Conceptualization of urban hydrogeology within the context of water sensitive urban design: case study of Cape Flats Aquifer

UNIVERSITY *of the*
WESTERN CAPE

Siyamthanda Gxokwe

A thesis submitted in fulfilment of the requirements for the

Degree

Master of Science

In

Environmental and Water Science

Department of Earth Science, Faculty of Sciences, University of the Western Cape

Supervisor: Prof Yongxin Xu

Co-Supervisor: Dr Thokozani Kanyerere

May 2017

DECLARATION

I declare that *Conceptualization of urban hydrogeology within the context of water sensitive urban design: Case study of Cape Flats Aquifer* is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete reference.

Full names: Siyamthanda Gxokwe

Date:

Signature:

DEDICATION

I would like to dedicate this thesis to my mother Ms Nomaphelo Gxokwe who raised the 4 of us all by herself and through the struggles of life that I am facing she is always there and for that I am grateful "Ncotshekazi".

ABSTRACT

Urban hydrogeology can be used to facilitate a decision-making process regarding the implementation of water sensitive urban design (WSUD) to manage water systems of peri-urban cities. This thesis was aimed at providing explanation of how that approach can be applied in Cape Town using Cape Flats Aquifer as a case study. To achieve this main objective, three specific objectives were set, namely, objective 1 which focused on estimating aquifer parameters using Theis analytical flow solution, in order to identify areas for implementation of managed aquifer recharge (MAR) suggested by WSUD principles; Objective 2 focused on conceptualizing groundwater flow system of Cape Flats Aquifer using the Finite Difference Method (FDM), in order to predict aquifer behaviour under stresses caused by the implementation of WSUD; Objective 3 focused on assessing gw-sw interaction using Principal Aquifer Setting, environmental isotope, and hydrochemical analysis, in-order to identify where and when groundwater surface water interaction is occurring, and thus informing the prevention strategies of the negative effluence of such exchanges on WSUD.

The analysis of data collected through pumping test approach which were conducted in March, October 2015 and June 2016, showed that average transmissivity ranged from 15.08m^2/d to 2525.59m^2/d, with Phillipi Borehole (BG00153) having the highest and Westridge borehole 1 (G32961) having the lowest transmissivity values based on Theis solution by Aqua test analysis. Theis solution by excel spreadsheet analysis showed that average transmissivity ranged from 11.30m^2/d to 387.10m^2/d with Phill (BG00153) having the highest transmissivity and Bellville 2 (BG46052) having the lowest transmissivity. Storativity values ranged from 10^{-3} to 10^{-1} with Phillipi borehole (BG00153) having the highest storativity and Lenteguer borehole 1(BG00139) having the lowest values from both analysis. Average transmissivity visual maps showed that highest transmissivity values within the Cape Flats Aquifer can be obtained around the Phillipi area towards the southern part of the aquifer. Storativity maps also showed that the greatest storativity values can be obtained around Phillipi and Lenteguer area. These findings reveal that MAR would be feasible to implement around the Phillipi and Lenteguer area, where aquifer storage and discharge rates are higher.

The analysis of three scenarios predicted from numerical simulations (varying recharge, varying abstraction rate and reduced recharge with varying abstraction rates) revealed that groundwater outflows, fluxes, and levels show direct proportionality to groundwater recharge in the area. Varying withdrawal rates scenarios showed that an increase in withdrawal rates causes a decline in groundwater levels, fluxes, and outflows observed from the water balance components of the area. A substantial decline in water levels, fluxes and outflows were observed at an abstraction rate of 20l/s. Results from the reduced recharge and varying abstraction rates scenarios showed that at a 25% less recharge and withdrawal rate of 20l/s; groundwater levels, fluxes, and outflows were substantially declined.

The Principal Aquifer Setting method revealed 16 possible points for gw-sw interaction. 5 of those points occurred within the Kuils River, 4 in Vygekraal River, 4 in Elsies Kraal, 1 within the UWC wetland and the other one in the Kuils River wetland. Stable isotopic analysis of samples from those points revealed that groundwater-surface water interaction was not occurring during dry season; however the summer rainfall of low isotopic ratios was feeding the shallow groundwater in Cape Flats Aquifer. In wet season, isotopic analysis results revealed the occurrence of significant mixing between shallow groundwater and surface water in the area, thus indicating the occurrence of two way interaction between shallow groundwater from the Cape Flats Aquifer and rivers as well as wetlands understudy. Hydrochemical analysis revealed that one way interaction was occurring during dry season, where shallow groundwater from the Cape Flats Aquifer was feeding rivers and wetlands understudy. Wet season hydrochemical analysis results revealed the presence of significant mixing between shallow groundwater from the Cape Flats Aquifer and rivers as well as wetlands understudy, and thus suggesting the occurrence of two way interactions between groundwater and surface water during wet season.

Recharge process in Cape Flats Aquifer is controlled by many factors including natural, urban drainage, import leakages, supply leakages and irrigation return flows. Aquifer parameters estimated revealed that managed aquifer recharge would be feasible to implement around the Phillipi area towards the southern part of the aquifer where discharge and aquifer storage values are high. It is therefore recommended that the existing network of boreholes be expanded to have full coverage of the entire Cape Flats Aquifer. As numerical simulation results revealed that varying abstraction and recharge rates influences groundwater levels distribution and outflows from the aquifer and fluxes, it is also recommended that dense distribution of boreholes along selected flow directions is needed to improve the modelling calibration. GW-SW interaction revealed that interaction does occur in the sites identified and an exchange of nutrients is likely to occur, it is further recommended that more hydrochemical and isotope data is needed to gain more conclusive evidence on the occurrence of GW-SW interaction.

ACKNOWLEDGEMENT

I would like to express my profound gratitude to the following people and organisations:

To my supervisory team from the department of Earth Science, University of the Western Cape Prof Yongxin Xu and Dr Thokozani Kanyerere for their valuable support and guidance during the course of the study.

To Water Research Commission (WRC) for their financial assistance, without which any of this research would be possible.

To collaborative partners University of Cape Town, Department of water and sanitation (Bellville) and Council of Scientific and Industrial Research for project formulation and allowing access to data.

I would also like to thank Dr Sumaya Israel from the council of scientific and industrial research for her advice and support during the course of the study.

To the staff members and postgraduate students from the Department of Earth Science who assisted in field and laboratory work for that, I am grateful.

I would also like to thank my mother Ms Nomaphelo Gxokwe, my three younger brothers Thabiso, Athayabonga and Onika Gxokwe, and my sister Nomabhelu Memani for their moral support and encouragement during the course of the study.

Above all I would like to thank God for providing me with strength and guidance through the course of this master’s study.

LIST OF FIGURES

LIST OF TABLES

Chapter 3: Methods and research design........ 31

Chapter 4: Aquifer parameters estimation........ 57

Chapter 1: General introduction

1.1 Background to the study

Water sensitive urban design (WSUD) is an approach used for water system management within urban areas. The approach is aimed at improving the management of urban water cycle through consideration of total management philosophy (Ashley et al. 2013). The main purpose of WSUD is to maintain or mimic the pre-development urban water cycle through the use of integrated techniques to create functionally equivalent hydrogeological landscapes. WSUD approach integrates urban stormwater, groundwater, wastewater management and water supply to urban development in order to minimise environmental degradation after urban development. In urban areas, most soils are impermeable due to compaction during development. This causes intensified flows in watercourses; stream contamination, severe flooding and reduced groundwater recharge (Lerner 2002). Groundwater recharge can sometimes increase in urban areas as a result of leakages from the underground pipes for water supply and sewer systems thereby recharging the underlying shallow aquifers (Mudd et al. 2004; Lerner 2002; Walsh et al. 2005). Ashley et al.(2013), reported that WSUD seeks to maximise opportunities for usage and sustenance of water resources, also the management of wastewater to enhance and support human health by minimising the impacts of urbanisation on the natural environment.

WSUD is based on five goals, which include reduction of potable water consumption, maximisation of water re-use, reduction of wastewater discharge, minimisation of stormwater pollution before discharging to aquatic environment and maximisation of groundwater protection (Armitage et al. 2014). These goals are achieved through the implementation of WSUD principles. The guiding principles of WSUD according to Wong (2006) include reducing potable water demand through water efficient actions and seeking alternative water sources such as rain and treated rainwater re-use, the minimization of wastewater generation and treatment of wastewater to a standard suitable for effluent re-use, the treatment of urban stormwater for re-use and increasing the suitability for storing it to surface water and groundwater systems, and lastly using stormwater in the land scape to maximise the visual and recreational amenity of developments. The study is assessing the role of urban hydrogeology in facilitating the decision-making process regarding the implementation of WSUD principles to manage water systems of the City of Cape Town and is using Cape Flats Aquifer as a case study.

WSUD principles have been implemented at various countries such as Australia where it began and within South Africa on various scales. Most of the projects are at local scale and include more projects from Australia. From an Australian context, the project on New Brompton estate in Adelaide demonstrates the role of urban hydrogeology in water system management through implementation of WSUD principles. The project involves collection and treatment of runoff harvested from rooftops of 15 residences surrounding central recreation reserve in New Brompton estate (Hoyer & Dickhaut 2011). The runoff collected is then passed through the gravel filled trench situated around three sides of the reserve. Some of the water passed through this trench is taken by plants and the other volume is conveyed to the aquifer which is 30 meters below the ground level. During the dry season, water stored in this aquifer system is pumped and used to irrigate the reserve. Monitoring of this system showed that downstream flooding is reduced (Hoyer & Dickhaut 2011). The demand for potable water for irrigation of public spaces is also reduced. The project demonstrated the role of urban hydrogeology in WSUD principles; however, the area to which it was implemented is not regarded as a peri-urban city compared to the area used as a case in the current study.

Parafield stormwater harvesting scheme in Parafield airport Adelaide Australia is also a project demonstrating the role of urban hydrogeology in water systems management through WSUD principles implementation. The project involves harvesting and treatment of storm water from residential and industrial catchments in the North and South of the Parafield area. The treated water is then conveyed to the underlying aquifer for subsequent extraction and re-use. Monitoring of the system showed that there is a significant reduction in demand for potable water usage; also pollutants loads entering the waterways are reduced (Myers et al. 2013). The scheme also demonstrates the role of urban hydrogeology in stormwater management through WSUD principles implementation, however similar to the New Brompton project the area where the project was implement is not classified as peri-urban.

Fig tree place housing development in the inner city of New Castle suburb of Hamilton is also an example of a project demonstrating the role of urban hydrogeology in water systems management through implementation of WSUD principles. Similarly to the New Brompton, the project involves runoff collection from rooftops and other impervious surfaces in the area and diverted to underground storage tanks and underlying aquifer (Ellis 2013). The stored water is then later used to wash cars, toilet flushing, garden irrigation and washing buses in the adjacent depot. Monitoring of this WSUD system showed that there is a reduction in demand for water supply in the area by up to 60% respectively (Ellis 2013). This project also shows the role of urban aquifers on WSUD initiatives, however similarly to the previously mentioned projects; the project was not implemented to a peri-urban area such as that of the current study.

From South African context WSUD principles have been implemented on a smaller scale. For example, Pick n Pay distribution centre in the Phillipi area within Cape Town. The centre has water sensitive management strategies documented in the WSUD principles incorporated into its system. The system consists of rainwater harvesting structures; re-use system and the grey water recycling plant directly linked to the distribution centre truck wash. The system collects water from rooftops through a siphonic drainage system and conveyed to storage tanks (Armitage et al. 2014; Ellis 2013). The water collected is then later treated and used to flush toilets, wash trucks and irrigation. The project demonstrates the achievement thus far in South Africa in using WSUD principles to manage urban water systems; however, the project does not show the role of urban hydrogeology in the management of water systems through WSUD.

Cape Town Grand parade is also a project of an area demonstrating the use of WSUD principles to manage water systems. The area has permeable paving and bio-retention ruts; which attenuate stormwater sheet flow thereby reducing damage as a result of flooding events (Ellis 2013). Century City wetland is also an example of WSUD principle implementation initiative. The system consists of constructed wetland, detention pond and the treatment train. Stormwater is collected from Century City and surroundings and conveyed to detention pond for storing and later re-used (Armitage et al. 2014). Both projects also show the progress thus far in South Africa regarding the use of WSUD principles to manage urban water systems, However similar to the Phillipi project, both projects do not clearly demonstrate the role of urban hydrogeology in the management of water systems of peri-urban cities.

1.2 Research problem

WSUD started in Australia due to serious water quality and quantity issues. Since then, the approach had been adopted in various countries Such as South Africa. From the South African context where cities are characterised as peri-urban settlements, there are limited studies done focusing on demonstrating the significance of urban hydrogeology information in the management of water system through WSUD principles implementation. This is a problem because not understanding the importance of hydrogeology in WSUD implementation will lead to fragmented decisions taken relating to groundwater during the planning of water systems management through WSUD implementation. The main driver to the problem is poor understanding of WSUD approach and its relationship with hydrogeology from the South African perspective.

1.3 Research question and thesis statement

To what extent does hydrogeology of the City of Cape Town functions to facilitate a decision-making process regarding the implementation of WSUD principles to manage water systems of the particular city?

The central argument of the study is that, if hydrogeology of the City of Cape Town is understood prior the decision-making process regarding the implementation of WSUD principles to manage water systems of such city, then WSUD implementation is likely to be facilitated.

1.4 Study aim and objectives

1.4.1 Aim

The study is aimed at understanding the hydrogeology of the Cape Flats Aquifer and groundwater surface water interactions within the area, in order to provide an explanation of how hydrogeology of the City of Cape Town can facilitate a decision-making process regarding the implementation of WSUD principles to manage water systems of the particular city.

1.4.2 Objectives

1. To estimate aquifer parameters using Theis analytical flow solution.
2. To conceptualize groundwater flow system of Cape Flats Aquifer using the Finite Difference Method.
3. To assess groundwater surface water interaction using principal aquifer setting, environmental isotopes and hydrochemical analysis.

1.5 Significance of the study

The study generates information on aquifer parameters, local groundwater flows of the Cape Flats Aquifer and groundwater surface water interaction. This information can be used as a reference for future hydrogeological studies carried out within the area. The information generated may also be used for teaching purpose in institutions teaching hydrogeological studies.

1.6 Scope and nature of the study

Hydrogeology highlights the interrelation of geological processes and materials with water. The concept is very broad and covers aspects like physical and environmental hydrogeology. The current study mostly falls on the physical hydrogeology aspect, where the focus is on parameter estimation and local groundwater flow system conceptualization. The current study also does a portion of environmental hydrogeology where the main focus is on assessing groundwater-surface water interaction in relation to water systems management through WSUD. These three aspects of hydrogeology are chosen in this study because of the significant influence that different land use activities pose on them.

The current study adopts the quantitative experimental and desktops design to achieve the three objectives. The quantitative experimental design, in this case, involves field trials for the collection of primary water level, water quality and environmental isotope data to achieve the objective of aquifer parameters estimation and groundwater surface water interaction. The desktop design, in this case, involves the collection of secondary, water levels, recharge, geological and hydrogeological data sets to achieve the objective focusing on local groundwater flow system conceptualization for the Cape Flats Aquifer.

1.7 Research framework

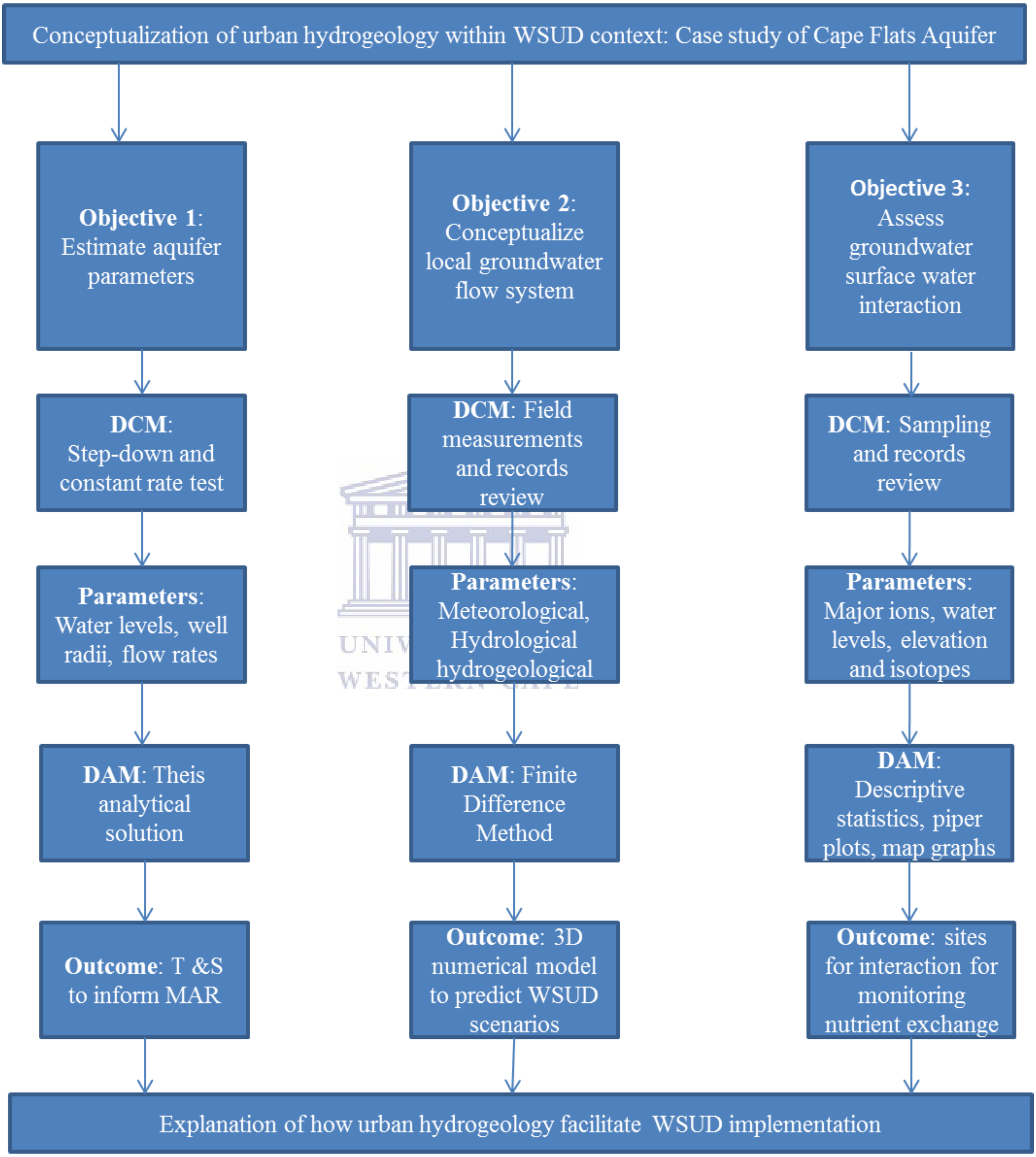


Figure 1.1: Framework of the study (authors construct)

The figure 1.1 above shows framework of the study. The study is aimed at understanding the hydrogeology of the Cape Flats Aquifer and surface water interactions in the area, in order to provide an explanation of how hydrogeology of the City of Cape Town, functions to facilitate a decision-making process regarding the implementation of WSUD principles to manage water systems of the particular city. To achieve the main objective the study had three specific objectives; Objective 1 which focused on estimating aquifer parameters using Theis analytical flow solution. The intention was to suggest possible sites for implementation of managed aquifer recharge (MAR) suggested by WSUD principles. Objective 2 focused on conceptualizing local groundwater flow system for the Cape Flats Aquifer using the Finite Difference Method. The intention was to predict aquifer behaviour under site-specific stresses caused by the implementation of WSUD principles. Objective 3 focused on assessing groundwater surface interaction using Principal Aquifer Setting, Environmental isotope and Hydrochemical analysis method. The intention was to identify where and when groundwater surface water interaction is occurring, in-order to inform the prevention strategies of the negative effluence of exchanges between groundwater and surface water the on the effectiveness of WSUD.

To achieve objective 1, the study carried out two types of hydraulic test namely step-drawdown and constant rate test within selected sites and parameters measured included water levels, wells radii and flow rates. To achieve objective 2, secondary data sets was collected from the review of records from various sources such as CSIR, DWS and CoCT. The parameters of focus were meteorological, lithological and hydrogeological parameters. To achieve objective 3, sampling was done during wet and dry season to collect data set for hydrochemical and isotopic analysis. Groundwater levels were also monitored on bi monthly basis in order to map out groundwater flow nets which give indication of possible sites where groundwater is discharging to the surface.

The data collected for objective 1 was analysed using Theis analytical solution, and the outcomes were transmissivity and storativity values which were used to decide on possible sites for managed aquifer recharge suggested by WSUD principles. Data collected for objective 2 was analysed using a 3-dimensional finite difference method and the outcome was a 3D site-specific numerical model which was used to predict aquifer behaviour under site-specific WSUD scenarios. Data collected for objective 3 was analysed using descriptive statistical analysis graphical, trilinear plots and maps. The outcome was information of where and when gw-sw interaction is occurring, and that information was used in explaining how exchanges between groundwater and surface water influence effectiveness of WSUD.

1.8 Study area description and justification

The Cape Flats Aquifer is located within the central part of the Cape metropolitan area, and covers an area of about 630km^3 of the Western Cape Province in South Africa (Adelana et al.2010). The geology of the aquifer is mainly sand which varies from unconsolidated to semi-consolidated, with clay and peat layers interbeded causing the aquifer to be semi-confined in some parts (Saayman & Adams 2010). Various land use activities exist on surface of the aquifer. These include, agricultural activities, formal and informal settlements, open spaces and sand mines (Maclear 1995). The hydrology of the area is represented in a number of rivers and wetlands in the area. These rivers include Elsieskraal River, Vygekraal River, Kuils River, Black River and the Deep River (Adelana et al.2010). As part of the feasibility study to assess the suitability of using the WSUD principles to strengthen the planning of water sensitive cities of the future in the South African context, Cape Flats Aquifer was chosen as a case study because of various land use activities in the area contributing towards the unsustainable use of water in the area.

1.9 Thesis outline

The thesis is divided into 7 chapters as follows. Chapter 1 gives an overview of the study with the background, the description of the research problem, research question and thesis statement, study aim and objectives, the significance of the study, scope and nature of the study, a framework of the study and the general outline of the thesis. Chapter 2 presents reviewed literature in an analytical and systematic manner to identify gaps in knowledge regarding urban hydrogeology and water sensitive urban design in South Africa and beyond. Chapter 3 describes the research design and methods used for data collection and analysis, in addition to data quality and ethics. Chapter 4 presents and discusses the findings on aquifer parameters estimation with emphasis on T and S. Chapter 5 presents and discusses the findings on local groundwater flow conceptualization. Chapter 6 presents and discusses findings on the assessment of groundwater surface water interaction. Chapter 7 provides conclusions and recommendations based on the findings of the study.

Chapter 2: Literature review

2.1 Introduction

Chapter 2 of the study reviews historical work on the concept of urban hydrogeology in general and within the context of water sensitive urban design (WSUD). The intention is to identify gaps in literature which the current study is trying to fill. The chapter covers in broader sense a review of previous studies done on the concept of urban hydrogeology, the overview and implementation of water sensitive urban design principles, hydrogeology of peri-urban cities, groundwater modelling in urban areas, and a review of methods for aquifer parameter estimation, groundwater modelling at local scale and the assessment of groundwater surface water interaction.

2.2 Previous studies on urban hydrogeology

Urban hydrogeology had been studied extensively from different angles and in different parts of the world. Most of these studies had been focusing more on aspects such as groundwater surface water interactions, aquifer parameter estimation, groundwater flow modelling and groundwater quality, and governance issues in relation to urban land-use activities for a particular area. The current study focuses on three aspects of hydrogeology which are aquifer parameters, groundwater flow system conceptualization and groundwater surface water interaction for the City of Cape Town in relation to water sensitive urban design and is using Cape Flats Aquifer as the case study.

Focusing on Aquifer parameters estimation on the coastal urban environment from the continental scale, Jha et al. (2003) estimated the hydraulic parameters of Konan groundwater basin in Japan using hydrographs computed from least squares to estimate hydraulic conductivity (K). Storativity values were also estimated, from time lag and tidal efficiency factor equation. The results shows that K values ranges from 4.5×10^{-3} m^2/s to $1m^2/s$ respectively. Storativity values ranges from 0.05147-0.05653 estimated from time lag and ranges from 0.11363-0.16124 when estimated from tidal efficiency equation. The study concluded that tidal response technique is a reliable method for estimating aquifer parameters in coastal zones. Jha et al. (2003) addresses objective 1 of the study focusing on aquifer parameters estimation and demonstrated one possible method for estimating aquifer parameters in coastal zones; however, the method allowed for estimation of S and K, whereas current study focused more on S and T which are chosen because they give indication of storage and discharge rates of the aquifer, and that information is crucial when planning managed aquifer recharge (MAR).

Mjemah et al. (2009) also estimated aquifer parameters of an unconsolidated quaternary aged forming the major aquifer in Der-es- Salam Tanzania. The study used single and multiple well hydraulic testing techniques to collect data. The analysis was done using Neuman’s curve matching, Walton type and Theim- Dupuit method. Results from the study by Mjemah et al.(2009) shows that the average estimated T value is 34m^2/d, K is 1.58m/d and S is 0.01. Mjemah et al. (2009) concludes that parameters estimated coincide with the geological conformation of the aquifer that he studied. The study by Mjemah et al. (2009) also addresses objective 1 of the study focusing on estimating aquifer parameters of an unconfined quaternary aged lithological unit, However Mjemah et al. (2009) used Neuman’s, Walton type and Theim-Dupuit method and the study used Theis analytical solution to estimate T and S for the Cape Flats Aquifer with similar lithological conformation. The current study uses Theis solution because sites being experimented are of infinite extent and even though the Cape Flats Aquifer is unconfined, there are piet and clay layers interbedded into the aquifer causing it to be semi-confined, hence the solution is used.

From the South African context, Adelana et al. (2010) used an integrated approach to analyse groundwater and surface water hydrology in addition to geological characteristics of the Cape Flats Aquifer. The purpose was to provide information on the hydrological and hydrogeological behaviour of Cape Flats Aquifer using the secondary data set to qualitatively evaluate these characteristics. The analysis of pumping test data from the study by Adelana et al.(2010) reveals that aquifer transmissivity ranges from 32-620 m^2/d. Similarly to Mjemah et al. (2009) and Jha et al. (2003), Adelana et al. (2010) also addresses objective 1 of the study, however, the current study estimates transmissivity as well as Storativity whereas Adelana et al. (2010) focuses more transmissivity values. The current study, however, expects transmissivity estimates which corroborate with those of Adelana et al. (2010).

Focusing on groundwater flow system conceptualization on a global scale is a study by He et al. (2008). The emphasis was on simulating groundwater flows in the coastal plain of Seto inland sea in Japan using a 3-dimensional Finite Element Method. The results from this study by He et al. (2008) suggest a high correlation between groundwater levels of the shallow coastal aquifer and ground elevation. He et al. (2008) addresses objective 2 of the study which focuses on local groundwater flow system conceptualization of Cape Flats Aquifer, which is of similar setting to the coastal plain of Seto, however, He et al. (2008) developed a regional numerical model using finite element method and the current study uses finite difference method to develop a site-specific model because the method is the simple to use and does not require larger data sets.

Elçi et al. (2007) also simulated groundwater flow system of the alluvial water table aquifer located within the country of Torbali-Izmi using a 2-dimensional steady groundwater flow model. The model was calibrated using hydraulic conductivity and aquifer recharge rates. Results suggest that the aquifer receives groundwater influx from the limestone in the southern part and also from the Gurgur Mountain in the east of Torbali, in addition, to recharge from precipitation. Results also show that groundwater flow varies regionally in the area. Elçi's study informs the current study about possible methods for simulating groundwater flow of shallow water table aquifers such as Cape Flats Aquifer, however, Elçi et al. (2007) solved a 2-dimensional numerical flow equation and the current solved a 3-dimensional numerical flow equation because of the code chosen in this study.

From an African perspective, Ayenew et al. (2008) simulated groundwater flows and occurrence in Akaki catchment Ethiopia with intentions to evaluate groundwater fluxes and also analyse subsurface hydrodynamics using a 3-dimensional steady state finite difference method. The model was calibrated using hydraulic head data measured from 131 wells in the area. Results suggest that groundwater flows regionally to the southern part of the study area converging to the major well field. Ayenew's study informs the current study about methods for simulating groundwater flows within the coastal aquifers; however, the study modelled groundwater flow at a regional scale and the current study focuses on flow conceptualization at site-specific scale because of the reason stated in chapter 1.

A study by Cook et al. (2006) also quantified groundwater contribution to Cock Burn River located in the Southeast of Australia using ^{222}Rn as an environmental tracer. An estimated groundwater contribution to the river is 18500m^3/d. This study demonstrates how isotopes can be used in quantifying groundwater contributions to surface water; however, Cook et al. (2006) focused on quantifying contributions using ^{222}Rn and the current study used ^{2}H and ^{18}O as tracers to confirm whether interaction occurs because these isotopes are stable and had proved to be successful in areas such as Cape Flats Aquifer.

From the South African context, Giljam (2002) studied the influence of Cape Flats Aquifer on water quality of False Bay north shore using historical data from Gerber (1981) and Henzen (1973) to calculate potential groundwater discharge to False Bay. Results showes that discharge calculated from the data collected by Gerber (1981) ranges from $3m^3$/d to $31m^3$/d. The discharge from data by Gerber (1981) varies significantly with the discharge calculated from the data by Henzen (1973) which ranges from $31m^3$/d to $119m^3$/d. Giljam (2002) also addresses objective 3 of the study focusing on assessing groundwater surface water interaction within the selected surface water bodies of the Cape Flats, However the main purpose of the study by Giljam (2002) was to quantify groundwater discharge to False Bay and the current study was focusing on assessing groundwater surface water interaction within wetlands and rivers within the area. The study however expected that the results of the current study to confirm the interaction between Cape Flats Aquifer and surface water bodies in the area.

2.3 Overview of water sensitive urban design and its principles

Water sensitive urban design approach started in Australia due to serious water shortage issues. The concept started at Murdoch University in Perth Western Australia and served as a guide on how to improve water infrastructure design in natural and build environment (Lottering et al., 2015).When the approach started, the central focus was on storm water management and by now had been expanded not only to include storm water management but also other components of urban water systems such as rainwater, snowmelts, wastewater which include greywater, black water and drinking water (McAlister 2007). As the cost of treating and delivering water for potable consumption increases rainwater harvesting and stormwater re-use for non-potable purpose reduced the demand for potable water and the costs of treatment and delivering water (Hoyer & Dickhaut 2011). WSUD approach allowed for such and had been proven to be successful in many different Australian projects such as Fig tree project, New Brompton project and Parafield projects which are discussed in details in chapter 1 section 1.1. Due to its effectiveness in Australian project, the approach had been adopted by various countries such as such as South Africa.

WSUD from the South African context is at its infancy stage and had been implemented on very small scale projects such as Phillipi Pick n Pay distribution centre, Grand parade permeable paving project, Century City wetland scheme and the hotel Verde green roofing

(Armitage et al. 2014) to mention a few within the Western Cape Province. These examples had shown the effectiveness of the approach from the South African perspective. Figure 2.1 shows the framework of WSUD, which translates WSUD as an approach which integrates landscape design to urban planning and sustainable water management therefore contributing towards a sound management of urban water cycles, therefore contributing to sustainability in urban cities and also creating conditions attractive to a human scale living environment.

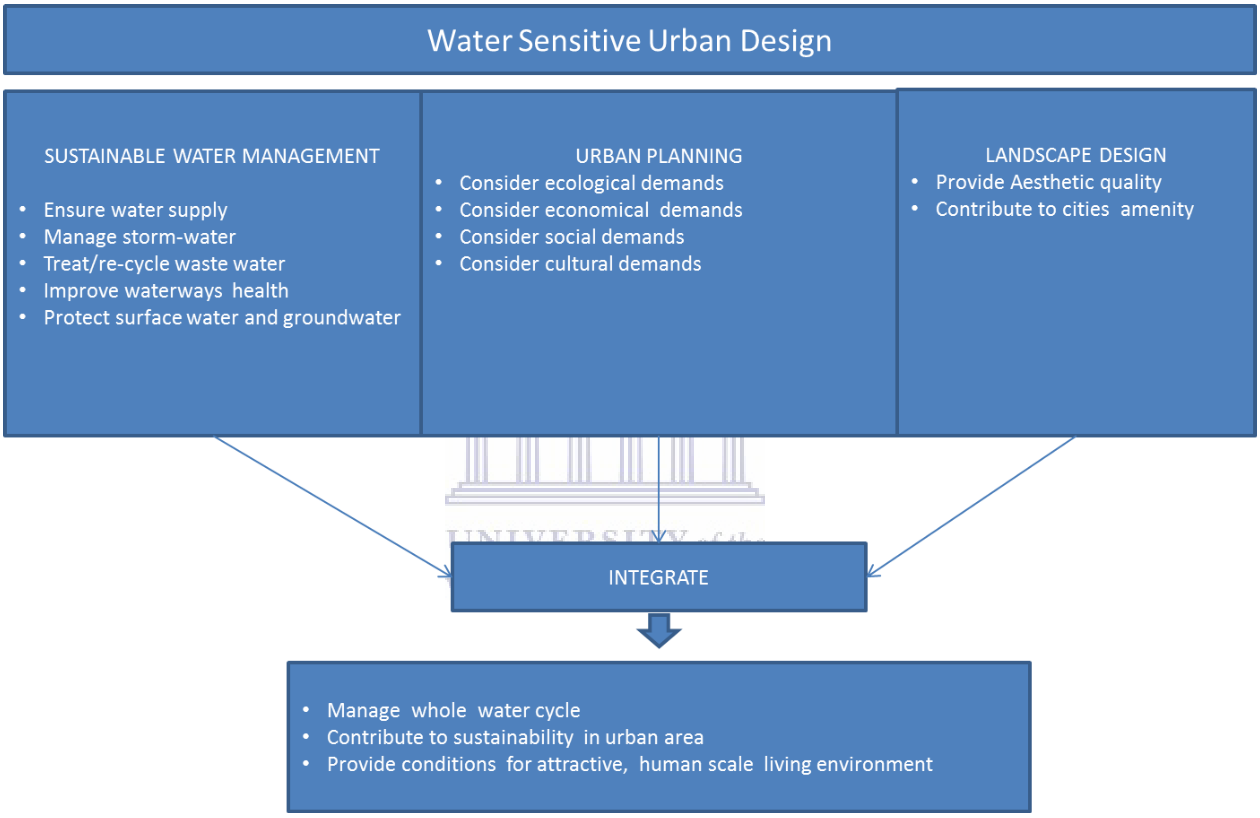


Figure 2.1: WSUD framework

Wong (2006) states that there are four guiding principles for water sensitive urban design, these are;

- Reducing potable water demand through water efficient appliances and seeking alternative sources of water such as rain and treated waste water re-use.

- Minimising wastewater generation and treatment of wastewater to a standard suitable for effluent re-use opportunities and/ or releasing it to the receiving waters.

- Treating urban storm water to meet water quality objectives for re-use and or discharging to surface water and groundwater.

- Using stormwater in the urban landscape to maximise the visual and recreational amenity of developments

These are implemented at various scales from small to regional scale. Ways to implement these guiding principles are fully discussed in section 2.4.

2.4 Implementing principles of water sensitive urban design

Principles of WSUD are implemented through two approaches namely, The Best Planning Practices (BPP) and the Best Management Practices (BMP). Both practices function interlinked to achieve implementation. Best Planning Practices or approaches involves the integration of sustainable urban features in planning and design of an urban area. The approach encompasses interlinked strategies which implement public open spaces, housing and road and streetscapes to water systems to achieve a safer and more user-friendly environment for city inhabitants (Armitage et al. 2014). These practices naturally and inherently enhance both physical and natural urban environment, providing amenity especially relating to the inclusion of stormwater rooted in the urban landscapes.

The Best Management Practices includes technologies or practices which perform the duty of conserving, storing, and collecting, treating, transportation as well as re-use functions of the relevant urban water streams. These can be grouped as structural or non-structural (Hoyer & Dickhaut 2011). The structural includes physical structures such as storage tanks and non-structural includes aquifers which can be used as conduits for treated stormwater. BMP consist of three elements namely demand management practices, supplementation of drinking water and stormwater treatment. Demand management practices include the use of water efficient fixtures and appliance to manage demand for water supply. The use of water efficient landscaping and planting of drought tolerant plants, and lastly using the water efficient irrigation system such as drip system or moisture control system to manage the demand of water for irrigation purposes (Ellis 2013). Supplementation of drinking water is all about using the alternative source of water for drinking. The source could be rainwater harvested and recycled wastewater. The stormwater treatment is all about treating stormwater harvested using gross pollutants traps, vegetated swales and buffers, Bio-retention system and natural as well as constructed wetlands.

2.5 Hydrogeology of peri-urban cities

Peri- urban cities are mostly found within developing countries, therefore peri-urban cities in this context refer to urban areas in developing countries with rural characteristics land-use such as informal settlements and agricultural lands. Developing countries worldwide are characterised by urban cities with rapid urbanization. The rapid urbanization within these cities are not as the result of industrialisation but rather caused by the rapid expansion of human settlement (Henderson 2002). This is due to migration of people from the rural areas in search of greener pastures; thereby leading to the establishment of new areas, which are mostly un-serviced informal areas. The informal areas normally contain a high proportion of urban population with low income. Poor land use practices in these settlements often significantly alter groundwater and surface hydrology. This section discusses hydrogeology within these cities with the specific focus on groundwater recharge, flows and groundwater quality.

2.5.1 Groundwater recharge

Groundwater recharge is the downward flow of water percolating through the soil particles reaching the water table (Xu & Beekman 2003). It can occur naturally or artificially. In peri-urban cities, groundwater recharge is limited by factors such as impermeable surfaces as a result of paved areas, buildings and roads. However, in some instances, groundwater recharge in these cities is substantially greater than the pre-urban values (Lerner 2002; Mudd et al. 2004; Walsh et al. 2005). There are many different sources contributing to groundwater recharge within these cities. The sources include recharge by rainwater, wastewater, stormwater systems and main leakages from water supply network contributing to groundwater recharge (Lerner 1990). Urban cities of developing countries are characterised by poor sanitation system and wastewater which is not properly drained. These often recharge groundwater thereby causing a significant change in groundwater quantity and quality (van Ryneveld & Fouri 1997). Leakages from septic tanks soak away drainage, water mains and onsite sanitation system also significantly recharge groundwater in the area. WSUD seeks alternative ways to manage the influence of these systems in order to minimise or mitigate problems associated with these issues.

2.5.2 Groundwater quality

Groundwater quality in the peri-urban cities is influenced by different contaminants from different sources. The groundwater contaminant sources are classified as direct and indirect sources. Direct sources of groundwater contamination in these cities include leakages from sewers, septic tanks, the solid waste material deposited on the ground surface and seepage from the contaminated streams resulted from the agricultural activities Folch et al. (2016) Contaminants from these sources often carry dissolved organic carbons, faecal coliforms, chloride, nitrogen compounds, Sulphate and Boron which then alters groundwater quality once recharged to groundwater systems.

Indirect sources include improper disposal waste from industries. Massone et al. (1998) analysed the relationship between land-use activity and groundwater quality of Mar de Plata in Argentina and found that groundwater quality is negatively influenced by agricultural activities, waste disposal sites and areas with poor sanitation services. Zingoni et al. (2005) also studied the influences of semi-formal urban settlements on groundwater quality in Epworth Zimbabwe and found that most parts of the settlements are contaminated with elevated nitrates and coliforms in groundwater. Both the studies by Massone et al. (1998) and Zingoni et al. (2005) proved that in most shallow aquifer within urban cities of developing countries groundwater is contaminated as a result of land use activities on the surface of those aquifers. WSUD helps in minimising the impact of these land use activities on water systems particularly groundwater systems.

2.6 Groundwater modelling in urban areas

The amount of information that needs to be included in urban groundwater models is one important aspect that should be taken into account when developing an urban groundwater model. Information is available from various sources and often at different stages of modelling requiring the frequent modification of the conceptual model throughout the period of modelling (Vázquez-Suńѐ et al. 2005). The process of developing urban groundwater models is very difficult due to lack of data set, lack of planning and difficulties in communication amongst the decision makers and scientific communities. Urban groundwater flow models usually show unique features which differentiate them from the non-urban aquifers (Elango 2017). Most of these models take into account historical changes of the urban areas including land use changes, different sources of groundwater recharge, groundwater abstraction by individuals or industries and underground structures that are interacting with the groundwater system. Steps involved in developing urban groundwater models are the same with steps used to develop non-urban groundwater models. These steps are presented in a sequential manner in figure 2.2.

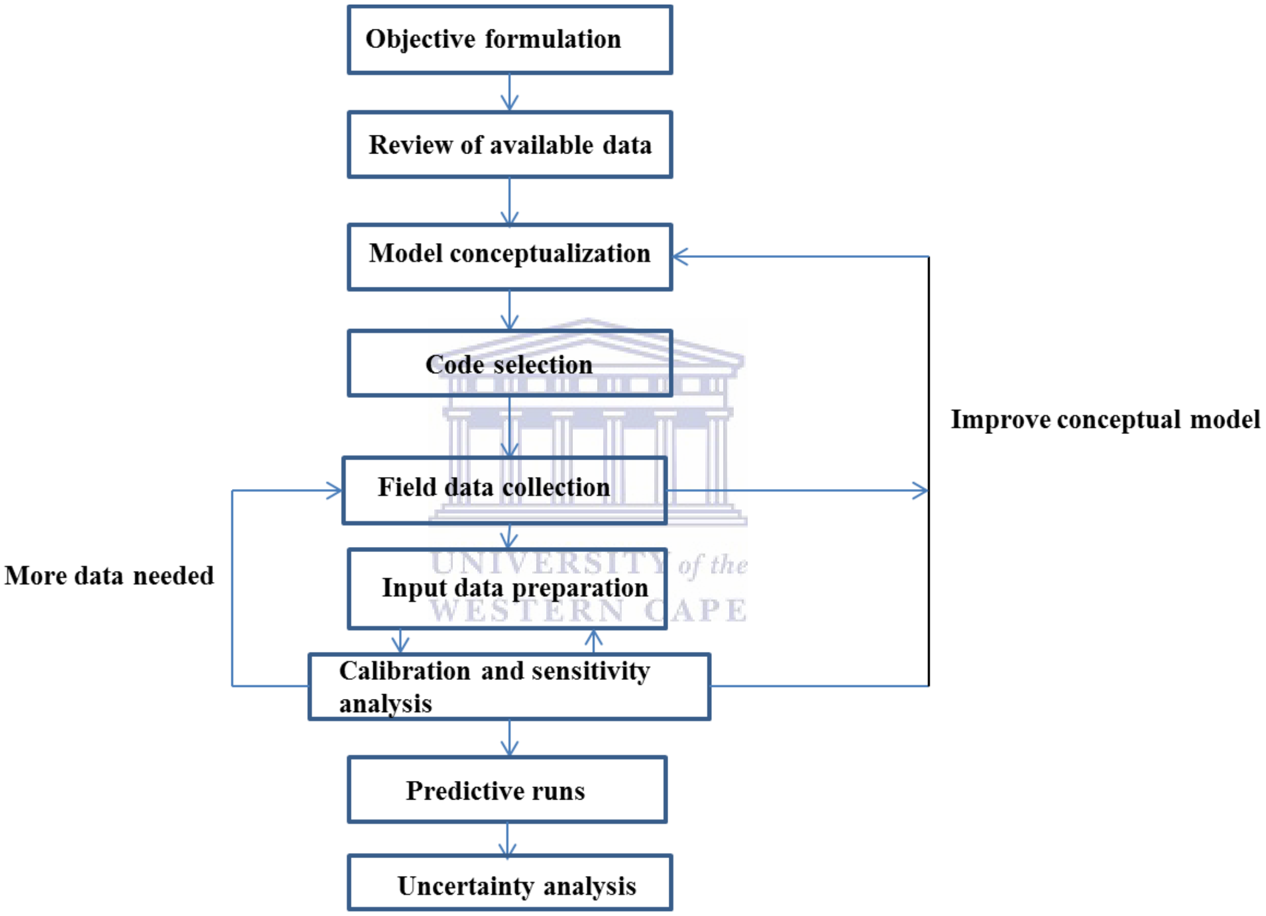


Figure 2.2: Steps of groundwater modelling (Anderson and Woessner 2002)

Formulation of objective- Involves the establishment of the model purpose. The common purposes of groundwater models include the synthesis of hydrogeological data, evaluation of aquifer behaviour under a certain stress applied and assisting in decision making regarding water resource management (Faust & Mercer 1980). This step helps in identifying data needed to be included in the model.

Review and interpretation of data- The step involves the proper characterization of hydrogeological data sets in order to understand the importance of relevant flows.

Model conceptualization- This is a process which involves assembling in a systematic manner the data set collected to describe groundwater flow condition of the specific site. This gives an understanding of groundwater behaviour for a specific area (Anderson and Woessner 2002). Also, the process aids to determine the modelling approach to be used either analytical or numerical model.

Code selection- The step involves the selection of the suitable model code based on the hydrogeological conditions, conceptual model and a nature of the problem being addressed. The model chosen should be able to simulate conditions encountered at the specific area. Certain questions need to be asked prior selecting a code to be used (Elango 2017). These include questions like "has the code been verified against analytical solutions?" "does it include water balance calculation?" and "has it been used in other field studies Codes which are commonly used include MODFLOW, PLASM and AQUIFEM-1.

Field data collection and input data preparation- The steps involves the collection of field parameters which are going to be used as input parameters to the groundwater model. These parameters include hydraulics data which include storage coefficient, Recharge data, evapotranspiration, hydraulic conductivity, rivers and wetlands stages data. Geological parameters include lithological information and aquifer thickness, Geomorphological parameters which include surface elevation. The information is available at different stages of modelling and can be changed over and over.

Calibration- Involves the change of input parameters in an attempt to match the simulated values with the field conditions for the selected calibration time period. The objective of the step is to minimise errors (Anderson and Woessner 2002). Parameters which are changed vary and could include field sources, sinks and boundary conditions for the selected calibration time period. This process is achieved in two ways, through trial and error and automated calibration. Trial and error involve manually changing of parameters through and a number of sequential runs in order to match the simulated parameters and field parameters. Trial and error are influenced by expertise and biasedness of a modeller. Automated calibration is done through the use of codes such as PEST, MODINV and INVERT-3.

Sensitivity analysis- Involves varying of model inputs parameters over a reasonable range and observing the relative change in model response from head residuals. The purpose of this step is to demonstrate the sensitivity of the model simulation to uncertainty in values of model input data.

Predictive runs and uncertainty analysis- This step involves the testing of the model using the predictive scenarios to see how it responds to any given scenario.

2.7 Methods for aquifer parameter estimation

This section reviews the common methods for estimating aquifer parameters of unconsolidated sandy aquifers. These methods are discussed based on their applicability and equation used to estimate T and S since the focus is on such parameters.

2.7.1 Theis analytical solution

Theis analytical solution studies the transient or non-equilibrium groundwater movement as a result of pumping in a confined aquifer. The method was formulated under the assumption that the total stress in the aquifer was constant and the mechanical behaviour of the confining unit was neglected (Xiao 2014). Transmissivity and Storativity are estimated using equation 2.7.1 and 2.72

$$s = \frac{Q}{4\pi T}\int_{u}^{\infty}\frac{e^{-y}}{y}dy \qquad (2.7.1)$$

$$u = \frac{r^2 S}{4Tt_2} \qquad (2.7.2)$$

Where:

s- Drawdown (L)

Q- Pumping rate (L^3/T)

T- Transmissivity (L^2/T)

y- Variable of integration

r- Radial distance from pumping to the observation well (L)

S- Storativity (dimensionless)

t- Time interval since pumping elapsed

The assumptions of Theis analytical solutions are; potentiometric surface is approximately horizontal before pumping, aquifer is confined and is of infinite extent, aquifer is homogeneous isotropic of uniform thickness over the area and influenced by pumping, well is pumped at the constant rate, well is fully penetrating the aquifer, water removed from the surface storage is discharged instantaneously with decline in head and well diameter is small such that well storage is negligible.

2.7.2 Cooper-Jacob method

The Cooper-Jacob method also known as the straight line method is a simplified Theis solution of flow for the well penetrating the confined aquifer. The method may be used to analyse both single and multiple well hydraulic test although it is highly recommended for a single well test (Meier et al. 1998). Cooper-Jacob analytical flow solution involves the plotting of drawdown on y-axis using arithmetic scale and time on x-axis using the logarithmic scale when estimating aquifer properties. The transmissivity and storativity estimated using equation 2.7.3 and 2.7.4 respectively.

$$T = \frac{2.3Q}{4\pi\Delta s} \qquad (2.7.3)$$

Where T= transmissivity (L^2/T)

Q= discharge rate (L^3/T)

Δs= change in drawdown per log cycle (L)

$$S = \frac{2.25Tt_0}{r^2} \qquad (2.7.4)$$

Where S= storativity

T= transmissivity (L^2/T)

t_o= time intercept (T)

r= well radius (L)

The assumptions of the Cooper-Jacob method are similar to those of Theis solution (Meier et al. 1998). The method requires drawdown versus time data set, pumping rate data set and distance from the pumping well to the observation well in the case of the analysis for the multiple well tests.

2.7.3 Neuman's curve fitting method

Neuman's curve fitting method specifically designed for unconfined aquifers. The solution accounts for transient or non-equilibrium flow conditions and anisotropy (Halford & Kuniansky 2002). Assumptions of this method are similar to those of Cooper-Jacob however in addition to those assumptions the solution also assumes that the influence of the unsaturated zone upon drawdown of the aquifer is negligible, diameter of the pumped and observation wells are small therefore the storage in a well is also negligible and lastly the solution assumes that the ratio of the specific yield versus the elastic early-time storativity is greater than 10. Using Neuman's curve fitting parameters are estimated using equation 2.7.4.

$$S = \left(\frac{Q}{4\pi T}\right) W(ua, ub, \boldsymbol{\Gamma}) \qquad \text{(eq2.7.4)}$$

Q= flow rate (L^3/T)

T= Transmissivity (L^2/T)

W (ua,ub,Γ)= well function of the water table

2.7.4 Theim- Dupuit method

The solution is commonly used to estimate transmissivity in the well penetrating through the unconfined aquifer when the drawdown differences in that well have become negligibly small with time (Kruseman & Ridder 1994). This analytical solution is based on the assumption that the aquifer is isotropic and the flow to the well is at steady state. The aquifer parameters using this solution are estimated from the following equation 2.7.5.

$$Q = \frac{2\pi KD(S'_{m1} - S'_{m2})}{2.30\log(r_2/r_1)} \qquad \text{(eq 2.7.5)}$$

Where

Q= flow rate

KD= Transmisivity

S'_{m1}= drawdown for observation well one

S'_{m2} = drawdown for observation well two

r_1 = distance from the pumping well to the observation well one

r_2 = distance from the pumping well to the observation well two

2.7.5 Bouwer-rice

The method is based on Theim solution. It was developed for determining hydraulic conductivity of the well penetrating the unconfined aquifer (Kruseman & Ridder 1994). Although the solution was designed for unconfined aquifers it can also be used to estimate hydraulic conductivity of wells penetrating a confined aquifer. The hydraulic conductivity of the solution is given as:

$$K = \frac{r_c^2 \ln(R_c/r_w)}{2d} \cdot \frac{l}{t} \cdot ln \frac{h_0}{h_t} \tag{2.7.6}$$

r_c = radius distance of the unscreened part of the well where the head is rising

r_w = horizontal distance from well centre to the undistributed aquifer

R_c = Radial distance over which the head difference is dissipated in the flow system of the aquifer

d= length of the well screen or open section of the well

h_o = head in the well at time t_0

h_t = head in the well at t> t_0

Assumptions of the methods are:

- The volume of water is injected into or is discharged from the well instantaneously t=0
- Well is of finite diameter and may penetrate the unconfined aquifer
- Well storage cannot be neglected

2.8 Groundwater modelling techniques

2.8.1 Analytical models

The analytical models are exact solutions to differential equations. These models are mostly applicable when the groundwater flow system and contaminants transport systems are simple. They are also used when establishing hydrogeological conditions. Analytical Models include Theis, Cooper-Jacob, Neuman's and Bower-rice analytical solutions. The advantages of using the analytical models in understanding groundwater flow system and contaminants transport include; the same solution can be applied to various numerical values of coefficients and parameters. The solutions, however, are not possible in some instances due to reasons such as heterogeneity of the area being modelled, irregularity in shapes of the boundary conditions, and non-analytic forms of various functions.

2.8.2 Numerical Solutions

These are models which are mostly applied when groundwater flow and contaminants transport systems are complex. These are applicable when there is spatial and temporal variation in groundwater flow systems, hydrogeological characteristics and hydraulic or chemical sources and sinks. Numerical models provide discrete solutions over the entire area that is being modelled. The models use direct methods to perform approximations. There two types of numerical models available; these are Finite Difference method and Finite Element Method. These methods use the different set of equation to solve groundwater flow systems. The equations used can be one, two or three dimensional depending on the conditions of the aquifer being modelled

2.8.2.1 Finite Difference Method

This is the oldest method used to model groundwater flow systems. It uses rectangles or quadrilateral grids to discretize the area being modelled. Within this model each rectangle grid cell used has an X, Y and Z co-ordinates and the hydraulic head is calculated within the centre of each grid cell (Spitz & Moreno 1996). For each grid cell, hydraulic head is computed as the average of the adjacent cells and there is no assumption made about the form of variation of the head from one centre of the cell to the next (Anderson and Woessner 2002). Inflows and outflows from each grid cell can be calculated depending on the equation being solved by the model. The advantages of this method are that the method has the intuitive basis, easy data input, efficient matrix techniques and programme changes are easy (Faust & Mercer 1980). The method, however, has low accuracy in some problems and regular grid.

2.8.2.2 Finite Element Method

These are methods which are based on the idea of dividing the domain area into finite elements equations and using these equations as one, such that they represent the original system (Smith 1985). It is the recently developed model with respect to Finite Difference Method and uses integration instead of differentiation (Faust & Mercer 1980). A Finite Element Method mostly uses triangles to discretize the area being modelled, and variation in the head in each element is defined by means of an interpolation basis functioning head. Hydraulic heads are calculated at the nodes for convenience but they are defined everywhere by means of basis function (Anderson and Woessner 2002). The Finite Element Method produces large linear or non-linear systems equations which can be solved by computer programmes. The advantages of Finite Element Method is that it allows for the better description of the geometry, better treatment of thin sections and complex shape, better treatment of fluid flows and allows for stress calculation. The method, however, has some advanced mathematical basis and also difficult data inputs and programming.

2.9 Methods for quantifying groundwater-surface water interaction

Groundwater is a very important source of water which sustains both ecosystems and human communities' globally (Morris et al. 2003). It interacts with surface water in almost all the surface water bodies such as lakes, wetlands, and rivers. These interactions often result in groundwater altering the quality and quantity of surface water in these water bodies and also surface water altering the quality and quantity of groundwater in aquifers (Winter 1999). Understanding these interactions is very crucial for the effective management of the water resource. This section reviews common methods for assessing GW-SW interaction.

The degree of quantifying groundwater surface water interaction is highly dependent on various factors such as topography, underlying geology, subsurface hydraulic properties, temporal variation in precipitation and local groundwater flow pattern. In quantification of groundwater-surface water interaction, various methods can be used. The most common methods used in peri-urban settlements are seepage meters, temperature monitoring, hydrometric analysis, hydrochemistry and environmental tracers, Geophysics and remote sensing, water balance analysis, hydrogeological mapping and modelling.

2.9.1 Seepage meters

Seepage meters are made from bags joined to a bottomless cylinder .The cylinder is then turned into the sediments to capture groundwater as it enters the surface water to the bag attached at given time intervals. The change in volume of water contained in the bag is measured to quantify groundwater fluxes at different periods of time. To measure groundwater recharge, the bag attached to the cylinder is filled with water before the cylinder is turned to the sediments. The changes in volumes of water in the bag are then measured which indicate the amount of water entering groundwater (Lee 1977). The seepage meters are mostly applicable at a local scale for a short period of time. The advantages of these seepage meters are that they measure groundwater directly as it enters surface water bodies, they are not expensive to construct and they provide semi-qualitative data sets, (Brodie et al. 2007). However, errors might occur due to their design and operation and also are not applicable for high stream flow and heavy clay sediment and gravel bed. Seepage meters are suitable for this type of environment.

2.9.2 Temperature monitoring

The method uses temperature differences between groundwater and surface water to delineate groundwater quantity, recharge and discharge zones using devices such distributed temperature sensors and temperature loggers (Lowry et al. 2007). The method allows for an identification of general character of the flow regime by recording temperature time series in the stream and surrounding sediments (Constantz 1998). These are then used to determine whether the stream is a gaining stream or a losing stream. A gaining stream normally has stable sediment temperature and surface water temperature which varies daily. Losing stream is characterised by high variation in temperature of the bed sediment and surface water. Temperature variation in bed sediments at different depths shows that there's relative influence of groundwater and surface water processes (Binley et al. 2007; Oxtobee & Novakowski 2003). The advantage of this method is that it is cheap, simple and robust (Brodie et al. 2007). However, the method only measures at one specific point and when used for monitoring, it requires confirmation assessment using another method.

2.9.3 Hydrometric analysis methods

This is Darcy's law based method corresponding to techniques used to evaluate groundwater flows in terrestrial aquifers (Brodie et al. 2007). Darcy equation (2.9.1) requires the following variables to be measured in order to understand the exchange between the two resources.

$$q = -K \, {}^{\partial h}\!/_{\partial h} \qquad (2.9.1)$$

q =Specific discharge (L/T)

K = hydraulic conductivity (L/T)

h = Hydraulic head

l = distance (L)

The method involves the installation of mini-piezometers within the bed material of the surface water body at certain depths to determine vertical hydraulic gradient beneath the surface water body. Vertical hydraulic gradient would be the difference between the water levels measured from the surface water body and the piezometers installed (Cey et al. 1998; Oxtobee & Novakowski 2003). In each piezometer installed slug tests are normally carried out to determine hydraulic conductivity. However, other methods such as grain size analysis of the bed material may also be used to determine hydraulic conductivity. The hydraulic conductivity and vertical hydraulic gradient are then substituted in equation 2.6.1 to establish groundwater fluxes (Cey et al. 1998). The hydrometric methods are mostly applicable at local to regional scale over a short to medium term period. The method allows for direct measurement of groundwater seepage to a surface water body. However the method relies more on estimated hydraulic conductivity to measure groundwater discharge into the stream, (Brodie et al. 2007). The method also measures the interaction at one specific point.

2.9.4 Hydrochemistry and environmental tracers

The method uses chemical compositions of surface water and groundwater to evaluate the interaction between these two resources. One particular characteristic of groundwater chemistry is used as an indicator for groundwater discharge into the surface water bodies and also used to calculate hydrological and chemical fluxes between groundwater and surface water bodies (Cook et al. 2006). The most common environmental tracers which are used are in-situ measured parameters such as pH and electrical conductivity, the major anions and cations such as Magnesium, Calcium, Chloride and bicarbonate. The stable and radioactive isotopes are also used as environmental tracers. The hydrochemistry and environmental tracers are mostly applicable over a short to medium term period on a local to regional scale. These methods are useful in measuring groundwater and surface water fluxes, and also defining key hydrological processes (Brodie et al. 2007).However, the methods can have long lag time between sample collection and final analytical results.

2.9.5 Geophysics and remote sensing

The methods use geophysical and imagery techniques to assess groundwater surface water interaction (Gorelick 2006; Oxtobee & Novakowski 2003). These techniques include resistivity, EM and Landsat images to map the landscape features showing groundwater surface water interaction. The features which are normally mapped include vegetation types and saline areas in the landscape. These features normally show where groundwater surface water interaction is taking place. The methods are mostly applicable at a local to regional scale over a short to medium term. Geophysical and remote sensing methods allow for mapping of landscape parameters that have good spatial resolution and may provide information at depth. These methods, however, require specific equipment technical expertise and logical support.

2.9.5 Water balance analysis

The water balance approach has been used to quantify the interaction between groundwater and surface water. The approach involves quantification of stream reach water balance to define seepage components with the assumption that any gains or loss of surface water or any change in surface water properties can be related to the water resource. Therefore, groundwater components can be identified and quantified (Kalbus et al. 2006). The water balance approach is based on the equation

$$P = ET + D_s + D_g + dS \qquad (2.9.2)$$

P = precipitation

ET= evapotranspiration

Ds= surface water discharge

Dg= fresh groundwater discharge

dS= Change in water storage

The method is mostly applicable at an intermediate to regional scale over a short to medium term. Water balance approach provides an estimated aggregate of groundwater seepage along the reach. However, the method can provide misleading estimates if water balance components are not adequately accounted for.

2.9.6 Hydrogeological mapping

This approach involves the mapping of groundwater flow system within the particular catchment incorporating aspects such as hydraulic properties (Transmissivity and storativity), geological conformation, aquifer geometry, groundwater recharge and discharge mechanism. The method provides pertinent information when evaluating the extent and direction of groundwater-surface water interaction (Brodie et al. 2007). Hydrogeological mapping is mainly applicable at an intermediate to regional scale over short to medium term period. The advantage of using this method is that the method provides the conceptual understanding of groundwater systems around the particular stream where the interaction is assessed, also the hydrogeological factors which control the interaction. The method, however, can be time-consuming and complex since it involves the compilation and interpretation of hydrogeological data.

2.9.7 Modelling

Involves the quantification of groundwater-surface water interaction using mathematical equations built within software packages such as an excel spreadsheet, MODFLOW and FEFLOW. The values for the parameters for these mathematical equations are based on the field measured values. These models mathematically simulate water flow regime around the streams and also generate simulated hydraulic heads. The simulated hydraulic heads are then used to simulate groundwater flow directions and calculate groundwater discharge to the particular surface water body, (Kalbus et al. 2006). The method is mostly applicable at intermediate to regional scale over medium to long term period. The advantage of using a model in quantifying groundwater surface-water interaction is that changes in seepages can be estimated through time and space and also model helps in defining the gaps in information. The method, however, can be time consuming, costly and require more data sets.

2.10 Theoretical framework

The section covers theories guiding the study. The theories are infiltration theory and Darcy law. These theories are explained in details and also explained in relation to their use in the study.

2.10.1 Groundwater recharge

Groundwater recharge is defined by (Xu & Beekman 2003) as the downward flow of water reaching the water table adding to the groundwater reservoir. This means that the surface or rainwater percolates through the soil reaching the groundwater reservoir thereby causing a rise in the water table. Sun et al. (2013) reported four major types of groundwater recharge, which are the vertical or lateral inter-aquifer flow, Induced recharge from the nearby surface water bodies which resulted from abstraction of groundwater, artificial recharge which is as the result of injection of water into the boreholes, and the flow of water through the unsaturated zone reaching the water table. Objective 3 of the study focuses on assessing groundwater surface water interaction the theory of groundwater recharge is used in the explanation of the interaction between groundwater and surface water.

2.10.2 Theory of Darcy's law

Darcy's law governs fluid flow through the porous medium. The law states that the fluid flow through the porous bed medium shows direct proportionality to the differences in heights of fluid between the two ends of the filter bed, and inversely proportional to the length of flow path (Freeze & Cherry 1979). The law also states that the flow quantity is also directly proportional to the coefficient K which is dependent upon the nature of the porous medium. Darcy's law directly translates to figure 2.10(a).

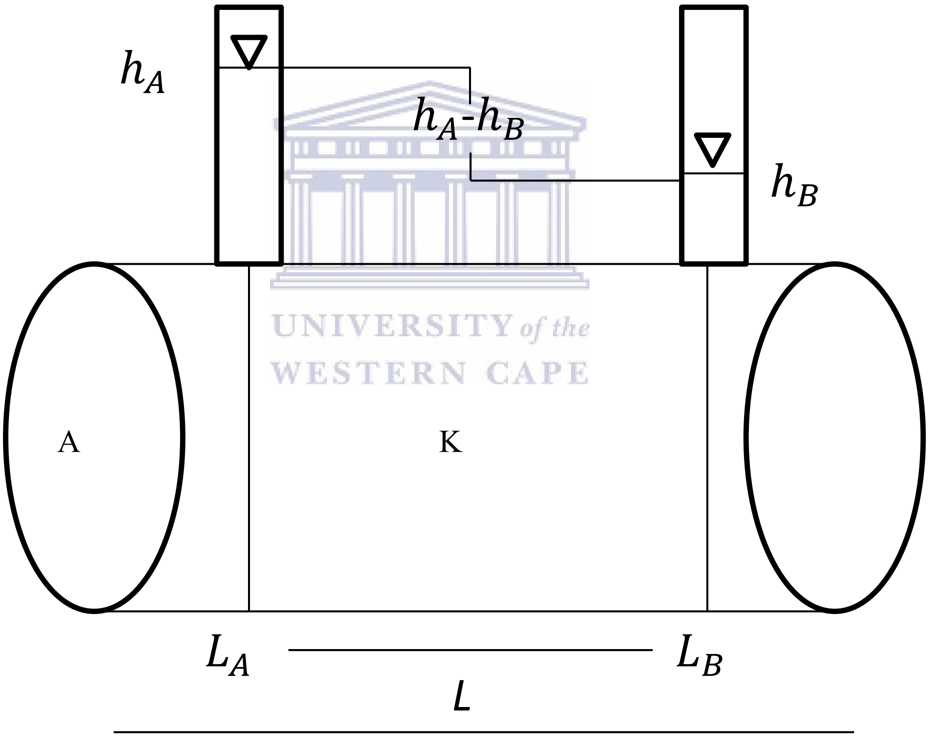


Figure 2.10(a): Schematic representation of Darcy's law

The figure 2.10(a) illustrates the example of the Darcy experiment, where water is applied at a known pressure to a horizontal pipe fitted with sand. The flow is from one end to another end. From the experiment Darcy found that discharge at the other end is directly proportional to the difference in heads measured between the ends, and inversely proportional to the flow length. The flow is also directly proportional to the cross-sectional area of the pipe. In this study the theory of Darcy’s law is used in explaining the results on objective two focusing on groundwater flow conceptualization of the Cape Flats Aquifer, where the Cape Flats Aquifer becomes the porous medium.

Chapter 3: Methods and research design

3.1 Introduction

Chapter 1&2 of this study covered in broader sense background, objectives, research questions, hypothesis and theories and practises guiding this work. The current chapter unpacks in detail methods and research design followed to achieve the three objectives of the study outlined in chapter 1. The following methods are discussed:

Step-down and constant rate tests

Theis analytical flow solution

Finite Difference Method

Groundwater and surface water sampling

Trillinear and isotopic analyses

The first section of this chapter describes research design and detailed description of the study area. The second section covers description of methods used in collection and analysis of data. The last section covers Ethical issues and study limitations.

3.2 Research design

3.2.1 Research design approach

The study followed the quantitative experimental design, involving the field measurements of mathematical data sets such as water table drawdown data which were used to estimate aquifer parameters and groundwater levels data used in calibration of the groundwater flow model developed. The study also collected water quality data which was used during the assessment of groundwater-surface water interaction in the area under study. Mathematical methods and models were used to analyse the collected data sets. These mathematical models included Theis solution which was used during the estimation of aquifer parameters and Finite difference method which was used in the conceptualization of local groundwater flow system.

3.2.2 Description of study area

The Cape Flats shown in figure (3.1) covers an area of approximately 630km^2 and is extending in the northern direction towards the west coast of South Africa. The area represents a region of the coastal sands between the Cape Peninsula and the mainland (Saayman & Adams 2002). Cape Flats is forming part of the large undulating sandy area connecting to the Cape Peninsula hard rock (Maclear 1995). This area is lowland, characterised by varied terrain which ranges from low-lying plains with the average elevation of 30m.a.m.a.l Adelana et al. (2010). Various land use activities are taking place within the area; these include formal and informal settlements, industrial areas, agricultural areas, open areas and even sand mining activities which significantly impacts groundwater movement, occurrence and quality of the shallow underlying Cape Flats Aquifer found in the area.

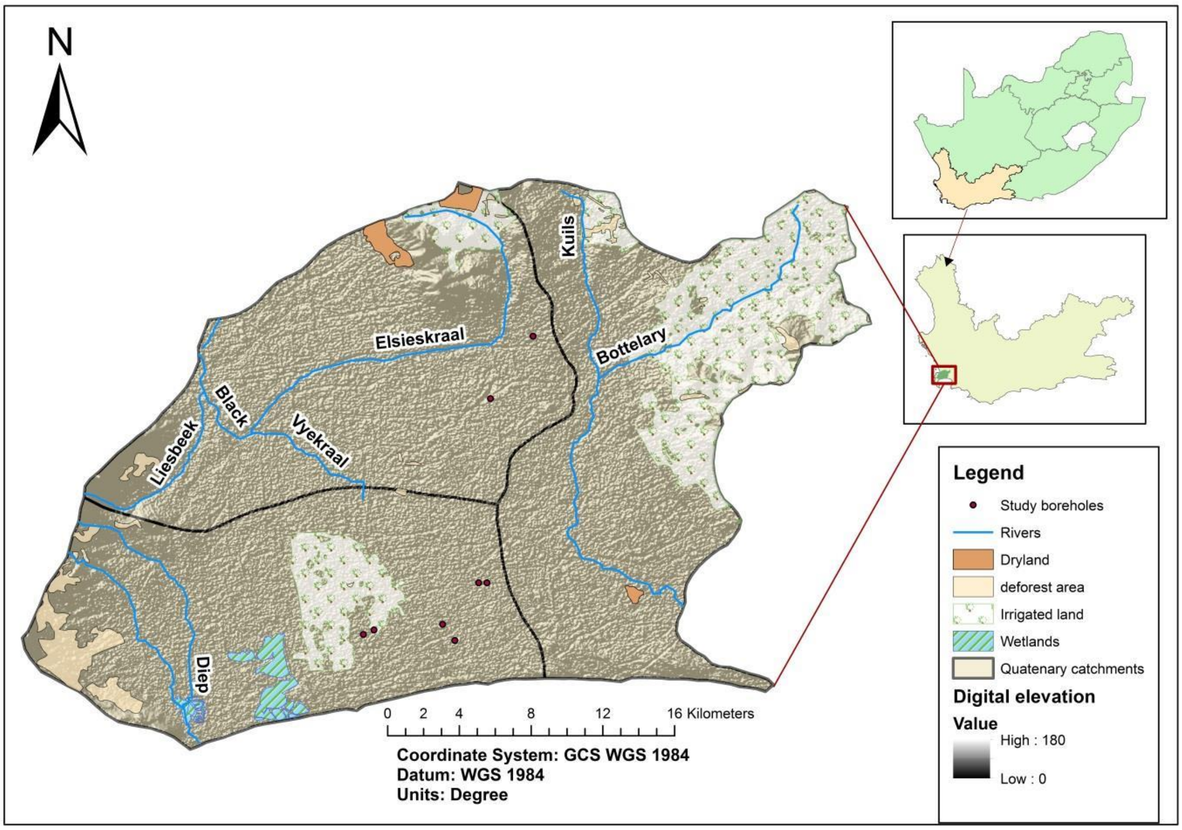


Figure 3.1: Study area map

- **Climate of the study area**

Climate by definition refers to the long-term change in weather conditions of a particular area. In this context, climate is referred to as rainfall and evaporation. Cape Flats falls within the Mediterranean climatic region characterised by wet winter seasons and dry summer seasons. The dry summers occur during the period of October to April and wet winter seasons during the period of May to September. According to Adelana et al. (2010), the area receives an average annual precipitation ranging from 400mm to 800mm with most of the rainfall occurring during the period of May to August. This has an important implication to groundwater recharge of the underlying shallow Cape Flats Aquifer as it is the shallow unconsolidated sandy aquifer recharged mostly by rainfall, and therefore in rainy season it is expected that more recharge will be taking place. The long-term average annual evaporation in the area according to Jones et al. (2014) is 2030mm/a and higher during the period of October to April ranging from 60mm/m to 300mm/m and lower during the period of May to September ranging from 55mm/m to 110mm/m.

- **Geology of the study area**

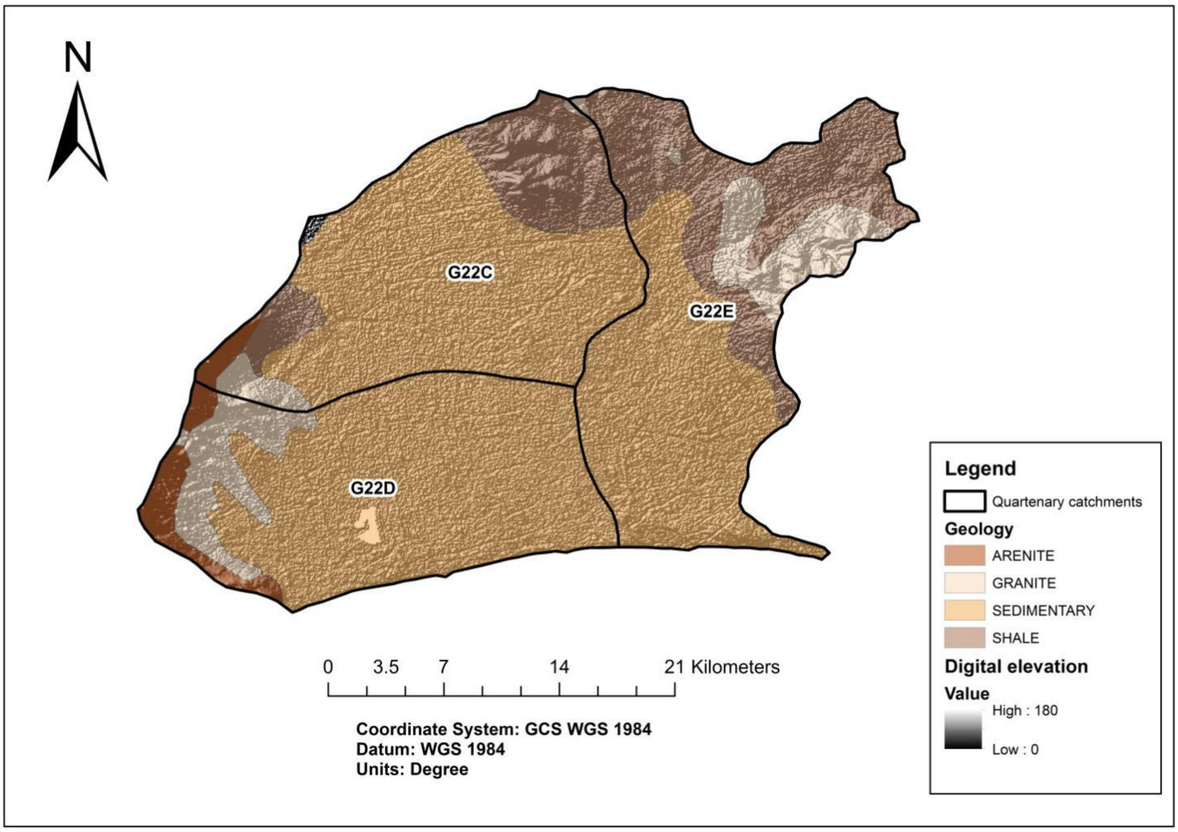


Figure 3.2: Geology of the research sites

The figure 3.2 shows the geological conformation of the Cape Flats. The area consists of Cenozoic sands overlying the Malmesbury shale (Tredoux et al. 1980). These sands cover the entire area and different sand formation exists. These are the Langebaan formation, Witzand formation, Springfontein formation, Elandsfontein formation, Velddrift formation and Varswater formation (Adelana 2010). The Langebaan formation is characterised by very fine to medium calcareous sands containing cross bedding along the coast. In the shorelines, the upper surface of this formation is seen as cliffs (Hartnady & Rogers 1990). Witzard formation forms very fine to coarse calcareous sand with shells forming vegetation bound coastal dunes. Velddrift formations are poorly consolidated intertidal sediments which are patchy deposited. Springfontein formation varies from fine to medium quartzes sands with grain size often increasing with depth. Varswater formation is of marine deposit with very fine to medium sands and often silty (Vandoolaeghe 1990). Elandsfontein consists of angular, fine to clayey sands (Tredoux et al. 1980). These formations control the rate and direction of groundwater flow within the area.

- **Hydrology of the study area**

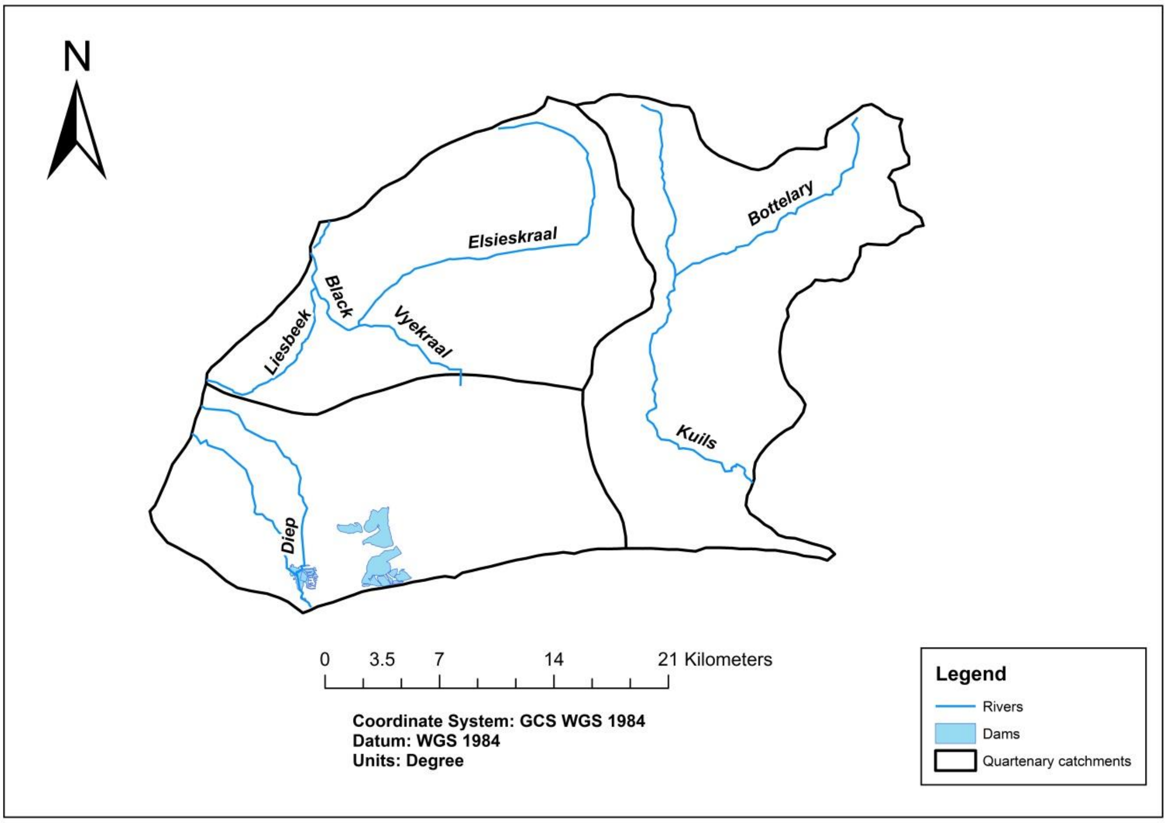


Figure 3.3: Hydrology of the Cape Flats

The figure 3.3 shows the hydrology on the Cape Flats. The area is characterised by a number of wetlands, Dams and streams flowing through and interacting with the shallow underlying Cape Flats Aquifer. Wetlands in the area include the Zeekovlei which is located in the southwestern part along the coastline. The wetland serves as habitat for a variety of different species. Streams in the area include Kuils River, Deep River, Vygekraal River, Black River, Liesbeek River and Elsieskraal River which are tributaries to major streams (Tredoux et al. 1980). Kuils River and Deep River are discharging to False Bay forming the southern boundary of the area (Adelana 2010). The Vygekraal, Black and Liesbeek River are discharging at Table Bay forming part of the northern boundary to the catchments understudy.

- **Hydrogeology of the study area**

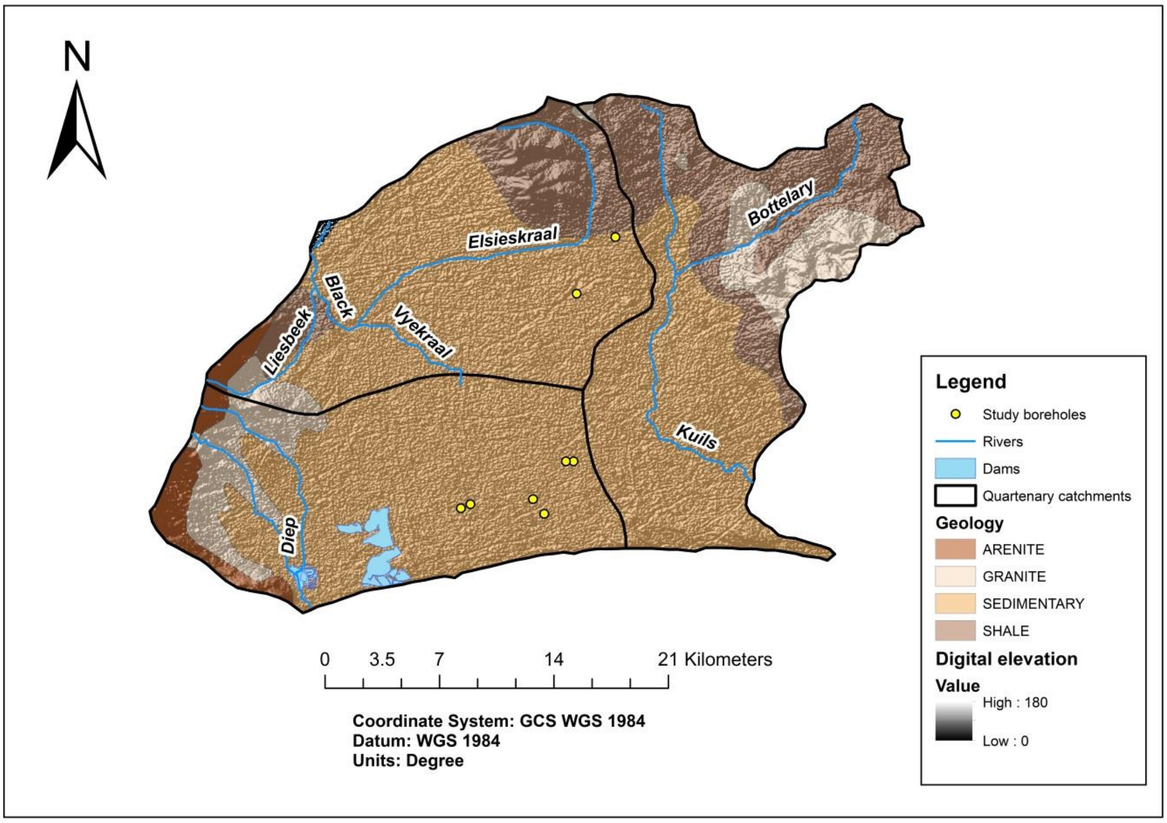


Figure 3.4: Hydrogeology of the Cape Flats Aquifer

The figure 3.4 shows hydrogeology of Cape Flats, which is characterised by the large undulating sandy aquifer known as Cape Flats Aquifer which is the central focus of this study. The aquifer forms shallow unconfined sand found within the central part of the area and pinches out against the impermeable rock forming the eastern, northern and western boundaries (Adelana 2010). Cape Flats Aquifer is mainly characterised by loose sands with interbedded clay and peat layer causing some parts of the aquifer to be semi-confined (Henzen 1973, Gerber 1976). Hydraulic conductivity of this shallow sandy aquifer varies spatially and range from 30-40 m/d in the central region and 15-50m/d within the eastern side. The typical storativity values range from 0.02-0.25 and transmissivity from <50-650m^2/d (Gerber 1979). Recharge to the aquifer is mainly occurring as a result of precipitation falling of the surface of the aquifer, even though there are some sources contributing to recharge of the aquifer which include leakages of sewer and water supply pipes and urban irrigation return flows. Some work on recharge estimation for the Cape Flats Aquifer was done by Adelana et al. (2010) however the recent work on recharge estimation was done by Hay et al. (2015) and the estimated value was 11.3Mm^3/annum. Groundwater levels are deepest during the period of December-March representing dry season and shallow during rainy season (April-July). The direction of groundwater flow is from high elevation area to lower elevated areas towards the coastline.

3.2.2 Selection and description of the study sites

To capture the full extent of Cape Flats Aquifer the study selected 5 different sites located in northern middle and southern parts of the aquifer. These sites are Bellville old department of water affairs offices well field located in the upper part of the aquifer, the university of the Western Cape well field located in the upper middle part, Phillipi horticultural area well field located in the lower middle, Westridge stadium well field located in the lower part and Lenteguer hospital well field also located within the lower part of the aquifer. Some groundwater monitoring points within the Khayelitsha area located along the False Bay coastline were also included in the study.

Bellville well field

Image above shows the Bellville well field located within Bellville area behind the old department of water affairs and sanitation offices (33°54’05.17”S and 18°38’40.71”S). The site is located within the highly developed area and is bounded by shopping centres, schools, residential areas, highways and municipality buildings. The well field consists of 4 boreholes all tapping from the Cape Flats Aquifer. Two rivers are located in the vicinity of the area. These are the Elsieskraal River and Kuils River. The site was chosen because it is within the northern part of the Cape Flats Aquifer and the assumption is that groundwater in this aquifer flows from the upper part towards the lower parts closest to the False bay Coast.

UWC well field

The University of the Western Cape well field falls with the quaternary catchment G22C (33°55’57.82”S and 18°37’24.37”E). The site is bounded by university buildings, industrial areas and residential areas. There are 6 boreholes which are found within the site, two of these boreholes penetrate deeper to the Mamulsbury aquifer and the other 4 penetrating only the Cape Flats Aquifer. These boreholes were drilled by the Department of water affairs in 2001 to gain an insight of the aquifer systems within the area. Since then these boreholes were adopted by the Institute of groundwater studies at the University of the Western Cape for practical purposes by undergraduate students and research purposes by postgraduate students at this institution. The site was chosen in this study because it is located in the upper middle part of the aquifer.

Phillipi Horticultural area

The Phillipi well site is located at 34°02’58.09S and 18°33’47.97 E within the lower middle part of the Cape Flats Aquifer. The site falls within G22D quaternary catchment and is mainly dominated by farming activities. Some of the vegetation grown in the area includes cabbages, carrots, potatoes, lettuce, onions and cauliflower (Meerkotter 2012). In this site, groundwater is pumped from the Cape Flats Aquifer and stored in ponds for irrigation purposes. Groundwater salinity studies in the area revealed that groundwater is brackish (Aza-gnandji et al. 2013).

Westridge stadium site

The Westridge stadium site is located between 34°02’52.20”S and 18°35’58.05” within the middle part of the Cape Flats Aquifer. The study site is the sports field and is bounded by mainly highways and residential areas. There are two shallow boreholes in the sites which are mainly used for irrigating the sport field. These boreholes are each 12 meters deep and are located furthest apart.

Lenteguer Hospital

The Lenteguer hospital site is situated between 34°01’27.07”S and 18°37’16.34”E within the southern part of the Cape Flats Aquifer. It is located within the quaternary catchment G22D, and is bounded by residential areas, hospital buildings and highways which sometimes might have significant impact on groundwater recharge. There are 4 boreholes within the sites and are all penetrating the Cape Flats Aquifer.

3.2.4 Analysis of study population

The study used boreholes, rivers and wetlands within the upper, middle and lower part of the aquifer as the study population. All boreholes used in this study penetrate through the Cape Flats Aquifer only. Rivers and wetland used are also on the surface of the Cape Flats Aquifer. The reason for choosing borehole penetrating Cape Flats Aquifer only is that the study used Cape Flats Aquifer as a case study to demonstrate how the concept of urban hydrogeology facilitates decision-making regarding the implementation of WSUD.

3.2.5 Sampling design and size

Various sampling design and approaches exist. These include purposive, reliance, cluster random sampling design amongst other. The study used a combination of purposive and random sampling design. Firstly a site reconnaissance was carried in 2015 to identify potential sites to conduct the study. During the time period potential sites for assessment of groundwater and surface water interface were identified, also borehole surveys were carried out to understand their spatial distribution for aquifer characterization. With the help of Principal aquifer setting method, surface water sampling points were identified for the assessment of gw-sw interaction and groundwater sampling points were randomly selected based on their closeness to the surface water sampling points. A total of 16 surface water sample points were identified and 16 groundwater sample points were selected.

For aquifer characterisation the idea was to capture the full extent of the aquifer, therefore experimental sites were chosen within the upper, middle and lower parts of the aquifer. Within the upper part of the aquifer, Bellville well field was chosen. The site consists of 2 wells and 1 monitoring piezometer. The experiment was conducted on the two boreholes. Within the middle part of the aquifer, two sites located in the upper middle and lower middle parts were chosen. The upper middle was UWC well field consisting 7 borehole points and 3 boreholes within the area were chosen. The lower middle part was Phillipi well field which consisted of 3 boreholes and 2 were selected. The lower part of the aquifer was Lenteguer hospital and Westridge stadium. In Lenteguer hospital 1 borehole was chosen and at Westridge 1 borehole was chosen.

3.2.6 Unit of analysis

For objective 1 which focused on estimating aquifer parameters using Theis solution, unit of analysis were transmissivity and storativity estimates for all borehole points distributed across the Cape Flats Aquifer. For objective 2 focusing on conceptualizing local groundwater flow system for the Cape Flats Aquifer, unit of analysis were hydraulic heads of fluxes and outflows. For objective 3 focusing on assessing groundwater surface water interaction using Principal aquifer setting, hydrochemical and environmental isotope analysis, the unit of analysis were principal aquifer settings, general chemistry parameters, major cations and anions and stable isotopes such as ^{18}O and ^{2}H measured from both groundwater points and surface water point under study.

3.3 Data collection methods

3.3.1 Estimation of aquifer parameters

- Data collection method and parameters measured

A variety of aquifers tests which are carried out to collected data for aquifer characterization exist. These include Slug tests, Bailer test, step down tests and constant rate pumping tests amongst other. These tests serve for the different purposes but the common purpose is that they all collect data used when estimating aquifer parameters. Slug tests are conducted in geological formations that exhibit low hydraulic conductivity and these involves the abrupt removal of a certain volume of water and observing the subsequent changes in water levels as an equilibrium condition returns. Bailer test is that test which involves the removal of water from the well using a bailer. Step down test is used to evaluate the performance of a particular well under a controlled discharge rate. The test involves increasing the discharge rate from an initially low constant rate through a sequence of pumping intervals of progressively higher constant rates. The intervals are of equal duration. Constant rate test involves the pumping of water out from the aquifer at a constant discharge rate and measuring the response from the surrounding observation wells.

To achieve objective 1 of the study which was focused aquifer parameter estimation, the current study used two types of hydraulic testing to collect data. These are the step-down test and the constant rate test. The step-down test was carried out in order to establish the rate at which the aquifer was going to be pumped at during the constant rate test and for aquifer parameter estimation. The constant rate test was also used to collect data sets for aquifer parameters estimation. The two types of test were chosen because they allow for the generation of data that allow for estimation of aquifer parameters; however, the tests are time-consuming and expensive.

The following parameters were measured prior and during these hydraulic testing:

- *Static water levels*- were measured before pumping started in both the pumping well and observation well. This variable was used calculating drawdown during pumping and recovery for each hydraulic testing.

- *Well diameter*- This was measured prior pumping in both pumping and observation wells and was used when estimating storativity for the pumping well in each hydraulic testing.
- *The distance between pumping and observation well*- This parameter was also measured before the pumping starts. It was used when estimating the storativity for the observation well in each hydraulic testing site.
- *Well location, Depths and elevations*- measured before pumping for both the pumping and observation well in each site.
- *Discharge rate*- The variable was measured during the pumping period for both hydraulic tests. It was used when estimating both Transmissivity and Storativity for each hydraulic testing.
- *Depth to water level*- This was measured at intervals during pumping and recovery for both hydraulic testing. The parameter was used when calculating the drawdown for pumping and recovery period in each hydraulic testing.

- Step down hydraulic test procedure

The Step-down test was carried out for 6 hours at each site. During this test, the time period was sub-divided into two equal intervals. The other interval was a pumping period and the other one was the recovery period. Pumping period was further sub-divided into three equal intervals of 1-hour duration each. For the first interval, water was pumped out at the rate of 1l/s. The response was measured at intervals in the observation well using TLC water level metre. In the second hour, the discharge rate was increased to 2l/s and response was measured at intervals. In the last hour, the discharge rate was increased to 3l/s and the response was measured in intervals in both the pumping and observation well. After the pumping period, the pump was switched off to allow the aquifer to recover for further 3 hours. Depth to water was monitored continuously for further three hours during the recovery period and was measured at intervals in both the pumping and the observation well. The data collected was then used to calculate the optimum rate which was used to carry the constant rate test.

- Constant rate hydraulic test

A constant rate test was also conducted at a rate of 3l/s for a period of 6 hours at each site because it is believed that to get the most reliable data; the overall duration of the pumping test should be at least 12 hours. The test was conducted immediately after the step-down test. In conductance of this test, the study followed the principle of hydraulic testing discussed by Freeze & Cherry (1979) where a stress was applied to the aquifer by pumping water at the constant rate of 3l/s from the pumping well, and measuring the aquifer response from stress in both pumping and surrounding observation wells. The duration of the pumping of water was 3 hours and the response was measured at intervals in the observation and pumping well. The rate that the test was carried out was established using the step-down test data. After the 3-hours, the pump was switched off. Water level depth was continuously monitored for another 3 hours and measured at intervals as the aquifer recovers.

3.3.2 Groundwater flow system conceptualization

To collect the data set that was used when setting up the groundwater model for the area two methods were used. These are record review and field measurements. The record review was used to collect already existing data set such as Geological, hydrological, climatological and geographical data set as these data are required when setting up a model. Geological data sets collected included boring log data, geological maps and geological cross sections of the study area. The hydrology data collected included the production well data, monitoring well data, previous investigations on the aquifer and surface waters. Climatological data that was collected included the rainfall data, evapotranspiration and distribution which was used in quantification of site-specific groundwater recharge rates. Geographical data sets collected included soil maps, land use maps, aerial photographs and topographical maps. The records that were reviewed are reports from government agencies, states, local and private organisations. Water levels were monitored on a bi-monthly basis on boreholes within the sites and were used during calibration process.

3.3.3 Assessing groundwater- surface water interaction

There are a number of different methods which are commonly used to assess groundwater-surface water interaction. These methods can be grouped as field measurements methods and desktop methods. Field measurements methods include hydrochemistry analysis, hydrometric analysis method, seepage meters, environmental tracers, artificial tracers, stable isotope analysis, heat tracer methods, geophysical and remote sensing, water budget and field indicators. The desktop methods include hydrographical analysis, hydrogeological mapping and modelling. All these methods differ in terms of their application, procedure, spatial and temporal scale. To achieve objective 3 of the study which was focusing on assessing groundwater-surface water interaction, Principal aquifer setting method was chosen as a qualitative method to identify potential sites for groundwater surface water interaction, however, the method does not allow for quantification of the interactions. Hydrochemistry and environmental isotope analysis were chosen as confirmatory methods for the interactions

I. Principal aquifer setting

- Data collection method

Data was collected using field trial measurements and review of records from various sources. The field measured parameters included groundwater levels which were measured during dry and wet season and boreholes elevations. The data collected through the review of records included the geological data, surface topographical data and groundwater levels data. The records reviewed were from sources such as the DWS, CoCT and CSIR.

- Data collection procedure and tools

During the field measurements of groundwater level, a procedure discussed by Weaver et al., (2007) was followed, where the sensor of dip meter was lowered down in each borehole understudy until the buzzer went on notifying the researchers that it had reached the water. The measurements were then taken using the datum point which was marked by the top of borehole casing. This measurement was rechecked and recorded to improve the accuracy of the data collected. A Field measurement of borehole elevations was done using GPS with less than 5% error margin. During these measurements, GPS was placed next to the borehole point and elevation values read were recorded.

II. Environmental isotope analysis

- Data collection methods

For environmental isotopes analyses, field sampling was carried out during dry and wet season. The samples were collected in April for the dry season and in June and July for the wet season. Secondary dataset of the isotopes was also collected from reviewed records from Department of Water and Sanitation, Council of Scientific and Industrial research and the City of Cape Town.

- Data collection procedure and tools

During sampling for environmental isotope analysis, grab sampling technique was adopted for sampling on rivers, wetlands, boreholes and rain gauges within the study area. Before the sampling of boreholes, purging was done. Purging was done to remove all the stagnant water that has been in contact with atmosphere and borehole material. During purging of boreholes a procedure discussed by Weaver et al. (2007) was adopted where rest water levels were measured from boreholes using TLC water level meter, followed by the removal of known volumes of water from the borehole and simultaneously measurements of general chemistry parameters such as pH, EC and Temperature using water quality multi-parameter device. After these field parameters stabilised the water samples were then collected because it was assumed that the water is derived from the geological materials as opposed to the stagnant borehole water. The samples in rivers, wetlands, rain gauges and boreholes were collected in plastic isotopic bottles with tight fitting caps. These plastic bottles were thoroughly rinsed before filling and were then filled to the top and tightly closed to prevent evaporation which might alter the isotopic ratio in the samples. Care was taken to ensure the correct labelling, packaging and transportation of samples to prevent spillage and/or misinterpretation of laboratory results due to incorrect labelling. The samples were preserved in the cooler box containing ice to keep the temperature standard which can enhance evaporation.

III. Hydrochemical analysis

- Data collection methods

During the collection of hydro-chemical dataset sampling was done during the wet and dry season. The dry season samples were collected in February and April 2016, and wet season samples were collected in June and July 2016. Secondary datasets were also collected from the review of records.

- Data collection procedure and Tools

During the collection of hydrochemical data, both groundwater and surface water were sampled using a grab sampling approach, where samples were collected using plastic bottles after purging and at the stream surface within the research sites. Weaver et al.(2007) described the procedure and methodological approach that were followed during this exercise. First, before the purging of the borehole, static water levels were measured using a TLC water level meter. Once the water levels were measured, three well volumes were removed as part of the purging process. The reason for this purging process is to remove all of the water standing in the borehole casing that has been in contact with the atmosphere and the borehole casing material. Once the recorded field parameters (pH, EC and Temp) have stabilised, it is assumed that the water is derived from the geological materials as opposed to the stagnant borehole water. The final measurements were taken along with the collection of water samples for hydrochemical analysis. Care was taken to ensure the correct labelling, packaging and transportation of collected water samples to prevent hydrochemical changes, spillages and/or misinterpretation of laboratory results due to incorrect labelling. As a precaution, latex gloves were brought along to each sampling campaign to prevent the practitioners from contracting unwanted illnesses or chemicals onto their skins.

3.4 Data analysis methods

3.4.1 Estimation of aquifer parameters

3.4.1.1 Data analysis methods

To analyse data set collected from two hydraulic tests, Theis analytical flow solution was used. As discussed in chapter 2 section 2.7, Theis analytical flow solution studies the transient groundwater movement as a result of pumping in confined aquifer. The solution was formulated under the assumption that total stress to the aquifer is constant and the mechanical behaviour of the confining unit was neglected. Theis solution in this study was chosen because Cape Flats Aquifer is assumed to be homogeneous at the experimental sites and of infinite extent, which these are some of the assumptions of Theis solution.

3.4.1.2 Data analysis tools/ software

The analyses were done using Aqua test software and excel spreadsheet. Aqua-test is graphical interface software created by Sun and Xu. The software allows for the selection of the variety of solutions based on boundary condition of the area under study. For The current study infinite boundary which is solved using Theis within the software was chosen. Microsoft excel was used to plot out semi-log drawdown versus time graphs which are required in manual calculation of T & S using Theis equations.

3.4.1.3 Data analysis procedure

- Aqua-test analysis

Data was prepared prior the input to Aqua-test software. In preparation, drawdowns were calculated from the static water levels and dynamic water for different time intervals and tests. After preparation, data was imported to the software and was run using the Theis infinite extent assumption to produce a graph of drawdown versus time with the estimated T and S values. The estimation was done for observation boreholes only as the observation well data represent natural drawdown.

- Excel spreadsheet analysis

Time versus drawdown scatter graphs were plotted on semi-log axis in an excel spreadsheet. The straight line was the fitted to the points. Two points were then randomly selected on a log cycle. These points were then used to calculate the change in hydraulic heads. The discharge rate measured during the pumping tests was also used together with the change in hydraulic head on simplified Theis equation for transmissivity to estimate transmissivity. To estimate storativity, the transmissivity estimated together with the distance between the pumping well and the observation well and an intercept of which is the value taken where the fitted straight line intersects with the x-axis of the semi-log plot were then used in the simplified Theis equation for storativity to estimate storativity. The same procedure was followed for the analysis of data collected during the recovery period.

3.4.2 Groundwater flow system conceptualization

3.4.2.1 Groundwater modelling method

To model local groundwater flow system of the Cape Flats Aquifer, 3-dimensional homogeneous anisotropic steady state numerical groundwater flow equation was solved equ (3.4.2a). This equation was solved using MODFLOW code which is the Finite Difference Method. As discussed in section 2.8 in chapter 2, the Finite Difference Method discretizes the domain area by rectangular quadrilateral grid cells and heads are approximated at the centre of each cell. MODFLOW code was chosen because it is the oldest used and proved to be useful for solving 3 dimensional partial differential equations.

$$K_{xx}\frac{\partial^2 h}{\partial x^2} + K_{yy}\frac{\partial^2 h}{\partial y^2} + K_{zz}\frac{\partial^2 h}{\partial z^2} + \frac{Q_s}{V} = 0 \qquad (3.4.2a)$$

Where:

$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2}$ Is the net inflow into each grid cell of the domain from the x, y and z-direction.

$\frac{Q_s}{V}$ Is the external source or sinks within the aquifer.

$K_{(x,y,z)}$ Hydraulic conductivity

3.4.2.2 Tool and software packages

The software package that was used during groundwater modelling in this study is the Model muse. The software is a graphical interface software developed by Winston (2009). Model muse has built in MODFLOW code which solves finite difference equations. ESRI ArcGIS 10 was also used for the production of maps and processing of various data sets for model input. Golden surfer version 9 was used to develop conceptual models and data preparation for numerical model development. SedLog software was also used to do the borehole logging.

3.4.2.3 Procedure

During the development of numerical groundwater flow model for the Cape Flats Aquifer, the data collected from two methods was assembled to develop a hydrogeological conceptual model for the aquifer using ArcGIS and Golden surfer software. After conceptual model development, the numerical model was then designed using MODFLOW-2005 code. The model design step included importing the hydrogeological map of the research site to the software and selecting the model domain. After the selection of model domain, the area was then discretised using 5x5m grid cells which were subdivided to 0.1×0.1m for the site of focus, then boundary conditions were set out. The boundary included the no-flow boundary and constant head boundary conditions which included the lakes, rivers and watershed. The next step was to specify the flow parameters such as hydraulic conductivity, recharge from all sources, aquifer thickness and external stresses such as pumping wells and drains. When the flow parameters were specified then the model was executed. After the execution, the model was calibrated such that the simulated hydraulic heads matches the observed hydraulic heads directly measured from the field work. Sensitivity analysis was then performed after calibration by varying different input flow parameters to check how sensitive the model to such changes. The last step was predicting various scenarios using the model developed.

3.4.3 Assessing groundwater surface water interaction

I. Principal aquifer setting

- Data analysis method

Groundwater levels, geological and surface elevations were analysed using a R^2 value determination equation (3.4.3a) together with a method discussed by Fernald & Guldan (2006). R^2 determination equation was used mainly to assess the relationship between the groundwater levels elevations data and surface topography. The method by Fernald & Guldan (2006) was used to determine groundwater flow directions and to establish possible sites of groundwater surface water interaction based on the geological composition, groundwater flow directions and surface topography of the area under study.

$$R^2 = \Sigma(Y_i - Y_i')/\Sigma(Y_i - Y') \qquad (3.4.3a)$$

Yi individual data point value

Yi' value from the line of best fit

Y' average *Yi* values

- Analysis procedure and tools

To analyse the data collected, firstly the geological data was used to delineate groundwater units within the area based on principal aquifer type's classification table reported in Le Maitre & Colvin (2008), in order to understand the nature of groundwater flow and discharge within the area. This was done using Arc Map within ArcGIS version 10.1 software package, where the geological coverage was imported to Arc Map and clipped to represent the area under study and classification reported in Le Maitre & Colvin (2008) was then used to manually delineate groundwater resource units. Secondly, groundwater level elevations were calculated by subtracting the depth to water measured from the borehole from the elevations of the surface near the borehole points, in order to understand elevation of groundwater table within the area. The groundwater elevations were then correlated with surface water topography in an excel spreadsheet to assess the relationship between the two variables to see how groundwater levels conform to surface elevations and to also establish groundwater flow direction. When groundwater flow directions were established, they were then mapped using Golden surfer version 9 software packages together with the study area and surface water features base map. The vector map created using surfer software showing the groundwater flow directions and surface water feature maps were interpolated with the delineated groundwater units using Arc Map and locations of groundwater surface water interaction were identified manually based on where the groundwater flow nets intersect the surface-water features on the map.

II. Environmental isotope analysis

- Data analysis method

The analysis of isotopic samples collected was done at the environmental isotope laboratory at the University of the Western Cape in Cape Town using the Laser spectrophotometer. The analysis was done following the standard method and results are given in the δ unit defined by the following equations.

$$\delta^{18}O = [(R_{sample} - R_{standard}) / R_{standard}]*1000 \qquad (3.4.2b)$$

$$\delta^{2}H = [(R_{sample} - R_{standard}) / R_{standard}]*1000 \qquad (3.4.2c)$$

Where:

R_{sample} and $R_{standard}$ represent $\delta^{18}O$ and $\delta^{2}H$ ratios for samples and standards, respectively. The standards used during the analysis were the avian water which was used as the high standard;

UWC borehole 4 water was used as the low standard and combination of equal volumes of avian water and UWC borehole water were used as the medium standard.

- Data analysis procedure

During the analysis of isotopic signature, the samples were filtered using 0.25mS filter to a vial of 1.5ml and vials were tightly sealed and placed in a vial tray. The reason for filtering samples was to prevent the effect of VOCs on the functioning of the laser absorption spectrometry. The trays were then placed in the syringe rack which was taking samples from the vials through the syringe needle. Six runs were performed for each sample to ensure the accuracy of the results. Care was taken to prevent the effect of evaporation on the isotopic signature during the filtering process. The data of stable isotopic signatures were graphically represented along the global meteoric water line suggested by (Craig 1961). Similarities between groundwater and surface water stable isotopic signatures were then manually identified, once groundwater and surface water points cluster together that was assumed they are similar in terms of isotopic signatures and that suggest interaction.

III. Hydrochemistry analysis

- Data analysis method

Groundwater and surface water samples collected for hydrochemistry analysis were sent to Bemlab for the analysis of major ions such as Ca^{2+}, Mg^{2+}, Na^{2+}, K^{+}, HCO_3^{-}, SO_4^{2-} and Cl^{-}. The analysis was done following the SANS hydro-chemical analytical procedure. The results of the analysis were verified using the Cation-Anion balance (CAB) to evaluate the reliability of the dataset and was subjected to descriptive statistics to summarise and to trilinear piper plots to identify dominant water types.

- Data analysis procedure

Hydrochemistry samples were sent to Bemlab for analysis of major ions and the analysis was done following the standard SANS procedure. Before analysis of the data from Bemlab was subjected to the anion-cation balance reported in Younger (2009). According to Younger (2009) any sample with an anion-cation balance <5% can be used and between 5-10% can also be used with caution, any sample with >15% cation anion balance must not be used. In the study samples with less ≤15% were used. After the check, samples which passed the cation-anion balance were subjected to trilinear piper plots using AQUACHEM software to characterise groundwater and surface water types. The intention was to check any similarities in groundwater and surface water types, with the assumption that similarities suggest interaction.

3.5 Quality assurance and quality control

3.5.1 Validity of results

How urban hydrogeology facilitates water sensitive urban design implementation cannot be measured directly, however measurements of components of urban hydrogeology such as aquifer parameters and groundwater flow system amongst other, can give information which can be used to provide an explanation of how urban hydrogeology facilitates water sensitive urban design implementation. In this study, measurements were done to estimate aquifer parameters, conceptualize local groundwater flow system and assessment of groundwater surface water interaction. The information generated on these aspects was then used to provide an explanation of how urban hydrogeology facilitates water sensitive urban design implementation. Even though the study did not measure directly how urban hydrogeology facilitates WSUD implemented, but information generated from the aspects of urban hydrogeology measured in this study allowed for such.

3.5.2 Reliability of results

To ensure the reliability of the aquifer parameter estimation results, the estimates obtained were compared with those estimates by previous authors such as Tredoux et al. (1980), (Gerber 1976) and Adelana (2010) who also estimated the aquifer parameters of Cape Flats Aquifer using the same boreholes as the study. To ensure the reliability of the results on local groundwater flow system simulation, comparison of the simulated hydraulic heads with those measured from the boreholes within the study sites were done and calibrations were performed to minimise residuals. To ensure the reliability of the results on groundwater surface water interaction, water quality parameters data were subjected to cation-anion balance (CAB) using equation (3.5.2) following the principle of electroneutrality stating that water cannot carry the net electrical charge, but must always be electrical neutral. According to (Younger 2007) all water samples conform to the principle of electroneutrality, this means that a value of < 5% in cation anion balance for a certain sample is more accurate and that sample can be used and a value between 5-15% that sample can be used with caution anything greater that 15% is not used. The results were also compared with those of the similar studies done within the area of similar setting

$$CAB(\%) = 100 \times \frac{\Sigma(cation\ concentration) - \Sigma(anion\ concentration)}{\Sigma(cations + anion\ concentration)} \qquad (3.5.2)$$

3.5.3 Science of heterogeneity

In this study, research sites chosen for the estimation of aquifer parameters and assessment of groundwater surface water interaction, were from the upper, middle and lower part of the aquifer. The assumption was that the aquifer is heterogeneous in terms of its geological confirmation, therefore estimating parameters and assessing groundwater surface water interaction in one site will not be representative of the entire Cape Flats Aquifer hence different sites within the aquifer were chosen.

3.6 Statement of ethical consideration

Permission to access privately owned boreholes and sites were obtained from the owners through the verbal agreement. Permission to access Department of water and sanitation boreholes and secondary data was obtained through the verbal agreement between the University of the Western Cape and the Department of water and sanitation. Permission to use data from the South African Weather Service was obtained through the agreement between the researcher and the institution. The attached non-disclosure form in addendum (C) serves as evidence. The permission to use data from the City of Cape Town and Council of Scientific and Industrial Research was obtained through the verbal agreement between the researcher and the institutions.

The benefits and risks associated with the research were clearly stated to the private owners of boreholes during the verbal agreement, and appointments were made prior each field visits through telephonic communications in-order to avoid denial of access to sites with boreholes. To avoid doing harm to the environment and to people the study did not use anything which can cause harm to environment and people. The study did not introduce any tracer to the environment during the assessment of groundwater surface water interaction, which can potentially change groundwater quality and end up harming the environment. When conducting pumping tests water was discharged properly and also after each test and sampling trip the boreholes were locked to avoid vandalism and stealing.

3.7 Limitations of the study

The first limitation of the study was the lack of previous studies done focusing on urban hydrogeology within the context of water sensitive urban design in the area. This prevented the analysis of trend and gaps in knowledge were not being clearly identified. The study solved this limitation by doing field measurement of the essential parameters and also conceptualization of the study. This provided an important first stepping stone for further detailed studies on the similar topic.

The second limitation of the study was time for collection of large amount data sets to clearly observe the trends over the longer term. This limited the understanding of trends in parameters being analysed for in the study. This limitation was overcome through the use of research design which enabled the generation of the key important aspects about groundwater surface water interaction, aquifer parameters and groundwater flow system.

The last limitation to the study was access to vehicles to for transportation of equipment and accessing the sites. This limitation caused a delay in time for the collection of data sets. To overcome this limitation, suitable vehicles were hired in-order to transport the equipment needed and accessing sites with bumpy roads.

Chapter 4: Aquifer parameters estimation

4.1 Introduction

Aquifer parameters play a pertinent role in groundwater resource management. These allow for determination of groundwater potential for a specific aquifer and can give an indication of the magnitude of influence that a certain stress has on the particular aquifer. Stress to the aquifer could be due to groundwater abstraction or artificial recharge. This chapter presents and discusses results on aquifer parameter estimation for the Cape Flats Aquifer, Thereby addressing objective 1 of the study outlined in chapter 1, which was to estimate aquifer parameters using Theis analytical flow solution. The intention was to suggest possible areas for implementation of Managed Aquifer Recharge (MAR) suggested by water sensitive urban design (WSUD) principles. The central argument in this chapter is that if the spatial distribution of aquifer parameters is well understood prior to managed aquifer recharge planning, then implementation of managed aquifer recharge would be facilitated. The question asked then was to what extent does the understanding of aquifer parameters distribution of the Cape Flats Aquifer assist in facilitating managed aquifer recharge implementation. The problem being addressed in this chapter is the lacking of consistent monitoring of aquifer parameters for the Cape Flats Aquifer in the context of WSUD.

To achieve objective 1 on aquifer parameter estimation, the study collected quantitative primary datasets from field measurements taken during step down and constant rate hydraulic testing. Secondary data sets were also collected from review of records from various sources such as the Department of water and sanitation, City of Cape Town Municipality and Council of Scientific and Industrial Research. Parameters that were measured during the collection of primary datasets included static water levels, well diameters for both pumping and the observation wells, flow rates, depth to water levels. The collected dataset were then analysed by Theis analytical flow solution. The analysis was done using Aqua test graphical interface software and semi-log plots on excel spread sheet.

4.2 Key results on parameters estimation

4.2.1 Results from Theis using Aqua-test

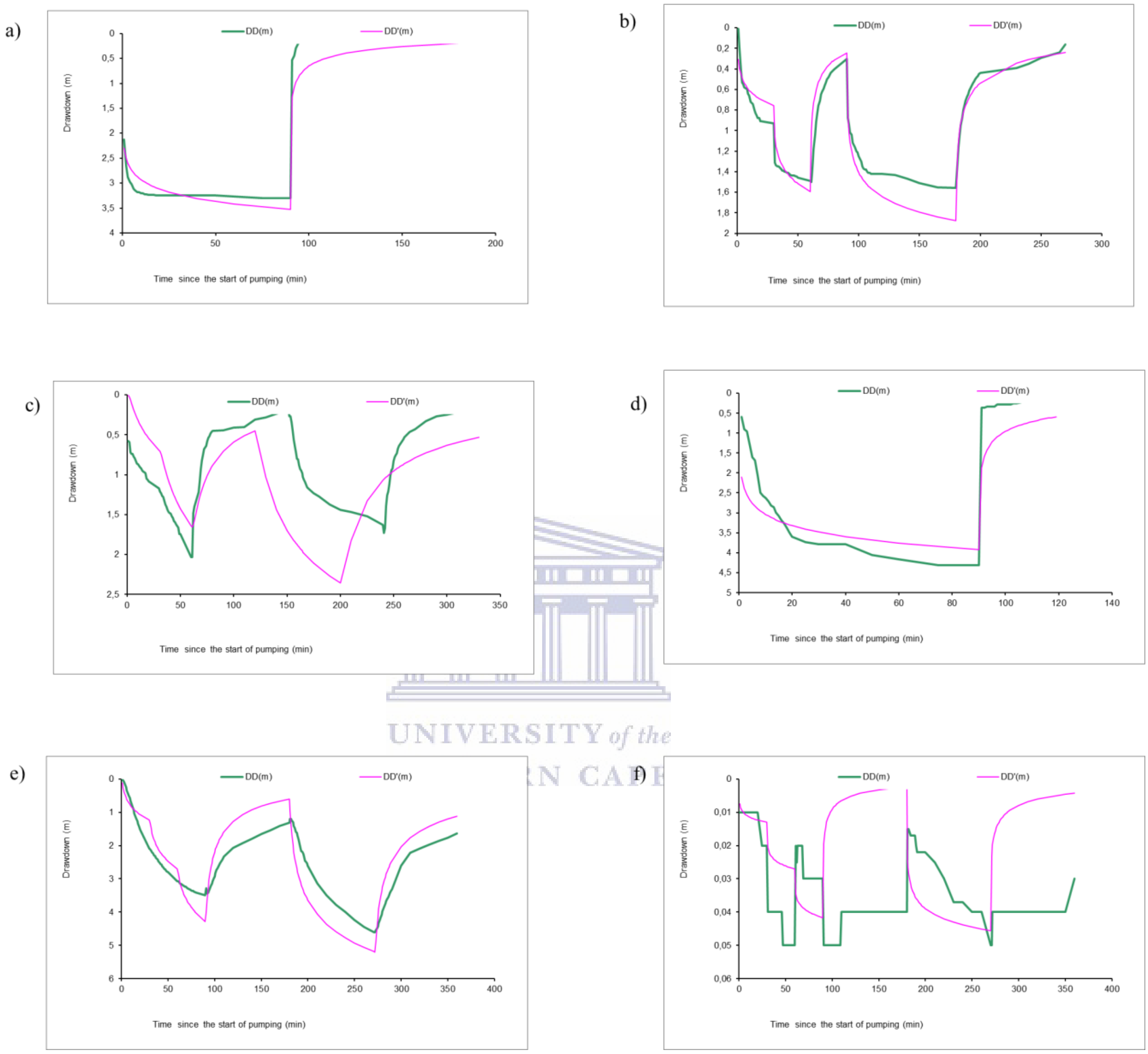


Figure 4.2.1(a): Drawdown versus time graphs as measured from six selected sites around Cape Flats Aquifer in March 2015.

The figure 4.2.1(a) shows drawdown versus time curves plotted from the step-down and constant rate test carried out during March 2015 on the Cape Flats Aquifer. Curve (a) was plotted from data collected from a borehole at Westridge stadium (G32961), b) plotted from data collected from UWC BH3b, c) from data collected from UWC BH3a, d) plotted from data collected from a borehole at Lent 1(BG00139), e) plotted from data collected from Bell 2 (BG46052) and f) plotted from data collected from Phill BH 2(BG00153). In these graphs, pink curve represents theoretical drawdown and the green curve represents measured drawdown. From all the curves, theoretical drawdown fitted perfectly with measured drawdown and follows a normal pattern of decreasing during pumping and increasing during the recovery period, except for the curve f) of Phill BH 2 where observed drawdown curve slightly differs in shape with that of theoretical drawdown. In plot f) drawdown fluctuates a bit even though it follows the normal pattern of decreasing during the pumping period and increasing during the recovery period. For Westridge plot (a) and Lenteguer plot (d), the step-down test was unsuccessful, boreholes dried up during the first step leading to constant rate test being carried out at even lower rate of 0.6l/s.

Table 4.2.1(a): Transmissivity and Storativity values estimated from selected boreholes around Cape Flats in March 2015

Boreholes	**T (m^2/d)**	**S**
Westridge 1 (G32961)	15.26	1.00×10^{-2}
UWC 3b	50.62	1.00×10^{-3}
UWC 3a	16.00	1.00×10^{-3}
Lenteguer 1 (BG00139)	10.28	1.00×10^{-3}
Bellville 2 (BG46052)	16.71	1.00×10^{-2}
Phillipi 2 (BG00153)	4276.76	1.00×10^{-2}

Table 4.2.1(a) shows estimated transmissivity and storativity of different boreholes within Cape Flats Aquifer during March 2015. The estimated transmissivity values are within the expected range of $< 50m^2/d$ to $620m^2/d$ suggested by Gerber (1976). The Phillipi borehole 2 was found to have the highest value of transmissivity which exceeded the range set out by (Gerber 1976). Phillipi borehole was however expected to have a high transmissivity value based transmissivity distribution map reported in Gerber (1976); Wright & Conrad (1995) which classifies Phillipi area where the borehole is located as a zone of high transmissivity. The Lenteguer borehole was found to have the lowest transmissivity value than all other borehole points. The storativity values in all boreholes points were within the expected range of 10^{-3} to 10^{-2}

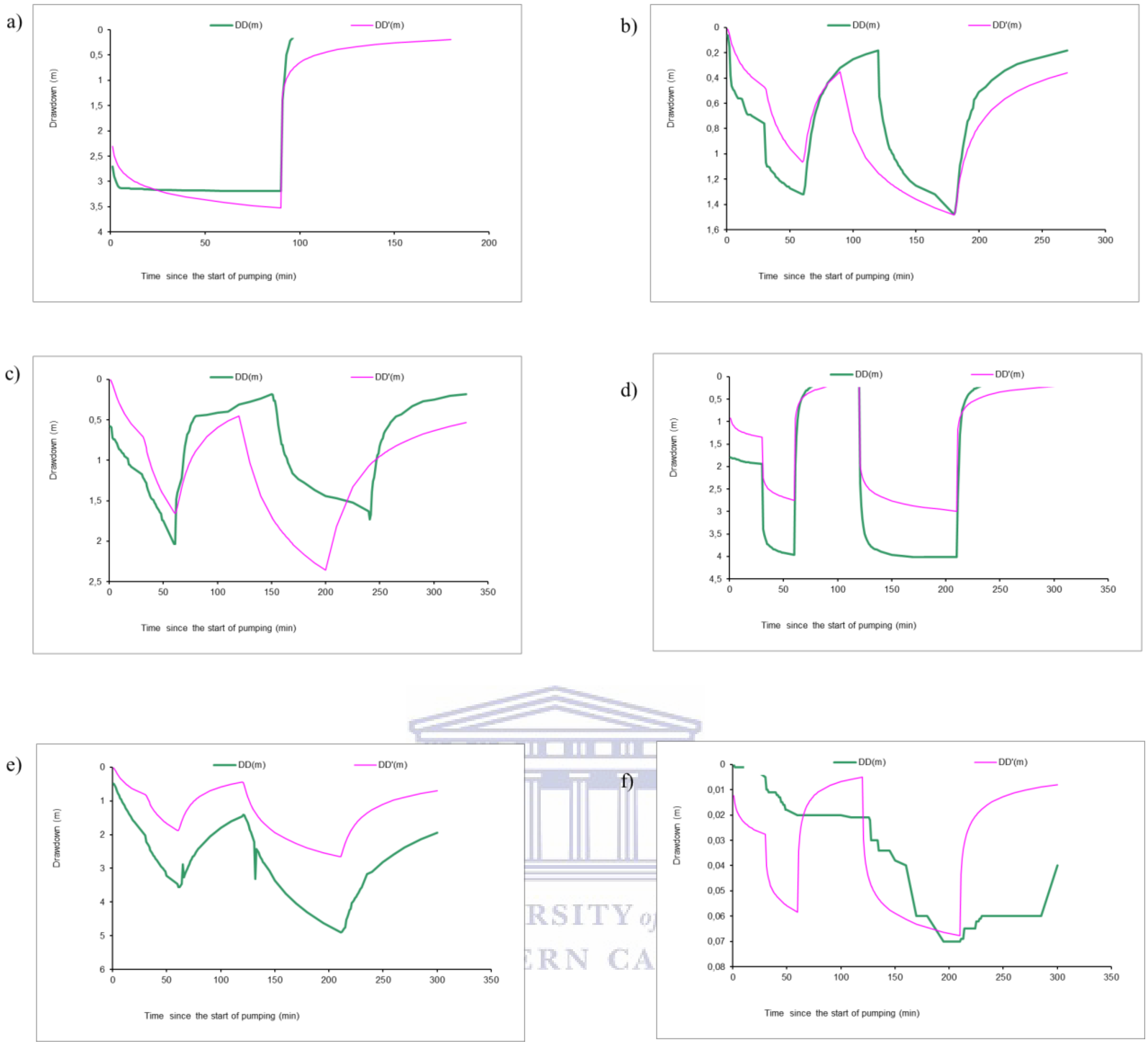


Figure 4.2.1(b): Drawdown versus time graphs measured from six selected sites around Cape Flats Aquifer in October 2015.

The figure 4.2.1(b) shows curves of drawdown versus time from six selected sites around Cape Flats Aquifer in October 2015. Plot a) show data from Westridge borehole 1, Plot b) data from UWC 3a, Plot c) data from UWC 3b, Plot d) data from Lent 1, Plot e) data from Bell 2 and Plot f) data from Phill 2. Observed drawdown in all the curves fits perfectly with the theoretical drawdown and follows a normal pattern of decreasing during pumping period and increasing during recovery period. Plot f) however shows observed drawdown was slightly deviating from a normal pattern. In this plot for the first minutes during step-down tests, drawdown starts to decrease as expected and during recovery instead of drawdown increasing it remained constant throughout. For the Westridge borehole, step-down test was unsuccessful the borehole dried up in the first minute of pumping, leading to the constant rate being carried out at even lower rate of 0.6l/s.

Table 4.2.1(b): Transmissivity and Storativity values estimated from selected boreholes around the Cape Flats Aquifer in October 2015

BOREHOLES	**T(m^2/d)**	**S**
Westridge (G32961)	15.26	1.00×10^{-2}
UWC 3b	33.62	1.61×10^{-3}
UWC 3a	16.00	1.61×10^{-3}
Lenteguer (BG00139)	55.00	1.00×10^{-2}
Bellville (BG46052)	16.71	1.00×10^{-2}
Phillipi (BG00153)	1500	1.00×10^{-2}

Table 4.2.1(b) shows estimated transmissivity and storativity values from selected boreholes around Cape Flats Aquifer during October 2015. Transmissivity values for the month of October were found to be within the expected range of <50m^2/d and 620m^2/d as suggested by (Gerber 1976) in all the sites except for the Phillipi borehole were the transmissivity value exceeded the range. The high transmissivity value however was expected in that area because, according to the transmissivity distribution map of Gerber (1976) the southern part of the Cape Flats Aquifer closest to the coast including Phillipi where the borehole is located is characterised by higher values of transmissivity than the upper and middle part. The storativity values for all the borehole points except for UWC BH 3b and UWC BH 3a were found to be similar with those of Adelana et al. (2010) where the values were equal to 10^{-2}. UWC BH 3a and 3b were found to have lower storativity values. However the storativity values were found to be within the expected typical storativity values for sandy aquifer, where the range is between 10^{-3} and 10^{-1}.

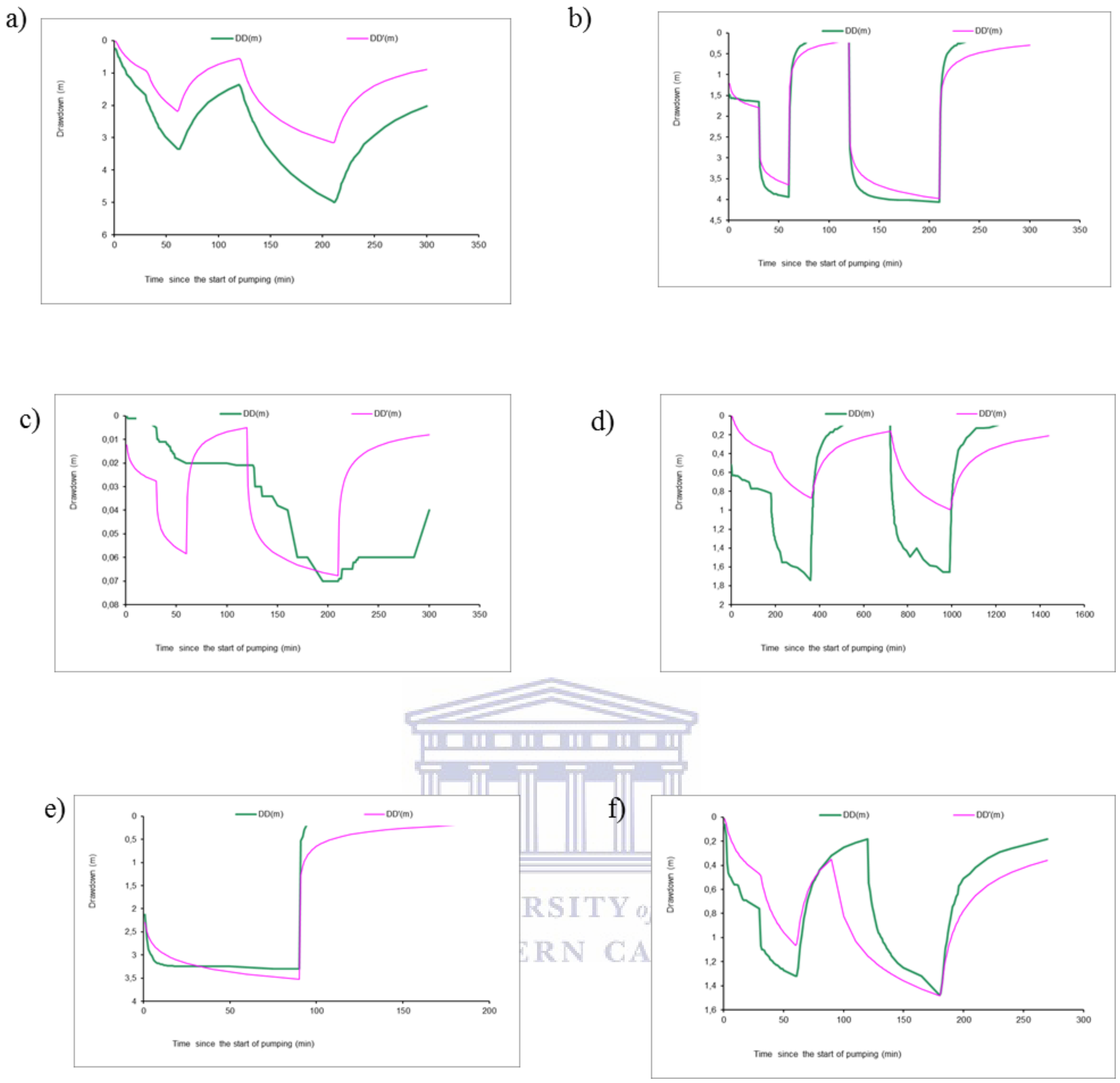


Figure 4.2.1(c): Drawdown versus time curves for borehole distributed within the Cape Flats Aquifer for the month of June 2016.

The figure 4.2.1(c) shows drawdown versus time curves for the selected boreholes within the Cape Flats Aquifer based on the pumping test data collected in June 2016. Curve a) represents data from borehole (BG46052), b) represents data from borehole (BG00139), c) represents data from borehole (BG00153), d) represents data from borehole (UWC 3b), e) represents data from borehole (G32961) and f) represents data from borehole (UWC 3b). For all the boreholes drawdown follows a normal pattern of decreasing during pumping and increasing during the recovery period. The observed drawdown matches perfectly with the theoretical drawdown for all the borehole points except for borehole (BG00152) where observed drawdown deviates away from the theoretical drawdown.

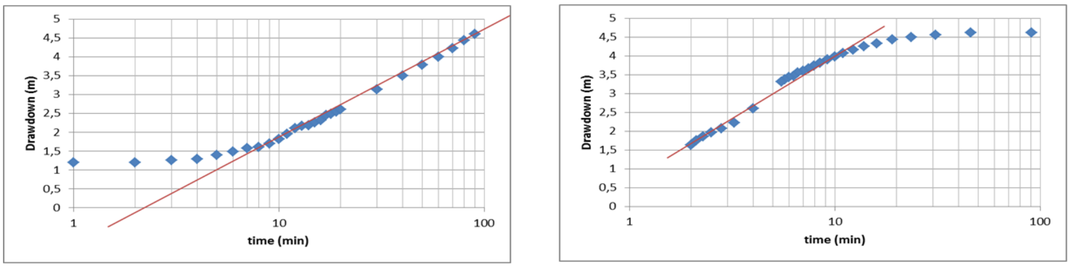
Table 4.2.1(d): transmissivity and storativity values estimated from selected boreholes around the Cape Flats Aquifer in June 2016

Boreholes	$T(m^2/d)$	S
Bellville (BG46052)	13.00	1.00×10^{-2}
Lenteguer (BG00139)	40.00	1.00×10^{-2}
Phillipi (BG00153)	1470.00	1.00×10^{-2}
UWC 3a	33.62	1.61×10^{-3}
Westridge 1 (G32961)	15.12	1.00×10^{-2}
UWC 3b	45.00	1.00×10^{-2}

Table 4.2.1(d) shows the estimated transmissivity and storativity values for the Cape Flats Aquifer in June 2016. Based on the estimates borehole BG00152 was found to have the highest transmissivity and borehole BG46052 was found to have the lowest transmissivity value. Transmissivity values for all the borehole points fell within the expected range of <50m^2/d to 620m^2/d suggested by (Gerber 1976) except for borehole BG00152 which exceeded the range. The storativity values for all the borehole points were found to be within the expected range of 10^{-2} reported in Adelana et al. (2010), except for UWC 3a were the storativity value was lower (10^{-3}).

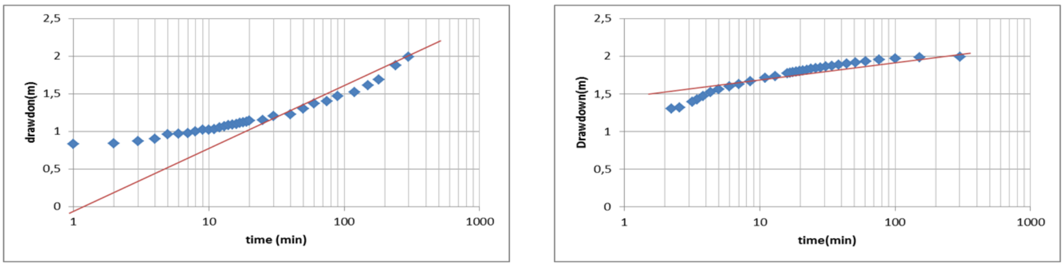
4.2.2 Results from Theis using excel spreadsheet

BELLVILLE BH2

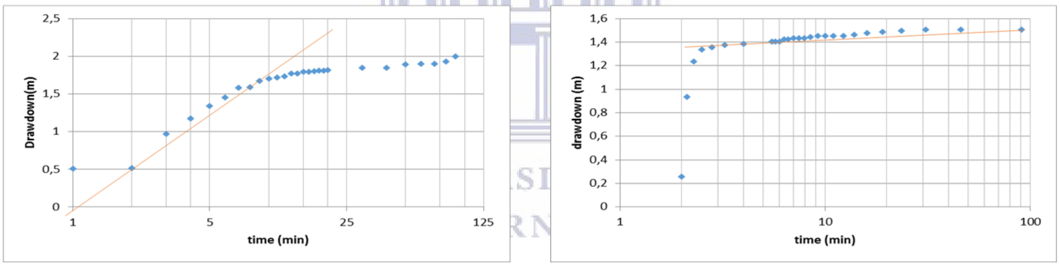

Pumping

Recovery

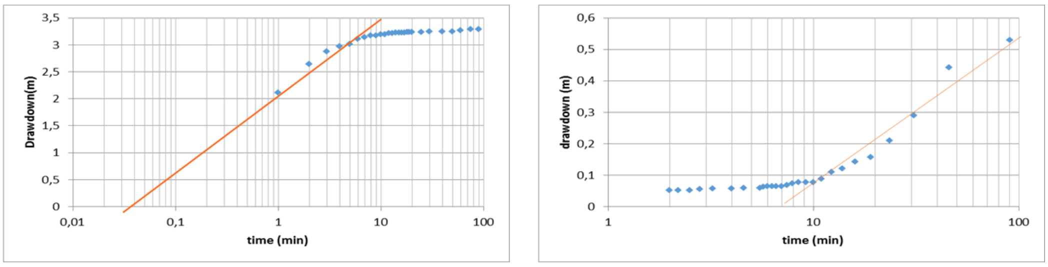
UWC BH 3



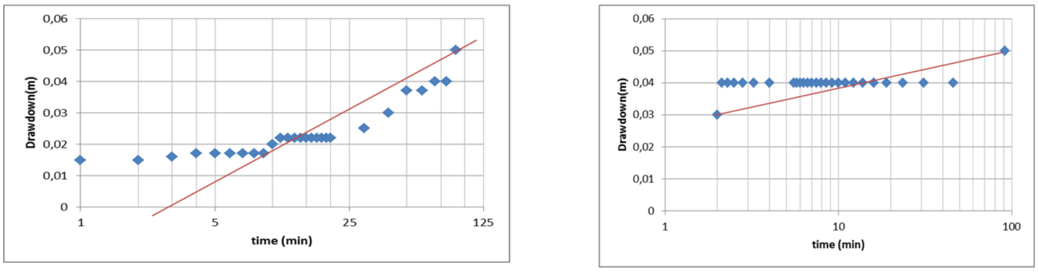
LENTEGUER BH 3

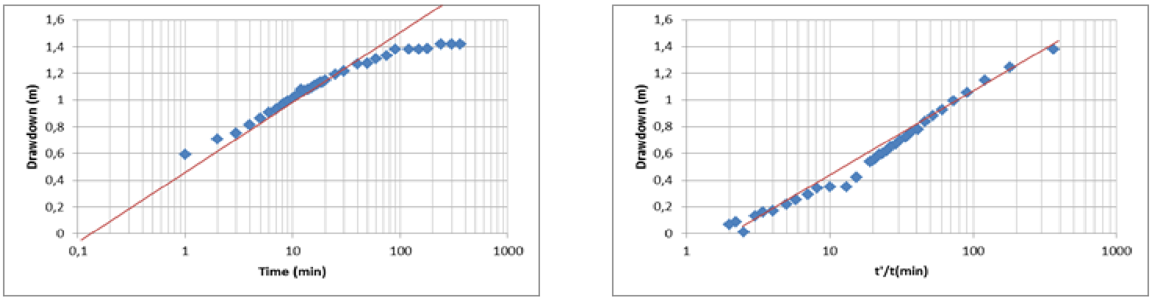


WESTRIDGE BH 1



PHILLIPI BH2





UWC 3a

Figure 4.2.2(a): log plots of drawdown versus time as measured from six different boreholes around the Cape Flats Aquifer during March 2015.

The figure 4.2.2 (a) above shows log plots of drawdown versus time calculated from six different boreholes distributed around Cape Flats Aquifer. The drawdown is based on the data set collect during the period of March 2015. From the plots it is evident that drawdown fits perfectly within the straight line for all the borehole points except for Phill BH 2 and Westridge BH1 where drawdown is scattered around the straight line.

Table 4.2.2(a): transmissivity and storativity values estimated from data collected in six different sites around Cape Flats Aquifer in March 2015.

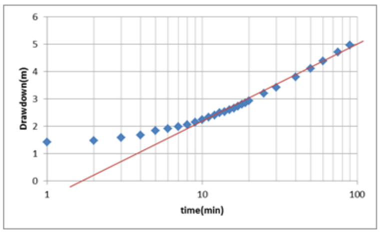
Boreholes	**$T_{pumping}$ (m^2/d)**	**S**	**$T_{recovery}$ (m^2/d)**
Bellville (BG46052)	11.45	4×10^{-3}	11.21
Westridge (G32961)	28.74	8×10^{-3}	9.73
UWC 3b	31.46	9×10^{-3}	31.30
Lenteguer (BG00139)	23.075	9×10^{-2}	16.82
Phillipi (BG00153)	790.33	0.12	3512.57
UWC 3a	30.23	2×10^{-3}	31.45

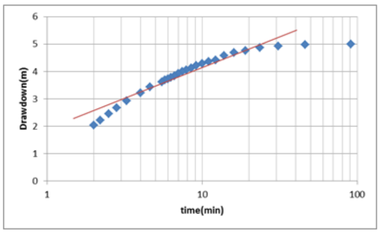
The table 4.2.2(a) shows the estimated transmissivity and storativity values of six selected boreholes around the Cape Flats all penetrating the Cape Flats Aquifer. From the table it is evident that for all the borehole points transmissivity values were found to be within the expected range of <50m^2/d to 620m^2/d except transmissivity for Phillipi 2 where the transmissivity was found to be higher and falling outside of the expected. The situation however was expected because the area were the borehole is situated is known to be the zone of high transmissivity. Bell 2 was found to have the lowest transmissivity values than the other sites; this was expected because the area to which the borehole is situated is known to have lower transmissivity values. Transmissivity values estimated from data collected during pumping period agrees with transmissivity values estimated from the data collected during the recovery period for all the Phill 2, Lent 1, and Westridge 1. Storativity values were found to be within the range of 10^{-3} to 10^{-1} with Phillipi 2 and having the highest storativity and UWC 3a having the lowest. For Lent 1 the storativity value was found to be within the expected range of 10^{-2} .

BELLVILLE 2

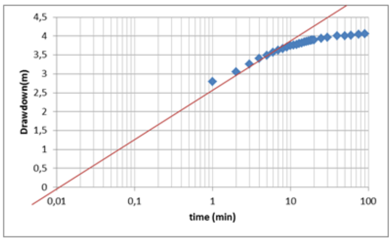
Pumping

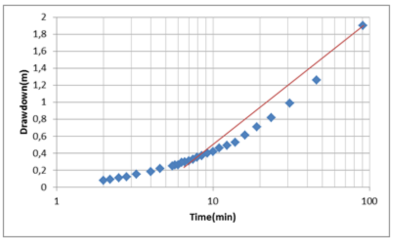
Recovery



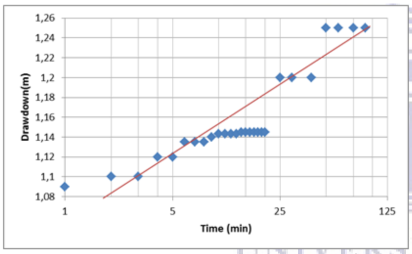


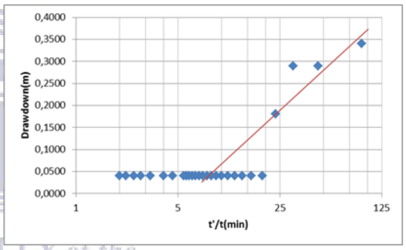
LENTEGUER BH2



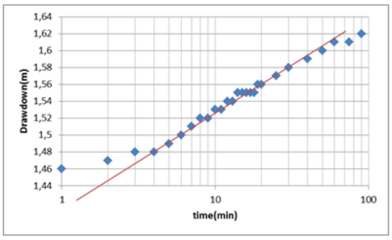


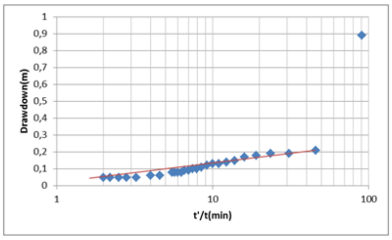
WESTRIDGE BH1



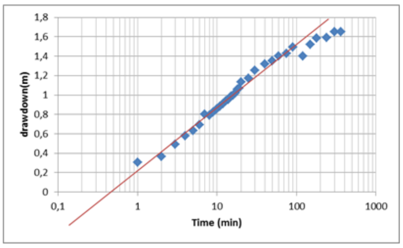


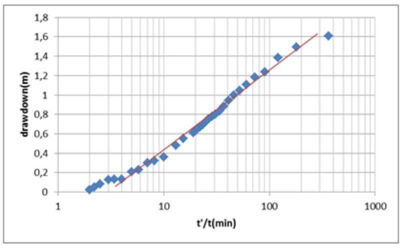
PHILLIPI BH2





UWC 3B





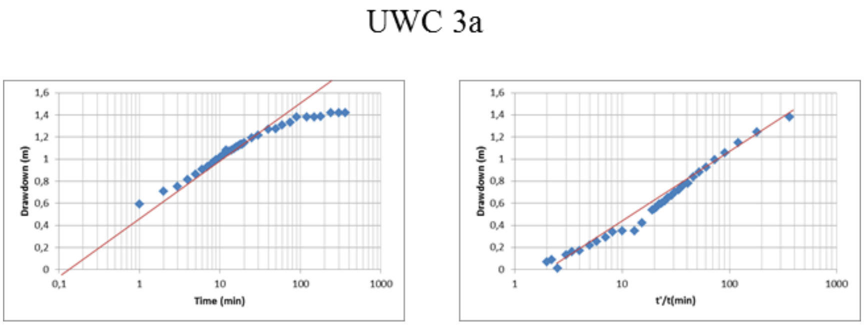


Figure 4.2.2(b): Drawdown versus time curves of borehole distributed within the Cape Flats Aquifer in October 2015.

The figure 4.2.2 (b) shows the plotted curves of drawdown versus time for 6 different boreholes distributed within the Cape flats Aquifer. The curves were plotted from the data collected from two hydraulic tests conducted within each borehole in October 2016. For all the boreholes the drawdown plots along the straight line suggesting radial flow except for Westridge borehole 1 where drawdown data is scattered along the straight line for both pumping and recovery period.

Table 4.2.2(b): Transmissivity and Storativity values estimated from data collected from six different boreholes distributed across the Cape Flats Aquifer in October 2016

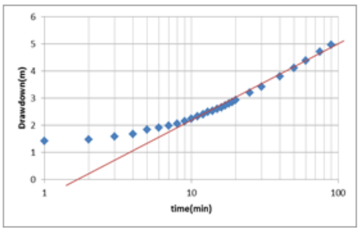
Boreholes	**$T_{pumping}$ (m^2/d)**	**S**	**$T_{recovery}$ (m^2/d)**
Bell (BG46052)	11.25	3×10^{-3}	15.80
Westridge (G32961)	59.28	1×10^{-3}	14.11
UWC 3a	68.13	3×10^{-3}	44.21
Lenteguer (BG00139)	33.28	8×10^{-2}	21.08
Phillipi (BG00153)	107.77	2×10^{-2}	84.68
UWC 3b	41.00	3×10^{-3}	35.76

Table 4.2.2(b) shows estimated transmissivity and storativity values for 6 different boreholes distributed within the Cape Flats Aquifer. The estimates are based on the data collected in October 2015 using the constant rate test carried out in each borehole. Based on these estimates the transmissivity values were found to be within the expected range of <50m^2/d to 620m^2/d for all the borehole points. The highest transmissivity was observed for Phillipi

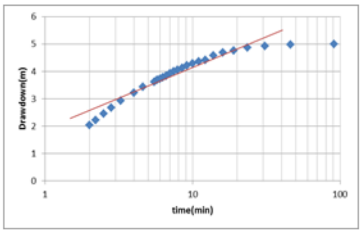
borehole 2 and the lowest for Bellville borehole 2. The highest transmissivity in the Phillipi borehole was expected based on the previous work in the areas by various authors such as Gerber (1976); Wright & Conrad (1995).

Bellville 2

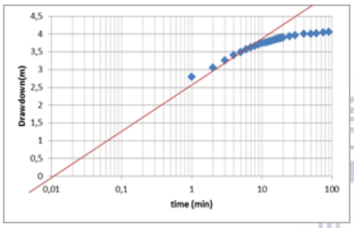
Pumping

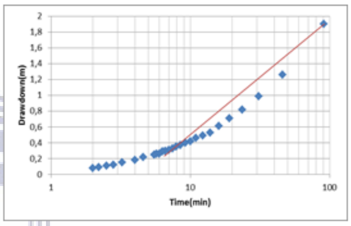


Recovery

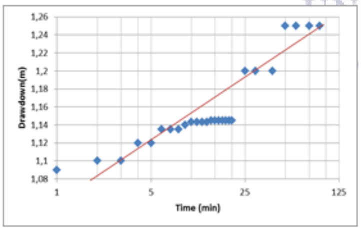


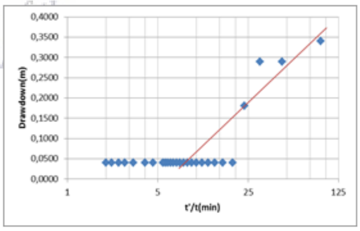
Lenteguer 1



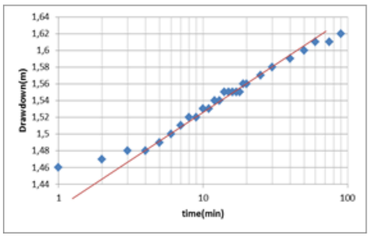


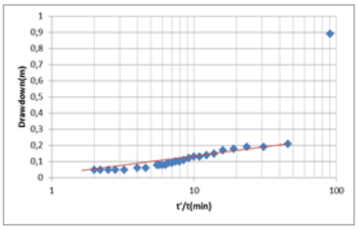
Westridge 1



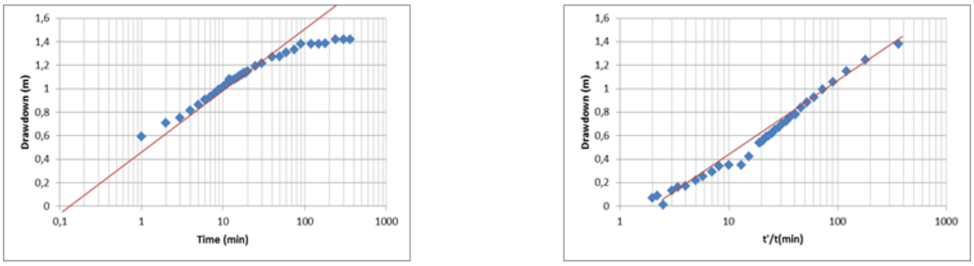


Phillipi 2





UWC 3a



UWC 3b

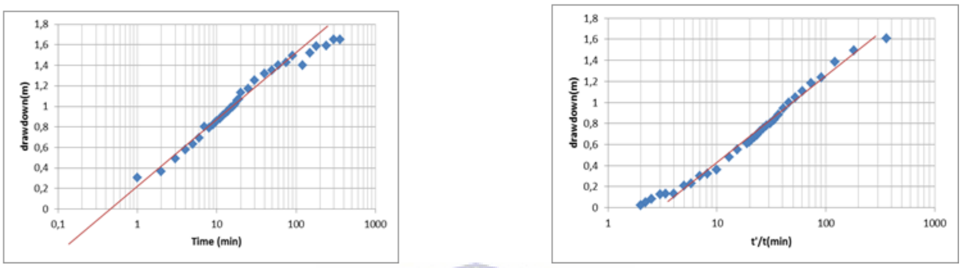


Figure 4.2.2(c): Drawdown versus time curves of boreholes on Cape Flats Aquifer based on data collected during June 2016.

The figure 4.2.2(c) shows drawdown versus time for boreholes distributed within the Cape Flats Aquifer for the month of June 2016. For all the plots drawdown fitted perfectly along the straight line suggesting radial flow, except for Westrigde BH1 where the values scattered around the straight line for both pumping and recovery period.

Table 4.2.2(c): Transmissivity and Storativity values estimated from six boreholes within the Cape Flats Aquifer during June 2016.

Boreholes	**T$_{pumping}$ (m^2/d)**	**S**	**T$_{recovery}$ (m^2/d)**
Bellville (BG46052)	11.2	3×10^{-3}	23.08
Westridge (G32961)	126.00	1×10^{-3}	42.15
UWC 3a	72.00	9×10^{-3}	46.83
Lenteguer (BG00139)	34.74	0.34	20.66
Phillipi (BG00153)	263.2	2×10^{-2}	210.75
UWC 3b	41.27	3×10^{-3}	34.51

Table 4.2.2(c) shows the estimated transmissivity and storativity values for 6 different boreholes penetrating the Cape Flats Aquifer based on the data sets collected in June 2016. Based on these estimates transmissivity values ranged between 11.2m^2/d and 263m^2/d with Phill BH 2 having the highest transmissivity and Bell 2 having the lowest values respectively. The storativity values ranged between 10^{-3} and 10^{-1} with highest storativity value observed for the borehole Lent 1 (BG00139) and lowest for borehole UWC 3a.

Table 4.2.2(d): Average transmissivity values for boreholes distributed within the Cape Flats Aquifer.

Boreholes	**Excel Sheet**	**Aqua-test**
	$T_{average}$(m^2/d)	**$T_{average}$(m^2/d)**
Bellville 2 (BG46052)	11.3	16.41
Westridge 1 (G32961)	71.34	15.08
Lenteguer 2 (BG00139)	30.34	33.76
UWC 3b	37.91	36.41
Phillipi 2 (BG00153)	387.1	2525.59
UWC 3a	56.79	21.88

Table 4.2.2(d) shows the average transmissivity values for the Cape Flats Aquifer based on estimates by Theis analytical solutions using a normal excel spread sheet and Aqua-test graphical interface software. Based on this table from both analyses Phill BH 2 (BG00153) had the highest transmissivity and Bell BH2 (BG46052) has lowest average transmissivity based on excel spreadsheet analysis; however, the Aqua-test analysis showed that Westr BH 1 (G32961) had the lowest average transmissivity.

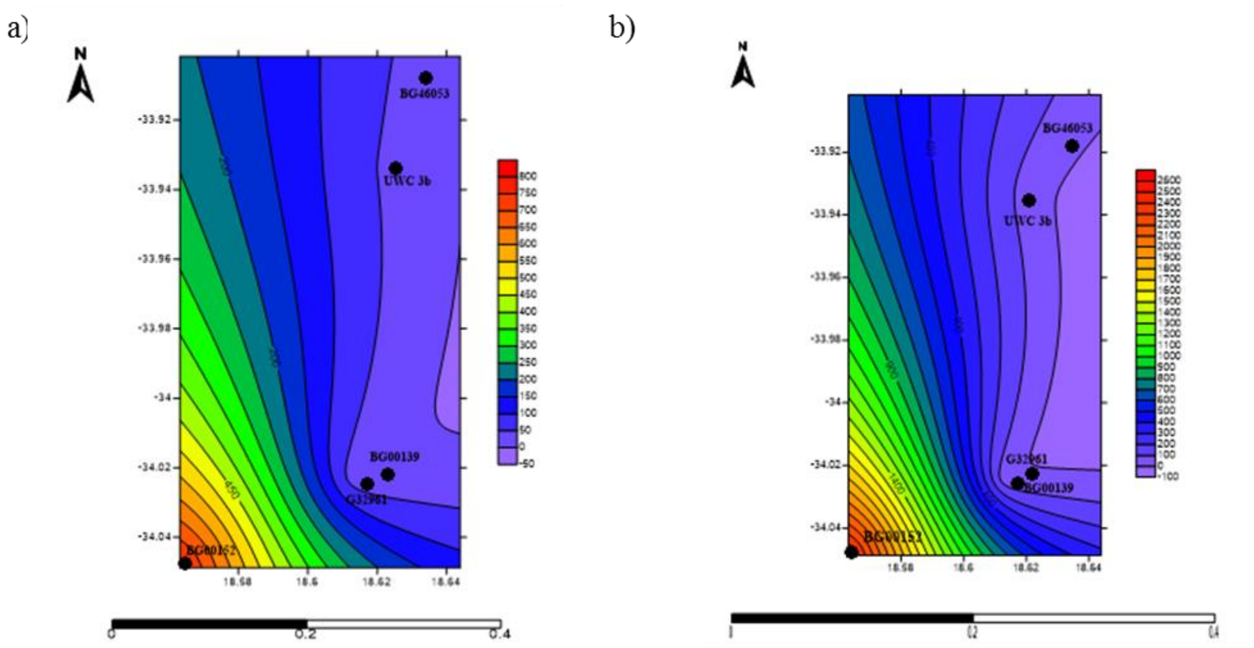


Figure 4.2.2(d): Average transmissivity distribution maps for Cape Flats Aquifer Based on Theis solution through excel spreadsheet a) and Aqua-test software b) analysis.

Figure 4.2.2(d) shows transmissivity distribution maps for the Cape Flats Aquifer based on Theis analytical solution by the normal spread sheet and Aqua-test graphical interphase software. The maps were done using kriging interpolation within Golden surfer software version 9.0. Based on these two maps borehole BG46052, UWC3b, BG00139 and G32961 fell within the zone of low transmissivity as compared to Borehole BG00153 which fell within the zone of high transmissivity.

Table 4.2.2(e): Average storativity values for boreholes distributed within the Cape Flats Aquifer

Borehole point	Excel spread-sheet analysis	Aqua-test analysis
Bellville 2 (BG4052)	3E-03	1E-02
Westridge 1 (G32961)	3E-03	1E-02
UWC 3a	5E-03	1E-03
Lenteguer 2(BG00139)	2E-01	7E-03
Phillipi 2 (BG00153)	1E-01	1E-02
UWC 3b	1.4E-02	4E-03

The table 4.2.2(d) above shows average storativity values for boreholes distributed within the Cape Flats Aquifer based on Theis analytical solutions through the Aqua-test and Excel spreadsheet analysis. From the Aqua test analysis average storativity ranged from 10^{-3} to 10^{-2} with lowest value observed for borehole lenteguer2 (BG00139) and highest observed in boreholes BG46052, Westr (G32961) and BG00153 which had the highest equal storativity value of 1.00×10^{-3}. Based on Excel spreadsheet analysis the average storativity ranged from 10^{-2} to 10^{-1} with lowest average storativity observed from borehole UWC 3a and highest observed from lent 1(BG00139) and Phill 2 (BG00153).

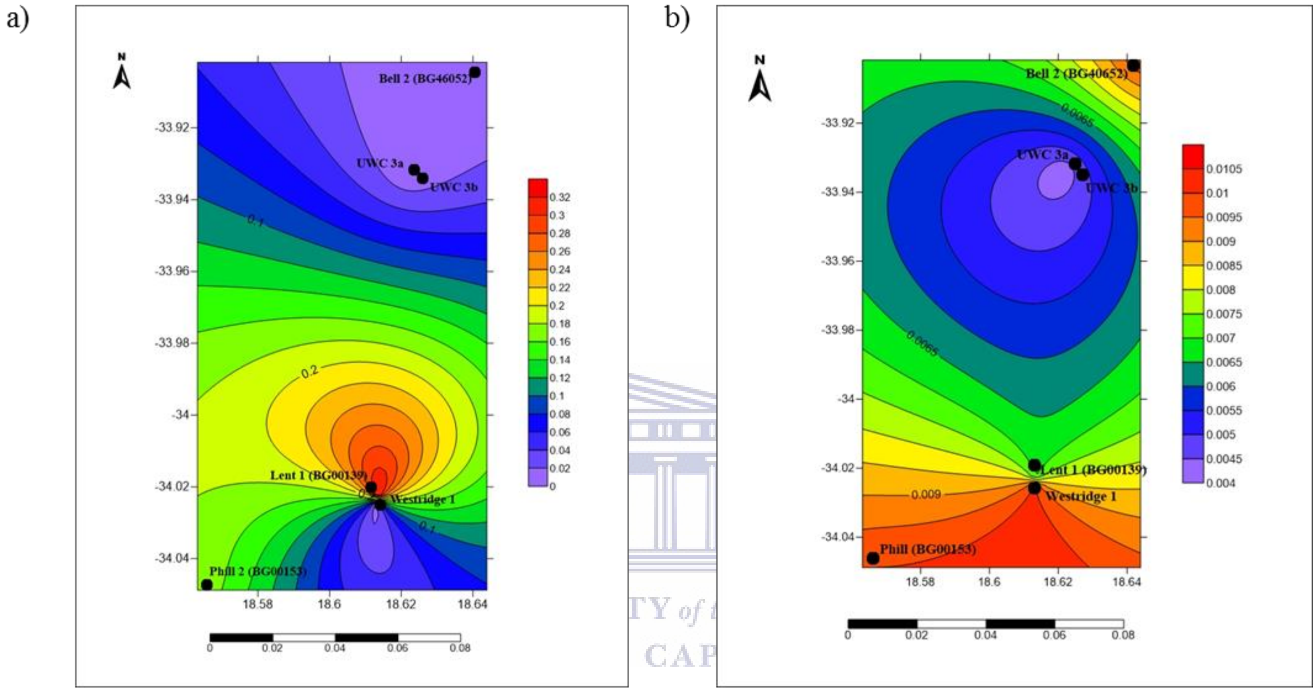


Figure 4.2.2(e): Average storativity distribution maps for Cape Flats Aquifer estimated from Theis using a normal excel spreadsheet and (a) and Aqua-test graphical interface (b)

The figure 4.2.2 (e) shows storativity distribution maps for the Cape Flats Aquifer based on Theis solution using an excel spreadsheet analysis and Aqua-test graphical interface software. These maps were completed through interpolation of storativity values from the two analysis using kriging interpolation method in Golden surfer software version 9. Based on the map (a) highest storativity zones are observed within the Mitchell’s Plain and Phillipi area, where borehole Phill 2, Lent 1, and Westridge 1 which is the southern part of the aquifer. UWC 3a, UWC3b and Bell 2 were found to be located within the zone of low storativity values which is the northern part of the aquifer based on the map (a). Based on the map (b), zones of high storativity were found to be located around boreholes Phill 2, Bell 2 and Westridge 1 and zones of lowest were found to be located around boreholes UWC 3a and UWC 3b.

4.3 Interpretation of results

Section 4.2 presented results on aquifer parameters estimated using Theis analytical flow solution for boreholes distributed within the Cape Flats Aquifer in different months of 2015 and 2016. The parameters of interest were transmissivity and storativity. Transmissivity assists in providing the basis for future groundwater exploration, development and abstraction, meaning that it can be used when zoning out areas were groundwater abstraction is possible (Gbmez-hernbnez 1997). In the current study, the average range for estimated transmissivity values based on Theis solution by excel spreadsheet analysis was between 11.3-387.1m^2/d with Phillipi BH2 (BG00153) having high average transmissivity values and Bell BH2 (BG46052) having the lowest transmissivity value. According to the classification of transmissivity magnitude table reported in Kránsý (1993), transmissivity values for a borehole ranging between 100m^2/d to 1000m^2/d falls within class 2 transmissivity zone. A class 2 transmissivity zone represents an area with high transmissivity and groundwater withdrawal in that area is of lesser regional importance. Boreholes within class 2 are expected to discharge between 5l/s to 50 l/s per 5m drawdown. Based on the transmissivity estimates by Theis solution through excel spreadsheet Phill BH2 (BG00153), falls under class 2 with the potential abstraction rate of 5 – 50l/s per 5m drawdown.

The average transmissivity values estimated from Theis through excel spreadsheet for other boreholes, Bellville BH 2 (BG46053), Lent BH1 (BG00139), UWC 3a and 3b, and Westr BH 1 (G32961) falls within the class 3 which represents intermediate transmissivity zone. The transmissivity range in this class is between 10-100m^2/d (Kránsý 1993). Based on the classification, it means that groundwater from these three boreholes can be abstracted up to a rate of 0.5- 5l/s per 5m drawdown. Using average transmissivity values estimated from Theis solution using Aqua-test graphical interface categorises all the boreholes within class 3 except for Phillipi which falls under class 1 regarded as very high transmissivity with groundwater of regional importance, and potential abstraction rates of >50l/s.

For managed aquifer recharge (MAR) to be possible in a particular area, groundwater table needs to be lowered through abstraction of substantial volumes of water to increase the aquifer storage without depleting the aquifer. Transmissivity values can give an indication of the potential rate at which groundwater can be abstracted without depleting the aquifer. In the case of Cape Flats Aquifer around the Phillipi area, the possible abstraction rates would be between 5-50l/s per 5m drawdown to increase the aquifer storage. For the other sites, the possible abstraction rate would be between 0.5-5l/s per 5m drawdown.

The average estimated transmissivity values for Phill BH 2 (BG00153) exceeded the range of <30m^2/d to 620m^2/d suggested by Gerber (1976) for the Cape Flats Aquifer from both analysis compared to other borehole points. Adelana et al. (2010) estimated transmissivity for borehole 4 located within UWC campus site, which is the same site for observation borehole UWC 3a and 3b used in this study. The estimated transmissivity value in the study by Adelana et al.(2010) was 618m^2/d which agree with the range of transmissivity for the Cape Flats Aquifer given (Gerber 1976) and higher than the transmissivity values estimated for borehole 3a and 3b in the study for all the months.

Another study focusing on determining aquifer properties was done in Akpabuyo aquifer within the cross river state south-east of Nigeria Amah & Anam (2016). Similar to the Cape Flats Aquifer, Akpabuyo aquifer is a coastal sandy aquifer with the thickness ranging from 30.29-64.8m respectively. The estimated transmissivity values in the study by Amah & Anam (2016) ranged from 485 to 13460 m^2/d estimated using Cooper Jacobs solution. When the estimates are compared with those of the Cape Flats Aquifer for the current study, the results by Amah & Anam (2016) agree with the estimated transmissivity values for the Phill BH 2 (BG00153) for all the months, thus proving that the method applied in this study was successful.

Mjemah et al. (2009) also estimated transmissivity of a quaternary age aquifer is Der-es-Salam Tanzania. Similar to the Cape Flats Aquifer, the aquifer is coastal and characterised by lithological formation ranging from fine-medium sand to gravel soils. The estimated transmissivity for this quaternary averaged to 34m^2/d. This value corroborate with the estimated transmissivity for the Cape Flats Aquifer for all the borehole points in all months except for the Phillipi BH 2 (BG00153) which had high transmissivity values. Another study estimating transmissivity was done in Tuti Corin Town, Tamil Nadu India (Rangarajan et al. 2009). The aquifer is characterised by alluvial wind-blown sands similar to the Cape Flats Aquifer. Estimated transmissivity values ranged between 0.8 – 80.0 m^2/d, which these values agrees to the estimated values for Cape Flats Aquifer, for all the borehole point except for Phillipi borehole, and therefore also proving that the method applied in this study was successful.

Storativity also known as the specific yield for an unconfined aquifer refers to the volume water that an unconfined aquifer takes in or releases from the storage per unit surface area of the aquifer and per unit decline in the water table (Younger 2007). It is a dimensionless quantity which varies with aquifer types, for unconfined aquifer storativity usually ranges between 0.02 and 0.30 and for confined aquifer ranges between 0.0005 and 0.005. In this case the study was conducted in an unconfined aquifer and the average estimated storativity values ranged from 0.0014-0.01 based on Theis solution by Aqua-test analysis, with UWC 3b having the highest and UWC 3a having the lowest, and ranged from 0.004-0.2 based on Theis solution by excel-spreadsheet analysis, with Phill BH2 (BG00153) having the highest and Bell BH2 (BG46052). The estimated values agree with the suggested storativity range of 0.02-0.30 for the unconsolidated sandy aquifer.

Storativity values give an indication of the volume of water that an aquifer can take or realise from the storage. When storativity is higher for a particular area then it implies that the aquifer can release or take in high volumes of water (Freeze & Cherry 1979). In the case of Cape Flats Aquifer based on average storativity maps, Phill 2 and Lent 1 fall within the high storativity zones which reveal that the zones of high aquifer storage are located around the Phillipi towards the southern part of the aquifer, Therefore implying that Managed Aquifer Recharge suggested by WSUD would be feasible around the Phillipi area towards the southern part of the aquifer. Adelana et al.(2010) estimated storativity for borehole 4 at UWC groundwater site where boreholes UWC 3a and 3b are located. The estimate was done using Cooper-Jacob solution which is an approximation to Theis solution used in this study and the estimated value was 0.01 respectively. The estimated storativity values for boreholes UWC3a and 3b in the current study were slightly less when compared with the estimates of Adelana et al. (2010).

Gehman et al. (2010) also estimated storativity for the unconfined aquifer located in the north-eastern Colorado using temporal gravity surveys. Similarly to Cape Flats Aquifer, the aquifer is unconsolidated and consisting of predominantly sand and fine gravel with minor interbeded silt and clay. The estimated storativity ranged between 0.21 and 0.03. The estimates by Gehman et al.(2010) agree with the storativity estimates of the current study, thus proving that the method applied in this study was successful.

Woodworth & Stednick (2011) also estimated aquifer parameters of an unconfined aquifer in a shallow alluvium near Fort Collins Colorado using Neuman's curve matching solution. Similarly to the Cape Flats Aquifer, the aquifer is an urban shallow aquifer characterised by varying sands. Estimated storativity values ranged between 0.25-0.65. The values are slightly high when compared to those estimates for the Cape Flats Aquifer in the current study. Amah et al. (2012) also evaluated groundwater potential of Calabar coastal aquifer in the south eastern part of Nigeria. Similarly to the Cape Flats Aquifer, the aquifer is a coastal aquifer characterised by tertiary to recent continental fluviatile sands and clay. Analysis of pumping test data showed that the average storativity value was 0.0024. The storativity value agree with the storativity values for the Cape Flats Aquifer estimated in the current study, thus proving that the method applied in the study was successful.

The results of aquifer parameters show that the higher storativity and transmissivity values can be expected within lower parts of the Cape Flats Aquifer, thus suggesting that managed aquifer recharge would be possible towards the southern part of the aquifer where discharge and aquifer storage are higher. Even though this is the case, Cape Flats Aquifer is located within a peri-urban city, where recharge to the aquifer is due to different components such as water supply leakages, urban irrigation return flows and urban drainage due to un-serviced informal settlements as discussed in chapter 2. As such these components need to be taken into account when planning for MAR. The comparison of the results with other studies within similar settings to that of the Cape Flats Aquifer prove that the method applied to achieve the objective was successful.

4.4 Chapter summary

The chapter presented findings on aquifer parameters estimation using Theis analytical flow solution for the Cape Flats Aquifer with emphasis on transmissivity and storativity values. The main aim was to suggest possible sites for implementation of managed aquifer recharge (MAR) suggested by principles of water sensitive urban design (WSUD). The central argument in this chapter was if the distribution of aquifer parameters is understood prior to planning of MAR, then MAR implementation would be facilitated. The question asked then was to what extent does the knowledge of spatial distribution of aquifer parameters for the Cape Flats Aquifer facilitates MAR implementation, and the problem addressed was the lacking of consistent monitoring of aquifer parameters for the Cape Flats Aquifer in the context of WSUD.

The findings suggested that transmissivity values for Cape Flats Aquifer ranged between 11m^2/d and 3000m^2/d from both analysis with Phillipi 2 (BG00153) having the highest values and Bellville (BG46052) was having the lowest transmissivity values. The storativity values ranged from 10^{-3} to 10^{-1} which is typical storativity values for a sandy aquifer. Both transmissivity and storativity estimates agree with results of different authors who conducted similar studies within the Cape Flats Aquifer and other aquifers of the similar setting to the Cape Flats Aquifer studied in the current study. Based on the finding, it was suggested that towards the southern part of Cape Flats Aquifer around the Phillipi area towards the southern part of the aquifer, MAR would be feasible to implement because of the high aquifer discharge and storage observed within the area; however, the study recommended an expanded network of boreholes to fully cover the entire Cape Flats Aquifer.

Chapter 5: Groundwater flow system conceptualization

5.1 Introduction

Groundwater models have been applied to solve a wide variety of hydrogeological problems. More recently have been used in prediction of fate and transport of contaminants in risk assessments studies. Chapter 5 of the study presents results and discussion on local groundwater flow conceptualization for the Cape Flats Aquifer, Thereby addressing objective 2 of the study outlined in chapter 1, which was focusing on local groundwater flow system conceptualization for the Cape Flats Aquifer using a Finite Difference Method (FDM), in order to predict aquifer behaviour under site specific Water Sensitive Urban Design (WSUD) scenarios. The chapter addressed the problem of limited studies done focusing on groundwater flow system conceptualization for the Cape Flats Aquifer in the context of WSUD, thereby answering the question asking how does the local Cape Flats Aquifer system behaves under various WSUD stress condition, and with the assumption that presence of these stresses at site specific level negatively and positively influences the aquifer behaviour.

To achieve this objective the study started by collecting secondary data through the review of literature from various sources such as Council of Scientific and Industrial Research (CSIR), Department of Water and Sanitation (DWS) as well as the City of Cape Town municipality (CoCT). The data collected included aquifer type, geometry, hydraulic parameters and time-varying inputs as well as boundary conditions. A conceptual model was then developed using the secondary data collected from these water resource management agencies. The conceptual model was then used as a basis for the development of sites-specific numerical groundwater flow model of the Cape Flats Aquifer, which was developed using MODFLOW-2005 code that uses finite difference method to solve partial differential equations. The numerical model developed was then calibrated using water level measured from 5 wells within the area, and was then used to predict various site-specific WSUD scenarios set.

5.2 Model conceptualization and results

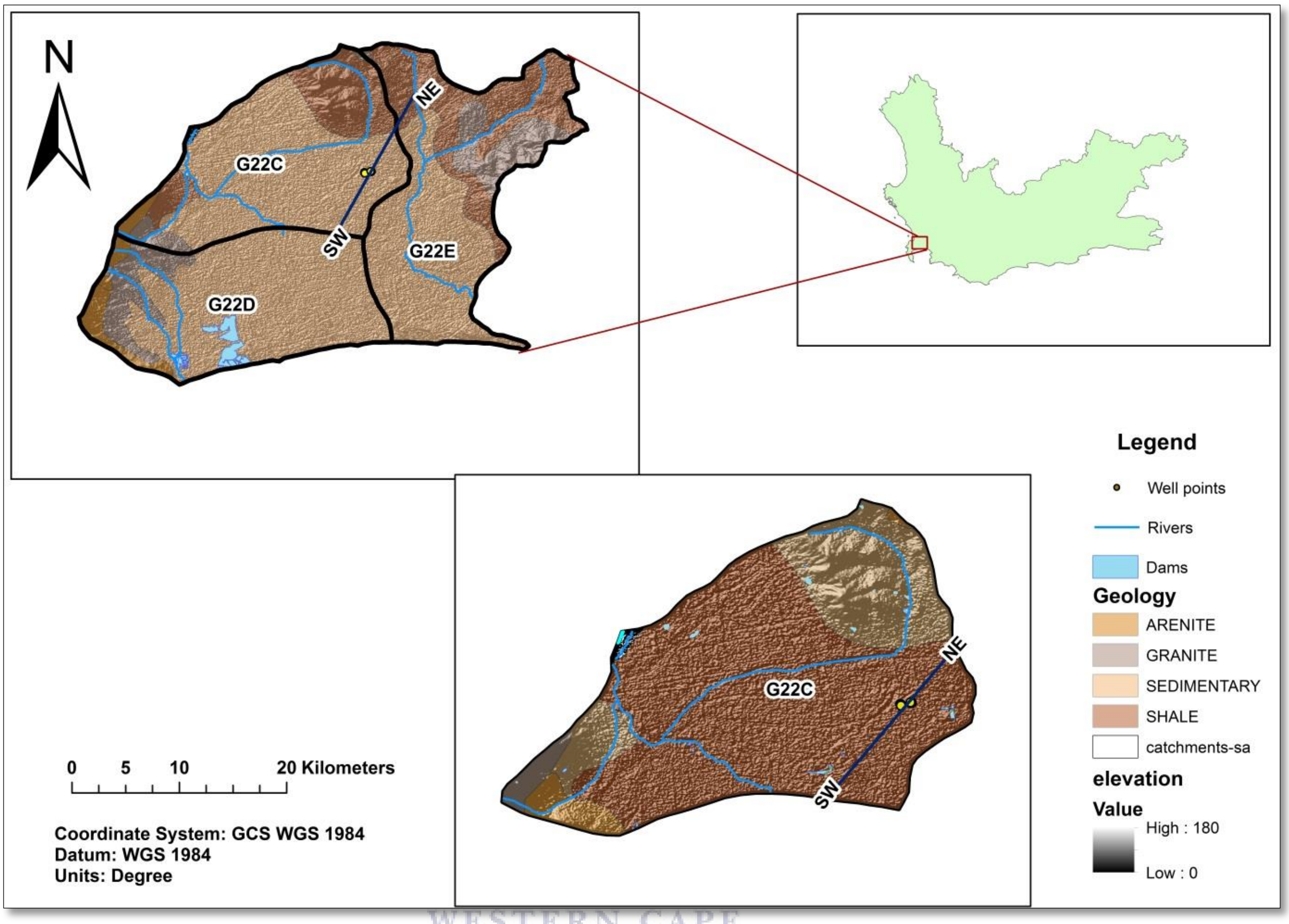


Figure 5.2(a): Model domain

The figure 5.2(a) above shows the area being modelled in this study. The site is located in the south-eastern part of G22C quaternary catchment within the south Western Cape. The site was chosen because of the availability of data required even though the study monitors the whole catchment. Also, the site is symmetrical to the other sites implying that groundwater flow system for the other sites can be easily determined based on simulations for this site. This site has a total of 5 borehole points which are penetrating through the Cape Flats Aquifer and monitored on the bi-monthly basis by the Department of Water and Sanitation.

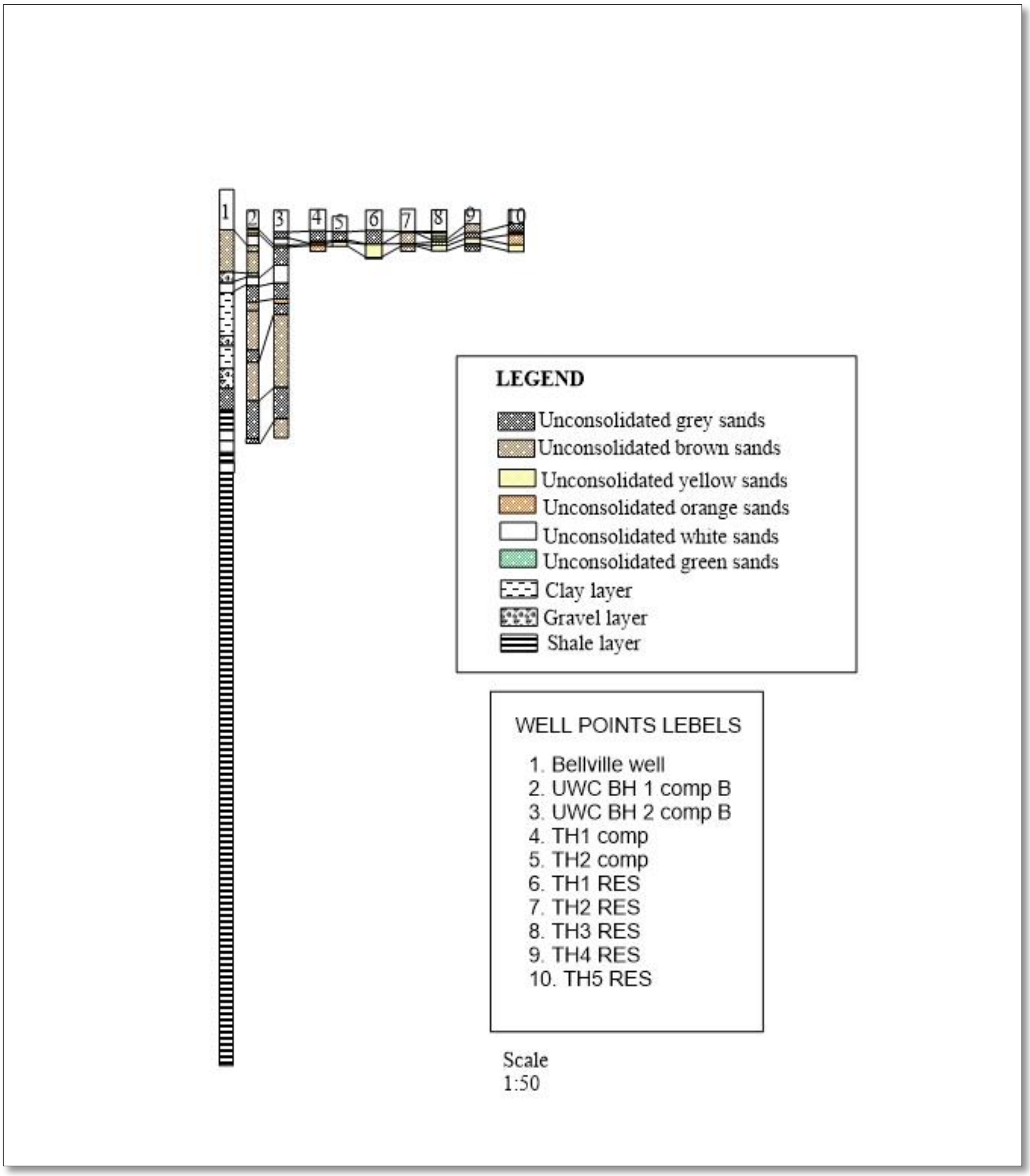


Figure 5.2(b): Geological logs for well points within the modeled area

The figure 5.2(b) above show the geological logs of groundwater points found within the domain area. These were completed using the Golden surfer software version 9 using the geological log data from the Department of Water and Sanitation. The borehole labelled 1 is located in Bellville and is one deepest borehole which shows a variety of lithological units ranging from unconsolidated brownish sands to gravel and shale layers. The other groundwater points are located at the University of the Western Cape and have similar lithological conformation as the borehole in Bellville. These were correlated to get an idea of the lithological conformation of the domain area; the results of lithological arrangement show that the lithology of the area comprises of witzand formation underlain by the Springfontein formation.

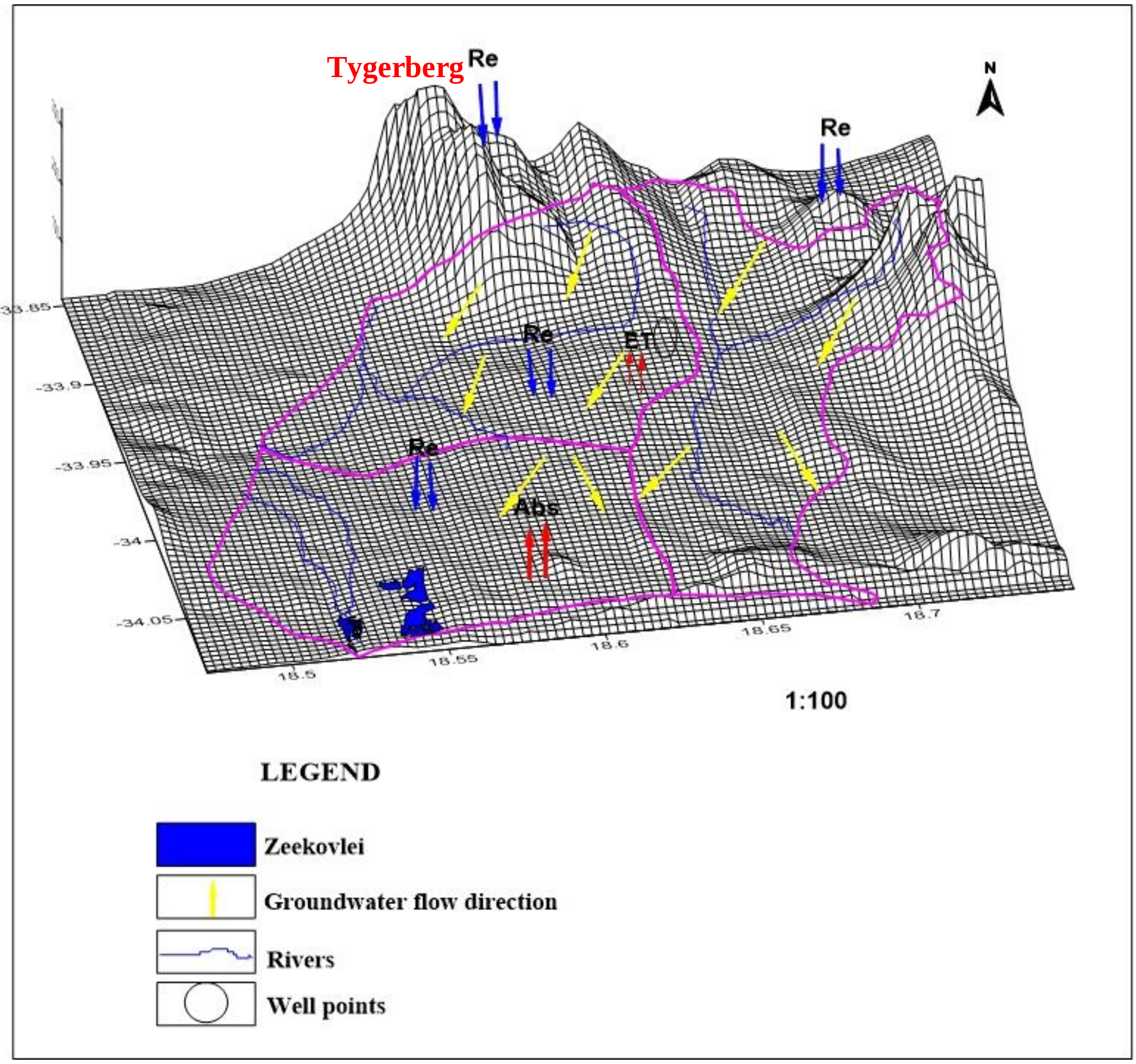


Figure 5.2(c): 3 dimensional regional hydrogeological conceptual Model for the Cape Flats Aquifer and vicinity

The figure 5.2(c) shows a 3-dimensional regional hydrogeological conceptual model of the Cape Flats Aquifer and vicinity developed using Golden surfer software version 9, From this diagram it is evident that groundwater flow direction is from areas of high elevation to areas of lower elevation mimicking the topographical arrangement. The regional groundwater flow is from the north, eastern and western side towards the south-western part of the aquifer depicted by the yellow arrows. The diagram also shows that groundwater recharge is mainly occurring on the surface and as a result of precipitation falling on the surface of the Aquifer and in highland areas such as the mountainous slopes and sand dunes around the area. These are depicted by the blue arrows. The conceptual model also shows that in this area groundwater is lost through evapotranspiration and groundwater abstraction within the Phillipi agricultural area where groundwater is abstracted for irrigation purposes. This is shown by the red arrows on the diagram.

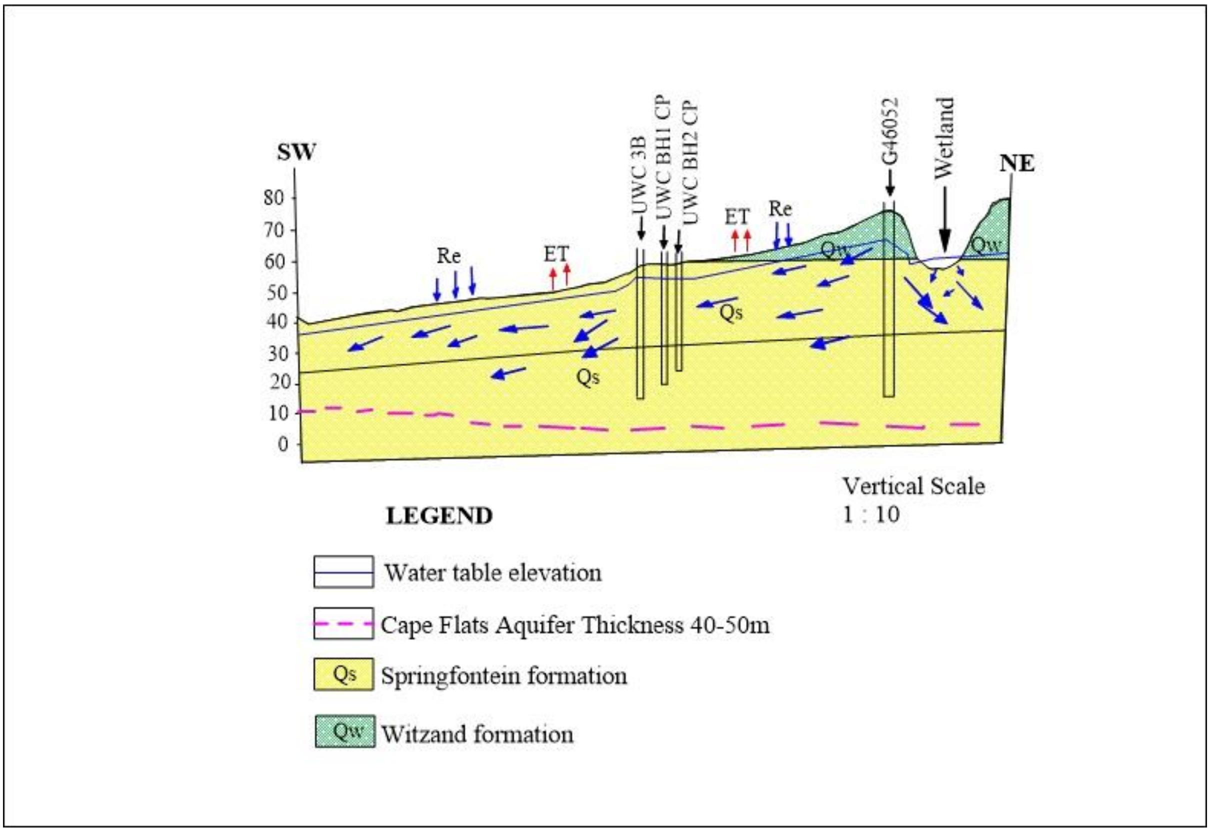


Figure 5.2(d): hydrogeological cross-section of the domain area

The figure 5.2(d) shows site-specific hydrogeological cross-section of the area from south-west to north east direction. The cross-section was done mainly to understand the local groundwater flow system for the area being modelled. Based on this hydrogeological cross-section two types of formations are found in the area. These are Springfontein formation which is characterised by well-sorted fine to medium grained quartz sands and witzand formation which is characterised by light-coloured calcareous sands. Cape Flats Aquifer in the area is 40-50m thick. Groundwater table is 2- 6 m deep with groundwater flowing from high elevation areas to low elevation areas. Groundwater recharge is mainly occurring on the surface of the aquifer. The aquifer interacts with surface water bodies such as rivers and wetland in the area

5.3 Numerical model development

5.3.1 Objective of the model

The objective of this numerical groundwater model was to conceptualize the Cape Flats Aquifer system at a site-specific scale in order to evaluate the future aquifer behaviour in that site under certain stress conditions posed by WSUD implementation.

5.3.2 Code Selection

To model local groundwater flow within the area the study used MODFLOW-2005 code within Model muse graphical interface software developed by Winston (2009). The code is a finite difference method and was used to solve a 3-dimensional groundwater flow equation (equ 5.3.2). In this study, it was chosen because it is the oldest used and proved to be useful in solving 3-dimensional partial differential equations.

$$K_{xx}\frac{\partial^2 h}{\partial x^2}+K_{yy}\frac{\partial^2 h}{\partial y^2}+K_{zz}\frac{\partial^2 h}{\partial z^2}+\frac{Q_s}{V}=0 \qquad (5.3.2)$$

Where:

$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}$ Net inflow into each grid cell from *x,y,z* direction

$\frac{Q_s}{V}$ External sources or sinks

$K_{(x,y,z)}$ Hydraulic conductivity from *x,y,z*

5.3.3 Spatial discretization

The model domain was divided into 161 rows and 170 columns making up the finite difference grids. The grids were 5x5m in size for the catchments however due to coarseness of these grid cells, the grid cells of the site of focus were further subdivided to 0.1×0.1m in size. From the vertical dimension, the model is single-layered, and the top elevation surface of the model represented the land surface of the study area. Elevations of the top grid cells were assigned using 30m resolution DEM which was obtained from the USGS earth explore website (figure 5.2a). Elevation of the bottom cells where determined using aquifer thickness of the section being studied.

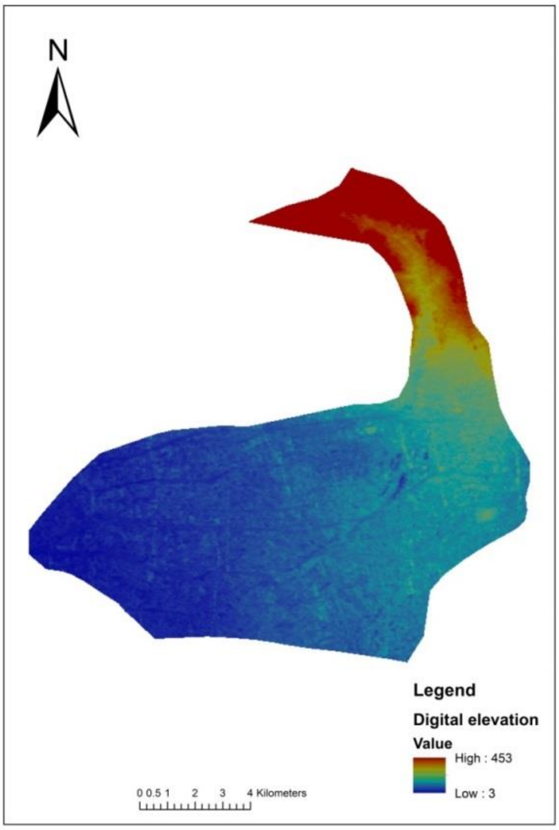


Figure 5.3(a): 30m digital elevation model for the domain area downloaded from the USGS earth explore.

5.3.4 Model hydraulic input parameters

- Hydraulic conductivity (K)

The area has spatial varying hydraulic conductivity. The hydraulic conductivity was estimated from the aquifer pumping test data conducted in March 2015, September 2015 and May 2016. Calculations were performed using equation (5.2.4a), and estimated hydraulic conductivity values are shown in table 5.2(a):

$$T = Kb \qquad (5.3.4a)$$

T transmissivity (m^2/d)

K hydraulic conductivity (m/d)

b Aquifer saturated thickness (m)

Table 5.3(a): Hydraulic conductivities for Cape Flats Aquifer estimated in different Months of 2015-2016.

Boreholes	$K_{March\ 2015}$ **(m/d)**	$K_{September\ 2015}$**(m/d)**	$K_{june2016}$ **(m/d)**
Bellville BG46052	0.25	0.37	0.29
UWC 3a	0.36	0.75	0.24
UWC3b	0.37	0.70	0.25

- Recharge (Re)

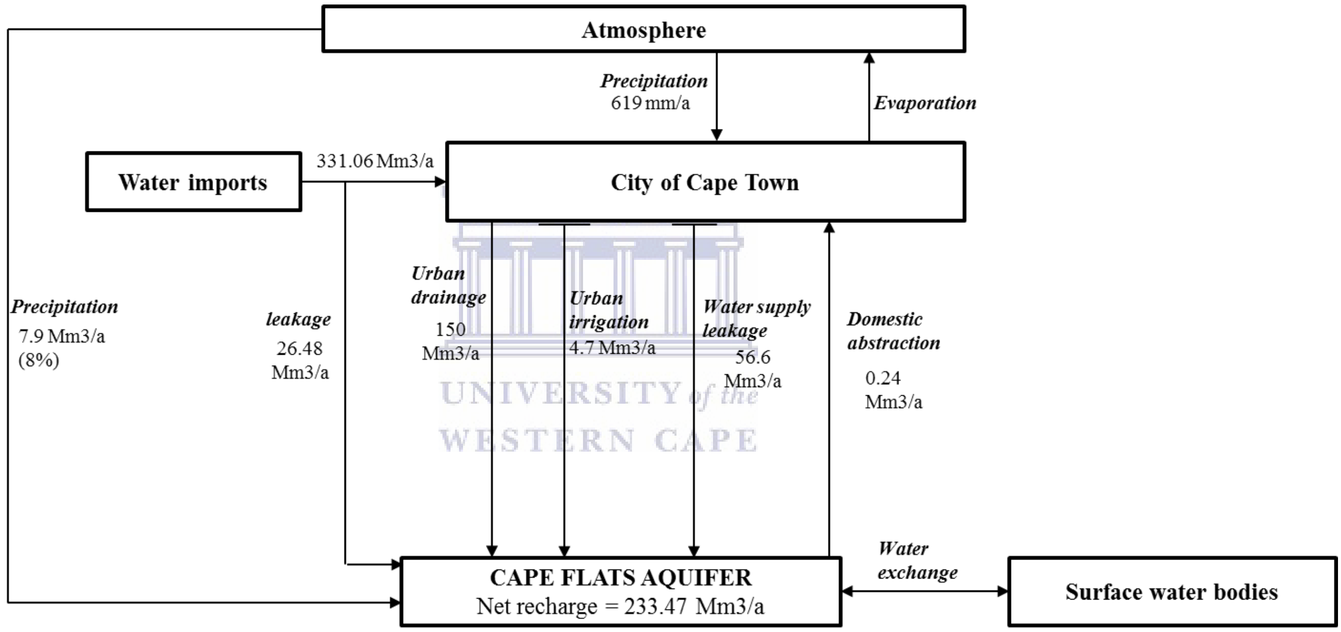


Figure 5.3(b): Recharge mechanism for the Cape Flats Aquifer

The figure 5.3(b) shows the mechanism of groundwater recharge within the Cape Flats Aquifer. Cape Flats Aquifer is within the peri-urban area and as discussed in chapter 2, recharge of aquifers in peri-urban area is due to many different components such as water supply leakages, urban irrigation and drainage, the exchange between the aquifer and surface water bodies and as a result of precipitation falling on the surface of the aquifer. As such, estimation of net recharge for the Cape Flats Aquifer requires the inclusion of all these components. In this study, all the components were included.

To estimate natural occurring recharge, the water table fluctuation method (WTF) was used. WTF analyses water levels fluctuations of observation wells to estimate recharge. The method is based on the assumption that a rise in water table elevation measured in shallow wells is caused by the addition of recharge across the water table (Xu & Beekman 2003). In estimation of recharge, the method uses equation (5.3.4b).

$$R_{(tj)} = S_y \times \Delta H_{(tj)} \qquad (5.3.4b)$$

Where:

$R_{(tj)}$ recharge occurring between t_0-t_j

S_y specific yield

$\Delta H_{(tj)}$ water table height at a certain time

In this study, specific yields were estimated as storativity values for the borehole points within the area using the pumping test data collected in 2015 and 2016. Water table heights were determined using the secondary water levels data obtained from the Department of Water and Sanitation. Table 5.2(b) shows recharge estimates based on WTF method.

Table 5.3(b): Recharge estimates for the Cape Flats Aquifer based on water table fluctuation method

Borehole	S_y	ΔH (mm)	Re (mm/year)	Re(%)
Bellville BH1	1.0×10^{-2}	6605.83	66.06	10.65
Bellville BH 2	1.0×10^{-2}	6091.00	60.91	9.82
UWC 4	1.0×10^{-2}	1098.33	11.42	1.84

Recharge due to urban irrigation return flows was quantified using the data from the City of Cape Town Municipality. The first step was to determine the average area of the zones being irrigated. This was achieved using Google Earth Pro, where the domain area catchment was imported to Google Earth and parks, stadiums as well as gardens within the boundaries of the domain area were selected out. A total of 35 parks, stadiums and gardens were randomly sampled out (Addendum 1), and the area of each polygon was calculated using Google Earth Pro calculator. The values gave an indication of the average area of each zone being irrigated. The average area was used in equation (5.2.4c) to determine the water requirements for each zone. The water requirement value of each zone was then subtracted from the values of water allocated by the City of Cape Town for irrigation purpose to determine agricultural return flows. The average estimate of return flows is shown in figure 5.3b.

$$WR = \frac{ET_0 \times PF \times SF \times 0.62}{IE} \qquad (5.2.4c)$$

WR water requirements in m^3/d

ET_o Reference crop evapotranspiration

PF plant factor in this study a value of 1 was used because it is grassland

SF area in m^2

IE irrigation efficiency (0.8 value was used for sprinkling system)

0.62 conversion value

Water supply leakage and water imports leakages values were obtained from the water balance of the City of Cape Town reported by Ahjum et al. (2015). Urban drainage values were obtained from the study by Hay et al. (2015). Domestic abstraction value was estimated using the rule of thumb used by irrigation contractors which says that every $1000m^2$ of landscape requires 4000L of water, therefore the average area being irrigated was used to extrapolate the volume of water abstracted from the Cape Flats Aquifer since groundwater in the area is mainly abstracted for irrigating gardens, stadiums and lawns. Groundwater recharge contribution proportions from each recharge component and recharge distribution are shown in figure 5.2(c) and figure 5.29(d) respectively.

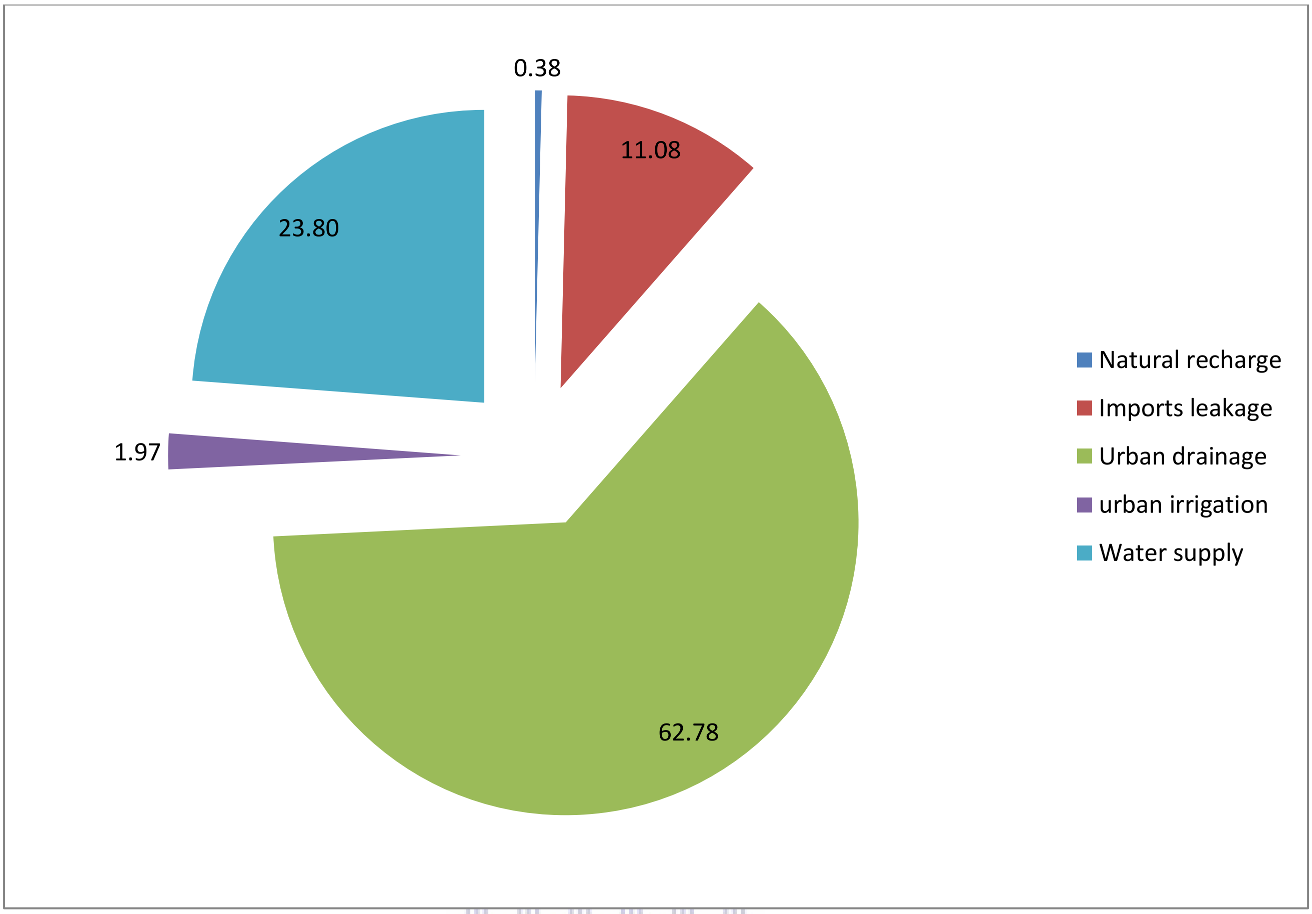


Figure 5.3(c): Proportion of groundwater recharge from different components

The Figure 5.3(c) shows the proportion of groundwater recharge from different components of groundwater recharge for the Cape Flats Aquifer within the modelled area. Based on the figure above the major contributor to groundwater recharge within the area is urban drainage with the proportion of 63%. The minor contributor to recharge is natural occurring recharge with a proportion of <1% and that is 8% (43.3 mm) of the mean annual precipitation of the area.

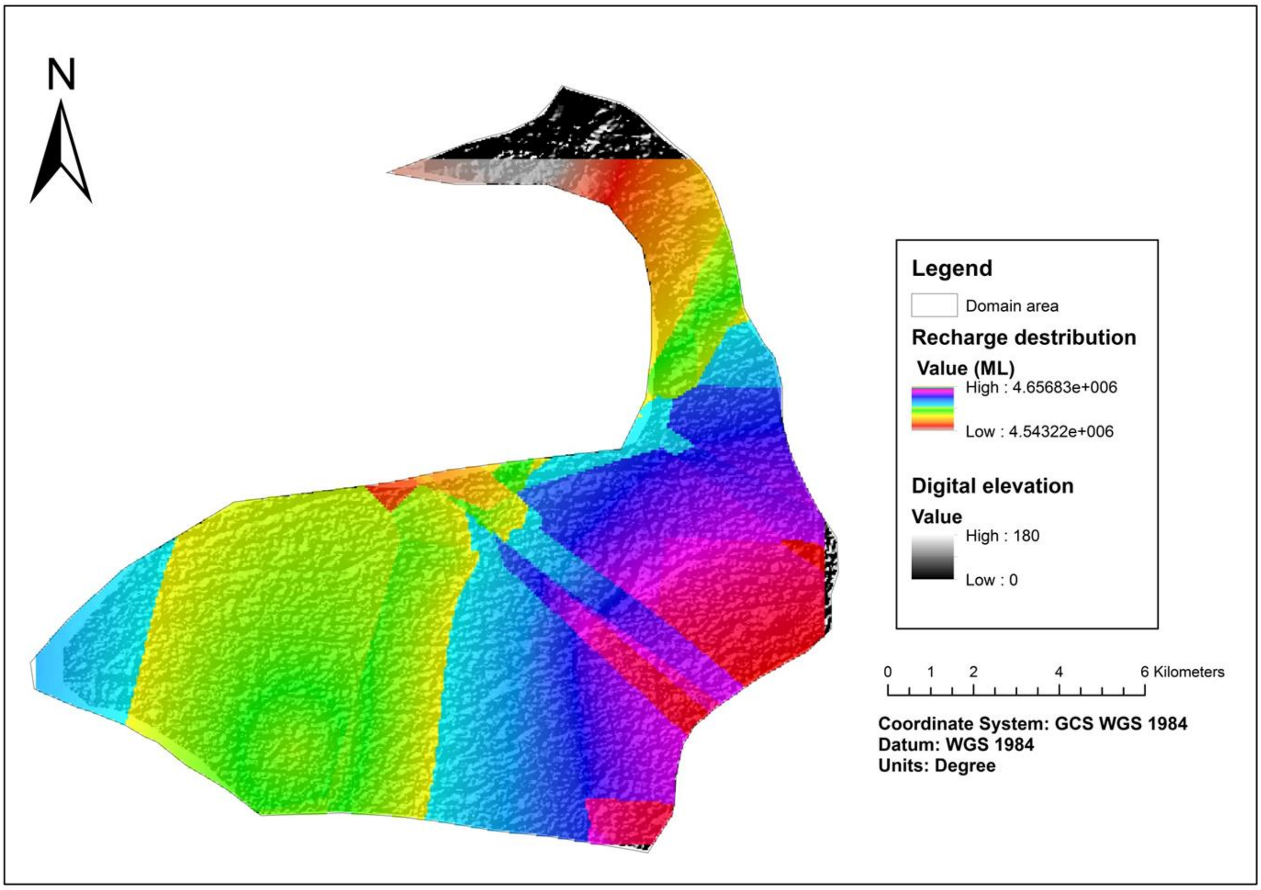


Figure 5.3(d): Distribution of groundwater recharge within the modelled area

The figure above shows the distribution of groundwater recharge within the modelled area. The map highlights that, areas of high recharge are located on the eastern side of the catchment along the catchment boundary towards the inner part. The areas of low recharge are located at the northern part of the area.

- Evapotranspiration (ET)

Evapotranspiration in this model refers to reference crop evapotranspiration ETo. Reference crop evapotranspiration is one key component of hydrological studies which is mostly in used agricultural planning, irrigation schedule, water balance studies and agro-climatological zoning (Hargreaves & Samani 1985). Evapotranspiration in this study was calculated using Hargreaves and Samani equation (5.2.3d). Data to do the calculations was obtained from South African Weather Services. Estimated ET values are presented in table (5.2c)

$$ET_0 = 1.25 \times 0.0023 \times R_a T_r^{0.5} (T_a + 17.8) \qquad (5.2.5d)$$

Where:

ET_0 reference evapotranspiration (mm/year)

R_a extra-terrestrial radiation (mm)

T_r temperature range °C

T_a average temperature °C

Table 5.3(c): Average monthly evapotranspiration rates

Years	ET (mm/month)
2014	3.98
2015	4.00
Average	3.99

5.3.5 Boundary conditions

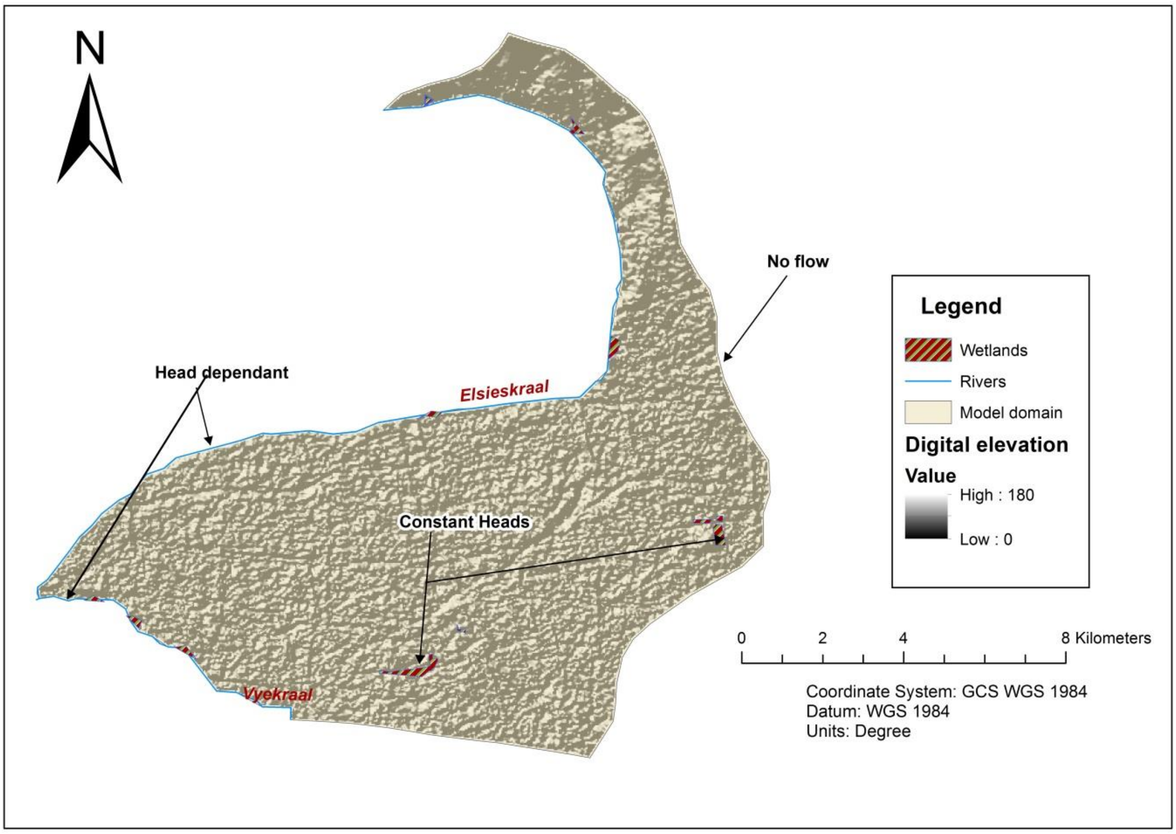


Figure 5.3(e): Boundary conditions to the area being modelled

Boundary conditions identified in this study included no flow, constant heads and head dependent boundary conditions shown in figure 5.2(e).

No flow boundaries – In this study these boundaries included the catchment boundary which is running from the north-western side through east to the south-western part of the domain area. This was specified by activating all the cells inside the catchment boundary and deactivating the cells outside the catchment boundary.

Constant head boundaries – These were identified as two big wetlands in the area and were specified using the CHD package in MODFLOW packages and programmes.

Head-dependent boundaries –These were identified as two rivers in the area. The first river is Elsieskraal River running from the north-eastern side towards the south western side and the Vygekraal River running from south western to the western part of the domain area. These head dependent boundaries were simulated using the DRAINS package within MODFLOW packages and programmes as there are standing water pools within the rivers.

5.4 Key results on numerical groundwater flow simulation

Table 5.4(a): Water budget of the domain area based on uncalibrated model

Flow m^3/s		**Flow m^3/s**	
IN		**OUT**	
Storage	0.00	**Storage**	0.00
Constant head	0.154	**Constant head**	0.151
Drains	0.000	**Drain**	2E-03
ET	0.000	**ET**	4E-03
Recharge	2E-06	**Recharge**	0.000
TOTAL IN	0.154	**TOTAL OUT**	0.1536
IN-OUT		4E-06	
percentage discrepancy		0.00	

The table 5.4(a) highlights the water budget results for the modelled area before calibration. The table shows that constant heads and recharge are major contributors to the water budget of the model domain. And some constant heads, drains and ET are major sinks to the area being modelled.

Table 5.4(b): Comparison between observed and simulated heads based on the uncalibrated model

	Observed	**Model**			
		Simulated	**Residuals**	**Residuals^2**	**Absolute residuals**
Well ID	m	m	m	m	m
UWC 4	4.30	5.56	-1.26	1.59	1.26
BG46051	3.68	3.85	-0.17	0.03	0.17
BG46052	3.14	4.07	-0.93	0.87	0.93
UWC 3a	4.55	5.59	-1.04	1.08	1.04
UWC 3b	4.50	5.76	-1.26	1.59	1.26
		Root Mean Square Error		**1.02**	
		Mean Error		**-0.93**	
		Mean Absolute error		**0.93**	

Table 5.4(b) shows the comparison of simulated heads with observed heads for 5 borehole points within the domain area. Assessment of error criterion was done using Root Mean Square Error, Mean Error and Mean Absolute Error and for each technique reveals an error

less than 10. Simulated heads were found to be higher than the observed heads giving rise to the negative residuals.

Table 5.4(c): Comparison between simulated and observed fluxes of two rivers with the model domain based on uncalibrated model

Model					
	Observed	**Simulated**	**Residuals**	**Residuals^2**	**Absolute residuals**
Observation name		m	m	m	m
Elsieskraal	-1E-03	-6E-04	-5E-04	2E-07	0.0005
Vygekraal	-4E-05	-2E-03	2E-03	3E-06	3E-06
		Root mean Square Error		**0.001**	
		Mean Error		**6E-04**	
		Mean Absolute Error		**0.0002**	

The table 5.4(c) above shows the comparison between observed and simulated fluxes of the Elsies Kraal River and Vygekraal River forming north and western boundaries of the domain area based on the uncalibrated model. The observations were made during the start of simulation process using DROB package. The simulation is within the expectable error margin of less than 10 based on RMSE, ME and MAE. Differences in stages are shown as residuals and based on these residual the differences between fluxes observed and simulated is slightly bigger.

5.5 Calibration

Calibration according to Anderson & Woessner (2002) refers to the process of demonstrating the capability of the model to produce the field measured heads and flows. This is achieved through finding input parameters, stresses or boundary conditions which produce simulated values similar to observed heads or fluxes. Calibration can be done in two ways, through forward modelling and inverse problem solution. In this study forward modelling was used by conventional trial and error technique where recharge and aquifer thickness were manually adjusted within the reasonable range, to match the simulated and observed heads and fluxes.

Table 5.5(a) shows the input parameters adjusted during calibration process.

Parameters	**Initial values**	**Calibrated**
Recharge (Re)	233.47 Mm^3/a	11.3 Mm^3/a
Aquifer thickness	45m	55m

Table 5.5(a) shows adjusted hydraulic parameters to match the simulated heads and fluxes with the observed heads and fluxes. Adjusted parameters were recharge rate and aquifer thickness. Recharge used to perform calibration was an estimate of 11.3Mm^3/a by Hay et al. (2015). Aquifer thickness of 55m suggested by Adelana et al. (2010) was also used as a calibration parameter.

Table 5.5(b): Water balance for the domain area based on the calibrated model

Flow m3/s		**Flow m3/s**	
IN		**OUT**	
Storage	0.000	**Storage**	0.000
Constant head	0.382	**Constant head**	0.378
Drains	0.000	**Drains**	3E-03
ET	0.000	**ET**	5E-11
Recharge	5E-06	**Recharge**	0.000
TOTAL IN	0.382	**TOTAL OUT**	0.381
IN-OUT		7E-04	
Percentage Discrepancy		0.19	

The table 5.5(b) shows water budget of the model domain based on the calibrated model. From the table it is evident that major contributors to the water budget of the domain area are recharge and constant heads. Drains and Evapotranspiration are major outflows within the area

Table 5.5(c): Comparison between observed and simulated heads based on the calibrated model

	Model				
Well ID	**Observed head** **m**	**Simulated** **m**	**Residuals** **m**	**Residual^2** **m**	**Absolute residuals** **m**
UWC 4	4.30	5.41	-1.11	1.230	1.11
BG46051	3.68	3.63	0.05	0.002	0.05
BG46052	3.14	3.60	-0.46	0.210	0.46
UWC 3a	4.55	5.50	-0.95	0.900	0.95
UWC 3b	4.50	5.67	-1.17	1.369	1.17
		Root Mean Square Error		**0.86**	
		Mean Error		**-0.73**	
		Mean Absolute Error		**0.75**	

The table 5.5(c) shows comparison between observed and simulated heads based on calibrated model. The differences between the simulated and the observed heads are showed as residuals which reveals small differences between observed and simulated heads for all the borehole points. This means that the calibration had been achieved. Error criterion also show an error of less than 1 based on all statistical checks applied.

Table 5.5(d): Comparison between observed and simulated fluxes of two rivers within the area based on calibrated model.

	Model				
Observation ID	**Observed**	**Simulated**	**Residuals**	**Residuals^2**	**Absolute residual**
Elsieskraal	-1E-03	-7E-04	-4E-04	1E-07	0.0004
Vygekraal	-4E-05	-3E-03	3E-03	9E-06	0.003
		Root Mean Square Error		**0.002**	
		Mean Error		**1E-03**	
		Mean Absolute Error		**0.002**	

The table 5.5(d) shows comparison of observed and simulated fluxes of two rivers forming the north and western boundary. The differences between the simulated and observed heads are showed as residuals and show smaller differences between the simulated and observed fluxes, therefore proving that calibration was achieved. The error criterion proves to be less than 1 for all the statistical checks which have been applied.

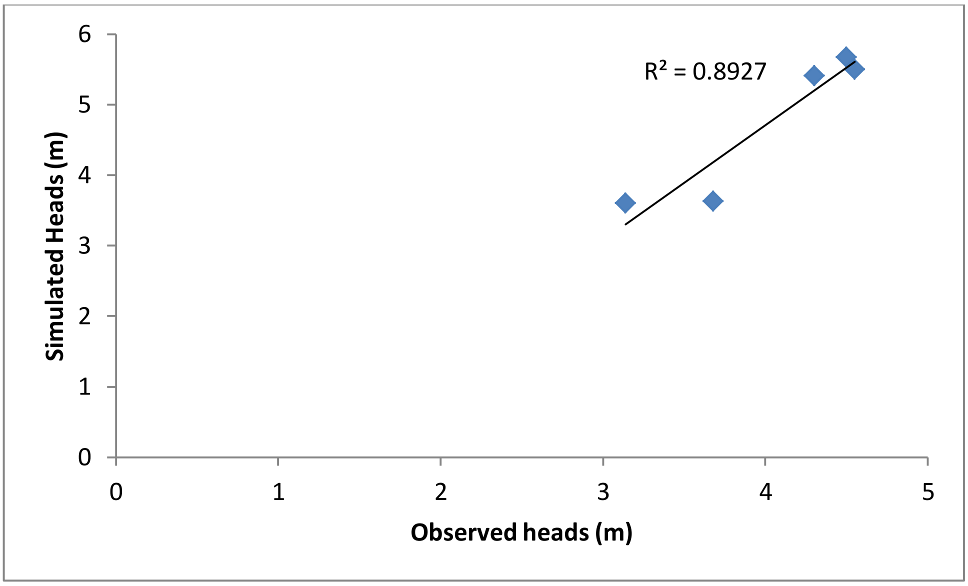


Figure 5.5(e): Relation of observed and simulated heads for the calibrated model

The figure 5.5(e) above shows a relationship between simulated heads and observed heads based on the calibrated model. The figure reveals R^2 of 0.89 proving a strong positive relationship between simulated and observed heads and therefore proving that calibration had been achieved.

5.6 Scenarios set-up and predictions

5.6.1 Varying aquifer recharge scenarios

This section presents results obtained from variable recharge scenarios based on the calibrated model. The aim was to test how varying groundwater recharge rates influences the water balance components, head distribution, fluxes and groundwater flow directions. Scenarios tested are presented in table 5.6.1 below. The assumption in this scenario was that varying recharge is as a result of MAR implemented.

Table 5.6.1: Groundwater balance components and varying recharge effects

Scenarios	water balance components	Inflow (m^3/s)	Outflow (m^3/s)	Change in outflow with respect to the calibrated value (%)
Scenario 1: ***Calibrated value***	Constant head	0.382	0.378	
	Drains	0	3E-03	
	ET	0	5E-11	
	Recharge	5E-06	0	
Scenario 2: ***increasing recharge by 25%***	Constant head	0.382	0.379	0.03
	Drains	0	3E-03	0.17
	ET	0	5E-11	0.16
	Recharge	2E-06	0	0
Scenario 3: ***decreasing recharge by 25%***	Constant head	0.319	0.378	0
	Drains	0	3E-03	-0.04
	ET	0	5E-11	-0.08
	Recharge	2E-06	0	0
Scenario 4: ***double calibrated recharge value***	Constant head	0.382	0.379	0.03
	Drains	0	3E-03	3.54
	ET	0	5E-11	-0.02
	Recharge	2E-06	0	0.00

The table 5.6.1 above shows groundwater budget components and predicted recharge influence on these components based on the calibrated model. The aim was to assess various water balance component response under variable recharge rates triggered by managed aquifer recharge using the calibrated model. Simulations were made based on three scenarios using a recharge value of 11.3 Mm^3/day as scenario 1. Increasing the recharge value by 25% was used as scenario 2. Decreasing the recharge value by 25% was used as a simulated as scenario 4 and double the recharge value was simulated as scenario 4. Water budget results presented in table 5.6.1 indicate that varying recharge rates impacts the water budget components for the domain area. When looking at the column of change in outflow with respect the calibrated value, the percentage differences change with changes in recharge rates. As recharge rate is increased by 25% the percentage difference of outflow with respect to the calibrated values increases. The similar pattern was observed when recharge rate was decreased by 25%.

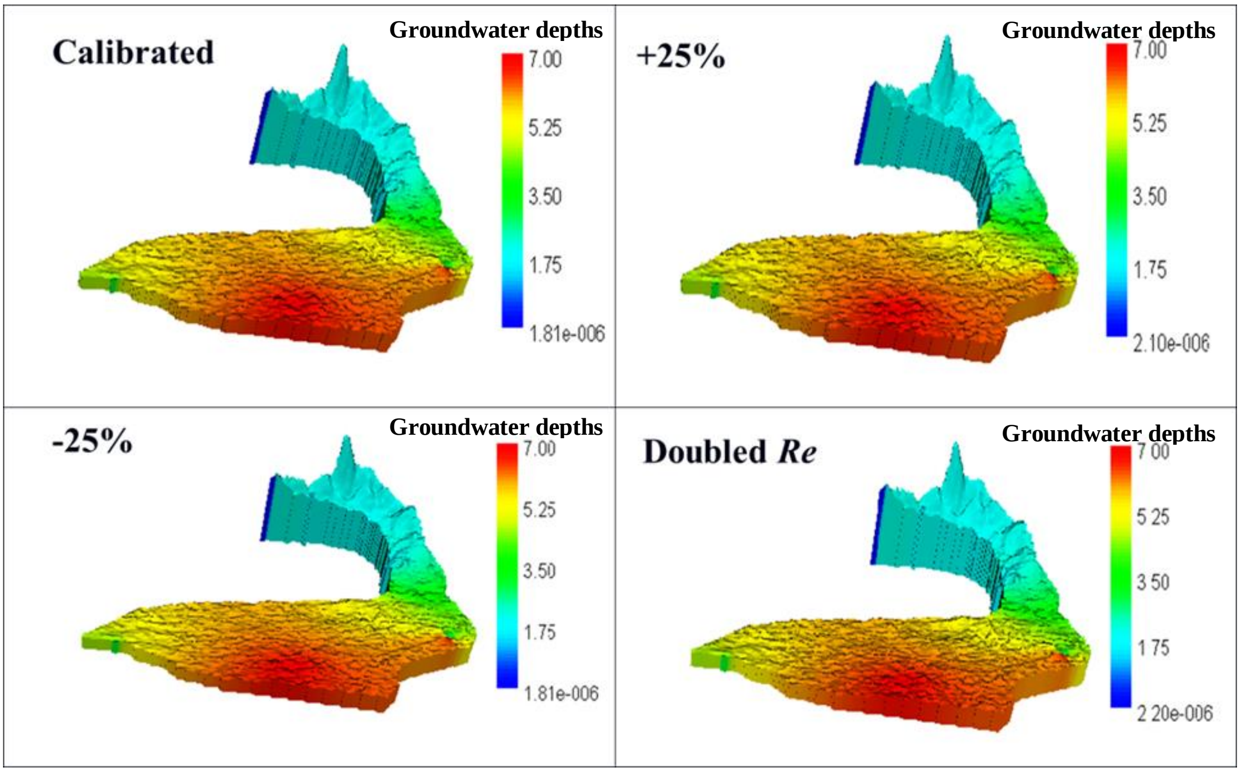


Figure 5.6.1(a): Groundwater depths distribution based on varying recharge rates scenarios

The figure 5.6.1(a) above shows the influence of varying recharge rates on groundwater depths distributions and flow direction for the Cape Flats Aquifer within the modelled area based on three scenarios tested. Scenario 1 was the calibrated value of recharge suggested by Hay et al. (2015), Scenario 2 involved increasing the calibrated recharge value by 25%, scenario 3 involved decreasing the calibrated recharge value and scenario 4 which involved doubling the calibrated recharge value. Plot a) shows the groundwater depths distribution based on the calibrated recharge value. Based on this scenario groundwater depths ranged from 3.6m to 5.67 m with borehole UWC 3b having the highest and borehole BG46052 having the lowest. Plot b) shows groundwater depths distribution based scenario 2, groundwater levels based on this scenario ranged from 3.63m to 5.68m with borehole UWC3b having the highest and borehole BG46051 having the lowest. Plot c) hydraulic head distribution based on scenario 3, groundwater levels based on this scenario ranged from 3.62m to 5.68m with borehole UWC 3b having the highest water level and borehole BG46051 having the lowest water level. Plot d) shows groundwater depth distribution based on scenario 4. The groundwater levels based on this scenario ranged from 3.63m to 5.72m with borehole UWC 3b having the highest water level and borehole BG46051 having the lowest. Groundwater flow direction for all the scenarios did not change and was from the north eastern part of the modelled area towards the south western part.

5.6.2 Pumping scenarios

This section presents results obtained from variable withdrawal rates simulation. The aim was to test the influence of varying withdrawal rates on water balance components, groundwater depths distribution and flow directions. Scenarios tested are presented in table 5.6.2. The assumption for this scenario was that it represents lowering of water table to increase storage for MAR.

Table 5.6.2: Groundwater balance components and varying abstraction rates

Scenarios	**water balance components**	**Inflow (m^3/s)**	**Outflow (m^3/s)**	**Difference per (m^3/s)**	**Change in outflow with respect to 5l/s based on T in the area (%)**
Scenario1:	Constant head	0.404	0.38		
Abstraction 5l/s	Wells	0	3E-02		
	Drains	0	2E-02		
	ET	0	4E-11		
	Recharge	2E-06	0		
Scenario 2:	Constant head	0.425	0.37	-0.003	-0.8
Doubling the	Wells	0	5E-02	0.025	100
abstraction rates	Drains	0	2E-02	-0.004	-17.5
	ET	0	3E-11	-7E-12	-17.1
	Recharge	2E-06	0	0	0
Scenario 3:	Constant head	0.4673	0.3658	-0.009	-3
Increasing	Wells	0	1.00E-01	0.075	300
abstraction rate 4 times	Drains	0	1.1540E-03	-0.023	-95
	ET	0	2.2150E-11	-2E-11	-44
	Recharge	2E-06	0	0	0

The table 5.6.2 shows the influence of varying pumping rates on water balance components of the Cape Flats Aquifer based on the calibrated model. The aim was to assess various water balance components, fluxes, and groundwater flow pattern and heads response under variable abstraction rates triggered by water withdrawals. These simulations were based on three scenarios, scenario 1 which included the groundwater withdrawal at a rate of 5l/s. The 5l/s was used as a reference abstraction rate and was decided based on the average transmissivity range (<50m^2/d to 620m^2/d) for the Cape Flats Aquifer. Scenario 2 included doubling the groundwater withdrawal rate to 10l/s and Scenario 3 increasing the withdrawal rate four times meaning abstracting at 20l/s. Water budget results presented in table 6.5.2 clearly show that varying abstraction rates influences the water balance components of the area. The results reveal that at an abstraction rate of 20 l/s substantially changed groundwater dynamics and fluxes. The biggest observed change in outflows was in drains and wells where the difference was 0.08m^3/s and -0.02m^3/s respectively. When abstracting at a rate of 10l/s there was a slight change in outflows observed in all outflow components. A great change when abstracting at a rate of 20l/s was observed in drains and wells where the difference was 0.025m^3/s and -0.004m^3/s respectively.

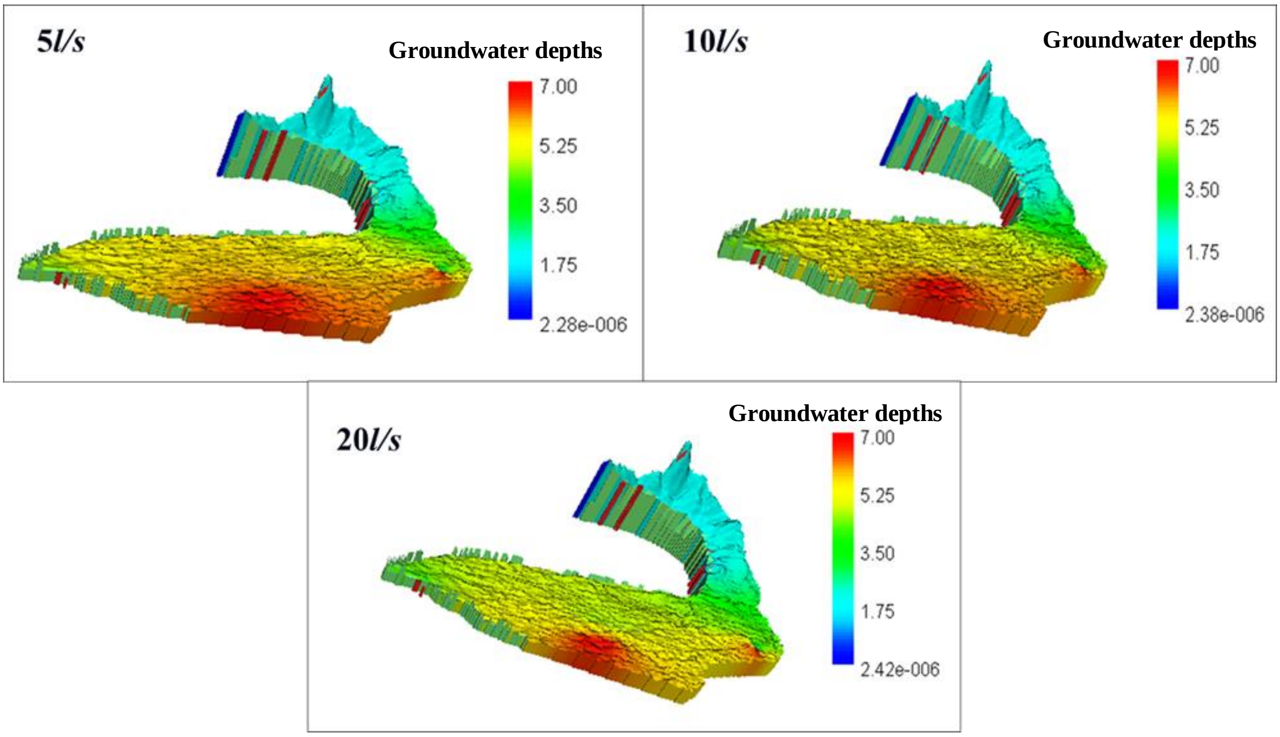


Figure 5.6.2 (a) groundwater depths distribution based on varying abstraction rates scenarios

The figure 5.6.2 (a) above shows the influence of varying abstraction rates on the groundwater depth and flow direction. The comparison was done using the results 5l/s abstraction as a reference. Based on the results of the abstraction of 5l/s groundwater depths for the area ranged from 3.57m to 5.56m with borehole BG46051 having the highest and borehole UWC 3b having the lowest. When the abstraction rate of 5l/s was doubled to 10l/s groundwater depths slightly dropped ranging from 3.51m to 5.45m with borehole UWC 3b having the highest and borehole BG46051 having the lowest. A substantial decline in depths was observed when groundwater was abstracted at a rate of 20l/s. Groundwater depths ranged from 3.39m to 5.21m with borehole UWC 3b having the highest and borehole BG46051 having the lowest. The direction of groundwater did not change for all the scenarios tested the flow was from the north eastern part of the modelled area towards the south western part.

5.6.3 Combined pumping and reduced groundwater recharge scenarios

This section presents results of combined influence of reduced groundwater recharge rate and varying withdrawal rates. The scenarios tested are presented in table 5.6.3 below. The assumption was that the scenario represents a situation in summer where groundwater recharge is reduced and abstraction varies.

Table 5.6.3(a): Combined influence of groundwater recharge and pumping scenarios

Scenarios	**water balance components**	**Inflow (m^3/s)**	**Outflow (m^3/s)**	**Difference per (m^3/s)**	**Change in outflow with respect to 5l/s based on T in the area (%)**
Scenario 1:	Constant head	0.404	0.375		
Decreasing	Wells	0	3E-02		
recharge by 25%	Drains	0	2E-03		
and abstracting at	ET	0	4E-11		
5l/s	Recharge	2E-06	0		
Scenario 2:	Constant head	0.425	0,372	-0.003	-0.83
Doubling the	Wells	0	5E-02	0.025	100.00
abstraction rates at	Drains	0	2E-02	0.018	724.77
25% less recharge	ET	0	3E-11	-8E-12	-18.91
	Recharge	2E-06	0	0	0.00
Scenario 3:	Constant head	0.467	0,366	-0.009	-2.51
Increasing	Wells	0	1E-01	0,075	300,00
abstraction rate 4	Drains	0	1E-03	-0.001	-52,73
times at 25% less	ET	0	2E-11	-2E-11	-44,40
recharge	Recharge	2E-06	0	0	0

The table 5.6.3 above show the influence of combined groundwater abstraction and decreased recharge on the water balance component of the Cape Flats Aquifer. The main aim was to assess how the outflows behave under variable abstraction rate and 25% less recharge. The simulations were based on three scenarios, Scenario 1 which included decreasing the calibrated recharge by 25% and abstracting at the rate of 5l/s. This scenario was used as a reference for comparison to other scenarios. Scenario 2 involved doubling the abstraction rate to 10l/s and still using the same recharge rate as scenario 1, and scenario 3 involved increasing the abstraction rate 4 times to 20l/s and still using the same recharge rate as scenario 1 and 2. Based on table 6.5.3 above outflows from the water balance components substantially changed as groundwater abstraction rate increases. A larger increase in was observed in scenario 3 where biggest difference was in outflows from wells, drains and constant heads with 0.075m3/s, -0.001m3/s and -0.009m3/s with respect to scenario 1. Scenario 2 also show a slight change in outflows on drains, wells and constant heads, where the differences with respect to scenario 1 were 0.018m^3/s, 0.025m^3/s and 0.003m^3/s respectively.

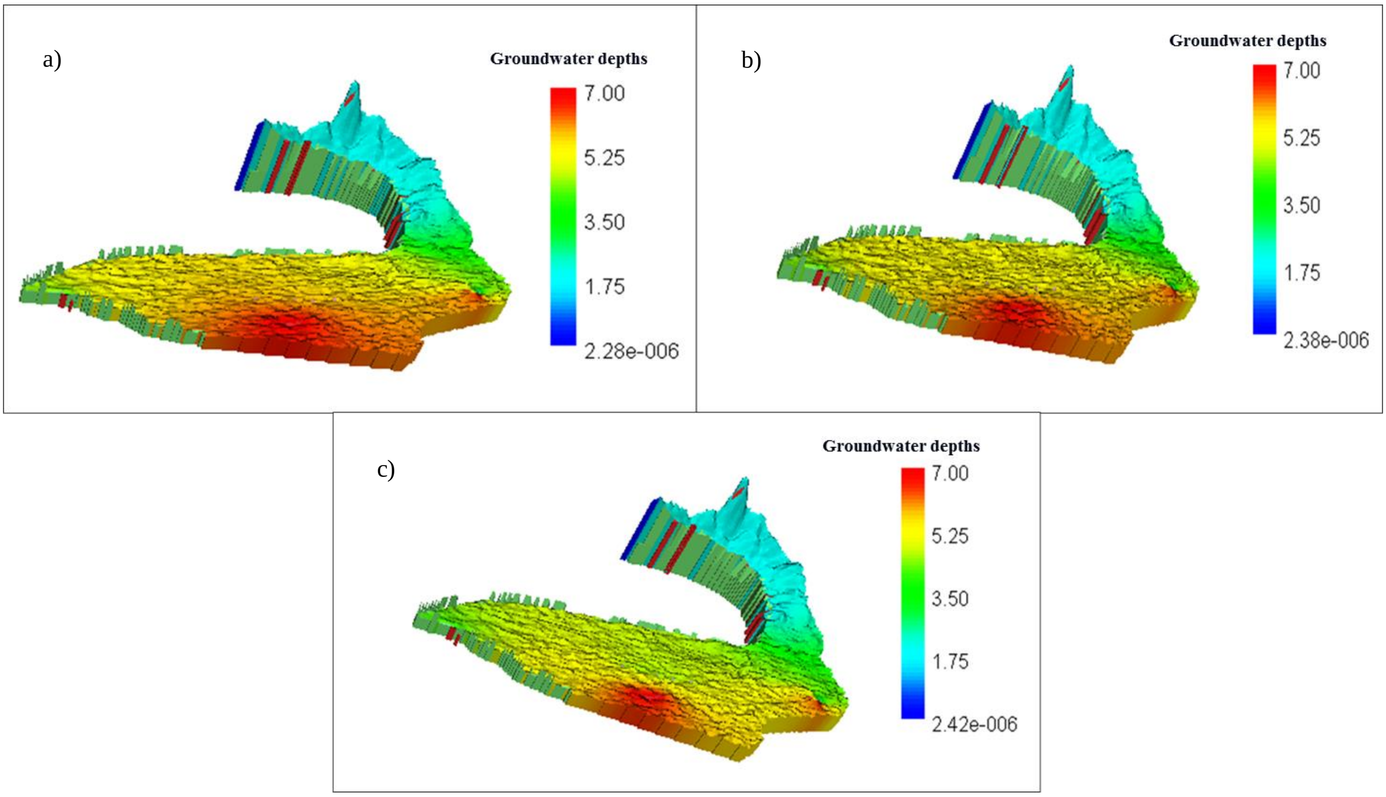


Figure 5.6.3(a) Groundwater depths distribution based on combined pumping and recharge scenarios

The figure 5.6.3 (a) above shows the groundwater depths and flow direction plots based on three scenarios. Plot a) shows depths distribution based on scenario 1, groundwater depths ranged from 3.57m to 5.56m with highest water level observed in borehole UWC 3b and lowest water levels observed in borehole BG46051. The plot b) shows groundwater depths distribution based on scenario 2 where depths were slightly less when compared with observations from scenario 1 ranging from 3.51m to 5.44m With shallow depths observed in borehole UWC 3b and lowest observed in borehole BG46051. Plot c) shows groundwater depths distribution based on scenario 3, the depths observed ranged from 3.39m to 5.23m with shallow depths observed in borehole UWC 3b and the lowest observed in BG46051. These water levels were substantially lower when compared with simulations from scenario 1 and 2. Groundwater flow direction from all the simulated scenarios did not change and was from north-eastern part of the modelled area towards the south western part.

5.7 Sensitivity analysis

Sensitivity analysis was done to understand uncertainty in the calibrated model caused by limitations in the estimates of aquifer parameters and stresses. Groundwater models tend to be sensitive to different model input parameters, A small change in those parameters will result in the larger difference between simulated and observed head and fluxes (Zhou & Li 2011). In this study constant heads and hydraulic conductivities were varied by 10%, 50% and 80% increases and decreases during successive runs to test the sensitivity of the model to the parameters. A total of 12 runs were made by varying constant heads and hydraulic conductivity within the specified percent from the calibrated value and the respected mean error, root mean square error and mean absolute error. Each parameter was changed uniformly of the entire area and other parameters were kept to the steady state calibrated value. The magnitude of change in heads and fluxes from the calibrated solution were used to measure the sensitivity of the model to the particular parameter.

Results from the sensitivity analysis are presented in Addendum (A2) as differences in water levels. Large differences between simulated heads and observed heads were noted for the boreholes at increased constant heads more than the decreased constant heads. This means the model is sensitive to increased constant heads values within the locations of the boreholes however; it was difficult to tell comprehensively over the entire domain where the model is sensitive due to the number of observation boreholes within the area. Based on the results on varying hydraulic conductivity presented in Addendum (A2) no large difference were observed between observed and simulated heads showing that the model is not sensitive to changes in hydraulic conductivity values.

5.8 Interpretation of results

A 3-dimensional steady-state site specific numerical model was developed to predict future Cape Flats Aquifer behaviour under stress conditions posed by the implementation of WSUD principles on Cape Flats Aquifer at site specific scale. The stresses included varying groundwater recharge rates, which the assumption was that, the scenario represents varying recharge due to implemented MAR suggested by WSUD principles, varying abstraction rate which was assumed that it represents a situation of lowering of the water table to increase the aquifer storage for MAR, and combined scenario of reduced recharge rates with varying abstraction rates, which the assumption was that the scenario represents a situation in dry season where recharge is reduced and groundwater abstraction varies. This section discusses findings from the predictions of the above-mentioned scenarios.

Model results from the varying recharge scenarios show that variation in recharge rates causes fluctuations in the water table, outflows from the water balance components and fluxes of the area. When recharge rate was doubled with the assumption that it represents a good managed recharge season, groundwater levels were increased substantially and outflows observed from water balance components and fluxes were also increased, these results show that with increasing groundwater recharge, the outflows, groundwater water table and fluxes also increase. A similar situation was observed when groundwater recharge was decreased. This then shows that fluxes, outflows and water table are directly proportional to increasing and decreasing recharge in the area. When looking at the influence of varying withdrawal rate scenarios, the results show that with an increase in withdrawal rate groundwater outflows and levels and fluxes decreases. A substantial decline in groundwater levels, outflows and fluxes were observed when abstraction rate was multiplied 4 times meaning abstracting at a rate of 20l/s. The results from the abstraction scenarios, therefore, showed that groundwater levels, outflows and fluxes are inversely proportional to varying abstraction rates within the area. Combined abstraction and reduced recharge rate scenarios showed that varying abstraction rates at reduced recharge negatively influences outflows from water balances components groundwater levels and fluxes. Substantial decline groundwater levels, outflows and fluxes were observed at a 25% less recharge with abstraction rate of 20l/s.

The model demonstrated how various future water sensitive urban design scenarios would influence the behaviour of the Cape Flats Aquifer at site-specific scale. However, due to lack of monitoring points, the study relied on observations made on 5 monitoring wells within the sites. This is one limitation of the model. Based on this limitation the study, therefore, recommends a denser network of boreholes along the flow direction to improve the calibration of the model. Groundwater abstraction was also grossly estimated, actual groundwater abstraction rates were difficult to quantify because within the modelled area groundwater is abstracted at a domestic scale and boreholes are not registered with the department of water and sanitation, thus locating the exact locations of those boreholes was not successful. Based on this limitation, the study also recommends inclusion of more abstraction boreholes to account for more accurate groundwater withdrawals within the area.

5.9 Chapter summary

Chapter 5 of the study presented and discussed results obtained from conceptualization of the local groundwater flow system of the Cape Flats aquifer using a Finite Difference Method. The main aim was to predict future aquifer behaviour under site-specific stress conditions posed by WSUD implementation. The problem being addressed in the chapter was limited studies done focusing conceptualizing local groundwater flow system of the Cape Flats Aquifer. The central argument was that presence of WSUD stresses such as MAR negatively and positively influences the aquifer behaviour. The question being asked then was how the Cape Flats Aquifer system behaves under WSUD stress conditions at a local scale.

To achieve the objective quantitative primary data from field measurements and secondary data from sources such as the department of water and sanitation and City of Cape Town municipality were assembled together to develop a hydrogeological conceptual model which gave an idea of the site-specific condition of Cape Flats Aquifer system. 3-dimensional steady state Finite Difference numerical flow model was then developed using MODFLOW-2005 code within the Model muse software package, in order to predict future aquifer behaviour under different scenarios that were set out. Scenarios that were simulated included varying recharge scenarios which was assumed to represents variation in recharge scenarios as a result managed aquifer recharge suggested by WSUD principles, varying groundwater withdrawal rates which the assumption was that varying abstraction represents rates for lowering water table to increase storage for the treated stormwater, and combined varying groundwater withdrawals and reduced groundwater recharge rates which the assumption was that the scenario represents dry season situation where recharge is reduced and abstraction varies.

The conceptual model revealed that local groundwater flow with the area follow the surface topographical pattern, where the flow is from high elevated areas to low elevated areas, with groundwater table ranging from 2m to 6m respectively. Three scenarios were simulated using the calibrated model and these included, varying groundwater recharge rates, varying groundwater withdrawal rates and last combining decreased recharge rate with varying abstraction rate. Recharge scenario showed that varying recharge rates has a substantial impact on hydraulic head distribution, fluxes and outflows on water balance components for the area. When recharge rates were decreased groundwater levels, outflows and fluxes also dropped and when increased, all the three components also increased, therefore, indicating that groundwater levels, outflows and fluxes are directly proportional to varying groundwater recharge rate within the area.

Varying groundwater withdrawal rates caused fluctuations in water levels, fluxes and outflows observed from the water balance components. When groundwater withdrawal rates were increased, groundwater levels significantly dropped. Also differences in outflows from the water balance components with reference to 5l/s abstraction values dropped. Minimal decline in water levels were observed at reduced withdrawal rates where, differences in outflows as observed from the water budget components of the area with respect to the 5l/s abstraction value decreased. The results from the varying abstraction scenarios indicate that a outflows components, fluxes and groundwater levels show an inverse proportionality to abstraction rates. Combined influence of reduced recharge and varying abstraction rates yielded results showing a substantial decline in water levels when withdrawal rate are higher and recharge rate lower. Water balance components also showed high outflows at higher abstraction rate and reduced recharge. Based on these findings the study concluded that with varying recharge and abstraction rate, fluctuations in outflows, fluxes and groundwater levels could be expect within the area. The study however recommends dense and extended network of boreholes to improve the calibration of the model and also to account for accurate abstraction value as this value was grossly estimated.

Chapter 6: Assessing groundwater surface water interaction

6.1 Introduction

Chapter 6 of the study presents and discusses results obtained during the assessment of groundwater surface water interaction within the Cape Flats Aquifer. The chapter addressed objective 3 of the study outlined in chapter 1, which focused on assessing groundwater surface water interaction between the Cape Flats Aquifer, and rivers as well as wetlands on the surface of the Cape Flats Aquifer, using principal aquifer setting, environmental isotope and hydrochemical analysis method. The intention was to identify where and when groundwater surface water interaction is occurring, in-order to inform the prevention strategies of the negative effluence of exchanges between groundwater and surface water on the effectiveness of water sensitive urban design. The central argument in this chapter was that if the spatial and temporal distribution of groundwater surface water interaction is understood prior to water sensitive urban design planning, then negative influence of exchanges between groundwater and surface water bodies on the effectiveness of WSUD could be managed. The question that was asked then was to what extent does the knowledge on spatial-temporal distributions of groundwater surfaces water interaction can assist in managing the negative influences of exchanges between groundwater and surface water on the effectiveness of WSUD, in the context of peri-urban cities such as Cape Town.

To achieve this objective, the study gathered quantitative primary data from samples collected in borehole points, rain gauges, rivers and wetlands, and also from measurements of water levels in boreholes within the area. Quantitative secondary data was also collected from water management agencies such as Department of water and sanitation and City of Cape Town municipality. The samples collected from borehole points, rivers and wetlands were sent to BEM lab in Strand Western Cape for analysis of major ions which were used as confirmatory tracers for groundwater surface water interaction. The samples for stable isotopic signatures (^{2}H and ^{18}O) were analysed at the University of the Western Cape isotopic laboratory. These isotopes were also used as confirmatory tracers for groundwater surface water interaction. Principal aquifer setting was mainly used as a qualitative method to identify possible sites for groundwater surface interaction.

6.2 Results on interaction using principal aquifer setting method

6.2.1 Key results

This section presents results obtained from the use of principal aquifer setting method in identifying sites of groundwater surface water interaction. The results presented in this section are based on 5 different borehole points distributed across the Cape Flats Aquifer. Firstly, the study delineated groundwater units based on the aquifer type classification table reported by Le Maitre & Colvin (2008). The reason for delineating the units was to identify nature of groundwater flow and discharge within the area. The results are shown in figure 6.2.1(a).

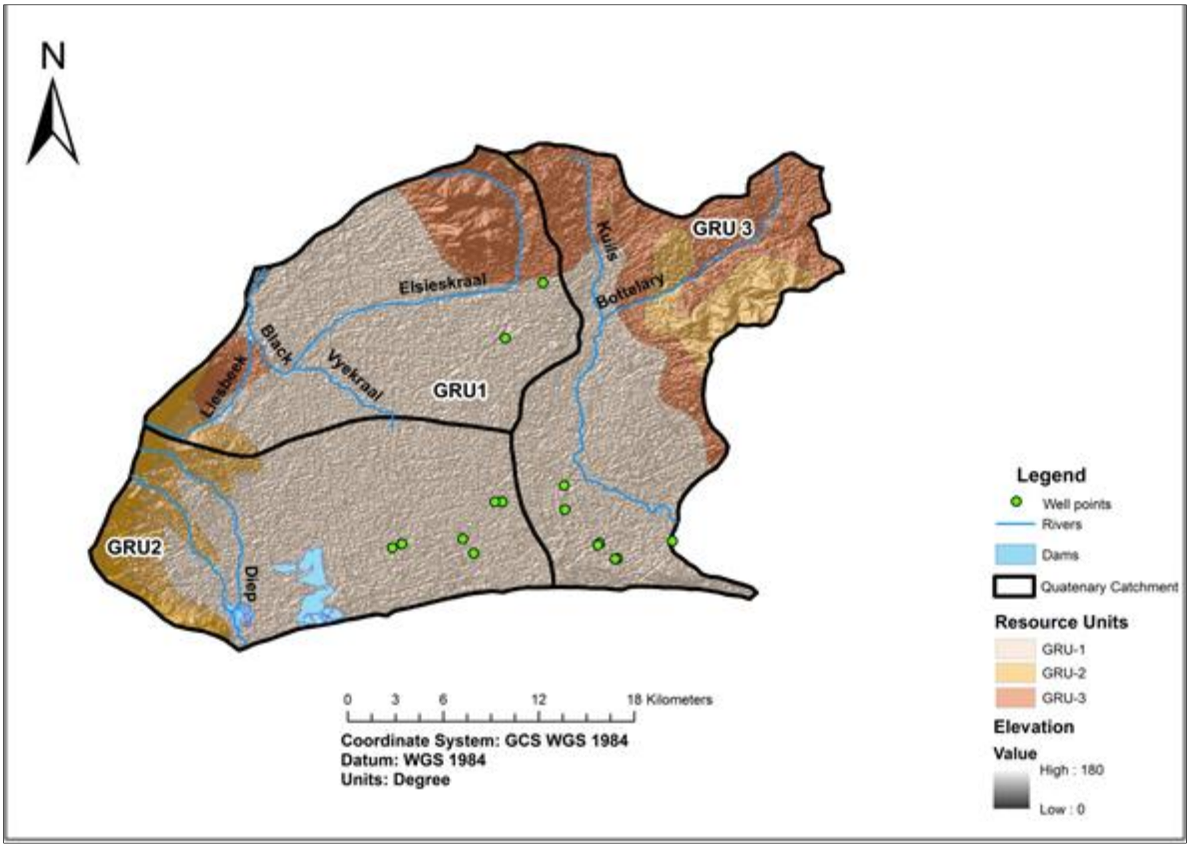


Figure 6.2.1(a): Delineated groundwater resources units (GRU) based on principal aquifer setting classification

GRU 1- Covers the larger portion of the study area and is located within the inner part. The resource unit encompasses a large unconsolidated sedimentary strata characterised by inter granular permeability varying from course sands and gravels to finer materials and clay. The resource unit has diffused discharge from the primary Cape Flats Aquifer to rivers and wetlands in the area and has moderate to high storativity values. Groundwater in the area is mostly recharged during the period of high flows and during the period of low flows groundwater sustains the rivers and wetlands in the area.

GRU 2- Covers the small portion and located within the western part of the study area. The resource unit mainly encompasses of basement complex and younger granites. The unit is known to be the secondary aquifer with limited groundwater storage in faults and fractures. There is discrete of groundwater discharge from this unit to rivers and wetlands within in the area but these surface water bodies are sustained through springs where there is an existence of a significant fracture or fault. The current study however did not assess the interaction in this unit as the primary focus of the study is Cape Flats Aquifer which falls within GRU 1.

GRU 3- Covers the small portion of the study area and is located within the north eastern side. The resource unit forms part of the fractured meta-sedimentary characterised by sedimentary rocks which are fractured, intruded and metamorphosed to varying degrees. The unit has a discrete to linear discharge from its fractures and faults in form of springs seeps and wetlands.

.

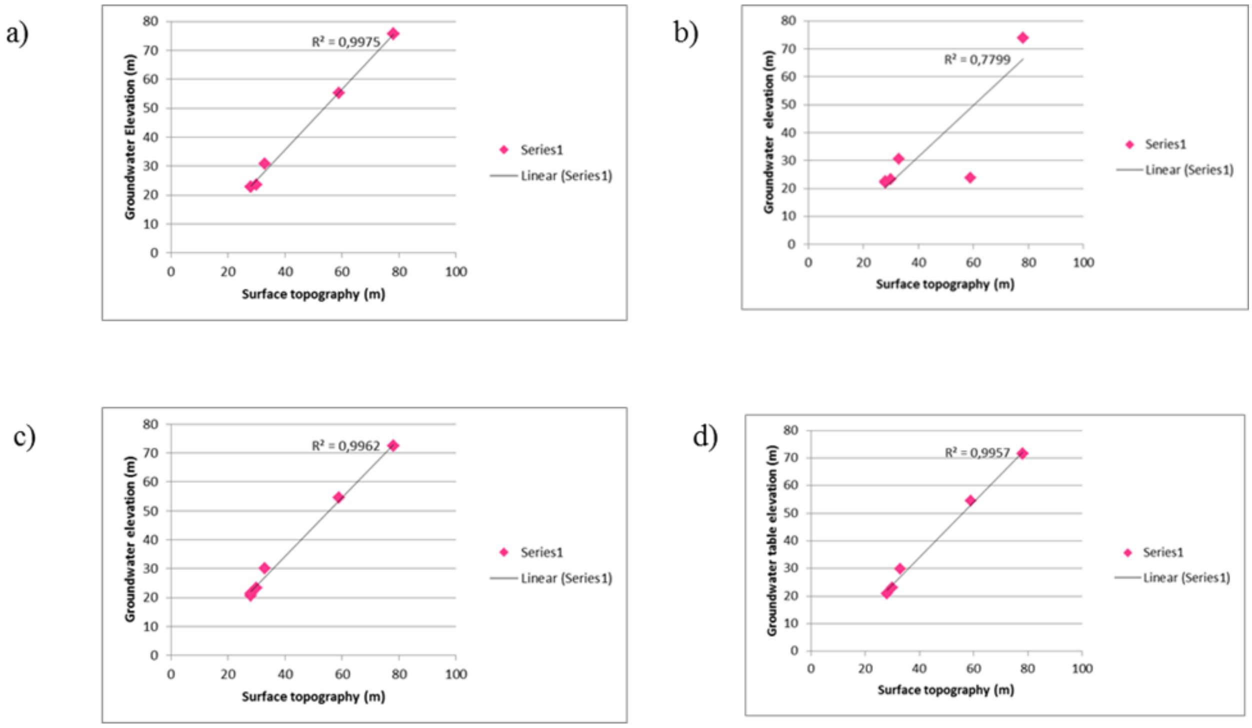


Figure 6.2.1(a): Relationship between groundwater table elevation and surface topography for the month of August 2015 (a), November 2015 (b), February 2016 (c) and May 2016 (d).

Findings of the relationship between groundwater table elevation and surface topography are presented in figure 6.2.1(a). The results show that R^2 determination ranged between 0.7-0.9 therefore showing a positive linear relationship between groundwater table elevation and surface topography during the months of the analysis.

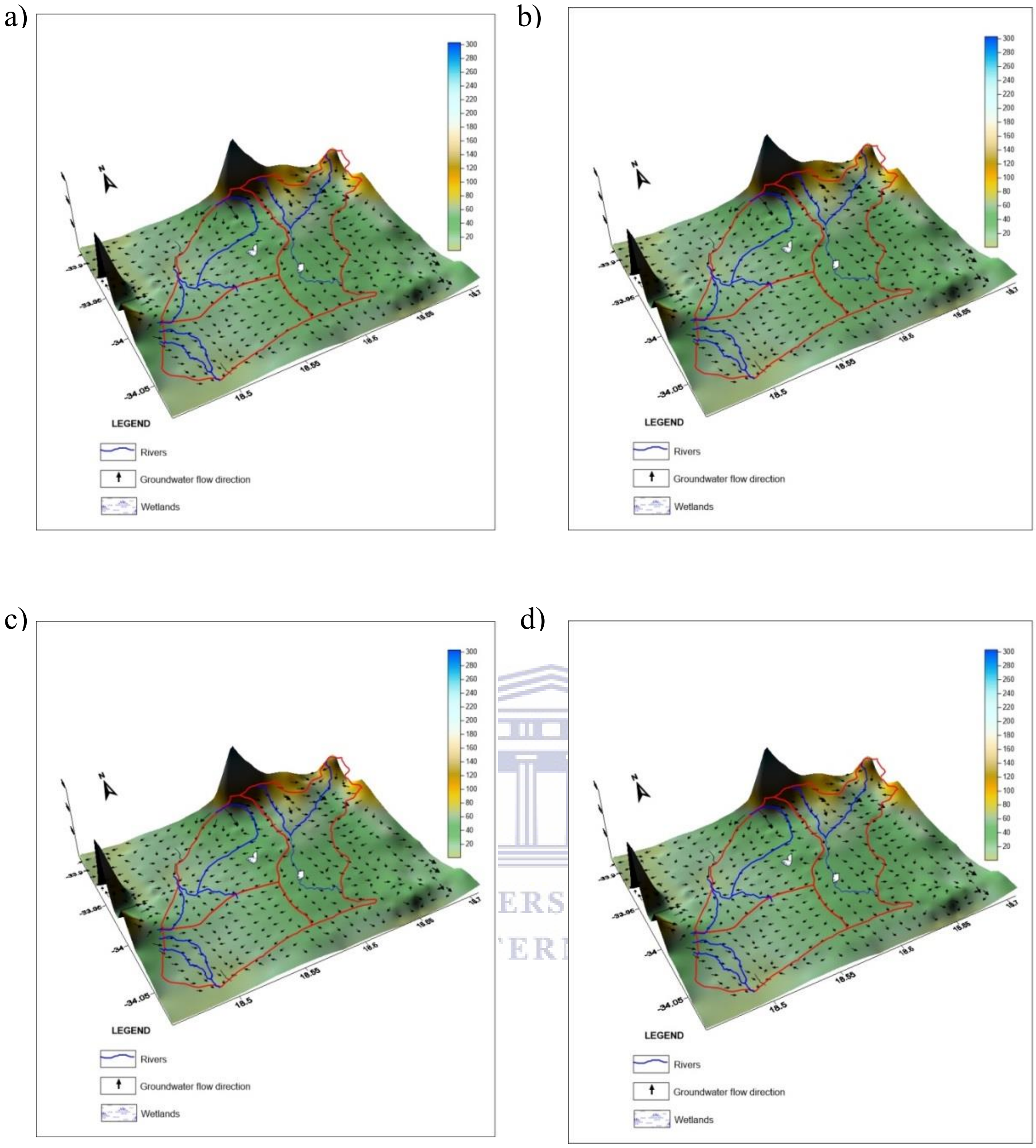


Figure 6.2.1 (b): Interpolated 3-D peizometric surface and groundwater flow direction for the month of August 2015 (a), November 2015 (b), February 2016 (c) and May 2016

The figure 6.2.1(b) shows groundwater flow direction of the Cape Flats Aquifer in relation to surface topography of the study area in different months of 2015 and 2016. Based on these maps groundwater flow pattern follows topography, where groundwater flows from high elevation areas to low elevation areas. Where the arrows intercept the rivers and wetlands entails possible sites of groundwater surface water interaction. Table 6.2.1 below shows sites that have been identified as possible sites for groundwater surface water interaction based on these 3D peizometric surface maps.

Table 6.2.1: Identified sites for groundwater surface water interaction

Surface water bodies	Identified sites	Longitude	Latitude	Groundwater unit
Kuilsriver	EK 11	18.730913	-34.051282	GRU1
	EK 8	18.721725	-34.04291	GRU1
	EK 5	18.669335	-33.950585	GRU1
	EK 9	18.672853	-33.932672	GRU1
	EK 19	18.674665	-33.915957	GRU1
Elsieskraal River	EL 1	18.62783	-33.9123	GRU1
	EL 2	18.627593	-33.9021	GRU1
	EL 3	18.625344	-33.902631	GRU1
	EL 4	18.62267	-33.904655	GRU1
Vygekraal River	Vyge 1	18,536433	-33.965499	GRU1
	Vyge 2	18.53057	-33.961499	GRU1
	Vyge 3	18.53057	-33.961499	GRU1
	Vyge 4	18.525790	-33.958835	GRU1
UWC wetland	UWC wet	18.624621	-33.934606	GRU1
Kuils River wetland	Kuils wet	18.663381	-33.954882	GRU1

The table 6.2.1 shows possible sites for groundwater surface water interaction identified based on figure 6.2.1 (b). The entire sites identified fell within groundwater unit 1 characterised by inter-granular permeability varying from course sands and gravels to finer materials and clay. Groundwater discharge in this unit is diffused. To further confirm that groundwater surface water interaction was occurring in these sites, sampling was done during dry and wet season on these sites and in boreholes and well points at the vicinity, for the analysis of stable isotopes (^{2}H and ^{18}O) and hydrochemistry (major ions) which were used as tracers for interaction. Results on these analyses are presented in section 6.2.2 and 6.2.3.

6.2.2 Interpretation of principal aquifer setting results

Section 6.2.1 presented results on identification of possible sites for groundwater surface-surface water interaction using the principal aquifer setting method. Prior to identification of sites, groundwater elevation and surface topography were related using R^2 determination method for different months of measurements in both seasons, and was found that R^2 determinant ranges from 0.7- 0.99 respectively. This showed that groundwater flow in these months followed topographical pattern, meaning that the flow of groundwater was from high topographic gradient to lower topographic gradient. This was expected because according to

Freeze & Cherry (1979) groundwater flows from high elevation to lower elevation area. Adelana et al. (2010) conceptual model of the Cape Flats Aquifer also show that the groundwater flow is from high elevated area to lower elevated areas, and that agrees with what was found in this study. 3D mapping of topographical gradient and groundwater flow produced from the golden surfer software also confirmed that groundwater followed the surface topographical pattern. 3D maps produced also allowed for the identification of possible sites of groundwater surface water interaction which all fell within GRU1 characterised by diffuse discharge. These sites were identified through visual interpretations of these maps produced for different months, where the points of intersection between groundwater flow net and rivers as well as wetlands were marked as possible sites for groundwater surface water interaction. The weakness associated with this method is that it does not allow for the quantification of groundwater discharge to surface water bodies. However, it can be used as a qualitative method to identify possible areas of groundwater surface water interaction.

6.3 Results on interaction using stable environmental isotope analysis

6.3.1 Key results

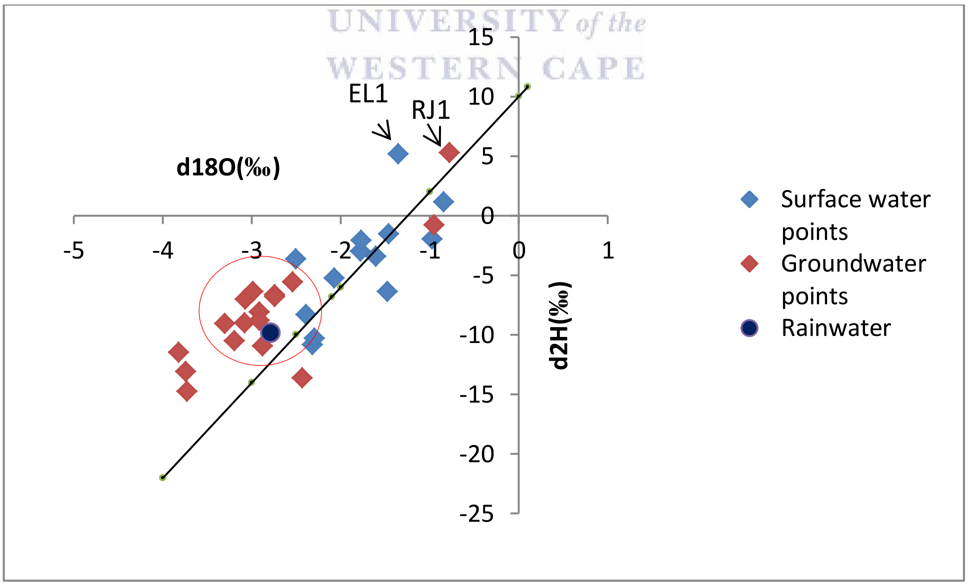


Figure 6.3.1(a): Plot of ^{18}O against ^{2}H for groundwater and surface water sample collected within the Cape Flats during dry season.

Figure 6.3.1(a) shows the stable isotopic analysis results of samples collected from boreholes, well points, rivers and wetlands within the Cape Flats Aquifer during dry season. The results show that the samples collected have more negative ^{2}H and ^{18}O values. This therefore suggests that the samples are depleted. The situation was not expected during dry season, the samples are supposed to be enriched as a result of high temperature effect in dry season which enhances evaporation and thereby causing enrichment of the signatures in water bodies sampled (Kendall & Coplen 2001). The results also show that most of the groundwater samples plotted above and further down the Global Meteoric Water Line (GMWL), thereby indicating recently recharged shallow waters. The clustering of the summer rainfall sample with some groundwater samples also give an indication of shallow groundwater recharge by summer rainfall of low isotopic concentrations. The samples RJ1 and EL 1 plotted above and further up the GMWL. This therefore suggests the effect of evaporation, and it was expected because of the high temperatures in dry season. ^{2}H and ^{18}O for rivers and wetland within the area, ranged from -10.86‰ to 5‰ and -2.5‰ to -0.84‰ respectively. For well points and boreholes within the Cape Flats Aquifer, ^{2}H and ^{18}O ranged between -14.76‰ to 5.27‰ and -3.81‰ to -0.77‰ respectively.

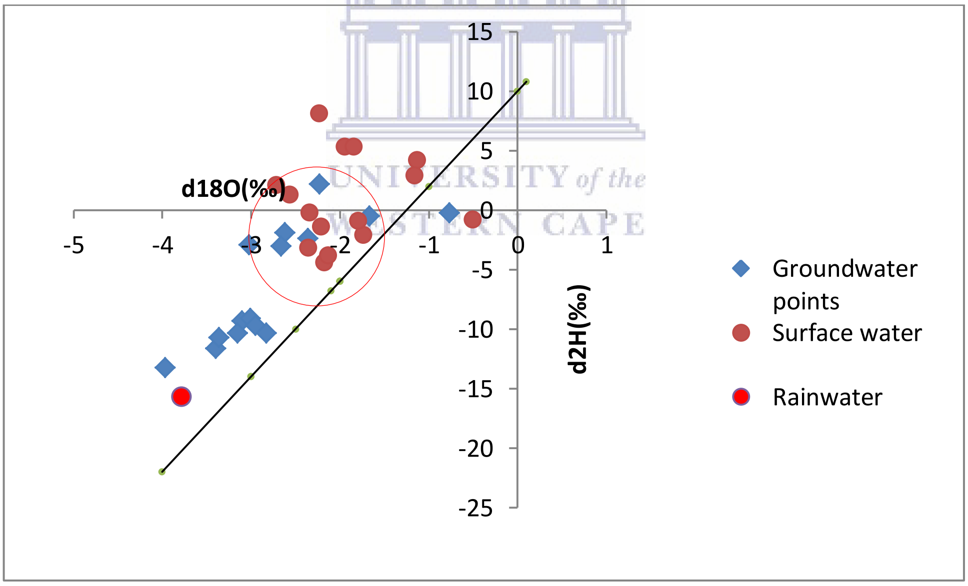


Figure 6.3.1(b): Plot of ^{18}O against ^{2}H for groundwater and surface water sample collected within the Cape Flats during wet season.

The figure 6.3.1(b) shows the results of isotopic analysis for the samples collected in rivers wetlands, boreholes, well points and rain gauges within the Cape Flats Aquifer during wet season. The results show that the samples have more negative ^{2}H and ^{18}O values. This therefore suggests that the samples are depleted. The scenario was however expected in this case because the samples were collected during wet season; as a result of the influence of precipitation the isotope concentrations are depleted (Kendall & Coplen 2001). The results also show that most of groundwater samples plotted above and further down the GMWL, indicating recently recharged shallow waters. Some surface water points such as EK 9, Kuils River wet, and EK19 plotted further up and above the GMWL, thereby indicating that the samples from these points are enriched with ^{2}H and ^{18}O signatures. The scenario was however not expected in wet season due to low temperature. A proportion of some surface water points were found to form a cluster with some groundwater samples, this therefore suggest mixing between the two resources. For groundwater points ^{2}H signature ranged between -13.2‰ to 2.2‰ and ^{18}O ranged between -2.71‰ to -0.5‰. For surface water, ^{2}H ranged between -4.4‰ to 8.1‰ and ^{18}O ranged between -2.71‰ to -0.5‰.

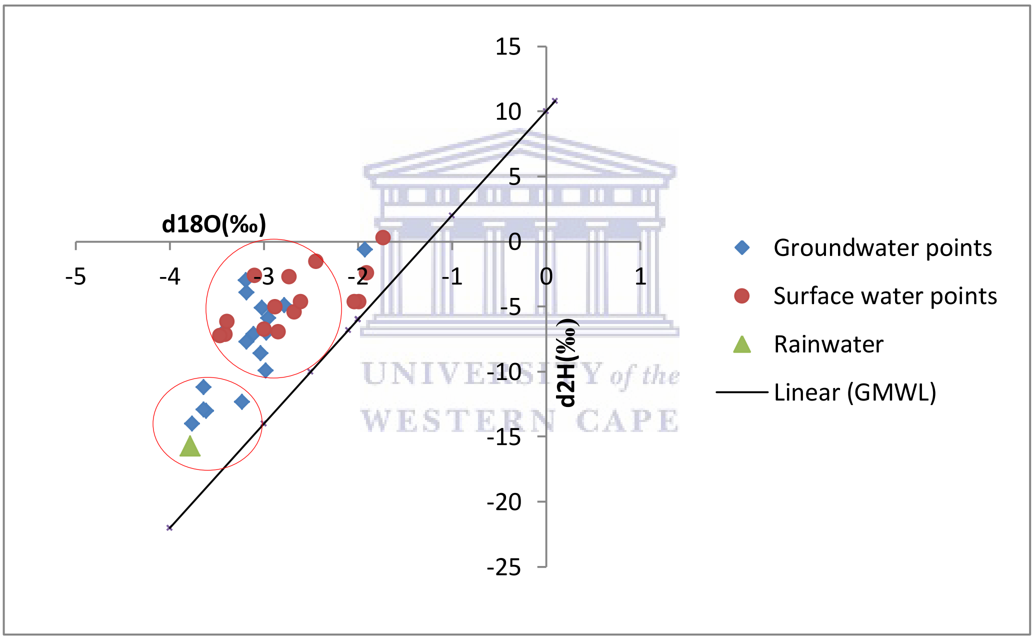


Figure 6.3.1(c): Plot of ^{18}O against ^{2}H for groundwater and surface water samples collected during wet season.

The figure 6.3.1 (c) also shows the results of isotopic analysis for samples collected in rivers wetlands, boreholes, well points and rain gauges within the Cape Flats Aquifer during wet season. Similarly to figure 6.2.2 (a) and figure 6.2.2 (a), the results show that most of the samples have more negative ^{2}H and ^{18}O values. This therefore shows that the samples are depleted. The scenario was however expected in this case, because the samples were also collected during wet season, and there is an influence of rainfall causing the isotope concentrations to be depleted. Samples from boreholes RJ1, Phillipi BG00152, Westridge stadium and Bellville BG46053 plotted above and further down the GMWL, indicating recently recharged shallow waters. The samples also form a cluster with the rainwater sample suggesting similarities between the samples and the rainwater sample, and therefore revealing that the recharge is as a result of rainfall on the surface of the aquifer with low isotopic concentrations. The situation was however expected because, Cape Flats Aquifer recharges mostly during wet season, and the details of groundwater recharge in Cape Flats Aquifer are elaborated chapter 3. The results also show that most of the groundwater samples form a cluster with surface water samples. This therefore suggests mixing between the groundwater and surface water resources within the area during wet season. For surface water samples, ^{2}H ranged between -7.2‰ and 0.3‰, and ^{18}O ranged between -3.47‰ and -1.73‰. For groundwater samples ^{2}H ranged from -14‰ to -0.6‰ and ^{18}O ranged from -3.76‰ to 2.71‰.

6.3.2 Interpretation of environmental isotope results

Section 6.3.1 presented results on the assessment of groundwater surface water interaction using stable isotopic analysis of ^{2}H and ^{18}O from boreholes, well points, rivers and wetlands within the Cape Flats Aquifer in dry and wet season. The assumption was that any similarities in stable isotopic signatures between the samples from boreholes, well points, rivers and wetlands suggest interaction between groundwater and surface water of the area. This section provides an interpretation of the results on assessment of groundwater surface water interaction using stable isotope analysis.

The results revealed that dry season samples had more negative values of ^{2}H and ^{18}O. This suggests that the samples are depleted (Kendall & Coplen 2001). The scenario was not expected in dry season, as discussed in chapter 3, Cape Flats Aquifer falls within the Mediterranean climatic region, with dry summers and wet winters. This means that depletion of isotopic signatures are expected during wet winter season where there is sufficient rainfall of low isotopic signatures to reduce the isotopic ratios in water bodies particularly the rivers, wetlands and the shallow Cape Flats Aquifer. The Cape Flats Aquifer however is a shallow aquifer within the peri-urban area. The recharge to the particular aquifer is as the result of many components such as leakage from water supply pipes, urban drainage and agricultural return flows. These recharge components together with little rainfall of low isotopic ratios in dry season could have contributed to the depletion of the isotopic concentration. The study however did not collect the samples from these recharge components, therefore it cannot be confirmed in this study that these components actually contributed to isotopic depletion during dry season.

The results of isotopic analysis in dry season also show that most of groundwater samples plotted above and further down the Global Meteoric Water Line (GMWL) suggested by Craig (1961). This therefore indicates the presence of shallow and recently recharged waters. The clustering of these groundwater samples with the rainwater samples confirm that the recently recharged water is as the result of summer rainfall with low isotopic ratios. The river sample EL 1 and shallow well point RJ1 plotted above and further up the GMWL. This therefore shows an influence of evaporation. The scenario was expected because the samples were collected in dry season, and in dry season temperatures are high and thereby enhancing evaporation which thereby causes more enriched samples. The results did not reveal any significant mixing between groundwater and surface waters of the area. This therefore shows that groundwater surface water interactions was not occurring during dry season, however summer rainfalls of low isotopic signatures were feeding groundwater.

Isotopic analysis revealed that the samples collected during wet season also had more negative ^{2}H and ^{18}O values. This shows that the samples were also depleted (Kendall & Coplen 2001; Clarke & Fritz 1997). The situation was however expected in this case because the samples were collected in wet season and the rainfall of low isotopic ratios influences the isotopic concentrations in water bodies particularly wetland and rivers and Cape Flats Aquifer since it recharges quickly as a result of its lithology. The results also show the presence of recently recharged shallow waters, where groundwater samples plotted above and further down the GMWL. In spite of other components of groundwater recharge in peri-urban cities which are highlighted chapter 2, the clustering of some groundwater samples with the rainwater sample show that the recharge during wet season was derived from rainfall on the surface of the aquifer. The results also show that most of groundwater samples clustered with some surface water samples. This therefore shows that there were similarities in isotopic signatures between groundwater and surface water in the area during wet season, thereby suggesting mixing of the two resources. The mixing therefore reveals a possible two way interaction between groundwater and surface water in the area during wet season. In comparison of the current study results on interaction using stable isotope, with other similar studies by Hunt et al. (2005); Romanelli (2011) & An et al. (2014), the method proved to be successful in this study.

Hunt et al. (2005) used the analysis of stable isotope (^{2}H and ^{18}O) to identify sources of water in 13 municipal wells at the City of Crosse. The results showed that 7 of the 13 municipal wells have received contributions from surface water indicating groundwater surface water interaction occurring in the area. The results by Hunt et al. (2005) agree with what was found in the current study even though the study by Hunt et al. (2005) was carried out in an area which is not regarded as a peri-urban. The agreement between the two studies results confirm that stable isotopic analysis is one method that can be successfully used in the assessment of groundwater surface water interaction.

An et al. (2014) characterised groundwater surface water interaction of a coastal watershed in Cu Lao Dung Island Mokang delta, Vietnam in dry season. The analysis of stable isotopic (^{2}H and ^{18}O) data of groundwater and surface water revealed that there was no connection between groundwater and surface water resource of the area in dry season. The results in the study by An et al. (2014) do not agree with what was found in the current study in dry season. The study by An et al. (2014) was not carried out within a peri-urban environment as compared to the current study.

Based on the findings and in comparison to other studies, isotopic analysis method proved to be successful when applied to the area in showing that interaction does occur, however the methods required more time series data to be collected to generate more conclusive evidence on the occurrence and extent of groundwater surface water interaction.

6.4 Results on interaction using hydrochemical analysis

6.4.1 Key results

The section presents results on assessment of groundwater surface water interaction using hydrochemical analysis for both surface water and groundwater points. Before the analysis the data collected was subjected to cation anion balance to ensure the reliability of the results. Table 6.4.1 shows the calculated cation anion balance for both groundwater and surface water samples collected within area during dry and wet season.

Table 6.4.1*:* Charge balance for groundwater and surface water sample in dry and wet season

	Dry season				**Wet season**			
Sample ID	**Balance**	**<15%**	**Balance**	**<15%**	**Balance**	**<15%**	**Balance**	**<15%**
Khayelitsha. Stadium	-8.09	√	-4.06	√	-52.93	X	5.8	√
Makhaza	2.97	√	-7.97	√	-14.57	√	-30.94	X
EK 19	2	√	-2.48	√	-0.2	√	-12.97	√
UWC 3B	6.04	√	-3.4	√	-13.06	√	-13.052	√
Esangweni Close 2	4.81	√	-59.3	X	-7.2	√	-11.98	√
EK8	2.65	√	-2.72	√	-12.15	√	-15.08	√
Lenteguer 3	1.31	√	1.69	√	-12.57	√	-10.98	√
Vyge 3	0.66	√	-6.93	√	-17.87	X	-28.62	X
Bell G46052	1.58	√	-0.03	√	0	√	-11.78	√
Phillipi BG00153	2.78	√	-0.42	√	-2.42	√	-4.99	√
Vyge2	-2.62	√	3.48	√	-14.04	√	-9.51	√
EK 5	3.45	√	-0.79	√	0.96	√	-8.98	√
RJ1	-6.33	√	-11.37	√	-23.55	X	-66.97	X
Khayelitsha hospital	-0.63	√	-3.77	√	-11.78	√	-11.5	√
EL 3	-2.36	√	0	√	-3.95	√	-11.22	√
EK9	1.89	√	-3.89	√	-6.79	√	-13	√
elsiskraal 1	2.63	√	-4.81	√	-0.88	√	-7.79	√
Khayelitsha TR section	3.63	√	-5.29	√	-45.93	X	-58.2	X
Phillipi BG00152	4.28	√	-2.16	√	-3.94	√	-2.38	√
Lenteguer BG00139	3.15	√	-1.76	√	-10.78	√	-16.91	√
Bell G46051	3.19	√	-3.83	√	-13.778	√	-13.3	√
UWC 4	5.15	√	17.03	X	-9.95	√	-9.95	√
EK11	-8.76	√	-3.65	√	-4.98	√	-13.06	√
Westridge	4.9	√	-0.46	√	-4.13	√	-11.095	√
UWC wetland	3.33	√	-2.48	√	-13.02	√	26.63	X
Vyge1	-7.09	√	-3.82	√	-12.73	√	-8.84	√
Elsieskraal 2	-7.05	√	-4.81	√	-10.44	√	-10.29	√
EL 4	0.88	√	-1.2	√	-7.57	√	-11.7	√
Kuils river-wetland	0.65	√	0.03	√	27.25	X	-62.28	X
Esangweni close 1	-16.54	X	-59.3	X	9.37	√	11.98	√

Table 6.4.1 shows the results of the cation-anion balance calculation for samples collected in rivers, wetlands, boreholes and shallow well points within the Cape Flats Aquifer during dry and wet season. The calculations were performed using the concentrations of majors ions (in mill-equivalents per litre) presented in addendum B and the procedure followed to calculate the balance is discussed in details in chapter 3 section 3.5.2. The table 6.4.1 was used to decide on which samples to be used when plotting the piper diagrams presented in figure 6.2.3 (a-d). As discussed in Younger (2007), the samples with cation anion balance of <±15% were used in plotting the piper diagrams which were used in identifying the predominant groundwater and surface water types within the area during dry and wet season shown in table 6.4.2.

Table 6.4.2: Predominant groundwater and surface water types during dry and wet season.

Season	Groundwater types	Surface water types
Dry season	Ca-HCO_3	Ca-Na-HCO_3-Cl
	Ca-HCO_3	Ca-Na-HCO_3-Cl
Wet season	Ca-HCO_3	Ca-SO_4
	Ca-SO_4	Ca-Na-HCO_3-Cl

Table 6.4.2 shows the predominant groundwater and surface water types identified based on piper diagrams presented in figures 6.2.3(a-d) for both dry and wet seasons. During dry season the predominant groundwater type for both sampling periods was Ca-HCO_3 which is indicative of recently recharged shallow groundwater with temporary hardness (Hiscock 2005). The predominant surface water type identified was Ca-Na-HCO_3-Cl from both sampling periods. The water type is indicative of mixed waters with characteristics of Ca-HCO_3 waters and Na-Cl waters. In wet season two dominant groundwater types identified, these are Ca-HCO_3 indicative of recently recharged shallow groundwater with temporary hardness, and Ca-SO_4 which is indicative of gypsum groundwater (Hiscock 2005). Two dominant surface water types were also identified during wet season; these are Ca-SO_4 indicative of gypsum waters and Ca-Na-HCO_3-Cl which is indicative of mixed waters with characteristics of Ca-HCO_3 waters and Na-Cl waters.

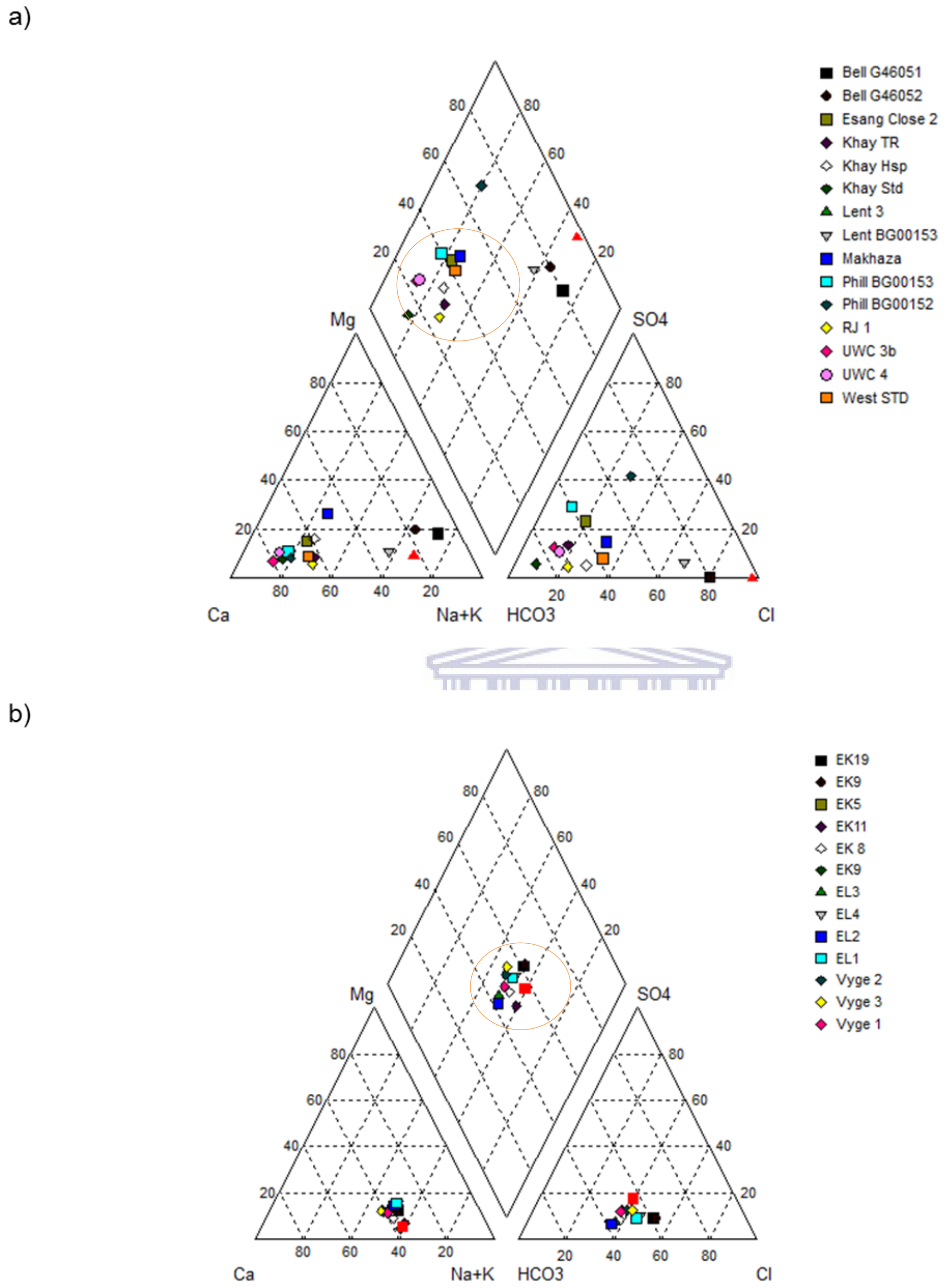


Figure 6.2.3(a): Piper diagram showing pre-dominant groundwater (a) and surface water (b) types for the Cape Flats during dry season.

Figure 6.2.3(a) shows the classification of hydro-chemical facies for groundwater and surface waters of the study area during dry season. These are based on percentage meq/L concentrations of major ions. Based on Plots (a) showing groundwater samples, two groundwater types had been identified. These are Ca-HCO_3 and Na-Cl type. The Ca-HCO_3

type indicative of shallow and recently recharged groundwater marked by higher dominance of Ca and HCO_3^- consisted of samples from well points Esangweni close 2, Khayelitsha TR, Khayelitsha hospital, Khayelitsha Stadium, Makhaza, RJ1 as well as samples from boreholes UWC 4, Westridge stadium and Phillipi borehole BG00152. This situation was however expected because the groundwater points sampled in this study are shallow with depths ranging between 5-6m for well points and between 12-25m for boreholes. The Na-Cl type indicative of typical marine and deep ancient groundwater consisted of samples from boreholes Bellville BG46051, Bellville BG46052, Lenteguer BG00139 and UWC 3b. It was not expected for boreholes Bellville BG4605, Bellville BG46052 and UWC 3b to have Na-Cl water type. Na-Cl waters are primarily derived from saltwater intrusions to groundwater and weathering of the geological material (Madlala 2015), and these boreholes are not located close to the coast and are shallow therefore salt water intrusions are not possible. However, since Cape Flats Aquifer is an urban shallow aquifer, Na-Cl water in these boreholes could be as a result of anthropogenic sources resulted from the land-use activities, however it cannot be confirmed in this study that Na-Cl waters are as the results of anthropogenic activities since the study did not sample the water from those sources. The borehole Lenteguer BG00139 was expected to have the Na-Cl water, since it located in an area closest to the coast. From plot (b) showing surface water samples, all the samples plotted within the centre of the diamond shape, and the water type identified was Ca-Na-HCO_3-Cl which is indicative of mixed waters from more than one quadrant in the diamond shape.

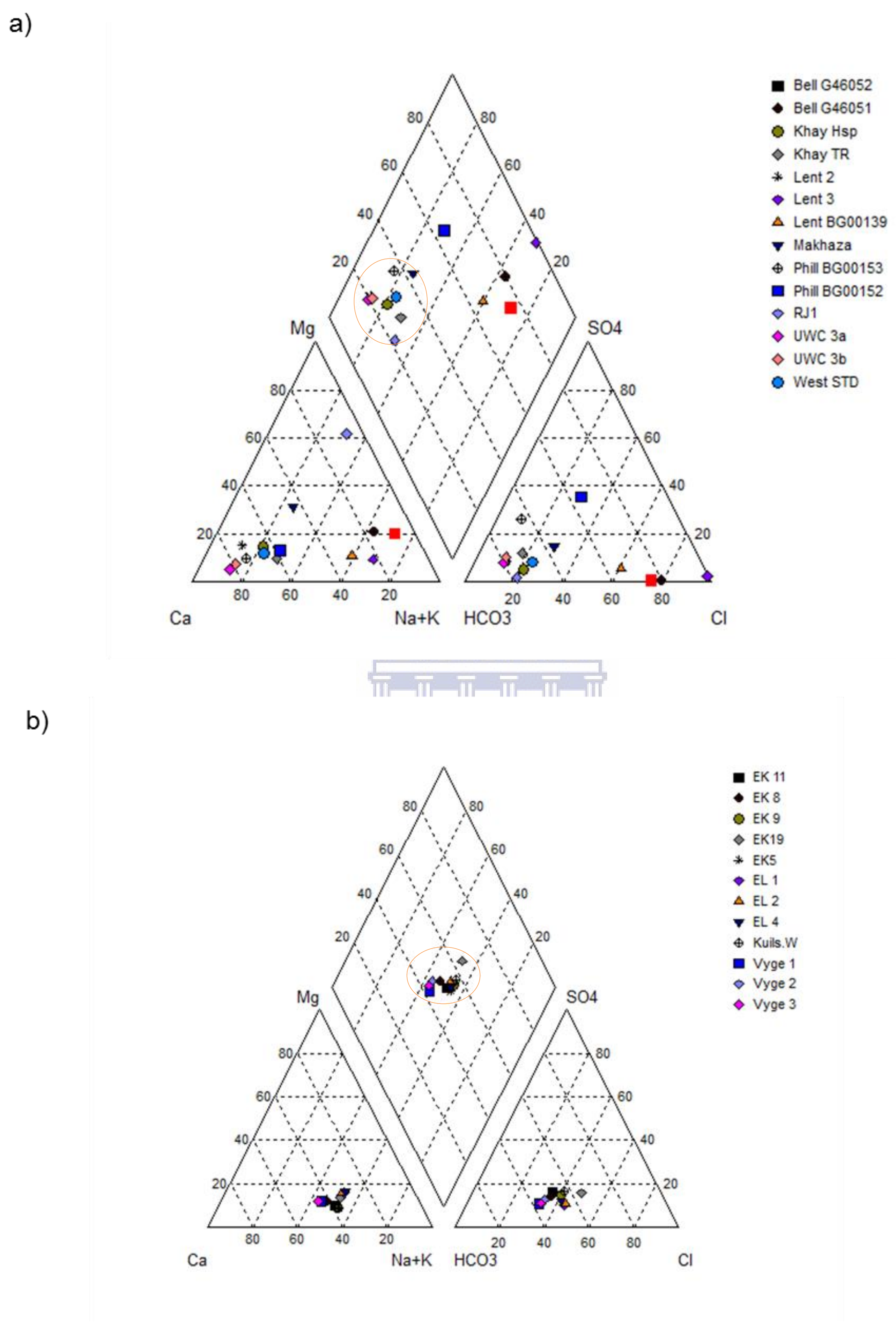


Figure 6.2.3(b): Piper plots of groundwater (a) and surface water (b) points in dry season

The figure 6.2.3(b) also shows the hydrochemical facies of groundwater and surface water within the study area during dry season. Based on plot (a) showing the groundwater samples, two dominant water types were identified. These are the Ca-HCO_3 and Na-Cl type. The Ca-HCO_3 types indicative of recently recharged shallow groundwater with marked higher dominance of Ca and HCO_3^- consisted of samples from boreholes UWC 3a, UWC 3b, Westridge stadium and Phillipi borehole BG00153 as well as well points such as Khayelitsha hospital, Khayelitsha TR and RJ1. This was expected because the samples in this study were collected from shallow well points and boreholes including these ones with previously mentioned depths. The Na-Cl type indicative of typical marine and deep ancient groundwater consisted of samples from boreholes Lenteguer 3, Bellville BG46051, Lenteguer BG00139. Na-Cl water is primarily derived from the saline water intrusion, weathering of geological material and anthropogenic sources. The borehole Bellville BG46051 was not expected to have the Na-Cl water type since it is located further away from the coast and salinity intrusion is not possible, also the well is shallow. For boreholes Lenteguer 3 and Lenteguer BG00139 the situation was expected because these boreholes are located towards the southern part of the aquifer closest to the coast, however it cannot be confirmed in this study that saline intrusion was occurring. Cape Flats Aquifer is located in a peri-urban environment where land-use activities such as agriculture and industrial area are occurring, these land-use activities could result in the release of contaminants which can therefore result in Na-Cl water types in boreholes. Based on Plot (b) showing surface water samples, all the surface water samples fell within the centre of the plot which is characterised by mixed waters from more than one quadrant on the plot. The water type identified was Ca-Na-HCO_3-Cl.

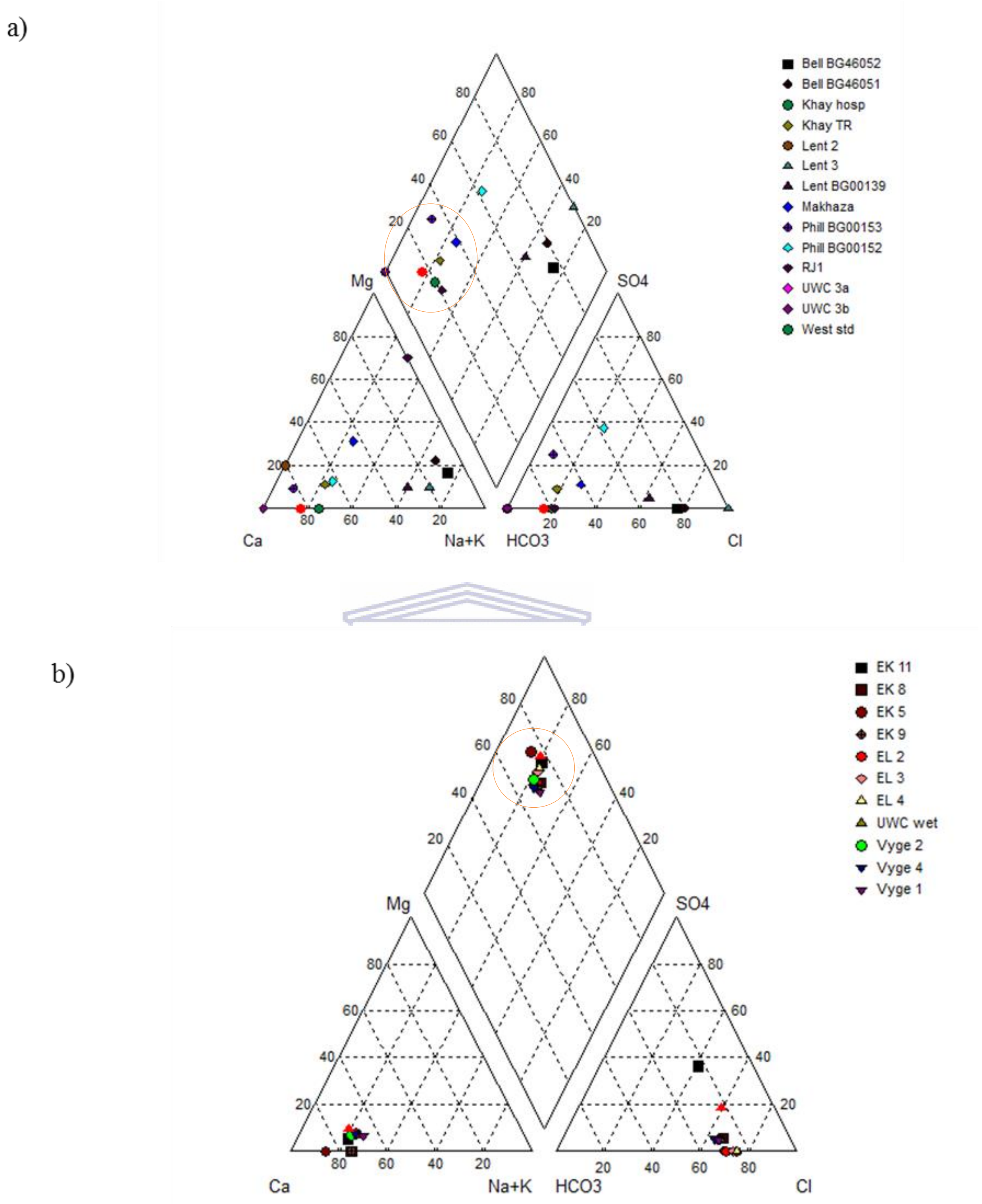


Figure 6.2.3(c): Piper plots of Groundwater (a) and Surface water points (b) during wet season.

The figure 6.2.3(c) shows the hydrochemical facies of groundwater and surface water of the study area during wet season. Based on plot (a) showing the groundwater samples, two dominant water types were identified. These are the Ca-HCO_3 and the Na-Cl type. The Ca-HCO_3 type indicative of shallow and recently recharged groundwater marked by higher dominance of Ca and HCO_3^- consist of samples from well points such as Khayelitsha TR and Makhaza as well as boreholes such as Lenteguer 2, Westridge stadium and UWC 3b. Similarly to dry season samples, the situation was expected because the sampled groundwater points in this study are shallow. The Na-Cl type indicative of typical marine and ancient groundwater consist of samples from boreholes such as Bellville BG46051, Bellville BG46052, Lenteguer BG00139 and Lenteguer 3. Boreholes Bellville BG46051 and Bellville BG46052 were not expected to have the Na-Cl, since this water type is typical of marine and ancient groundwater; therefore considering the distance of the location of these boreholes to the coast, saline intrusion is not possible. Na-Cl could also be derived from anthropogenic sources, as the results of the land-use activities in the area it is possible that the Na-Cl in those boreholes could be originating from such activities. The boreholes Lenteguer 3 and Lenteguer BG00139 were expected to have the Na-Cl water type since these boreholes are located in and area closest to the coast and saline intrusion could be occurring resulting in Na-Cl waters. Based on plot (b) showing the surface water samples, all the samples fell within the top part of the diamond shape characterised by Ca-SO_4 indicative of gypsum groundwater.

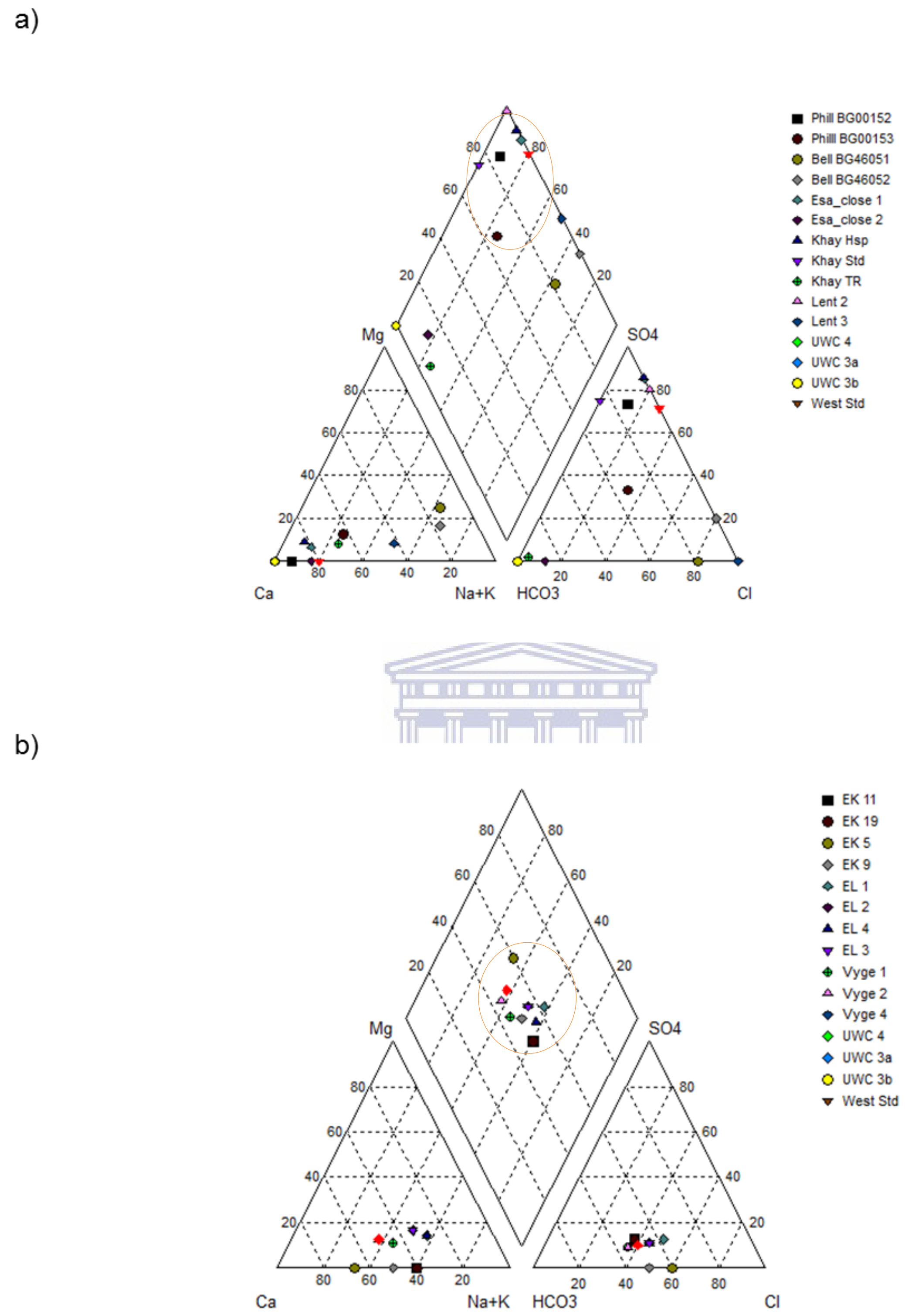


Figure 6.2.3 (d): Piper plot of groundwater (a) and surface water (b) points during wet season.

The figure 6.2.3 (d) also shows the hydrochemical facies of groundwater and surface waters of the study area during wet season. Based on plot (a) showing the groundwater samples, three water types were identified. These are the Ca-HCO_3, Ca-SO_4 and the Na-Cl type. The Ca-HCO_3 type indicative of shallow and recently recharged waters with marked higher dominance of Ca and HCO_3^- consisted of samples from borehole UWC 3a as well as well point Esangweni_close 2. This was expected since the study sampled the shallow groundwater points. The Ca-SO_4 indicative of gypsum groundwater consisted of samples from boreholes Phillipi BG00152, Phillipi BG00153 and Lenteguer 2 as well as well points such as Khayelitsha stadium well point, Khayelitsha hospital well point and Esangweni_close 1. It was expected for boreholes Phillipi BG00152 and Phillipi BG00153 to have the Ca-SO_4 water type. As discussed in chapter 3 the boreholes are located in an irrigated land, therefore the elevated SO_4 in water type could be due to such land-use activity. The other groundwater points were not expected to have the Ca-SO_4. The Na-Cl water type indicative of typical marine and deep ancient groundwater consisted of samples from boreholes BG46051 and BG46052. The boreholes were not expected to have the Na-Cl water since there is no possible saline intrusion resulting to Na-Cl waters in these boreholes, however since the boreholes are located in a peri-urban city, land-use activities could have resulted in Na-Cl waters. Based on plot (b) showing surface water samples, all the surface water samples fell in the centre of the plot characterised by mixed waters from more than one quadrant within the diamond shape. The dominant water type identified was Ca-Na-HCO_3-Cl.

6.4.2 Interpretation of results on hydrochemistry analysis

Major ions plotted in piper diagrams within section 6.4.1 were used to identify predominant groundwater and surface water types of the study area during dry and wet season. The intention was to establish similarities between groundwater and surface water types identified, with the assumption that any similarities between groundwater and surface water types suggest interaction between the two resources. The predominant groundwater type identified during dry season was Ca-HCO_3 type. This water type is indicative of recently recharged shallow groundwater with temporary hardness (Younger 2007; Freeze & Cherry 1979), thus showing the presence of shallow groundwater recharge occurring during dry season. The hydrochemical analysis however did not reveal the source of recharge during dry season, but based on the isotopic analysis results for dry season in section 6.3, the source of groundwater recharge during this season was the summer rainfall. The scenario was expected because, even though the area receives most of its rainfall during winter season which is classified as wet season in this study, the area also receives minimal rainfall of low intensity during summer season classified as dry season in this study, which quickly infiltrates through the sandy particles and thereby recharging the shallow Cape Flats Aquifer. The analysis of wetlands and rivers samples collected in dry season showed that the predominant surface water type identified was Ca-Na-HCO_3-Cl. This water type is indicative mixed waters between more than 2 end members solution. The water type was found to be similar to the Ca-HCO_3 type of groundwater, thus indicating the contribution of shallow fresh groundwater from the Cape Flats Aquifer to the rivers and wetlands understudy, and thereby mixing with other sources of different water types from different preferential pathways. The dry season hydrochemical analysis results reveal that one way groundwater-surface water interaction was occurring in the area during the particular season, where groundwater from the shallow Cape Flats Aquifer was feeding rivers and wetlands understudy. The scenario was expected because rivers and wetlands are known to be discharge points for groundwater during dry season (Winter 1999), especially given the topographical pattern of the study area discussed in chapter 3 section 3.2.2.

During wet season, two predominant groundwater types were identified. These are the Ca-HCO_3 and Ca-SO_4 type. The Ca-HCO_3 type is indicative of shallow and recently recharged groundwater with temporary hardness, therefore showing the presence of shallow groundwater recharge also occurring during wet season. The hydrochemical analysis however did not reveal the source of groundwater recharge but based on isotopic analysis results for wet season presented in section 6.3 the source of groundwater recharge during wet season was rainfall. The scenario was expected because the area understudy receives most of its rainfall of high intensity during winter which is classified as wet season in this study, and thereby recharging the underlying shallow Cape Flats Aquifer. The groundwater results also show that as the recently recharged shallow groundwater (Ca-HCO_3) was flowing through the Cape Flats Aquifer it undergone a change in chemical character, due to increasing residence time and addition of possible solution of gypsum or anhydrite, the Ca-SO_4 water type was formed. The analysis of samples collected in wetlands and rivers within the area showed that the predominant surface water types identified during wet season were Ca-Na-HCO_3-Cl and Ca-SO_4 respectively. The Ca-Na-HCO_3-Cl is indicative of mixed waters between more than 2 end members solution. The Ca-SO_4 is indicative of gypsum water. Both the surface water types identified were similar to those of groundwater types within the area during wet season, and thus suggesting mixing between groundwater and surface water of the area thereby proving that a two way interaction was occurring during wet season.

In comparison of the hydrochemical analysis results from the current study with other studies by Kumar et al. (2008); Oyarzún et al. (2014) and Guggenmos et al. (2011) from the similar setting, the method proved to be successful in the area. Kumar et al.(2008) analysed major ions from samples collected in Yamuna River in India and in shallow groundwater points along the river with the intention to assess the extent of groundwater surface water interaction in the area. The results from the study by Kumar et al. (2008) showed an empirical relationship between shallow groundwater and surface water of the Yamuna River. The results from the current study were found to be similar with what was found in the study by Kumar et al. (2008), therefore proving that hydrochemical analysis was successful when used to assess groundwater surface water within the area.

Oyarzún et al. (2014) used multi method approach to assess connectivity between surface water and shallow groundwater in Limari River basin Chile. One of the aims was to characterise groundwater surface water interaction occurring in the Limari Basin. Analysis of major ions data through piper plots show that surface water and groundwater in the area are of Na-Cl types, thus indicating the occurrence of groundwater surface water interaction in the area. The results by Oyarzún et al.(2014) agree with what was found during the assessment of groundwater surface water interaction using hydrochemical analysis in this study, thereby proving that the method was successful in the area.

Guggenmos et al. (2011) also used hydrochemistry and multivariate statistical methods to identify groundwater surface water interaction in the Wairarapa Valley, New Zealand. Analysis of hydrochemical data with hierarchical cluster analysis (HCA) created 7 groups which 3 of those had both groundwater and surface water points grouped together and therefore indicating interaction. The results agree with what was found in the Cape Flats even though the current study did not use HCA to group the data points. The findings based on hydrochemical analysis has proved that groundwater surface water interaction does occur within the sites identified in both seasons, and also the method used offered the reliable evidence of groundwater surface water interaction when applied to the area, and when the results were compared to the results of the other studies in similar setting.

6.5 Implications of results to water sensitive urban design

Both the environmental and hydrochemical analysis results show that groundwater surface water interaction was occurring in the sites identified from principal aquifer setting method in two ways. During dry season one way interaction was occurring, where shallow groundwater from the Cape Flats Aquifer was feeding rivers and wetlands understudy. During wet season a two way interaction was occurring, where there was significant mixing between shallow groundwater from the Cape Flats Aquifer and rivers as well as wetlands understudy. The central argument in this chapter was that if the spatial and temporal distribution of groundwater surface water interaction is understood prior to water sensitive urban design planning, then negative influence of exchanges between groundwater and surface water bodies on the effectiveness of WSUD could be managed. The question that was asked then was to what extent does the knowledge on spatial-temporal distributions of groundwater surfaces water interaction can assist in managing the influences of exchanges between groundwater and surface water on the effectiveness of WSUD, in the context of peri-urban cities such as Cape Town.

As discussed in chapter 2, principle two of WSUD talks about the harvesting of rainwater and stormwater in an area and treating that water to improve its quality through the use of bio-retention and natural as well as constructed wetlands, and storing the treated water to the receiving groundwater and surface water bodies. Groundwater surface water interaction involves the exchange of water and nutrients between the two resources. Since there is also exchange of nutrients between groundwater and surface water systems interacting, contaminations of the treated stormwater and rainwater stored within these systems can occur due to these exchanges. To avoid such problems the spatial and temporal distributions of groundwater surface water interactions need to be investigated in-order to put in measures that could mitigate the problem. Knowing when and where groundwater surface water interaction is occurring could also assist in planning of when Managed Aquifer Recharge (MAR) could be implemented.

In the case of the Cape Flats Aquifer, the results reveal that two ways interaction is occurring during wet season and in dry season one way interaction is occurring where shallow groundwater from the Cape Flats Aquifer feeds the wetlands and rivers in the area. This information reveals that MAR would be feasible during dry season, where there is minimal rainfall recharging the Cape Flats Aquifer. Even though the current study did not assess the nutrient exchange between groundwater and surface water, the wet season results provides basis on when nutrients exchange between groundwater and surface water is taking place, and that information provides basis on when should such process be monitored to prevent the negative impacts associated with such. In the case of Cape Flats Aquifer nutrient exchange is likely to be taking place during wet season; therefore measures to prevent the influence of such exchange should be put in place during wet season where significant mixing between groundwater and surface water is taking place.

6.6 Chapter summary

Chapter 6 presented results on the assessment of groundwater surface water interaction using principal aquifer setting, environmental isotope and hydrochemical analysis. The intention was to identify where and when groundwater surface water interaction is occurring, in-order to inform the prevention strategies of the negative effluence of exchanges between groundwater and surface water on the effectiveness of water sensitive urban design. The central argument in this chapter was that if the spatial and temporal distribution of groundwater surface water interaction is understood prior to water sensitive urban design planning, then influence of water exchanges between groundwater and surface water bodies on effectiveness of WSUD could be managed. The question that was asked then to what extent does the knowledge on spatial-temporal distributions of groundwater surfaces water interaction can assist in managing the negative influences of exchanges between groundwater and surface water on the effectiveness of WSUD, in the context of peri-urban cities such as Cape Town. Principal Aquifer setting method was used as a qualitative method to identify possible sites for groundwater surface water interaction, and environmental isotope and hydrochemical analysis were used to confirm whether interaction occurs within the identified sites.

A total of 16 sites had been identified based on principal aquifer setting method, 5 identified at the Kuils River, 4 at the Elsieskraal River, 4 at the Vygekraal River, 1 at the UWC wetland and 1 at the Kuils River wetland. Environmental isotope analysis showed that during dry season interaction was not occurring however shallow groundwater was fed by summer rainfall of low isotopic signatures. The wet season results showed that there was significant mixing between groundwater and surface water of the area, and thus indicating that interaction between the shallow groundwater from the Cape Flats Aquifer and rivers as well as wetlands under study.

Hydrochemical analyses showed that in dry season, one way interaction was occurring at the identified sites were the predominant groundwater type identified was Ca-HCO_3 type which was found to be similar with surface water type Ca-HCO_3-Na-Cl identified, thus indicating the contributions of groundwater from the underlying shallow Cape Flats Aquifer to the rivers and wetlands understudy. During wet season, hydrochemical analysis revealed that two way interactions was occurring within the identified sites where dominant groundwater and surface water types identified showed characteristics of mixing between the two resources, and thus suggesting interaction. Environmental isotope and hydrochemical analysis methods proved to be successful when applied in the area. This is shown by the agreement of the results from current study with results from the study of the similar nature within other areas of the similar setting to that of the Cape Flats Aquifer. The study further recommends more isotopic and hydrochemical data to be collected to gain more conclusive evidence of the occurrence of groundwater surface water interaction.

Chapter 7: Conclusion and recommendations

The main objective of the study was to understand the hydrogeology of the Cape Flats Aquifer and groundwater surface water interaction, in order provide an explanation of how hydrogeology of the City of Cape Town functions to facilitate a decision-making process regarding the implementation of water sensitive urban design (WSUD) to manage water system of the particular city,. To achieve the main objective, the study had three specific objectives, namely, objective 1 which was focusing on estimating aquifer parameters using Theis analytical solution. The intention was to suggest possible sites for the implementation of managed aquifer recharge (MAR) suggested by WSUD principles. Objective 2 focused on conceptualizing groundwater flow system of the Cape Flats Aquifer using the Finite Difference Method. The intention was to predict future aquifer behaviour under stress condition posed by WSUD implementation at site specific scale. Objective 3 focused on assessing groundwater surface water interaction using principal aquifer setting, environmental isotope and hydrochemical analysis. The intention was to identify where and when groundwater surface water interaction is occurring, in-order to inform the prevention strategies of the negative effluence of the exchanges between groundwater and surface water on the effectiveness of WSUD.

For objective 1 focusing on estimation of aquifer parameters using Theis analytical solution, the results revealed that highest transmissivity and storativity values can be observed around the Phillipi area towards the southern part of the aquifer. Based on these findings, the study concluded that managed aquifer recharge stipulated by WSUD principles would be feasible to implement around the Phillipi area towards the southern part of the aquifer, where transmissivity and storativity are high (>100m^2/d, 10^{-1}) indicating high discharge rates (>50l/s) and aquifer storage. Based on these findings it is further recommended that the network of boreholes be expanded to obtain the full coverage of the aquifer.

For objective 2 focusing on conceptualizing local groundwater flow system, the site specific numerical model developed, showed that varying groundwater recharge rates impact ground water level and outflows on water balance components for the area. Varying groundwater abstraction rates (5l/s, 10l/s and 20l/s) also showed that at high abstraction rates (i.e 20l/s), groundwater table is significantly lowered by up to 50%. At less recharge and varying abstraction scenarios, the results showed that water table is lowered by up to 50%. Based on these findings, the study concluded that varying abstraction and recharge rates significantly influences groundwater levels distribution, fluxes and outflows from the water balance components. It is also recommended that a denser network of boreholes along the flow direction is needed to improve the calibration of the model.

For objective 3 focusing on the assessment of groundwater surface water interaction using principal aquifer setting, environmental isotope and hydrochemical analysis. The principal aquifer setting method yielded a total 16 potential points for groundwater surface water interaction along the rivers and wetlands within the area. Analysis of stable isotopes from those points showed that during dry season, interaction was not occurring; however summer rainfalls of low isotopic signatures was feeding the Cape Flats Aquifer. During wet season, isotopic analysis showed that there was significant mixing between shallow groundwater and surface water in the area, thus indicating the presence of interaction between the shallow groundwater from the Cape Flats Aquifer and rivers as well as wetlands understudy. Hydrochemical analysis showed that during dry season, one way interaction was occurring in the area, where shallow groundwater from the Cape Flats Aquifer was feeding wetlands and rivers understudy. During wet season, the hydrochemical analysis showed that there was significant mixing between shallow groundwater and surface water in the area, and thus indicating the occurrence of two way interaction in the area. Based on these finding, the study concluded that interaction does occur within the identified sites, and nutrients and water exchange could be monitored on those sites identified to prevent the effect of such processes on the effectiveness of WSUD. It is further recommended that more data needs to be collected for hydrochemical and environmental isotopic analysis to gain more conclusive evidence on the nature and extent of groundwater surface water interaction within the identified sites.

References

Adelana, S., 2010. *Groundwater resource evaluation and protection in the Cape Flats, South Africa*. PhD thesis, Department of Earth Science, University of the Western Cape.

Adelana, S., Xu, Y. & Vrbka, P., 2010. A conceptual model for the development and management of the Cape Flats Aquifer. *water SA*, 36(4).

Ahjum, F., Hughes, A. & Fant, C., 2015. *Climate , land , energy and water strategies in the City of Cape Town*, Univesity of Cape Town

Amah, E.A. & Anam, G.S., 2016. Determination of Aquifer Hydraulic Parameters from Pumping Test Data Analysis : A Case Study of Akpabuyo Coastal Plain. , 4(1), pp.1–8.

Amah, E. a., Ugbaja, a. N. & Esu, E.O., 2012. Evaluation of Groundwater Potentials of the Calabar Coastal Aquifers. *Journal of Geography and Geology*, 4(3), pp.130–140.

An, T.D. et al., 2014. Chemical Characteristics of Surface Water and Groundwater in Coastal Watershed, Mekong Delta, Vietnam. *Procedia Environmental Sciences*, 20, pp.712–721. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1878029614000863.

Anderson, M.P. & Woessner, W.W., 2002. *APPLIED GROUNDWATER MODELING : Simulation of Flow and Advective Transport*, New York: Academic Press.

Armitage, N. et al., 2014. *Water Sensitive Urban Design (WSUD) for South Africa: Framework and Guidelines*, Cape Town.

Ashley, R. et al., 2013. Water-sensitive urban design: opportunities for the UK. *Municipal Engineer*, 166(2), pp.65–76.

Ayenew, T., Demlie, M. & Wohnlich, S., 2008. Application of numerical modeling for groundwater flow system analysis in the Akaki catchment, Central Ethiopia. *Mathematical Geosciences*, 40(8), pp.887–906.

Aza-gnandji, C.D.R. et al., 2013. Salinity of irrigation water in the Philippi farming area of the Cape Flats , Cape Town , South Africa. *Water SA*, 39(2), pp.199–210.

Binley, A. et al., 2007. Temporal and Spatial Variability of Groundwater-Surface Water Fluxes : Development and Application of an ... Temporal and spatial variability of groundwater – surface water fluxes : Development and application of an analytical method using temperature tim. *Journal of Hydrology*, 336(April 2016), pp.1–6.

Brodie, R. et al., 2007. An Overview of Tools for Assessing Groundwater-Surface Water Connectivity. *Bureau of Rural Sciences, Canberra.*, (October), p.133.

Clarke, I. & Fritz, P., 1997. *Environmental isotopes in hydrogeology*, USA: CRC Press.

Constantz, J., 1998. Interaction between stream temperature , streamflow , and groundwater exchanges in alpine streams. *Water Resources Research*, 34(7), pp.1609–1615.

Cook, P. et al., 2006. Quantifying groundwater discharge to Cockburn River, southeastern Australia, using dissolved gas tracers 222Rn and SF6. *Water resource management*, 42(10), pp.1–12.

Craig, H., 1961. Isotopic variations in Meteoric waters. *Science*, 133(3465), pp.1702–1703.

Elango, 2017. *Numerical simulation of groundwater flow and solute transport*, Anna Salai, Chennai: Allied Publishers PVt.LTD.

Elçi, A., Gündüz, O. & Şimşek, C., 2007. Torbalı Ovasındaki Yüzeysel Akiferindeki Yeraltı Suyu Akımının Matematiksel Modelleme İle Tespiti. *V. Ulusal Hidroloji Kongresi*, pp.69–78.

Ellis, D.M., 2013. *Identification and Review of Selected WSUD Case Studies in South Africa*. University of Cape Town.

Faust, C.R. & Mercer, J.W., 1980. Ground-Water Modeling: Numerical Modelsa. *Groundwater*, 18(4), pp.395–409. Available at: http:https://dx.doi.org/10.1111/j.1745-6584.1980.tb03414.x.

Folch, A., Carles-Brangarı, A. and Carrera, J., 2016. Emerging Organic Contaminants in Aquifers: Sources, Transport, Fate, and Attenuation. Emerging Contaminants in River Ecosystems: Occurrence and Effects Under Multiple Stress Conditions, 46, p.47.

Fernald, A.G. & Guldan, S.J., 2006. Surface Water – Groundwater Interactions Between Irrigation Ditches , Alluvial Aquifers , and Streams. , (2005), pp.79–89.

Freeze, R. & Cherry, J., 1979. *Groundwater*, London: Prentice Hall.

Gbmez-hernbnez, J.J., 1997. Stochastic simulation of transmissivity fields conditional to both transmissivity and piezometric data-I . Theory. *Journal of Hydrology*, 203(97), pp.162–174.

Gehman, C.L. et al., 2010. Estimating specific yield and storage change in an unconfined aquifer using temporal gravity surveys. *Water Resources Research*, 46(4), pp.1–16.

Gerber, A., 1976. *An investigation into the hydraulic characteristics of the groundwater source in the Cape Flats*. MSc thesis, Institute for groundwater studies, University of Orange Free State.

Gorelick, S.M., 2006. Quantifying Stream - Aquifer Interactions through the Analysis of Remotely Sensed Thermographic Profiles and In Situ Temperature Histories. *ENVIRONMENTAL SCIENCE & TECHNOLOGY*, 40(10), pp.3336–3341.

Guggenmos, M.R. et al., 2011. Regional-scale identification of groundwater-surface water interaction using hydrochemistry and multivariate statistical methods, Wairarapa Valley, New Zealand. *Hydrology and Earth System Sciences*, 15(11), pp.3383–3398.

Halford, K.J. & Kuniansky, E.L., 2002. *Documentation of Spreadsheets for the Analysis of Aquifer-Test and Slug-Test Data*, Carson City. Available at: http://nevada.usgs.gov.

Hargreaves, G.H. & Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. *American Society of Agricultural Engeneering*, 1(2), pp.96–99.

Hartnady, C. & Rogers, J., 1990. *The scenery and geology of the Cape Peninsular.Guidebook Geocongress '90 Geological Society South Africa*,

Hay, R. et al., 2015. Cape Flats Aquifer and False Bay – Opportunities To Change. , pp.1–16.

He, B., Takase, K. & Wang, Y., 2008. Numerical simulation of groundwater flow for a coastal plain in Japan: Data collection and model calibration. *Environmental Geology*, 55(8), pp.1745–1753.

Henderson, V., 2002. Urbanization in developing countries. *World Bank Research Observer*, 17(1), pp.89–112.

Hiscock, K., 2005. *Hydrogeology: Principles and practice*, United Kingdom: Blackwel publishing.

Hoyer, J. & Dickhaut, W., 2011. *Sustainable Water Management in the City of the Future:*

Water Sensitive Urban Design Principles and Inspiration for Sustainable Stormwater Management in the City of the Future. available at: http://www.switchurbanwater.eu/outputs/pdfs/W5-1_CHAM_PAP_WSUD_for_a_Sustainable_Stormwater_Management.pdf

Hunt, R.J. et al., 2005. Investigating surface water-well interaction using stable isotope ratios of water. *Journal of Hydrology*, 302(1–4), pp.154–172.

Jha, K.M., Kamii, Y. & Chikamori, K., 2003. On the Estimation of Phreatic Aquifer Parameters by the Tidal Response Technique. *Water resource management*, 17, pp.69–88.

Jones, S., Mason, S. & Conrad, J., 2014. *Groundwater Specialist Study - Cape Town International Airport Runway Re-alignment and Associated Infrastructure Project*, Cape Town.

Kalbus, E., Reinstorf, F. & Schirmer, M., 2006. Measuring methods for groundwater – surface water interactions : a review. *Hydrol. Earth Syst. Sci*, 10, pp.873–887.

Kendall, C. & Coplen, T.B., 2001. Distribution of oxygen-18 and deuterium in river waters across the United States. *Hydrological Processes*, 15(September 2000), pp.1363–1393.

Kránsý, J., 1993. Classification of Transmissivity magnitude and variation. *Groundwater*, 1(2), pp.230–236.

Kruseman, G. & Ridder, N., 1994. *Analysis and Evaluation of Pumping Test Data* 2nd ed., Delft: International Istitute for Land Reclamation and Improvement.

Kumar, M., Ramanathan, A. & Keshari, A.K., 2008. Understanding the extent of interactions between groundwater and surface water through major ion chemistry and multivariate. *Hydrological Processes*, pp.1–14.

Lee, R.D., 1977. A device for measuring seepage flux in lakes and estuaries. *Limnology and Oceanography*, 22(1), pp.140–147.

Lerner, D.N., 1990. GROUNDWATER RECHARGE IN URBAN AREAS. In *Hydrological processes and water management in urban areas*. pp. 59–66.

Lerner, D.N., 2002. Identifying and quantifying urban recharge: A review. *Hydrogeology*

Journal, 10(1), pp.143–152.

Lowry, C.S. et al., 2007. Identifying spatial variability of groundwater discharge in a wetland stream using a distributed temperature sensor. , 43(April), pp.1–9.

Maclear, 1995. *Cape Town Needs groundwater: A note on the portential of the Cape Flats Aquifer unit to supply Groundwater for Domestic use in the Cape Town Mtropolitan area*, Cape Town, Geohydrology Directorate, Department of water affairs and forestry Report no:Gh3868

Madlala, T.E., 2015. *Determination of groundwater-surface water interaction , upper Berg River catchment , South Africa*. MSc thesis, Department of Earth sciences, University of the Western Cape.

Le Maitre, D.C. & Colvin, C.A., 2008. Assessment of the contribution of groundwater discharges to rivers using monthly flow statistics and flow seasonality. *Water SA,* 34(5), pp.549–564.

Massone, H.E. et al., 1998. Suburban Area in Developing Countries and Their Relationship to Groundwater Pollution: A Case Study of Mar Del Plata, Argentina. *Environmental Management*, 22(2), pp.245–254. Available at: https://link.springer.com/article.

Meerkotter, M., 2012. *SOURCES OF HEAVY METALS IN VEGETABLES IN CAPE TOWN , AND POSSIBLE METHODS OF REMEDIATION SOURCES OF HEAVY METALS IN VEGETABLES IN CAPE TOWN , AND POSSIBLE METHODS OF REMEDIATION*. PhD thesis, Department of Biodiversity and Conservation Biology, University of the Western Cape.

Meier, P.M., Carrera, J. & Xavier, S., 1998. An evaluation of Jacob â€™ s method for the interpretation of pumping tests in heterogeneous formations approximation Streltsova ,. *Water Resources Research*, 34(5), pp.1011–1025.

Mjemah, I.C., Camp, M. Van & Walraevens, K., 2009. Groundwater exploitation and hydraulic parameter estimation for a Quaternary aquifer in Dar-es-Salaam Tanzania. *Journal of African Earth Sciences,* 55(3–4), pp.134–146. Available at: http://dx.doi.org/10.1016/j.jafrearsci.2009.03.009.

Morris, B.L. et al., 2003. *Groundwater and its susceptibility to degradation: A global* *assessment of the problem and options for management*, Nairobi: United Nations environmental programme.

Mudd, G.M. et al., 2004. A review of urban groundwater in Melbourne: Considerations for WSUD. *Water Sensitive Urban Design Conference*, pp.428–438.

Myers, B., Pazzaniti, D. & Gonzalez D, 2013. *Hydrological Modelling of the Parafield Harvesting Scheme Catchment for Hazard Analysis Planning Goyder Institute for Water Research Technical Report Series No . 13 / 3*, Adelaide, South Australia.

Oxtobee, J.P. & Novakowski, K.S., 2003. Goundwater/Surface water interaction in a Fractured Rock Aquifer. *Ground Water*, 41(5), pp.667–681.

Oyarzún, R. et al., 2014. Multi-method assessment of connectivity between surface water and shallow groundwater: the case of Limarí River basin, north-central Chile. *Hydrogeology Journal*, 22(8), pp.1857–1873. Available at: http://link.springer.com/10.1007/s10040-014-1170-9.

Rangarajan, R. et al., 2009. Estimation of natural recharge and its relation with aquifer parameters in and around Tuticorin town, Tamil Nadu, India. *Current Science*, 97(2), pp.217–226.

Romanelli, A., 2011. Integrated Hydrogeological Study of Surface & Ground Water Resources in the Southeastern Buenos Aires Province, Argentina. *International Journal of …*, 5(4), pp.1053–1064. Available at: http://search.ebscohost.com/login.aspx?direct=true&profile=ehost&scope=site&authtype=crawler&jrnl=17356865&AN=67708630&h=nGvmZAZYuzKF1FHdvDsB3Gc4/YeKjfU1TVtmnhUekbY5fGC+AKcLv967R/wUgX538Esq/jsM3hcbnIwltIcU4g==&crl=c.

van Ryneveld, M. & Fouri, A., 1997. A strategy for evaluating the environmental impact of on-site sanitation system. *water SA*, 23(4), pp.279–291.

Saayman, I.C. & Adams, S., 2002. The use of garden boreholes in Cape Town , South Africa : lessons learnt from Perth , Western Australia. , 27, pp.961–967.

Smith, G., 1985. *Numerical solutions of partial differential equations: partial differential equation* 3rd ed., New York: Oxford university press Inc.

Spitz, K. & Moreno, J., 1996. *A practical guide to groundwater and solute transport* *modeling* 3rd ed., New York: John Wiley & Sons.Inc.

Sun, X. et al., 2013. Application of the rainfall infiltration breakthrough (RIB) model for groundwater recharge estimation in west coastal South Africa. *water SA*, 39(2), pp.221–230.

Tredoux, G., Ross, W. & Gerber, A., 1980. The potential of the Cape Flats Aquifer for the storage and abstraction of reclaimed effluents. *Z. dt. geol .. Ges*, 131(2).

Unland, N.P. et al., 2013. Investigating the spatio-temporal variability in groundwater and surface water interactions: A multi-technique approach. *Hydrology and Earth System Sciences*, 17(9), pp.3437–3453.

Vandoolaeghe, M., 1990. *The Cape Flats Aquifer*, Directorate geohydrology, Technical Report no:Gh3687

Walsh, C. et al., 2005. The urban stream syndrome: current knowlegde and the search for a cure. *Journal of the North American Benthological Society*, 24(3), pp.706–723.

Weaver, J.M.C., Cavé, L. & Talma, A.S., *Groundwater sampling second edition*,Water Research Commision Report no:TT303/07

Winston, R.B., 2009. *ModelMuse — A Graphical User Interface for MODFLOW – 2005 and PHAST*:US.Geological Survey techniques and methods 6-A29, 52p, Available only online at http//pubs.usgs.gov/tm/tm6A29.

Winter, T.C., 1999. Relation of streams , lakes , and wetlands to groundwater flow systems. , (September 1998), pp.28–45.

Wong, T., 2006. Water sensitive urban design-the journey thus far. *Australian Journal of Water Resources*, 10(3), pp.213–222. Available at: http://search.informit.com.au/documentSummary;dn=308430980450150;res=IELENG.

Woodworth, J. & Stednick, J., 2011. *Submitted by*. Colorado University.

Wright, A. & Conrad, J., 1995. *The Cape Flats Aquifer-current status*, Stellenbosch.

Xiao, L., 2014. *EVALUATION OF GROUNDWATER FLOW THEORIES AND AQUIFER PARAMETERS ESTIMATION*. University of the Western Cape. Available at: etd.uwc.ac.za/xmlui/handle/11394/4366.

Xu, Y. & Beekman, H.E., 2003. *Groundwater Recharge Estimation in Southern Africa Edited by Printed in Cape Town*, Paris: UNESCO IHP.

Younger, P., 2007. *Groundwater in the Environment: an Introduction* 1 ed., New Castle: Blackwel publishing.

Zhou, Y. & Li, W., 2011. A review of regional groundwater flow modeling. *Geoscience Frontiers*, 2(2), pp.205–214. Available at: http://dx.doi.org/10.1016/j.gsf.2011.03.003.

Zingoni, E. et al., 2005. Effects of a semi-formal urban settlement on groundwater quality Epworth (Zimbabwe): Case study and groundwater quality zoning. *Physics and Chemistry of the Earth*, 30, pp.680–688.

ADDENDUM A

Location of irrigated zones and sensitivity analysis results

A1

Names	Lattitudes	Longitudes	Area m2
Zone 1	-33.844436	18.634927	1436
Zone 2	-33.844436	18.634927	8292
Zone 3	-33.851635	18.635585	68868
Zone 4	-33.854696	18.630139	16685
Zone 5	-33.855817	18.640410	7120
Zone 6	-33.855817	18.640410	42071
Zone 7	-33.855817	18.640410	18950
Zone 8	-33.861901	18.635341	46448
Zone 9	-33.861901	18.635341	28328
Zone 10	-33.861901	18.635341	164228
Zone 11	-33.866732	18.642400	34423
Zone 12	-33.866732	18.642400	3025
Zone 13	-33.866732	18.642400	1362
Zone 14	-33.866732	18.642400	799
Zone 15	-33.877419	18.642360	4090
Zone 16	-33.923451	18.582753	55656
Zone 17	-33.923451	18.582753	2595
Zone 18	-33.923451	18.582753	3450
Zone 19	-33.923451	18.582753	17460
Zone 20	-33.934112	18.600985	33941
Zone 21	-33.934112	18.600985	7174
Zone 22	-33.932030	18.587397	2847
Zone 23	-33.932030	18.587397	1129
Zone 24	-33.932030	18.587397	9874
Zone 25	-33.932030	18.587397	2297
Zone 26	-33.941099	18.613504	6287
Zone 27	-33.940671	18.614412	1711
Zone 28	-33.940660	18.614412	2927
Zone 29	-33.964534	18.550452	66158
Zone 30	-33.964534	18.550452	6607
Zone 31	-33.964534	18.550452	1175
Zone 32	-33.976914	18.549701	21786
Zone 33	-33.976918	18.549701	9641
Zone 34	-33.976922	18.549701	64132
Zone 35	-33.976930	18.549701	7457

A2

		Head differences			Head differences		
		Reduction			Increasing		
		-10%	-50%	-80%	10%	50%	80%
Parameters	**Observation**	m	m	m	m	m	m
Constant heads variations	BG46051	5.02E-02	0.88	1.4	5.04E-02	-0.78	-1.12
	BG46052	-0.7	0.29	0.98	-0.7	-1.69	-2.15
	UWC 4	-1.11	0.68	1.9	-1.11	-2.89	-3.7
	UWC 3a	-0.95	0.78	1.9	-0.95	-2.67	-3.36
	UWC 3b	-1.18	0.74	2.01	-1.18	-3.09	-3.87
Hydraulic conductivity	BG46051	5.14E-02	4.70E-02	3.66E-02	5.21E-02	5.22E-02	5.10E-02
	BG46052	-0.7	-0.69	-0.69	-0.7	-0.7	-0.71
	UWC 4	-1.11	-1.1	-1.09	-1.11	-1.12	-1.12
	UWC 3a	-0.94	-0.94	-0.93	-0.95	-0.95	-0.96
	UWC 3b	-1.17	-1.17	-1.15	-1.18	-1.18	-1.19

ADDENDUM B

Cation-anion balance for all water samples used in the study

Sites	Na	K	Ca	Mg	Cl	HCO3	SO4	verdict
Khayelitsha. Stadium	1,235319704	0,296690368	6,911522531	0,740588356	0,912591	9,259881	0,630401	use
Makhaza	3,945193562	0,163691237	7,819751485	4,278954948	4,876658	8,112639	2,282485	use
EK 19	6,302740322	0,432247174	4,246718898	1,604608105	6,274062	4,687303	1,130373	use
UWC 3B	0,74815137	0,056268863	4,845551175	0,419666735	0,655925	4,048125	0,673876	use
Esangweni Close 2	1,335363201	0,092076321	3,902390339	0,946307344	1,11222	3,261445	1,326015	use
EK8	5,524140931	0,70080311	4,421378312	1,053281218	4,306288	5,572318	1,217325	use
Lenteguer 3	8,007829491	0,046038161	2,67977444	1,102653775	11,23628	0,295005	0	use
Vyge 3	4,249673771	0,294132692	4,017166525	1,201398889	3,992585	4,425076	1,217325	use
Bell G46052	7,024793388	0,117653077	1,881331404	2,213536309	8,783687	2,081425	0,021738	use
Phillipi BG00153	1,6876903	0,529438846	9,082289535	1,382431598	1,311849	7,162068	3,521548	use
FYG 2	4,162679426	0,358074582	3,822546035	1,143797573	3,935548	4,802027	1,260801	use
EK 5	4,654197477	0,521765819	3,128898648	0,50195433	3,222587	3,540061	1,456443	use
RJ1	2,870813397	0,56780398	7,490393732	0,650072002	2,851847	9,686	0,608663	use
Khayelitsha hospital	1,887777294	0,153460535	4,720794451	1,316601522	2,338514	5,408426	0,434759	use
EL 3	4,027838191	0,265998261	3,133888917	1,291915244	3,365179	5,080643	0,695614	use
EK9	4,419312745	0,519208144	3,11891811	0,411437976	3,222587	3,540061	1,391229	use
Elsieskraal 1	5,102218356	0,19694102	3,423324517	1,637523143	4,391844	4,523411	0,912994	use
Khayelitsha TR section	3,040452371	0,593380736	7,754877988	1,053281218	2,024811	7,981526	1,565132	use
Phillipi BG00152	3,505872118	0,342728528	14,19731524	1,645751903	5,104805	5,424815	7,543068	use
Lenteguer BG00139	13,64941279	0,058826538	7,590199112	2,575601728	15,05775	5,900101	1,456443	use
Bell G46051	10,90909091	0,104864699	1,297469934	2,731948159	11,32183	2,704213	0,086952	use
UWC 4	0,530665507	0,028134431	2,999151654	0,419666735	0,541851	2,655046	0,391283	use
EK11	3,740756851	0,465496956	2,43525126	0,50195433	3,137031	4,293963	1,086897	use
Westridge	2,1661592	0,079287943	5,514247218	0,765274635	2,623699	4,474244	0,630401	use
EK 19	6,180948238	0,424574147	4,306602126	1,497634232	6,13147	4,392298	1,086897	use
Vyge1	4,184428012	0,378535986	3,568042317	1,045052458	3,90703	5,408426	1,260801	use
Elsieskraal 2	3,875598086	0,281344314	2,844453316	1,19317013	3,365179	5,441205	0,630401	use
EL 4	4,184428012	0,209729398	2,714706323	1,300144003	3,792956	3,622007	0,84778	use

Sample ID	Na(meq/L)	K (meq/L	Ca(meq/L)	Mg(meq/L)	Cl(meq/L)	HCO3 (meq/L)	SO4(meq/L)	CAB
KW	4,401913876	0,432247174	3,353460752	0,84756223	3,678882076	3,851455113	1,499918483	0,027280596
ek5	4,571552849	0,455266254	3,428314786	0,806418432	3,45073435	4,457854428	1,499918483	-0,787115536
el1	4,767290126	0,186710318	2,949248965	1,514091751	4,534436047	4,769248671	1,065159502	-4,808926246
ek19	5,193562418	0,355516906	3,6029742	1,464719194	5,44702695	3,949790137	1,760773871	-2,483738432
fyg2	4,132231405	0,273671288	4,506212885	1,242542687	3,194068159	5,059336992	1,217325145	3,484914273
lentegure G00139	12,94910831	0,053711187	6,597135586	2,443941576	13,83145587	7,719299396	1,282538992	-1,759017405
UWC3b	0,735102218	0,051153512	4,48126154	0,427895495	0,712961643	4,752859501	0,630400522	-3,399095372
add sample	4,210526316	0,189267993	2,949248965	1,324830282	3,764437473	4,621746135	1,021683604	-4,059308595
uwc3a	0,313179643	0,033249783	2,300513998	0,148117671	0,370740054	2,523932287	0,260855388	-6,057663279
Khay TR	2,862113963	0,478285334	6,936473876	1,086196256	2,195921859	8,915708856	1,521656432	-5,293377412
EK 8	3,314484559	0,414343445	3,218723489	0,979222382	2,994438899	4,179238526	1,195587196	-2,715327086
EK 11	3,540669856	0,414343445	2,899346275	0,773503394	2,908883502	3,949790137	1,34775284	-3,653864671
west STD	1,765985211	0,117653077	5,349568342	0,979222382	1,939255668	5,654263889	0,695614369	-0,464834234
Lent 2	0,769899957	0,084403294	4,850541444	1,028594939	0,884072437	5,244534621	0,565186675	0,295264857
esang cl1	5,571987821	0,17392194	5,419432107	2,065418638	5,218879224	12,22632134	1,369490789	-17,42503388
esang cl2	1,357111788	0,081845619	3,672837966	0,995679901	1,083701697	21,51898112	1,304276941	-59,30308022
Bell BG46052	9,739016964	0,094633997	1,097859175	2,781320716	10,32368459	3,31061248	0,086951796	-0,030684501
Makhaza	4,040887342	0,158575886	7,320724587	5,24994857	5,64665621	11,09546856	2,934623118	-7,974924492
UWC 4	0,539364941	0,317151772	0,069863766	4,91256943	0,541850848	3,097553261	0,499972828	17,03264484
FGY 1	4,258373206	0,28390199	4,406407505	1,234313927	3,536289748	6,260663204	1,195587196	-3,823012982
khay std	0,84384515	0,140672157	3,258645641	0,370294178	0,884072437	31,74418471	0,413021031	-75,49600554
khay hosp	1,196172249	0,076730268	3,857477918	0,905163547	1,391701126	4,769248671	0,347807184	-3,772334565
lent 3	7,864288821	0,043480485	2,569988522	1,094425015	10,86553543	0,278615902	0,043475898	1,689625742
Bell G46051	6,415832971	0,102307023	1,671740107	2,164163752	8,840724369	2,228927214	0,108689745	-3,828175411
EK 9	4,306220096	0,434804849	3,288587255	0,789960913	3,821474405	4,277573551	1,434704636	-3,891281008
Phillipi BG00153	1,596346237	0,524323495	9,122211687	1,226085168	1,254812491	8,014304468	3,304168252	-0,416570461
FGY3	4,036537625	0,273671288	4,466290733	1,217856408	3,792955939	6,40816574	1,282538992	-6,934088175
EL2	4,541104828	0,181594966	2,96921004	1,448261675	4,420362185	4,556189452	1,086897451	-4,807830761
EL4	5,197912136	0,163691237	3,06901542	1,670438181	4,306288322	4,802027013	1,239063094	-1,204598051
RJ1	3,310134841	0,552457926	7,575228305	0,806418432	3,137031228	11,96737244	0,282593337	-11,37393
Phillipi BG00152	2,183558069	0,381093662	5,179899197	1,19317013	2,766291174	3,261444968	3,304168252	-2,15758849

sites	Na(meq/l	K(meq/l)	Ca(meq/l)	Mg(meq/l	Cl (meq/l)	HCO3(meq/l)	SO4 (meq/l)	CAB
makhaza	3.775555	0.199499	15.07061	4.065007	6.487462	23.4856816	1.020185091	-14.5695
Khay std	0.7699	0.161134	9.481511	0.39498	0.874397	33.92558333	0.312301558	-52.9287
UWC 3B	0.591562	0.046038	3.163831	0.362065	0.733365	4.326741063	0.353941766	-13.0571
BG46051	4.710744	0.125326	2.100903	1.966674	8.461907	2.933661554	0.353941766	-13.7793
rj1	2.92736	0.601054	6.287739	0.765275	3.779652	13.11133655	0.208201039	-23.5463
asa cl1	3.23619	0.204614	5.105045	1.604608	3.836065	3.638395894	0.936904675	9.369187
BG00152	2.427142	0.373421	6.826688	1.143798	3.779652	4.523411111	3.352036727	-3.94206
esa cl2	1.200522	0.089519	3.044064	0.839333	1.269286	3.769509259	0.936904675	-7.19573
lent 3	6.428882	0.048596	3.927342	1.06151	14.38524	0.376950926	0	-12.566
G32961	1.300565	0.227633	5.234792	1.184941	1.889826	6.096771497	0.645423221	-4.126
Khay tr	2.822967	0.585708	7.215929	1.341288	2.442671	28.3532653	1.49904748	-45.9302
UWC3A	0.347977	0.030692	2.310495	0.139889	0.507714	2.884494042	0.208201039	-11.9972
Khay Hps	1.23097	0.089519	3.782624	0.888706	1.805207	5.473983011	0.312301558	-11.7768
Lent2	0.717703	0.089519	3.827536	0.493726	0.93081	4.212016868	0.333121662	-3.2766
BG00153	1.622445	0.358075	7.650082	0.938079	2.200096	5.998436473	2.893994441	-2.41836
BG00139	10.42627	0.0665	8.009382	2.246451	18.05207	6.588446618	1.12428561	-10.7844
UWC4	0.508917	0.025577	2.689755	0.26332	0.648746	3.130331602	0.47886239	-9.94604
EK 11	4.262723	0.664996	14.93057	1.481177	9.709936	5.162588768	8.702803427	-4.978
EL 3	3.444976	0.171364	10.84955	1.259	11.43798	4.769248671	0.811984052	-3.95283
UWC wet	4.262723	0.079288	15.16449	2.139477	16.45752	6.588446618	5.08010535	-13.0196
EL 4	3.949543	0.153461	10.50117	1.398889	12.75458	4.933140378	0.936904675	-7.5707
EL 2	3.919095	0.189268	9.968646	1.39066	12.91915	5.342869645	0.811984052	-10.4405
kuils wet	1.683341	0.271114	12.71587	0.452582	6.089282	2.015867995	0.541322701	27.24696
EK9	2.474989	0.358075	6.947693	0.419667	7.241308	3.654785064	0.791163948	-6.79302
EK5	1.85298	0.301806	6.459961	0.477268	6.253857	2.081424678	0.582962909	0.964837
Vyge 3	3.984341	0.322267	9.207187	1.242543	13.49517	6.539279106	1.145105714	-17.8741
Vyge1	4.14963	0.352959	10.98392	1.267229	13.49517	6.981786715	1.165925818	-12.7332
EK 8	3.749456	0.565246	9.366446	0.896935	12.17856	5.244534621	1.186745922	-12.1483
Vyge 2	3.958243	0.317152	10.27223	1.234314	13.41288	6.555668277	1.12428561	-14.4025
Vyge 4	3.99304	0.32994	9.859155	1.234314	12.83686	6.293441546	1.145105714	-13.6136

Sites	Na(meq/L)	K (meq/L)	Ca (meq/L)	Mg (meq/L)	Cl (meq/L)	HCO3 (meq/L)	SO4 (meq/L)	Balance
EL 4	4.036537625	0.161133562	2.67977444	1.43180416	4.7386681	4.670913647	1.103465506	-11.7084
EL3	3.910395824	0.176479615	2.60991067	1.3824316	4.82328717	4.277573551	1.020185091	-11.2187
Vyge 4	3.897346672	0.30692107	4.03213733	1.22608517	4.76123318	5.834544766	1.270026337	-11.2682
Vyge 3	3.932144411	0.30692107	4.04710814	1.22608517	4.85149353	11.06269022	1.22838613	-28.6264
Vyge 1	4.088734232	0.335055502	4.24172863	1.28368648	4.59763631	6.031214814	1.249206234	-8.8369
Vyge 2	3.932144411	0.314594097	4.15689406	1.23431393	4.4001918	6.014825644	1.249206234	-9.51207
EL 2	3.975641583	0.171364264	2.57996906	1.39066036	4.87969988	4.080903502	1.020185091	-10.2946
EL 1	4.036537625	0.166248913	2.5250761	1.39888912	4.51301723	3.966179307	1.020185091	-7.78747
Kuils wet	1.213571118	0.171364264	1.01801487	0.39498046	9.16706626	2.622267311	0.249841247	-62.2847
UWC wet	4.262722923	0.079287943	15.2053496	2.13947747	5.64127154	6.588446618	0.333121662	26.63966
EK9	2.474989126	0.396439716	2.89435601	0.43612425	3.61041379	3.654785064	0.791163948	-13.0062
EK5	1.852979556	0.289017341	2.49513449	0.650072	3.6668265	2.081424678	0.582962909	-8.98583
EK 8	3.749456285	0.565246304	2.61490094	0.89693479	4.17454094	5.244534621	1.186745922	-15.0783
EK 11	3.545019574	0.419458796	2.91431708	0.84756223	3.86427101	4.851194525	1.332486649	-13.0615
EK 19	3.479773815	0.386209013	2.75961874	0.82287595	3.6668265	4.752859501	1.249206234	-12.9717
BG46051	5.571987821	0.122768428	1.39727531	2.15593499	9.16706626	2.622267311	0.297727486	-13.3072
Khay TR	3.01000435	0.557573277	8.93258147	1.62929438	2.25650862	49.34779295	1.87380935	-58.2016
Lent BG00	10.56111353	0.074172592	5.81366336	2.3369677	18.3341325	6.932619203	1.165925818	-16.9107
Makhaza	3.597216181	0.199498696	10.1801487	3.19275869	5.16176346	27.05852081	0.333121662	-30.939
West std	1.887777294	0.092076321	4.41638804	0.7323596	2.70781034	5.637874718	0.562142805	-11.0949
BG00152	1.635493693	0.342728528	12.7251859	0.91339231	2.03085776	11.53797617	2.810714025	-2.38386
Khay Std	0.813397129	0.156018211	9.58131643	0.37852294	0.7333653	6.916230032	2.082010389	5.796704
BG46052	4.771639843	0.127883779	1.66674984	1.87615717	8.20805009	2.343651409	0.145740727	-11.7817
BG00153	2.496737712	0.375978311	5.30465592	1.14379757	3.52579471	3.736730918	3.039735168	-4.99959
Khay hsp	1.913875598	0.191825669	9.01741604	1.36597408	2.2000959	12.61966143	0.916084571	-11.5031
Esa_Close	2.583732057	0.19694102	12.5854584	1.43180416	3.10269935	17.52002347	0.74952374	-11.984
Lent 2	0.752501087	0.094633997	4.01217626	0.46081053	1.04363524	4.146460185	0.333121662	-1.873
RJ1	3.545019574	0.580592358	1.93123409	0.50195433	3.24373114	12.73438563	17.17658571	-66.9694
Esa_Close	1.326663767	0.097191672	5.52921802	0.86401975	1.38211153	7.063732568	0.895264467	-8.88214
Lent 3	6.48107873	0.051153512	5.66894556	1.06150998	15.7955603	0.442507609	0.297727486	-10.9841
UWC 4	0.50891692	0.025576756	2.68975498	0.2633203	0.64874623	3.130331602	0.47886239	-9.94604
UWC3A	0.347977381	0.030692107	4.17186486	0.13988891	0.50771444	2.884494042	0.208201039	13.14722
UWC3b	0.591561548	0.046038161	3.16383053	0.36206542	0.7333653	4.326741063	0.353941766	-13.0571

ADDENDUM C

Ethical clearance letters and forms