to take place prior to injection/infiltration. This will ensure that concentrations of all SANS 241 listed species are known prior to any artificial recharge, and suitability is properly defined.
The artificial recharge method and engineering issues	1. Identify project phases if a phased approach is required. 2. Develop preliminary infrastructure design for the treatment and conveyance, and for the recharge facility. 3. Describe how the design will minimize clogging. 4. Compile a detailed project implementation plan.	The phased approach requires the following actions. Phased approach for injection option: - Engineering infrastructure in place o Pilot tests o Injection volumes and rates o Groundwater flow and seepage tests o Borehole clogging - Groundwater quality modelling - Need for water treatment - Monitoring programme Phased approach for infiltration:

TABLE 8.3 Consolidated feasibility assessment for Langebaan Road aquifer MARS implementation based on the checklist by DWA (2009)*		
Success Criteria	**Check list that addresses the success criteria**	**Progress with respect to implementation plan/success criteria**
		- Engineering conveyance infrastructure in place, except delivery to basin - Pilot tests o Infiltration tests o Siting and construction of basins in low-lying area o Basin volume and capacity o Clogging and maintenance o Groundwater quality modelling - Need for water treatment - Monitoring programme
Environmental issues	1. Identify environmental benefits, risks and constraints. Certain tests may need to be designed specifically to determine environmental impacts. 2. Discuss the probability of unforeseen risks, e.g. the use of reclaimed water for any purposes that were not intended.	The following broad impacts have been identified during the stakeholder workshop (Chapter 6): - Impacts on water users upstream - Impacts on ecosystems, specifically Langebaan lagoon and Berg River estuary - Impacts of phosphate mine These have to be investigated during pilot and testing phase.
Legal and regulatory issues	1. Describe and discuss legal status and requirements for MARS scheme. 2. Obtain authorization to do feasibility tests. 3. Establish authorization requirements for full scale operation.	Saldanha Bay Municipality have obtained water use licenses with the provision of drilling alternative water supply boreholes should the existing production boreholes show a reduction of pumping rates (new wellfields were established). No authorization was, however, granted yet by DWS for artificial groundwater recharge and this may also be subject to environmental authorization based on the listed activities that require the Basic Assessment. The piloting phase, however, may not require such authorization as no water will be used above the authorized allocation. Environmental flows required through release from the Voëlvlei dam into the Lower Berg reaches (including flows supporting the estuary) could represent, however, an environmental legislative requirement.
Economics	1. Costing of the MARS project, including the cost per m^3 of supplied water. 2. Costs need to be compared to other water supply options. 3. Other economic benefits (whether quantifiable or non-quantifiable) that relate to the objectives need to be described/costed.	Costing has not yet been completed, however, Saldanha Bay Municipality has agreed to cover the required costs involved. Due to infrastructure already being in place in certain parts of the area, costs are likely to be comparable or much lower than some other costs, e.g. desalination. Costing still needs to be done for the implementation at this stage. Other economic benefits include the ability to supply water throughout the year with less pressure on the system, to sustain the West Coast water supply during the peak holiday season, and during periods of drought.
Management and technical capacity	1. Describe the skills needed to operate the scheme, i.e. management, maintenance, monitoring, hydrogeological, etc. 2. List the available skills and shortfalls. 3. Communicate the outstanding skills that are required to successfully operate the scheme.	Required skills would include: engineering, water level and quality monitoring and data interpretation, ability to perform maintenance as required, understanding of the hydrogeology of the area, ability to interpret responses of the aquifer to pumping and injection/infiltration. Saldanha Bay Municipality is likely to acquire skilled professionals on a subcontract basis where they lack the required skills. Research teams from the Institute for Water Studies (UWC), the CSIR and consultants are currently working in the area.
Institutional arrangements	Who will be responsible for the scheme? Who will pay for the source water? Who will ensure suitable water quality of source water? Who will monitor water levels and quality? How will oversee the scheme being regulated? Especially relating to source water quality, final water quality, water levels, recharge rates, environmental monitoring.	In terms of responsibilities, Saldanha Bay Municipality has been proactive with taking the responsibility of drilling additional wellfields and starting up monitoring of the wellfields and their surrounds to understand the aquifer's response to pumping. Saldanha Bay Municipality is the main investor as the provider of bulk water supply services. The main regulatory and overseeing authority is DWS. The WRC project currently underway is providing scientific support and support in monitoring of the greater West Coast area.

TABLE 8.3 Consolidated feasibility assessment for Langebaan Road aquifer MARS implementation based on the checklist by DWA (2009)*		
Success Criteria	**Check list that addresses the success criteria**	**Progress with respect to implementation plan/success criteria**
		The Municipality works closely with trained professionals on all matters pertaining to groundwater supply, monitoring and management. Source water and final water quality may be regulated by SANS241 guideline water quality limits, as the water treatment works in the area abide to these. Groundwater abstraction regulations may be linked to a maximum drawdown allowable or at which artificial recharge is required, and based on the 12 principles of the groundwater management plan as outlined in Chapter 8.1. Recharge rates can only be determined or finalized once the system behavior under abstraction and recharge is pilot-tested. Environmental monitoring is an ongoing aspect of groundwater monitoring. This will most likely include groundwater, surface water, flora and fauna in the region as it is known for its biodiversity and large parts are considered nature reserves.

* Reference: *DWA (2009) Strategy and Guideline Development for National Groundwater Planning Requirements. A check-list for implementing successful artificial recharge projects. PRSA 000/00/11609/2 – Activity 12 (AR02), September 2009, Department of Water Affairs, Pretoria, South Africa.*

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The Western Cape Water Supply System (WCWSS) is currently stretched past its limit as revisions of water use volumes in the system for both municipal supply and agricultural use showed that water use volumes are greater than the volume of water that can be supplied from the system at the current assurance of supply. There is therefore a need to consider alternative water supply options. This project demonstrated that a feasible source to increase water supply to the West Coast area is the LRA augmented through MARS from the Berg River.

The hydrogeological and groundwater flow characterization contributed to identifying the areas and mechanisms of natural groundwater recharge and interactions between aquifer units. The West Coast aquifer system comprises four aquifers, namely Langebaan Road, Elandsfontein, Adamboerskraal and Grootwater. The general hydrostratigraphic units include an upper unconfined aquifer unit, a clay aquitard and a lower confined/semi-confined aquifer overlying basement rock. The thickness of the aquitard is variable and it had to be estimated through geophysical surveys. Aquifer properties are highly variable. Hydraulic conductivity of the unconsolidated sediments are estimated to range between 0.1 and 86.4 m/d in the UAU and between 0.1 and 34.6 m/d in the LAU, with conductivities of aquitard and bedrock being very low. Borehole yields are also very variable, spanning from 5 to 27.5 L/s at Langebaan Road aquifer. The thickness of the aquifer storage area spans between none and >100 m.

The groundwater quality shows a clear link between the geology of the area and its setting close to the sea. Most of the area has a surprisingly good water quality for an aquifer system close to the sea, and it is important to do everything possible to protect this water quality that is so important for the environment and human needs in this area. The electrical conductivity of the major part of the study area is less than 100 mS/m, with the best quality of water occurring in the central part. The water quality deteriorates towards the Berg River in the north and Saldanha Bay in the west. The unconfined aquifer layers at times have water quality comparable to that of the lower semi-confined to confined layers. Based on the groundwater quality and isotope data, there seems to be a connection between the Adamboerskraal, Langebaan Road and Elandsfontein aquifer units, but the exact extent of this connection is still uncertain.

A conceptual model of the system was developed to inform numerical modelling. Numerical modelling simulations with MODFLOW indicated that recharging at the natural recharge area (south-west of Hopefield) can make groundwater level rise in a larger area, with associated benefits compared to recharging in the discharge region such as the Berg River and coastline. Tracing flow time shows that the time needed for the recharged water to flow from the infiltration ponds to the discharge area varies from dozens of years to thousands of years. Implementing MARS in the UAU is feasible according to the modelling, with an estimated storage capacity for MARS in the UAU in the region of 336.2 Mm^3.

Based on the above information, the stakeholder workshop and the establishment of a new wellfield in the Hopefield Reserve to the west of Hopefield, commissioned by Saldanha Bay Municipality, an implementation plan for MARS was developed. The need for groundwater utilization and MARS was recognized by the The Western Cape Water Supply System Reconciliation Strategy due to the projected increase in water demand by industry and urbanization. The excess winter flows of the Berg River and water treated in the Withoogte treatment plant is the most feasible option for a secure source of water for MARS. The amount of water that could be supplied by Withoogte WTW is estimated to be 2.84 million m^3/a (full capacity minus the water demand of local municipalities). Numerical modelling indicated that the available groundwater storage space for MARS in LRA is 366.2 Mm^3 of water. The groundwater in the UAU appears to be suitable for MARS, however this should be monitored through the newly developed monitoring program. A framework for groundwater management was also established. For the engineering aspects of the project, a pilot phase is recommended. The small-scale pilot phase is also aligned with identification of potential environmental, legal and regulatory issues (no water licensing may be required because no water will be used above the authorised allocation). A dedicated economic study is required to quantify capital and operational costs of different options, including the "do nothing" scenario. The economic analysis should result in the estimated cost per m^3 of water as well as the projected price of water to the users. The main implementation agent of the MARS scheme at Langebaan Road aquifer is envisaged to be Saldanha Bay Municipality under the regulatory framework of the DWS, and with the strong participation and guidance from stakeholder groups.

9.2 Recommendations

The main outcomes of the project were an improved understanding of the inter-relationships of the Langebaan Road Aquifer and Elandsfontein Aquifer, and the implementation plan for a sustainable MARS scheme that should secure a continued, sustainable water resource within the WCWSS to meet increased water requirements. It is recommended that a piloting phase for MARS should commence.

It was clear from the aquifer characterization and groundwater flow studies, however, that the aquifer system is complex and that many questions still remain:

- There are still large uncertainties regarding groundwater flow and natural recharge due to lack of data. The project team attempted to fill these gaps through targeted sampling and isotope analyses in key areas, however more work is required in the long term to provide conclusive answers.
- The link between surface water bodies and groundwater dependent ecosystems in the study area is not clearly understood yet. It should receive more attention, as it is important to ensure that activities such as abstraction do not damage the ecosystem.
- There seems to be a high correlation between streamflow and groundwater levels along the Berg River, but the extent of the interaction is not well documented. The contribution of non-perennial rivers to recharge has not been investigated, nor the contribution of the aquifers to baseflow in these rivers and the Berg River. Further analysis of the correlation between stream flow (Berg River) and groundwater levels may be necessary in order to have a better idea of the contribution of the river to recharge and the aquifer to baseflow in the river during low flow periods.
- The effects of MARS practice on the broader area should be considered if the Berg River water is to be used for artificial recharge, e.g. the impact on the estuary of the Berg River, the effects on water availability for farmers upstream, etc.
- The role and dynamics of groundwater in the Adamboerskraal and Grootwater aquifers, where historic data are scarce, still needs to be defined.

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