Analysis of temporal and spatial variations in water storage by means of gravimetric and hydrologic methods in the region around the South African Gravimetric Observation Station

by

Gaathier Mahed

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Supervisor: Professor Maarten de Wit

Co-Supervisor: Dr Moctar Doucouré

DECLARATION

I, Gaathier Mahed (Student Number : 212438751), hereby declare that the thesis, Analysis of temporal and spatial variations in water storage by means of gravimetric and hydrologic methods in the region around the South African Gravimetric Observation Station, for the PhD in Geosciences is my own work and that it has not previously been submitted for assessment or completion of any postgraduate qualification to another University or for another qualification

Gaathier Mahed
30 November 2012

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All thanks and praise is due to The Almighty, the One who has assisted me to accomplish my cherished wish – the completion of this thesis.

The Holy Prophet [peace and blessings be upon him] said: "Whoever is not grateful to people can never be grateful to his Creator."

In view of the above injunction, I am duty-bound to extend my heartfelt gratitude to certain people, without whom, this endeavour would not have been possible.

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LIST OF ABBREVIATIONS

AEON	Africa Earth Observatory Network
AMCOW	African Minister's Council on Water
ASR	Aquifer Storage and Recovery
BEM	Name of lab used for analysis of samples
FOSS	Free Open Source Software
GCM	Global Climate Models
GFZ	German Research Centre for Geosciences
GHYRAF	Gravity and Hydrology in Africa
GMWL	Global Meteoric Water Line
GOCE	Gravity field and steady state Ocean Circulation Explorer
GPS	Global Positioning System
GGP	Global Geodynamics Project
GRACE	Gravity Recovery and Climate Experiment
HDPE	High Density PolyEthelyne
IAEA	International Atomic Energy Agency
IFR	Instream Flow Requirements
IGS	Institute for Groundwater Studies
IHP	International Hydrological Programme
IWRM	Integrated Water Resource Management
JPL	Jet Propulsion Laboratory (California Institute of Technology)
Km	Kilometre
LMWL	Local Meteoric Water Line
m	metre
mamsl	metres above mean sea level
mbgl	metres below ground level
mbcl	metres below casing level
meq	milliequivalents
MENA	Middle East North Africa
μ **S/cm**	microsiemens per centimetre
μ	microns
mm	millimetre

NGDB	National Groundwater Database
NGO	Non Governmental Organisation
NRF	National Research Foundation
NWA	National Water Act of South Africa (Number 36 of 1998)
NWRS	National Water Resource Strategy
PET	Polyethelyene
RWH	Rainwater Harvesting
SAAO	South African Astronomical Observatory
SADC	Southern African Development Community
SAGOS	South African Gravimetric Observation Station
SDI	Subsurface Drip Irrigation
SG	Superconducting Gravimeter
SMOS	Soils Moisture and Ocean Salinity
SVAT	Soil Vegetation Atmosphere Transfer Scheme
SVF	Saturated Volume Fluctuation
SWAT	Soil and Water Assessment Tool
TWS	Terrestrial Water Storage
UNESCO	United Nations Education and Scientific Organisation
VIP	Ventilated Improved Pit latrines
WGHM	WaterGAP Global Hydrological Model
WISH	Windows Interpretation System for the Hydrogeologist
WRC	Water Research Commission

DEFINITIONS

These definitions can all be found on the website www.wikipedia.org

Aquifer
An aquifer is an underground layer of water bearing permeable rock or unconsolidated materials from which groundwater can be usefully extracted using a water well

Artesian Aquifer
A confined aquifer with groundwater under pressure. This causes the water within the well to rise and flow to the subsurface due to the pressure.

Baseflow
The portion of streamflow that comes from the sum of deep subsurface flow and delayed shallow subsurface flow

Ephemeral Stream
Streams that only flow during and immediately after precipitation events

Geohydrology
the study of hydrology from the perspective of the influence on geology.

Groundwater
The saturated zone below the groundwater table

Hydrology
The study of the movement, distribution and quality of water on the Earth and other planets, including the hydrologic cycle, water resources and environmental watershed sustainability

Hydrogeology
is the area of geology that deals with the distribution and movement of groundwater in the soil and rocks of the earth's crust

Infiltration
The process by which water on the ground surface enters the soil

Interflow
The lateral movement of water that occurs in the upper part of the unsaturated zone

Percolation
The hydrologic process where water moves downward from the surface water to groundwater

Potentiometric surface
This is the imaginary line where a given reservoir of fluid will flow to if released from storage

Recharge
The addition of water to a groundwater system

Rhizosphere
The zone immediately surrounding the actively growing region of a plant root

Streamflow
The flow of surface water in streams, rivers and other channels
Vadose Zone
The unsaturated zone below the surface and above the saturated zone composed of soil, air and water

QUOTE

‘Science without religion is lame, religion without science is blind’
-Albert Einstein-

DEDICATION

For my Mother, Fatima Najjaar, without her love, support, care and passion for education, none of this would be possible

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ABSTRACT

This work examines the use of gravity data and its application to subsurface water reservoirs in the immediate vicinity of the South African Geodynamic Observatory, Sutherland (SAGOS), situated in a semi-arid region of the Karoo region of South Africa, and underlain by the Karoo sedimentary rocks intruded by dolerite dykes and sills. SAGOS houses the only supergravity metre (SG) in Africa, and this thesis sets out to test its use in monitoring groundwater dynamics using hydrological and gravity data. The main aim of this work is the application of the SG data, in conjunction with hydrological data, to better understand episodic recharge of subsurface reservoirs.

The importance of water as a resource, globally and specifically the Karoo, is reviewed in conjunction with supply and demand of water. This is to contextualise the socio-economic, technical as well as policy issues related to water resource management. Applicable technologies for water resource management and efficient water use are highlighted and the application of gravity to hydrology is introduced, including satellite as well as ground based tools.

In addition, arid zone hydrology as well as recharge and its mechanisms are analysed in order to better understand these processes when examined from gravity measurements. Issues related to understanding flow within the vadose zone as well as in secondary aquifers are examined, and gravity residuals and subsurface hydrology are highlighted. Thereafter, a conceptual groundwater flow model of the study area is developed using multiple tools. First, the geology around SAGOS was mapped using SPOT 5 imagery and then ground truthed. Second, stable isotopes and water chemistry analysis was undertaken on water samples from selected boreholes. The results allude to preferential flow acting as the main mechanism for groundwater recharge. Follow-up pump-tests illustrate that fracture connectivity is greatest at close proximity to the dyke.

Soil mapping, using aerial photography was also undertaken. Duplex soils, enriched with clay at depth, dominate the study area. Using in-situ infiltration tests, it is shown that the alluvium, which lines the river beds, has a higher hydraulic conductivity than the other soils, confirming that these streams act as preferential conduits for subsurface recharge.

Precipitation events were correlated against gravity residuals at 4 wells, over different time periods. The results are examined using time series analyses. Gravity residuals from well SA BK07, over a period of 24 hours after the rainfall event, delineate instances of negative correlations, as well as strong positive correlations (of up to 0.9). On the whole however, correlations between gravity and groundwater at SA BK07 are variable and weak, and in conjunction with water level measurements and water chemistry, the data suggest that this well is located in a dynamic conduit (throughflow) and not in a permanent groundwater reservoir. By contrast, other wells show strong positive correlations between gravity residuals and water levels following episodic recharge events for a later time series. Correlations between the water levels and gravity residuals in wells SA BK04, SA BK05 and SA BK 01 are in excess of 0.7 for specific rainfall events.

In summary, the results suggests that gravity is an excellent tool for measuring episodic groundwater recharge within the immediate vicinity of the SAGOS. This implies that gravity can aid in monitoring groundwater losses/gains in arid and semi-arid areas.

Recommendations for future work are highlighted at the end; these include the possible use of hydrological modelling of reservoirs at various scales and then comparing these results to the SG as well as GOCE and GRACE satellites data, and then improving numerical modelling of the groundwater dynamics for sites like Sutherland and the surrounding arid Karoo region, where sparse water shortages, and potential pollution related to fracking for shale-gas, are likely to compete with established water needs for farming and human consumption. It is also suggested that the gravity modelling be examined to better understand site specific scenarios and thus aid in improving the processing of the gravity signal.

CHAPTER 1

1.1 Background to Global Water Issues

Water plays an important role in our daily lives and the sustainable management of this finite resource is critical for the advancement of our society (Hering and Ingold, 2012). Groundwater is even more important due to the fact that it comprises a large portion, approximately 30%, of the freshwater available for human consumption (Gleick, 1993) (Figure 1.1). Many of the issues related to the problems faced in the water sector are summarized in this chapter and possible solutions and challenges in meeting them are proposed to paint a picture of the broad landscape of technical, socio-economic as well as legal issues related to the water sector in general (Braune et al., 2008 and Mahed and Xu, 2010). This chapter focuses primarily on groundwater because a large fraction of South Africa is underlain by fractured rock aquifers and many of the towns in the semi-arid region of the Karoo rely on this subsurface water (e.g Woodford and Chevallier, 2002). The Karoo is also the location for the Superconducting Gravimetre and the study area.

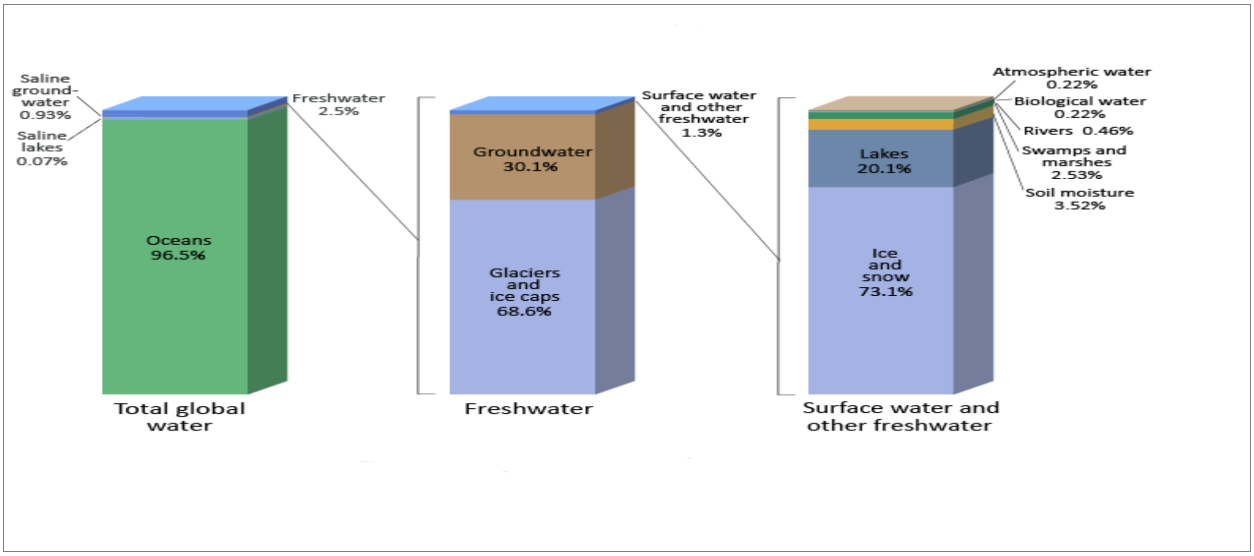

Figure 1.1: A comparison between the total global water reserves (left), freshwater (middle), and surface water and other freshwater (right). The groundwater forms 30% of the total freshwater available, whereas surface water and other freshwater constitutes only 1.3% (Gleick, 1993).

In the Introductory section an understanding of geophysical applications to groundwater, specifically related to gravimetry is outlined. Furthermore gravity studies are discussed in order to understand their applications to hydrology. Lastly the work addressed in each chapter is showcased, along with some major conclusions.

1.1.1 Supply and demand of water

Water resources have always played an important role in determining the location of great civilizations. This can be seen from the strategic placement of the City of Cairo, Egypt, along the Nile River (Pavan, 2006). The location of Detroit city along the major lakes in North America is another case (Miller, 2008). A South African example is the city of Bloemfontein (translated it means fountain of flowers) that was chosen due to its proximity to the spring the city was named after (Woodford and Chevallier, 2002). It can truly be said that water is the source of life, and without it we would not be able to survive.

In line with the strategic placement of settlements is the economic principle of supply and demand. Water is important in the functioning of industries, irrigation for crops as well as for daily human consumption. Therefore the quality and the quantity at specific locations is important for the designated use (Hem, 1986).

On a global scale relatively recent historic data sets point to the changes of rainfall patterns, due to climatic variability. Some argue that this is cyclical and is bound to the laws of nature, whilst others believe that it is anthropogenic and we, as humans, are the cause of much global warming and climate change (e.g. IPCC, 2012). The changes of climate patterns will affect the previous distribution of rainfall and in turn the available runoff and recharge (Xu and Beekman, 2003). This means that the available amount of water would also be affected, and strategies related to increasing supply or limiting demand have to be implemented (Butler and Memon, 2006). A prime example of this is the construction of the largest man made canal in Libya linked to network of pipes extending all across the country, and is approximately 2820 km long (Keys, 2011). Water is piped from the Kufra basin in the south to towns on the coast. These fossil waters, which are not being recharged and are out of contact with the atmosphere, have been mined for the purpose of irrigation (Wright et al, 1982). Due to the fact that these geological formations are not being recharged presently the aquifers are now drying up. This is the reason for an expansion project in order to pump water from other aquifers, besides the Kufra Basin (Figure 1.2).

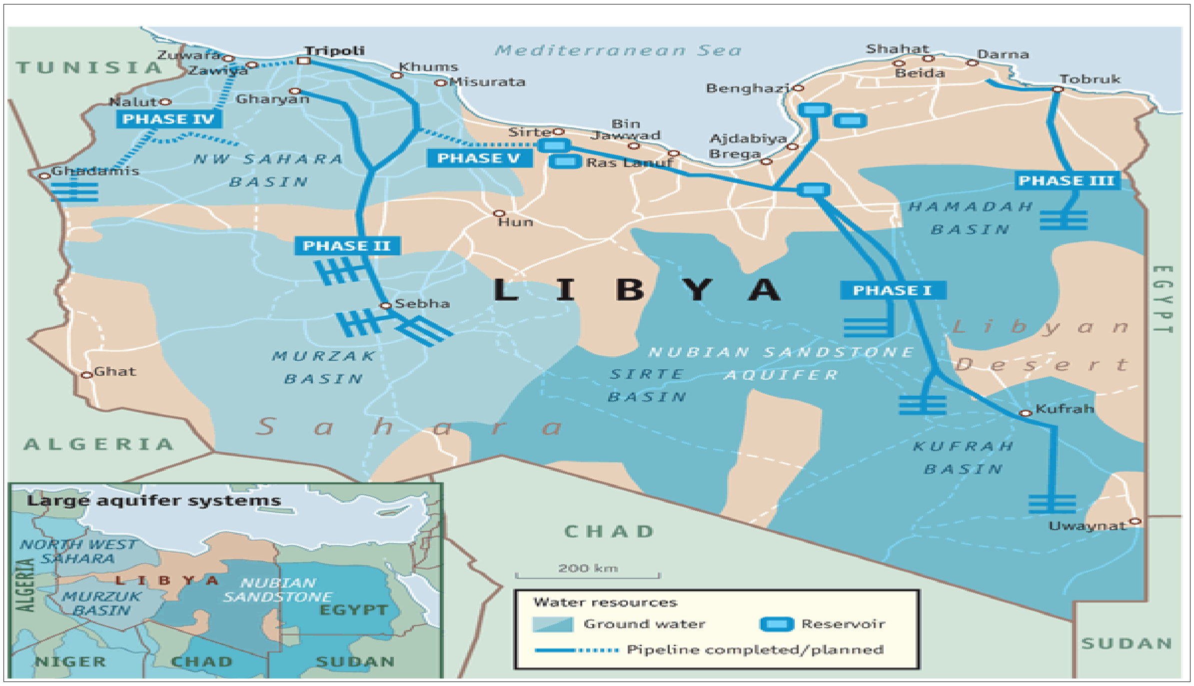

Figure 1.2: Canal systems used to pump water from the aquifers in Libya, North Africa. The aquifers in the south are pumped and then the water is piped northwards, by means of gravity flow to the coastline. These fossil waters are used primarily to irrigate crops. The Nubian sandstone aquifer as well as northwest Sahara and Murzuk Basin aquifers are all transboundary in nature and are thus shared by Libya and its neighbouring countries, potentially leading to political instability.(North is towards the top of the picture)

(Source: http://www.economist.com/blogs/dailychart/2011/03/libyas_water_supply?zid=298&ah=0bc99f9da8f185b2964b6cef412227be)

Ragab and Prodhomme (2002) amongst others, have examined scenarios of climate change in arid and semi-arid regions across the world. They concluded that adaptation to climate change is of the utmost importance. It is also important to note that the changing rainfall, often reflected in floods in some areas and drought in others, would affect the volumes of water available for humans and ecosystems (Xu and Beekman, 2003). Thus, strategic planning is critical, and alternatives, such as demand management, recycling and efficient irrigation need to be applied (Miller, 2008) These are all discussed at a later stage in this chapter.

De Wit and Stankiewicz (2006) have modelled multiple possible future water scenarios across Africa in order to determine the impact climate change will have on surface water supply across major river basins of Africa. An extensive database of digitised river channels for the African continent was utilised in a model to illustrate that 25% of river systems on the African continent will be impacted by predicted precipitation changes by 2050-2100 (de Wit and Stankiewicz, 2006). This would require a serious adjustment of our water demand management for future scenarios. This could also lead to water wars due to river basins and aquifers being transboundary (Miller, 2008). A prime example is the Nile river, which has its source in East Africa and flows through Sudan and Egypt. If any one of these two countries decides to build a dam it directly affects the country downstream.

The increasing demand in water has led to the depletion of many water resources. A good example is the Aral Sea which, in a period of 40 years, has dropped 15 metres and is now less than half its original size (McNeill, 2000). This is due to upstream diversion, overexploitation and excessive demand (Miller, 2008).

In Africa it has been speculated that most of the water in Africa will be utilised for agricultural activities in the near future due to the rapidly expanding population (Dobbs et al., 2011). An African example of the Aral sea can be seen with the disappearance of Lake Chad (Figure 1.3).

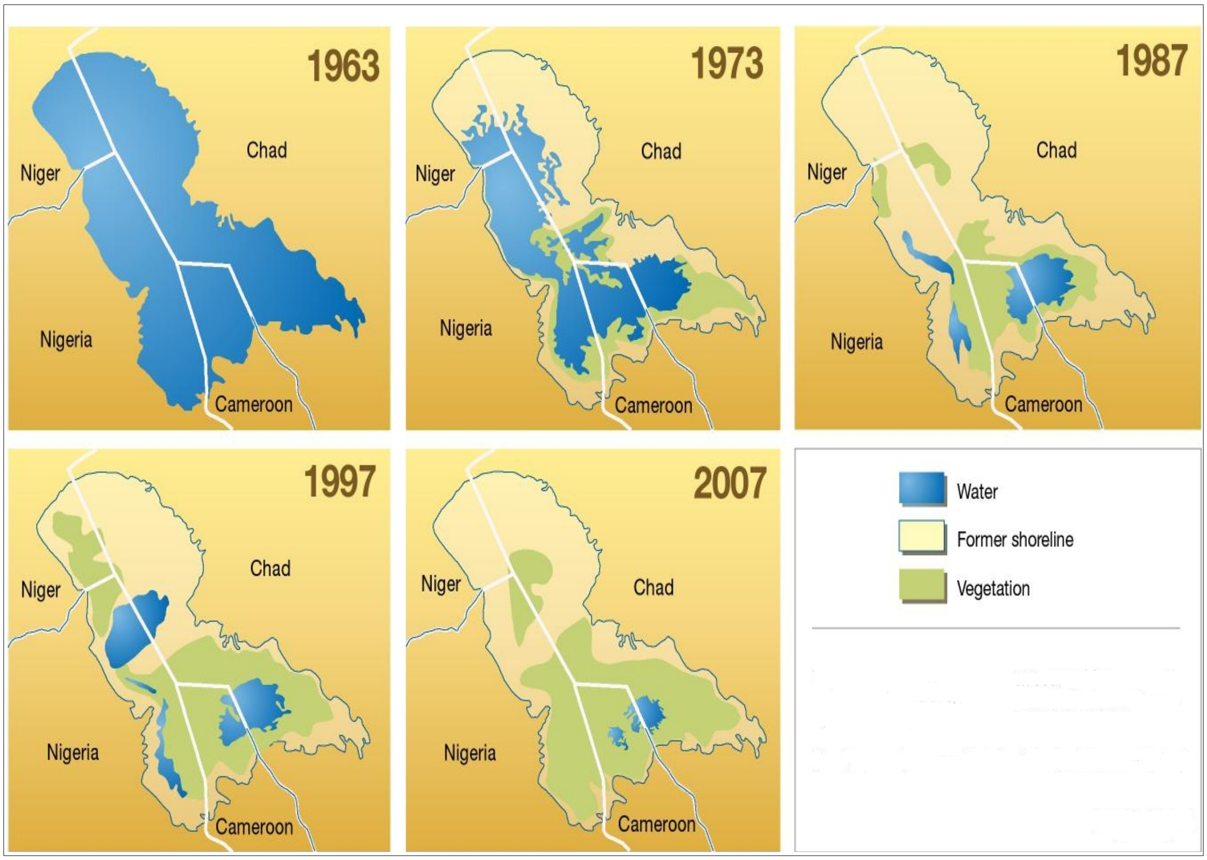

Figure 1.3: Decline of the total surface area of Lake Chad covered by water and its decline in volume from 1963 to 2007. It has been clearly documented that large volumes of water are being diverted and used, before it is able to reach the Lake. This has been attributed to the regional increase of population and industrial activities (from: UNEP, 2008). (North is towards the top of the picture)

In a South African context, it has been shown that a drop in groundwater levels has occurred over the past 20 years in the vicinity of Beaufort West. Mahed (2010) has reported that water levels in the municipal well fields supplying the Karoo town have fallen by as much as 25 metres in some locations. De Villiers and de Wit (2010) have re-examined data from the South African Department of Water Affairs (DWA) National Water Resource Strategy (NWRS). De Villiers and de Wit (2010) have concluded that the NWRS calculations underestimate the water deficit for the country to be 4424 Mm^3/a by 2025 (De Villiers and de Wit, 2010). This has implications for resource planning, allocation of resources as well as availability for human consumption and the reserve.

1.1.2 Technical issues related to water supply

A plethora of issues relate to the supply of potable water. These include, but are not limited to, infrastructure, quality and quantity. Furthermore when one examines fractured rock aquifers the quality and quantity of groundwater are of even greater concern due to uncertainties related the properties of these secondary aquifers (Cook, 2003). For example, Dennehy (2002) has critically examined the state of one of the largest aquifers in the United States of America, the High Plains aquifer, which has had deteriorating water quality, increase in salinity, marked increases in pesticides as well as lowering of the water table over a period of 60 years in many places. The major conclusion was that the anthropogenic impact on the aquifer has altered water quality and water quantity (Dennehy, 2002). Xu and Usher (2006) have shown that many of the previously mentioned anthropogenically caused problems can be avoided with the proper management of our groundwater resources. Most studies agree that sustainable extraction forms the cornerstone of management plans of all groundwater resources and should be understood and monitored by means of recharge studies (Xu and Beekman, 2003)

Water quality has always been an issue of great concern, specifically when it comes to the application of the water resource and the sector in which it is to be used (Hodgson and Manus, 2006). The deterioration of water quality in wells in Bangladesh is a well known problem. This is a prime example of the arsenic contamination experienced in groundwater related to overexploitation. Akter and Ali (2011) argue that the major source for the contamination from the Holocene alluvial and deltaic sediments. It has been postulated that the concentration of the arsenic has occurred due to the decrease in water levels, furthermore the highest levels of arsenic occur in the shallowest wells within the aforementioned Holocene deposit (Harvey et al., 2001)

Fetter (1999) has highlighted, by means of case studies and major contaminant properties, the effects which human activities such as mining can have on water resources. In this scenario prevention is better than cure due to the excessive costs involved in remediation of groundwater resources (Fetter, 2001). This can clearly be seen from the impact which Acid Mine Drainage (AMD) has had on the water supplies of this country, McCarthy (2011) summarises the AMD problem and the impact it has had on the Vaal River system in South Africa by showing an increase of up to 1000mg/l in the monitored levels of the concentration of sulphate in the aforementioned surface water. Furthermore the mobilisation of heavy metals occurs, due to an increase in the acidity caused by sulphates (Fetter, 1999).

Recent work has attempted to examine the use of chemical and biological treatment methods in order to remove the sludge formed after the treatment of the water (Diz, 1997). Other possibilities include the use of sulphate reducing bacteria in conjunction with geothermal energy in order to remediate the problem (Ntholi, 2011). These ideas are all in the developmental stages and still need fine tuning in order to lower costs and make them commercially viable.

Xu and Usher (2006), have compiled multiple case studies related to groundwater contamination in Africa. It has been shown that faecal contamination stemming from Ventilated improved Pit latrines (VIP) is still a major cause of deterioration in groundwater quality on the African continent (Xu and Usher, 2006). In the past micro and macro-chemistry were the focus for hydrogeological studies but recent advancements, as well as an increase in contaminants and pathogens, require the sampling of microbial water quality as well (Kovalevsky et al., 2004)

Water quantity and supply are also of major concern in many other parts of the world. With an ever increasing population and a constant water supply, it will be difficult to provide clean potable water for everybody (Miller, 2008) (Figure 1.4). It is envisaged that expansion of current water supply infrastructure will be costly and therefore groundwater supplies may be a cheaper alternative (Dobbs et al., 2011).

Optimisation of water supply infrastructure has always been a problem for water resource managers. This is because issues related to water quality, demand, as well as spatial and urban planning, all directly affect distribution of water resources and the infrastructure associated with it (Bowonder and Chettri, 1984). Reliability of these systems is also of the utmost importance and therefore maintenance and continued improvement of infrastructure is critical (Howe, 1994). This also affects forecasting demand and supply and thus the expansion process of an urban water resource supply system (Zhu et al., 2004).

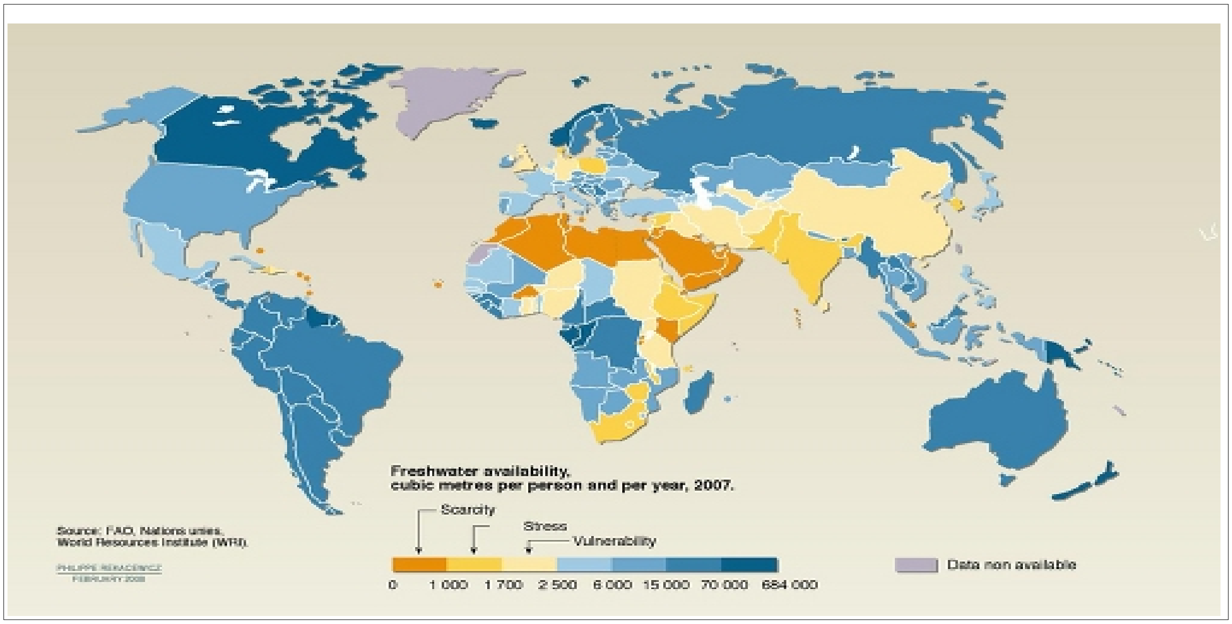

Figure 1.4: Global Freshwater availability in cubic metres per person for the year 2007. It can clearly be seen that South Africa is under water stress, and parts of the Middle East and North Africa are suffering from water scarcity. This can be attributed to the increasing population and limited amounts of water in these semi-arid to arid areas (UNEP, 2008).

In a South African context it has been estimated that R360 Billion ($43.522 Billion) is required in order secure the future water supply of the country (de Villiers and de Wit, 2010). These problems raise many issues related to the strategic planning for water resources, as well as wastewater management.

A recent report by the Department of Water Affairs (DWAE, 2009) examined the state of wastewater treatment facilities in South Africa. Only about 50% of the wastewater treatment systems in the country were sampled due to:

- Municipalities not managing waste services according to expected requirements
- Municipalities not adhering to the call to be assessed for the Green drop report
- Municipal officials not sufficiently confident in their levels of competence to be subjected to assessments for wastewater treatment

It was concluded 55% of the 449 plants sampled, especially those in smaller municipalities, were in a poor state or not even operational (DWAE, 2009). This further complicates the problem of water quality and the interaction between resources could lead to contamination of surface and groundwater supplies (Xu and Usher, 2006).

Similar problems occur throughout South Africa, but in the study area of the Karoo a substantial amount of basic data is sorely lacking (SRK, 2012). A large part of South Africa is underlain by these Karoo sediments. These rocks host fractured aquifers which supply many small towns with their basic water supply (Woodford and Chevallier, 2002). Extensive work carried out by a consortium of researchers into the characterisation of the hydrogeological regime in the Karoo basin has lead to the development of a Karoo Groundwater Atlas (SRK, 2012). This compilation of work, based largely on previously completed reports and datasets, maps the attributes affecting groundwater/aquifer geometry in the Karoo. It was concluded that the major factors influencing groundwater in the Karoo are :

- Aquifer yield
- Depth to water table
- Groundwater quality
- Dolerite intrusions

It was concluded also that groundwater above the threshold of 300 metres below ground surface is fairly well understood, but that there is a large gap in knowledge related to the aquifers below 300 metres. Thus it can clearly be stated that our knowledge of the deep aquifer processes is unfortunately lacking in South Africa. This is due to the lack of drilling at depth, minimal geophysical data and a poor understanding of the geology at great depth (SRK, 2012)

Software licenses are a limiting factor in terms of the available modelling applications for optimising water resource management, despite the fact that these applications are normally simple to use. This hurdle is slowly being overcome with an increasing availability of Free and Open Source Software (FOSS). The United States Geological Survey (USGS) has pioneered this effort and has distributed software from their website for many of the applications in the hydrological sciences. The codes are also freely available for modification and redistribution. Locally, in South Africa, the Water Research Commission (WRC) has also made great strides on this front with projects developing modelling software and freely distributing it.

1.1.3 Socio economic issues of water supply

The Dublin principles of 1992, state that the involvement of women and children in the management of water is critical for the socio-economic upliftment of societies. Therefore the needs of these individuals must always be taken into account. Mutual consensus within a society is important to address these needs as well as for the development of the community as a whole (Faruqui et al., 2001). This process of consensus was practised in the past and is still present today in many African cultures, in the form of Ubuntu (Ubuntu can be defined as the spirit of togetherness and is present in most African cultures). It is also applied by large companies in the form of stakeholder engagement (World Bank, 2006). Furthermore, Public participation creates transparency and accountability, two issues that are often lacking in many societies (Mahed and Xu, 2010).

Groundwater addresses the basic needs of water supply, due to its ease in terms of accessibility and location (Merret, 2005). This means that if a borehole is sunk closer to a village, less time is spent on collecting water from distant wells or rivers. Therefore, women and children, who collect the water in rural African areas, could direct their efforts towards other important issues such as education, and ultimately the upliftment of their community.

Education relating to water resource management at grassroots level is of critical importance. This is especially so for groundwater resources, as anthropogenic activities often adversely affect the quality due to contamination (Xu and Usher, 2006). The implementation of education relating to water management in general should be inculcated into school curricula as well as broadcasted in general media. The clergy could also be brought into play due to their great societal influence (Faruqui *et al*., 2001).

The construction and management of a Qanat is an ideal example of the application of the principle of consensus. These are constructed by means of multiple wells which intercept the flow of water and then transport it to an area higher than the water table by means of gravity flow (Figure 1.5). It is estimated that about 75% of all water supplies in rural Iran stems from Qanats (Todd and Mays, 2005). Faruqui *et al.* (2001) explain this process of construction. It is initiated by means of consensus within the community and all the people involved would then decide on who should distribute the water. Similar systems can also be found throughout the MENA region (Todd and Mays, 2005). A downside is that the construction of a Qanat is extremely laborious and boreholes seem to be a much simpler modern solution.

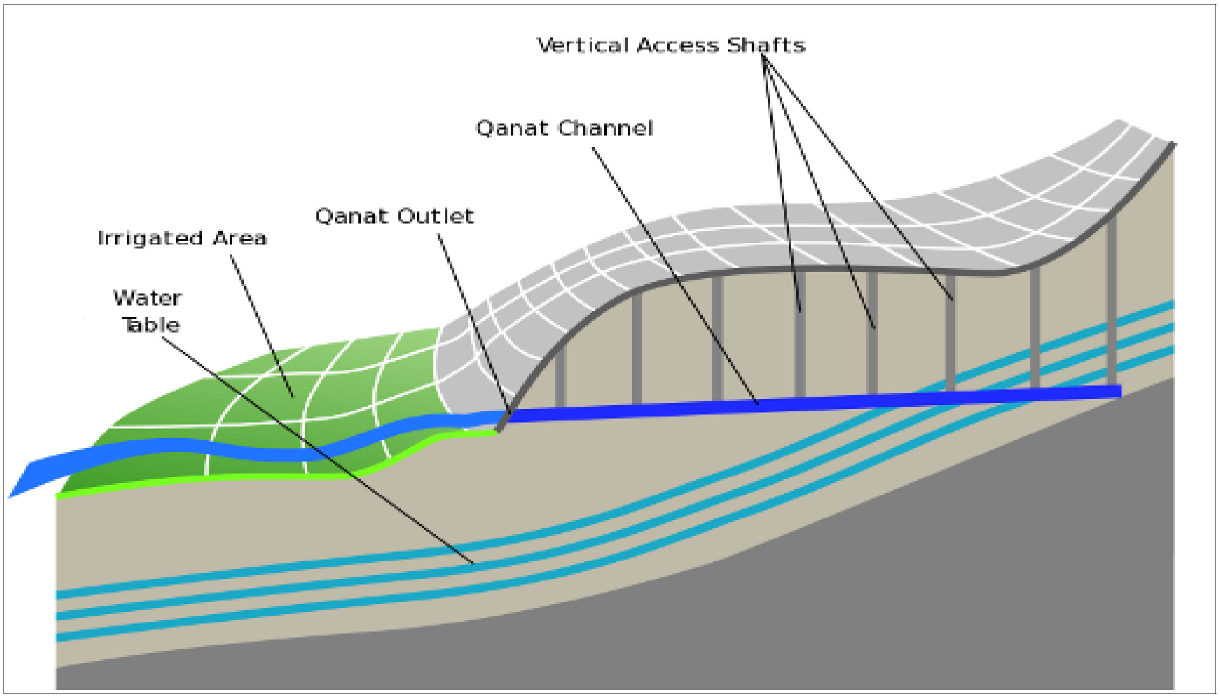

Figure 1.5: Schematic cross section of a Qanat irrigation system. The water table is intersected by the Qanat channel in order to intercept the water and then transport it along a gravity gradient to the irrigated area. Vertical access shafts are used to aid in maintenance as well as for dipping buckets into the Qanat channel to access water (http://quezi.com/1202)

Charitable endowments have been shown to be a major tool for financing water wells all over the world for NGO's. It can play a role in terms of financing the initial stages of a groundwater supply project as well as the maintenance of other related infastructures. Costs associated with groundwater resource development are minimal when compared

to the maintenance of infrastructure associated with surface water supplies. Furthermore, irrespective of the source of the supply, costs are fully recoverable as demonstrated in terms of the Islamic law (Faruqui et al., 2001). Thus all funds from charitable endowment projects are effectively utilized.
In certain scenarios the governments of countries resort to the privatisation of water resources. Currently global firms are the major stakeholders in the water privatisation sector. For example Suez, RWE/Thames Water and Vivendi are major players in this sector, globally.

The World Bank (2006) has written a guide to aid municipalities with the process of privatization in which financial, legal as well as policy instruments for the privatisation of a water resource system are outlined. This is done by using successful case studies along with the theoretical background needed for success. Furthermore, the companies and organisations involved in the process of privatisation are included in this guide (World Bank, 2006).

1.1.4 Policies, protocol and legislation related to water supply

There are many international policies related to water supply beyond the scope of this theses to mention individually. From a socio-economic, as well as political perspective the most interesting are transboundary agreements. This is a global issue as political boundaries are not necessarily dictated by lakes, river basins or aquifer boundaries (Figure 1.6). The various agreements entered into by countries sharing rivers, lakes, aquifers and water bodies is carefully documented on www.internationalwaterlaw.org.

This is divided by region and continent and also documents the major factors within the treaties as well as the date of agreement and the countries entered into the agreement. A prime example is the Jordan River which has also been examined from a political perspective by Selby (2003). The aquifer as well as the river in the region are critical water resources and could possibly be the next reason for a war in the water scarce Middle East (Miller, 2008). The Oslo Agreement II was entered into by the state of Israel and Palestine in order to equitably distribute water amongst the two states. A critical analysis of the resource management and allocation between the two states has been completed by Selby (2003). It was concluded that the strategy of the Israeli government is to control the water resources for the region and maximise the use of this precious resource for the advancement of its own issues (Selby, 2003).

Figure 1.6: The major river basins of the world on each continent, Most of these river basins span the borders of two or more countries and there are agreements in place between these countries in order to allow access of the water resources to all parties. A prime example of this is the Orange Basin (No 26), which flanks the borders of South Africa, Namibia and Botswana (UNEP, 2008).

On the continent of Africa we find major river basins, aquifers and lakes being shared by multiple countries as well. The Nile river is a prime example of one resource flowing through many countries (Pavan, 2006). The agreement entered into by all the states along the Nile river is regularly reviewed in order to maintain mutual satisfaction amongst all countries. The most recent tri-state agreement, which was between Ethiopia, Sudan and Egypt, has lead to investigations related to the distribution of the Nile waters as well as the effective use of the resource for these three major countries (Hassan and Al-Rasheedy, 2007)

In a South African context 59 agreements related to the freshwater bodies shared with other SADC countries have been completed (Ashton et al., 2006).
One of these treaties included the diversion of water from the Lesotho Highlands into the economic hub of South Africa, Gauteng. This has meant that more water is available for industry, agriculture as well as human consumption.

Compliance, in terms of legislation and quality control, is critical in order to effectively manage a water resource. This is also done to maintain a standard in terms of sample quality and integrity. In turn sampling methodologies also affects the quality of the data stemming from the laboratory (Weaver et al, 2007). This would thus affect the decisions made by resource managers if the quality of the data is poor. Jousma and Roelofsen (2003) have compared protocol and guidelines related to groundwater (Table 1.1).In excess of 400 international documents were reviewed. It was concluded that a large gap in knowledge related to fractured rock aquifers is present (Jousma and Roelofsen, 2003). The reviewed policy and protocol documents form the fundamental backbone of

a compendium of guidelines for the practitioner. This can also be seen from some of the sampling manuals developed by the United States Geological Survey (USGS). A prime example is the protocol for the measurement of oxidation potential of a water sample outlined by Nordstrom and Wilde (2005). Step by step guidance is given so that technicians are able to execute simple steps without the help of a senior scientist.
The UNESCO IHP has also developed numerous guidelines for hydrological studies. These include studies in small catchments, Groundwater as well as numerical modelling (e.g Kovalevsky et al., 2004). In many cases the literature is freely available online and could be used as teaching aids and standard textbooks for courses at Tertiary institutions. Some of the texts are a product of workshops and technical meetings held by professionals in the arena (Wheater et al., 2010). Others are written for a specific purpose as those previously mentioned.

Category	Type of document	Definitions and Explanation
Guidelines	Handbook	A book that primarily focuses on giving information about a subject
	Guide	A compendium of information or series of options that focuses on providing methodological guidance
	Manual	A book that provides instructions for use of a toll or program or for performing a specefic operation
Protocol	Standard guide	A standard compendium of information or series of options that focuses on providing methodological guidance, rather than specifying a course of action
	Standard test method	A standard procedure for determining or testing the properties of a system or the relation between them, aimed a t producing a test result
	Standard practice	A standard definite set of instructions for performing one or more specific operations, not aimed at producing a test result

Table 1.1: A comparison between Guidelines and protocols related to groundwater (modified after Jousma and Roelofsen, 2006)

The International Atomic Energy Agency (IAEA) has also completed and compiled manuals and textbooks related to isotope hydrology (www.iaea.org). Furthermore sponsored training in aspects of isotope hydrology is also available for practitioners and academics in the field, at various centres across the world.

These guidelines, manuals, textbooks and training all aid in better understanding water resources and groundwater in particular. Together they are important for the development of the science as well as in order to increase the knowledge base of the practitioner and researcher. This will hopefully lead to better management practices for water resources.The various legal instruments used to regulate water use and distribution are outlined in Table 1.2.

In many other parts of the world, riparian rights, which give preference to land owners in the immediate vicinity of a water body, still apply. This principle is utilised in many parts of the western United States of America, but in the eastern more arid parts we find that the application of first come first served principle is utilised (Miller, 2008).

Legal Instrument	Definition	Advantages	Disadvantages
Statute	Legally binding document passed by the legislature	• The highest form of law (excluding the constitution) • Indicates government commitment • The most certain way of providing for something legally	• Typically time consuming • Requires consensus between the executive and the legislature • Inflexible • Can be changed without operator's consent
Executive Order	Documents with legal force issued by the executive arm of the government, typically the president	Where the legal system permits-for example in the Philippines and some Soviet Republics-allows the executive to establish a legal basis for the arrangement without needing to go to the legislature	• Not possible in many legal systems • Can be changed without operator's consent
Regulation	Legally binding document issued by the executive under the power granted by a statute. Differs from executive orders in that the regulations must be strictly within the scope of the authority delegated tot he executive by the relevant statute	• Flexible quick to implement and legally effective • Generally used to govern a number of companies, not just one	• Can be changed without operator's consent • Regulations must be within the powers granted by the relevant statute
License	A document issued by the executive powers granted by a statute that confers rights and obligations on a particular company	• Flexible quick to implement • Similar to regulations, but suited to granting rights and obligations to a specific company	• More scope for the unilateral change than contracts • More doubt about how an operator can enforce a license
Contract	A legally binding agreement between two or more people or companies	• Very flexible • Almost anything can be agreed on in a contract to make it legally effective • Can be changed by consent of both parties, providing real certainty to an operator	• Can be overridden by law • May be subject to certain mandatory rules • Inability to change the contract unilaterally may be a disadvantage • Generally only confers rights and obligations on the parties to the contract, not third parties, so cannot be used for some purposes, such as creating exclusivity.

Table 1.2: Legal instruments used in the approaches to privatisation of water resources (modified after the World bank, 2006).

In a SADC (Southern African Development Countries) context it is known that the AMCOW (African Ministers Council on Water) have regular meetings to tackle issues related to water resources and agreements within the region. Braune et al. (2008) have shown that these platforms are ideal for raising issues related to IWRM, specifically from the perspective of groundwater resources.

It is generally acknowledged that South Africa has one of the world's most advanced water legislation (Godden, 2005). The National Water Act (NWA), number 36 of 1998, is an extensive legal document outlining the manner in which water in South Africa is to be used. In essence the water resource is the property of the state, be it surface or groundwater. Catchment management agencies, according to river basins, have been mentioned in the act in order to aid in the management of water consumption and quality. Furthermore the "in stream flow requirements" (IFR), or Ecological Reserve, have been mentioned in order to allow for an estimated 20% of the natural runoff to be available for riverine fauna and flora (de Villiers and de Wit, 2010). Islamic water law also highlights this, but only after human consumption has been cared for, and not as a condition to be fulfilled before human consumption as in the NWA. Furthermore the riparian principle does not apply in a South African context and the resource, including groundwater must be made available for the greater community in terms of the NWA.

1.1.5 Applicable technologies for optimising water use

With a current population of approximately 7 billion, set to rise to 9.4 Billion by 2050, and 40 % of the projected population calculated to suffer from water stress in the future, it can be said that we definitely have a serious water shortage issue on our hands

(UNEP, 2008). This will lead to alternatives being sought for water use and water reuse. The first of which is greater use of greywater. A prime example of this is taking place in Palestine (Faruqui et al., 2001). Multiple issues arise when using greywater for irrigation purposes. These have been outlined extensively by McIlwaine and Redwood (2010) and include:

- Water Quality.
- Impact on soils and plants.
- Permaculture practices (such as mulching).
- Project sustainability.
- Financial and economic viability.

An extensive study was undertaken in South Africa, in order to determine the applicability of greywater for irrigation purposes (Murphy, 2006). This scoping study has lead to a follow up study related to greywater use in non sewered areas (Rodda et al., 2011). Both reports conclude that a substantial amount of work is still required in order to determine the applicability of greywater use in a South African context. Research should be focused around issues previously mentioned by McIlwaine and Redwood (2010), but to also examine microbial water quality (Murphy, 2006).

A second alternative for potable water supply, is extremely expensive, e.g reverse osmosis of salt water (Sherwood et al., 1967). Recent research into this area has made great advances in terms of lowering the energy costs and increasing efficiency (Greenlee et al., 2009). Williams (2003) reviews the theoretical considerations related to reverse osmosis and shows that the increasing costs are caused by the use of energy in order to force saltwater through a porous membrane, thus removing the salts. Despite this fact many of the Middle Eastern Countries have resorted to desalination as a viable source for water supply (Figure 1.7). Problems also arise with the creation of a small volume of brine water as an end product (Miller, 2008). This is where alternative uses for brine water could be implemented. In certain cases, like Israel, it has been determined that the saline, geothermally heated, waters have been used for aquaculture as well as irrigation (Nativ et al., 1987). In other cases it has shown that the application of these groundwaters for balneotherapy could have positive effects on health and well-being of people (Kubota et al., 1997). Kim (2011) also suggests that these brine waters could be used for the production of salts, by the simple process of evaporation. Thus it can be seen that alternative uses for certain waters needs to be implemented for optimal use of the resource.

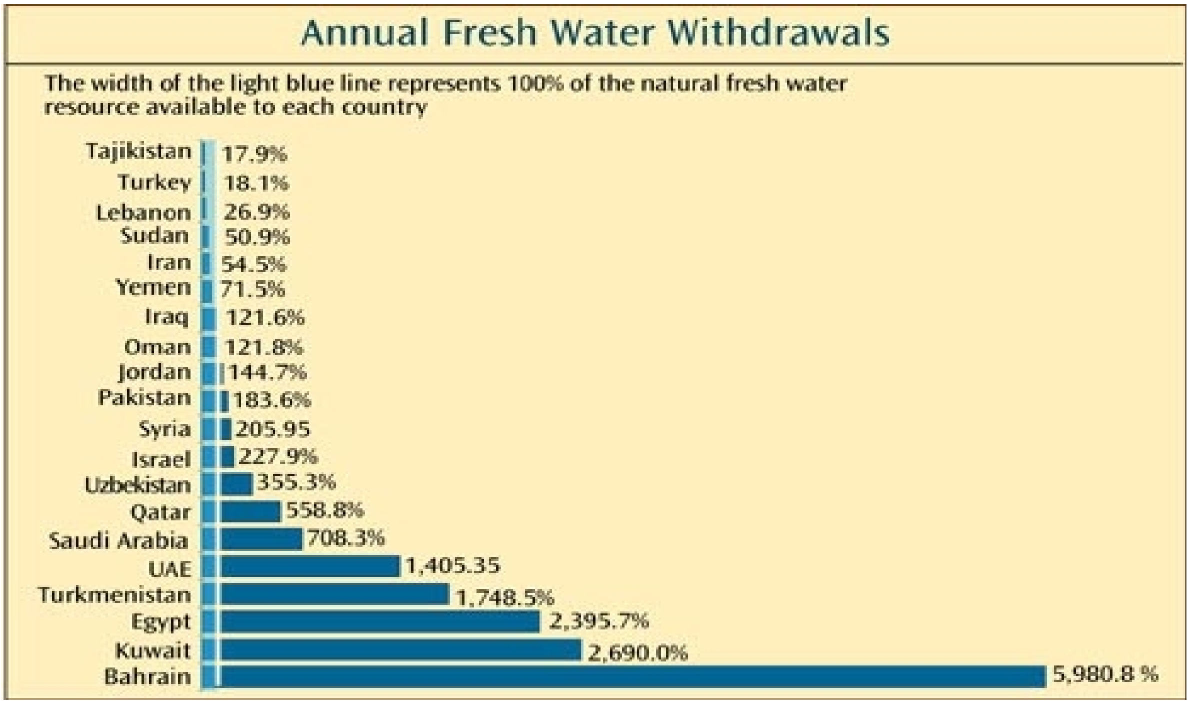

Figure 1.7: The Annual freshwater withdrawals for the countries in the Middle East and surrounding areas. It can clearly be seen that many of the countries by far exceed the available natural freshwater available to them. This is done in most cases by reverse osmosis and is fueled by the large amounts of energy, normally petroleum, available to these countries (UNDP, 2001).

Bottled water seems to be the more costly solution to potable water, yet this industry has grown exponentially over the past few years (Staddon, 2009). Ferrier (2001) has shown that 1.5 million tonnes of plastic are used in bottling 89 billion litres of water, annually. The study commissioned by the World Wildlife Fund (WWF) further delves into issues of quality control and labels used in marketing bottled water. This growth in bottled water sales has soared, despite the fact that the quality control is not as stringent as for tap water in certain countries (Potera, 2002). The possible explanation for the ca. 7% annual growth of the industry, as shown by Ferrier (2001), is due to the association of a product with an elite lifestyle (Staddon, 2009). This logic goes against the negative environmental impact that bottled water has. The production of plastic waste, excessive use of energy in production and the Carbon dioxide produced from transportation are only some of the environmental impacts (Miller, 2008). Gleick and Cooley (2009) outline the energy implications for bottled water production and prove that the costs involved in transporting, by far exceeds the production of the product.

Aquifer Storage and Recovery (ASR) is also being explored as an option for purifying as well as storing water for potential future use (Dillon et al., 2010). The process involves the injection of water into an aquifer and then extracting the resource at a later stage. In certain cases, depending on the water quality, injection occurs via filters to remove the excess salts in the water. Murray and Tredoux (2002) have concluded, from numerous South African case studies, that ASR is a cost effective solution for water storage in semi arid to arid regions. Problems however arise due to clogging through physical, biological or chemical processes (Rinck-Pfeiffer et al., 2000). This is the reason and the need for regular maintenance, specifically for the filters (Murray and Tredoux., 2002)

Rainwater harvesting (RWH) has been in use since at least 3000 BC (Pandey et al., 2003). It is an effective low-cost system for water security and can be implemented in almost any environment. Kahinda et al. (2008) suggest that water resource managers should integrate Domestic Rainwater harvesting (DRWH), specifically in a South African context, into Integrated Water Resource Management (IWRM) strategies. This strategy has been shown to tie in effectively with ASR in urban areas of India (Dillon et al, 2010). Andersson et al. (2009) have applied RWH to the Thukela river basin, in South Africa, and concluded that RWH reliability in this agricultural area averages around 10%. Kahinda et al. (2008) also concluded that the use of DRWH, when applying strict South African legislation, could be considered illegal.

Subsurface Drip Irrigation (SDI) has been proposed as a major water saving technology. This simple yet effective irrigation method slowly releases water to the roots of the plant over suspended time periods. Case studies from India have shown the efficacy, and applicability to an African context seems economically viable (Juma, 2011). The ability of drip irrigation to reduce the volumes of water used on commercial farming, and still produce the same yields as other irrigation methods, has been proven by Camp (1998). Furthermore, Postel et al., (2001) support the distribution of low cost drip irrigation to poor rural communities. This will potentially aid in more effective subsistence farming methods and alleviate problems of food security and development, specifically in Africa (Juma, 2011).

Whilst all of the abovementioned technologies are important, they need to be implemented along with strategy and policy in order to be effective (Juma, 2011). This is where principles such as demand management play a key role. Butler and Memon (2006) advocate demand management as a strategy for effective control and utilisation of current water supplies. One such strategy implies that the expansion of a water resource system and the inclusion of other possible supply sources is not examined. Al Dadah (2000) outlines the implementation of this strategy in the Palestinian occupied territories and conclude that in certain scenarios this application is a necessity, but should be done in conjunction with other conservation strategies, like the use of greywater.

From the above brief overview it is clear that no one technology is the ultimate solution for any environment (Butler and Memon, 2006). A multi faceted approach to water resource management, which includes the socio-economic aspects of resource management, should be implemented in conjunction with the affected parties (Braune et al., 2008).

1.2 The application of geophysics to hydrology

In this section a brief overview of the modern geophysical tools applied in the field of hydrogeology is undertaken. Furthermore the application of gravimetry to hydrology is highlighted in order to contextualize the scientific work which follows. Lastly each chapter of the scientific work undertaken, which forms the core of this thesis, is summarized.

Cook (2003) has listed applicable tools for maximising groundwater exploration and aquifer characterisation in fractured rock aquifers. Understanding these secondary fractured saturated units are becoming increasingly important as they underlie a large part of South Africa (Woodford and Chevallier, 2002a). Sami and Murray (1998) have shown that these aquifers, with the right management, can aid in the water supply of rural areas. Xu and Beekman (2002) highlight the problems relating to managing groundwater in Southern Africa by examining methods for recharge estimation, as well as many local case studies.

Kirsch (2006) has highlighted the many geophysical tools applicable to groundwater studies. Resistivity, magnetic surveys and gravimetry aid in aquifer characterisation and groundwater exploration. Milsom (2003) shows that resistivity can be applied succesfully to groundwater exploration with resistivity of water being directly proportional to its quality, due to the lack of conducting ions. This means that the quality of the groundwater could also be inferred from resistivity studies. Magnetic surveys on the other hand are used in fractured rock environments, such as the Karoo, to target dykes, which may act as flow barriers for groundwater (Woodford and Chevallier, 2002).

These tools were initially extensively used in mineral exploration as shown by Kearey and Brooks (1991). With the recent advancements in technology and a greater understanding of the subsurface we find that the same tools are now being used in groundwater exploration (Kirsch, 2006). With regards to gravimetry and its applicability to hydrogeology, Kearey and Brooks (1991) mention the fact that local aquifer geometry could be inferred from gravity surveys. Kovalevsky et al., (2004) further state that gravity should be used in conjunction with other tools in order to improve its efficacy as a tool to delineate aquifer boundaries.

The combination of the aforementioned methods has also lead to the need for more robust tools for understanding subsurface fluid flow. It has recently been shown that the use of gravity data could shed a substantial amount of light on geohydrology at the basin as well as field scale, as shown by Rodell et al. (2006) and Christiansen et al. (2011), respectively. Recent advances in satellite technology have meant that regional gravity experiments can be conducted to track, for example, change in groundwater levels from space. The first satellite to successfully accomplish this was the Challenging Mini Satellite Payload (CHAMP). Multiple studies have been published with reference to satellite gravimetry and its application to the hydrological sciences (Guntner, 2008). More recently the European Space Agency (ESA) has launched the Gravity field and steady state Ocean Circulation Explorer (GOCE), which will act as a successor to GRACE.

Land based methods for gravimetry include the mobile gravimetre as well as the Superconducting Gravimetre(SG). The latter is the focus of this study and is based at the South African Geodynamic Observatory, Sutherland (SAGOS). The instrument forms part of the Global Geodynamics Programme (GGP) with Superconducting Gravimetres(SG), just like the one in Sutherland, placed all over the world (Figure 1.8)

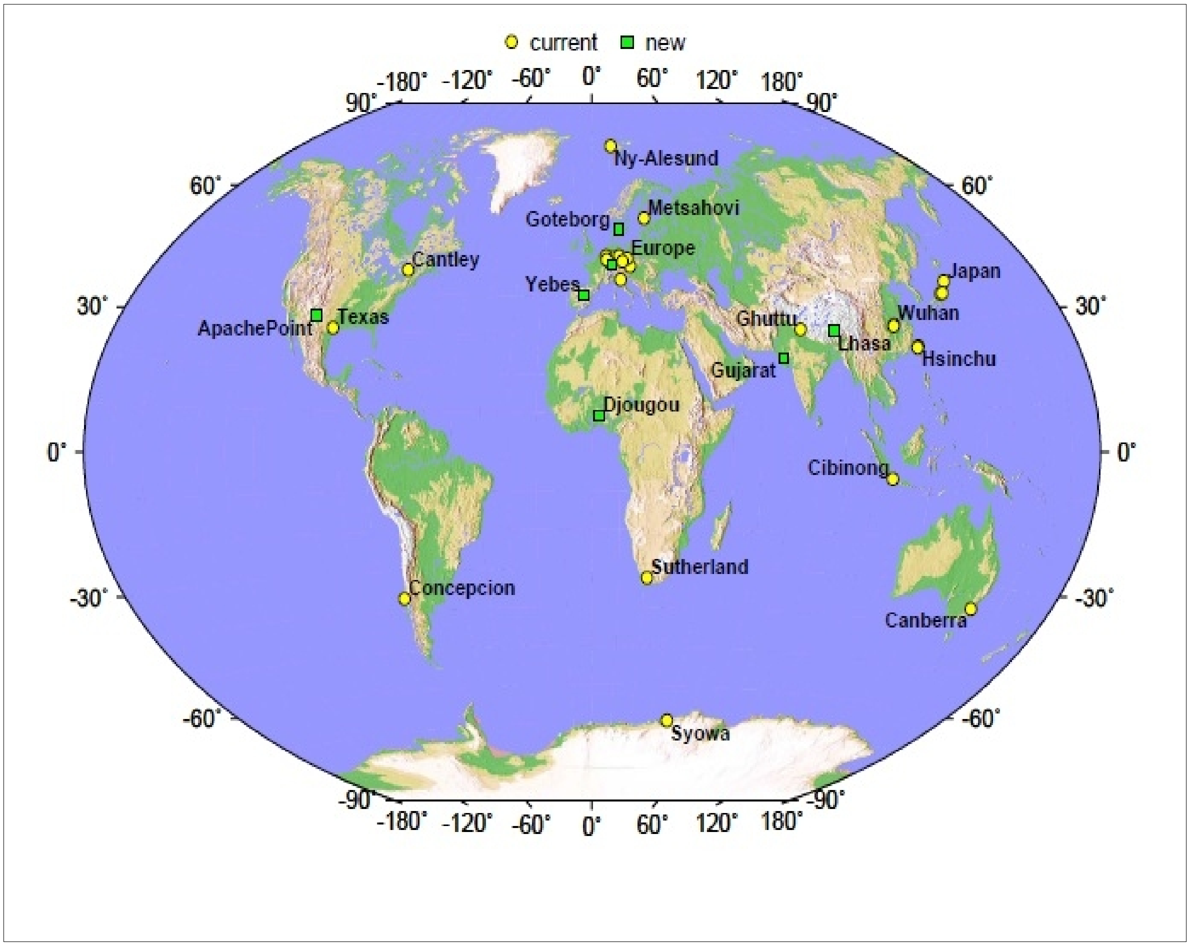

Figure 1.8:The distribution of SG stations across the Globe. The newly installed, or future planned stations, are indicated with a green square. Those already installed and operational are indicated with a yellow circle.

The ability to implement such a programme requires co-operation between various global research facilities as well as between the countries hosting the facilities. Neumeyer et al. (2006) outline such an agreement of co-operative activities between the National Research Foundation (NRF) South Africa and the GFZ as an interdisciplinary programme of research activities in the field of geosciences. “In realisation of this programme the South African Geodynamic Observatory Sutherland (SAGOS) of GFZ has been constructed by GFZ at the site of the South African Astronomical Observatory (SAAO) near Sutherland” (Neumeyer et al, 2006).

The use of the SG at SAGOS in this study is important for the quantification of our water resources, which directly impact the growth of our economy as reviewed earlier. The scientific work is done by using the SG to understand subsurface fluid flow in the semi-arid Karoo. This is the location for SAGOS, typical of a large percentage of the South African landscape in terms of geology, climate and hydrology. The transfer of skills and exchange of knowledge is another critical component for the aforementioned development.

Research over the past few decades has been directed towards understanding fractured rock aquifers, also known as secondary aquifers. In a South African context, The Water Research Commission (W.R.C) has invested substantially to maximise the use of the secondary aquifers. Proof of this lies in the development of groundwater modelling and management tools which aid in aquifer characterisation and in turn the sustainable development of our subsurface water resources.

The scientific part of this thesis is introduced by the possible applications of gravity to the field of hydrology and geohydrology in Chapter 2. Here recharge is examined in order to conceptualise mechanisms for inputs into geohydrology and therefore to better understand mass storage changes that directly affect the gravity signal. The use of gravimetres as well as the GRACE satellites in the water sciences is examined by means of case studies. The chapter concludes by examining hydrological modelling as a a tool for better understanding of surface and subsurface water reservoirs. The correlation between various models and the gravity signal at numerous sites is shown to be a significant indicator for subsurface water storage changes.

In chapter 3, the hydrogeology and geology in the vicinity of the SAGOS is examined in detail. It will be shown that a secondary saturated geologic unit displays high fracture connectivity in the immediate vicinity of the dolerite dykes. This can be inferred from the rapid hydraulic recovery of wells adjacent to this dolerite. Further evidence for preferential subsurface fluid flow is shown to be related to the orientation of fractures and joints, which were measured in-situ. These brittle features are possible conduits for flow and recharge. It will be shown that hydrogeochemistry points towards possible localised water tables, whilst the isotopic data suggests preferential flow as the major mechanism for recharge, consistent with previous work completed in the area. In addition, signs of groundwater contamination possibly stemming from a mechanical workshop, has been detected in one of the wells, and the source of groundwater seems to be a mixture of various rainfall events.

Chapter 4 describes the soil within the study area in order to characterise their properties, and in turn the dominant processes controlling the local hydrological regime. The rivers are preferentially more hydraulically conductive due to the coarse nature of the underlying gravel material. Soil mapping, by means of satellite imagery, and thereafter field verification, was undertaken over a period of two weeks. In conjunction with the mapping, profiles were exposed, by means of excavation, in order to examine the subsurface characteristics of the soil. Infiltration tests were carried out across the terrain to specifically detemine the in-situ hydraulic properties of the soil surrounding the SAGOS. Laboratory tests indicate a low clay content at surface, which is attributed to high-speed wind velocity removing clay in the upper layer, and the consequent enrichment of clay at depth. It was also determined that the infiltration capacity of the duplex soils surrounding the gravimeter decreases with depth. These investigations all point to great spatial variability, laterally as well as vertically, within the soil.

Chapter 5 describes transient rainfall events and their significance to the residual SG gravity data. The water levels at one well are correlated to the gravity residual data in order to determine possible patterns and relationships. Strong correlations are found between the water level data and the gravity residual, especially following multiple precipitation events. With regards to the individual rainfall events strong correlations are found between the water level in the well SABK07 and the gravity residual. This sheds light on the variability of the hydrological regime. In both cases weak and inverse correlations were found. Furthermore the fact that one reservoir is not the only contributor to the mass storage in the subsurface is also highlighted. Data examined for ten days after each rainfall event shows even weaker correlation between the water level and gravity residual.

A time series analysis of the hydrological data for the area as well as correlations between gravity and soil moisture, as well as groundwater levels are presented in Chapter 6. The sets of time series data include soil moisture, groundwater levels, precipitation and the gravity residual. The study of these precipitation events in conjunction with hydrological time series and the gravity shed light on episodic recharge in the immediate vicinity of the SAGOS.

Chapter 7 summarises and concludes the most significant outcomes of this project and future research needs are examined. Lastly some new very applicable tools are examined and their possible contributions to hydrology, especially in a South African context, are outlined.

CHAPTER 2
REVIEW OF HYDROLOGY RELATED TO GRAVIMETRY

2.1 Introduction

This chapter reviews the major factors affecting subsurface water storage, specifically within a South African context and how this might be detected by gravimetry. Firstly, the surface water processes in arid areas are examined to better understand their direct impact on soil moisture and groundwater. Secondly, the unsaturated zone processes and related conceptual models are outlined. Fractured rock hydrogeology and flow within these secondary aquifers is highlighted to better understand movement of groundwater as well as its storage. This is done because the study area, Sutherland, falls within an area with a typical arid zone hydrological regime encapsulating the aforementioned areas of review.

Thirdly, studies related to the application of ground based and satellite gravimetry to the field of hydrology and hydrogeology are reviewed. The major outcomes of these studies are shown and the importance of methods used, as well as common errors are mentioned. Finally, the hydrological models used in studies related to gravity are appraised and the advantages and disadvantages as well as applicability of many of these models are critically evaluated.

2.2 Arid Zone hydrology

Wheater et al. (2008) highlight the fact that arid zone hydrology should be better understood, in light of the ever expanding global population and thus the greater need for water resources, since arid zone hydrology plays a major role in recharge and thus is a critical contributor to subsurface moisture movement (e.g. Xu & Beekman 2003). Unfortunately quantifying these processes is difficult due to erratic rainfall and ephemeral stream flow, which are the dominating processes controlling arid zone hydrology (Hogan et al., 2000)

Rainfall in arid regions usually originates in areas of higher elevation such as mountains (e.g. Hogan et al. 2004). In certain instances it has been shown that infiltration along the mountain front is the predominant process contributing towards recharge. This depends heavily on the underlying geology, but infiltration may also occur in ephemeral streams as well as from a lag response due to interflow (Hughes 2010). Wheater and Al-Weshah (2002) have compiled an extensive document examining the technical aspects related to processes within ephemeral streams, or Wadis as they are known in the arid Arab world. It is clear that the data, modelling and in turn management of these arid zone hydrological systems differs from those in other, wetter climatological regimes (Wheater et al., 2008).

Evaporation and transpiration, which is the surface water loss, within the semi-arid to arid regions by far exceeds the precipitation, which is the surface water gain (Warner, 2004). This process of water loss plays a critical role in the hydrological regime of the arid areas of the world as it determines the volumes of water available for run off, river flow and groundwater recharge (Healy, 2010). Understanding and quantifying the process of evapotranspiration has been dealt with extensively by Munn (1966). Furthermore concepts of evapotranspiration and integrating the process into hydrological modelling has been analysed by Beven (2001). The most important point to note is that the process of evapotranspiration is dynamic and varies in space and time, therefore extrapolating measurements over an entire area could be problematic when attempting to understand large scale processes with microscale measurements (Healy, 2010).

Hydrological modelling within arid areas is problematic due to the above mentioned factors, as well as the spatial and temporal variation of vegetation (Wheater et al. 2008). Despite this, Hughes (2008) has shown, specifically in Southern Africa, that five hydrological models work best when attempting to understand the hydrology of a local arid region. These regionally developed models are :

- Pitman.
- ACRU.
- VTI.
- Monash.
- Namrom.

The Pitman model was initially developed by its namesake (Pitman, 1973). The model has undergone many changes over the past decades in order to improve and adapt it (Kapangaziwiri and Hughes, 2008). These modified models have been used in multiple studies across the Southern African region (Midgeley et al., 1994; Hughes, 1997; Hughes et al., 2006). Time series of precipitation and potential evaporation are the major inputs for the Pitman model (Figure 2.1). Using a monthly time step, the model has the moisture storage depleted by means of evapotranspiration and drainage (Hughes, 1995).

The VTI model uses a daily time step, as well as evapotranspiration as its major driver for moisture depletion. These are the discerning character traits distinguishing the VTI from the Pitman model. One of the most recent modifications of the Pitman model is the Spatial and Time Series Information Modelling (SPATSIM) system for Windows (Hughes, 2002). The software has a user friendly Graphical User Interface (GUI) with links to databases and other resource estimation tools, including groundwater (Hughes, 2008) (http://www.ru.ac.za/institutes/iwrv)

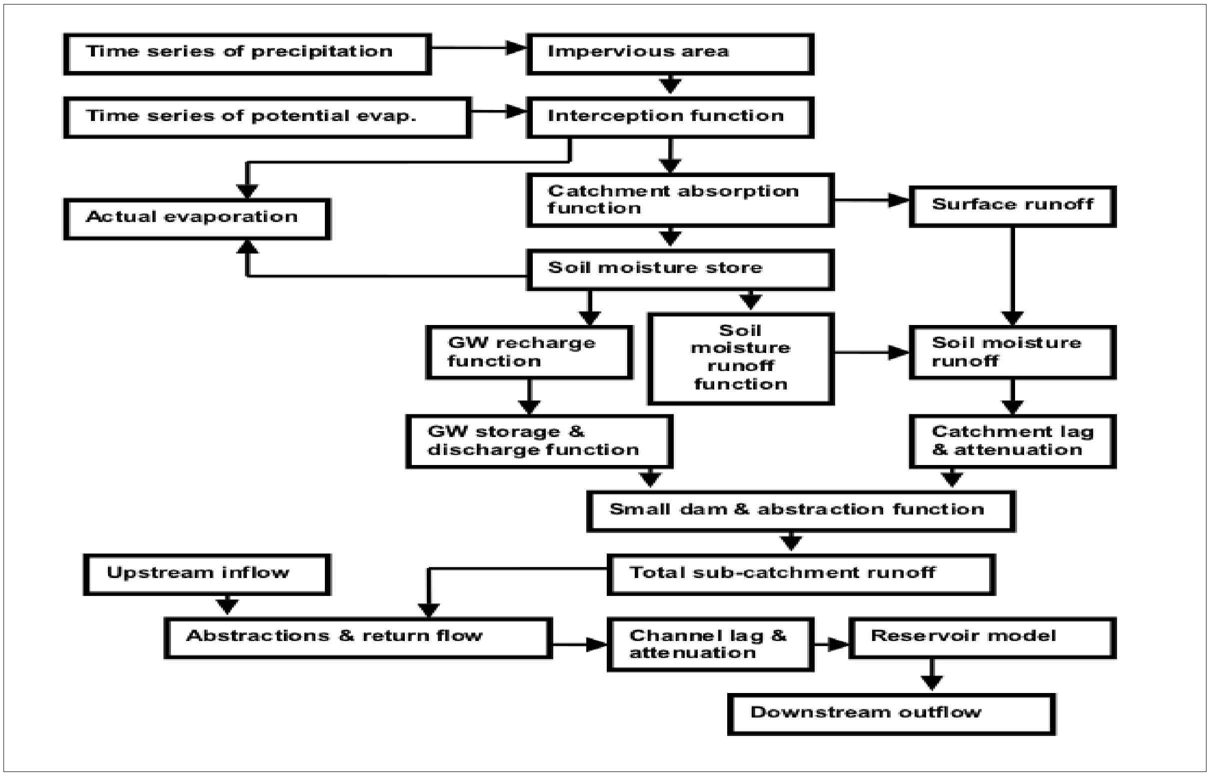

Figure 2.1: Structure of the Pitman hydrological model. The major driving force for the model is time series of precipitation. Time series of potential evaporation on the other hand removes moisture from the model. Subsurface storage and flows occur in the form of soil moisture and Groundwater. Lastly outflows occur by means of surface runoff and downstream flow (modified after Hughes, 2008).

The Agricultural Catchment Research Unit (ACRU) model was developed at the University of KwaZulu Natal(UKZN). The use of the model has seen applications to assess the impact of various land use modifications (Hughes, 2008). The model itself is based on a daily time step, similar to the VTI, designed around a complex soil moisture accounting scheme with a large number of parameters requiring data inputs (Schulze, 1994). The impact on groundwater resources from afforestation has also been modelled using ACRU. Kienzl and Schulze (1992) have shown that the lowering of the groundwater table has an impact on the water balance in an area of KwaZulu Natal. Furthermore a strong correlation betweeen the ACRU simulation and reality was found in a eucalyptus plantation in South Africa (Kienzl and Schulze, 1992). However, Hughes (2008) argues that applications for the ACRU model to arid and semi arid regions are too few to test its validity.

The Variable Time Interval (VTI) model was developed in South Africa at Rhodes University as part of a detailed study applied to a medium sized semi arid basin (Hughes, 2008). The model utilises rainfall events as the major driving input for the simulation (Figure 2). A daily time step for the model also exists (Hughes, 1995). Sami and Hughes (1996) have stated that the VTI model takes into account the catchment slope, drainage, as well as hydraulic gradient as factors that affect the infiltration of water. Runoff for the model can be generated by either infiltration excess (mainly controlled by rainfall intensity) or by saturation excess (mainly controlled by soil water content and total rainfall amount) (Hughes, 1995). A major difference between the VTI and Pitman is that the soil is vertically divided into two zones in the former model : an upper zone from the surface to 150mm below ; and a lower soil zone below this upper boundary (Figure 2.2).

The Monash Model has options for both monthly and daily time steps (Hughes, 2008). This rainfall runoff model was developed at Monash University, Australia, by Porter and McMahon (1976). Hughes (2008) has shown that the Monash model has had a strong numerical correlation with the monthly Pitman model for a basin in Namibia, with even better results using the daily time step rather than the monthly based data.

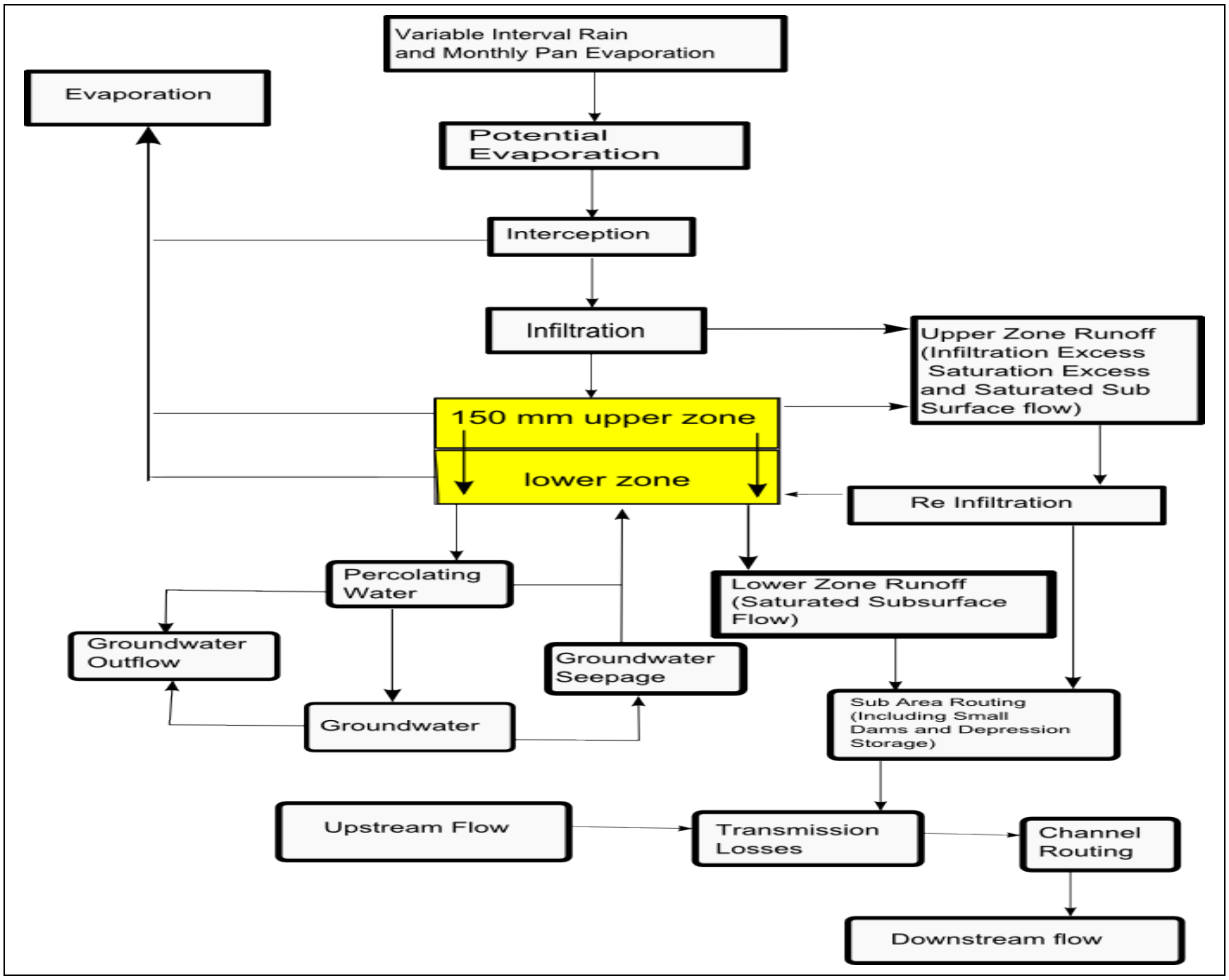

Figure 2.2: Flow Diagram outlining the structure of the Variable Time interval (VTI) Model. It can clearly be seen that the vadose zone is divided into an upper and lower zone (highlighted in yellow). Model inputs are Variable rainfall and monthly pan evaporation (modified after Hughes ,1995).

The Namrom model attempts to indirectly simulate most of the physical processes thought to be of major significance in runoff generation in Namibia (Hughes and Metzler, 1998). This monthly time-step model was developed by Mostert et al. (1993) in order to aid water resource management in Namibia. Hughes (2008) summarises the model as a statistical regression type model with multiple parameters based on a single equation for total effective precipitation. The ability of this model to address issues specific to Namibia, such as non-seasonal vegetation cover, is the reason for its general success in arid regions (Hughes and Metzler, 1998)

Despite all of the positive aspects of the models mentioned above, Xu & Beekman (2003) argue that hydrological modelling in general has significant limitations to determine recharge, specifically when ephemeral streams are studied. Smakhtin (2001) has compiled an extensive review of low hydrologic flows, including flows in episodic streams, and shows that seasonal streams are difficult to model. This is further reitterated by Al-Qurashi et al. (2008) who produced high uncertainty rates for a rainfall runoff model in desert conditions of Oman. Hughes (1995) also states that the availability of reliable data (or lack thereof) , specifically in the SADC region, poses a serious problem for effective hydrological modelling. In turn, this affects management decisions related to resource planning. Thus, one can see the plethora of complex issues related to modelling arid zone hydrology and the need to further understand processes that dominate fluid flow in this arena.

2.3 The importance of understanding the vadose Zone

The zone directly below the terrestrial surface of the earth, but above the water table is termed as the vadose or, unsaturated zone. This zone comprises soil, moisture, and gas, and thus is usually referred to as a three phase system (Hillel, 1982). Due to the presence of moisture, soil particles generally coalesce, forming large clusters known as peds (Allaby and Allaby, 2003) . The presence of peds usually means that the flow of water occurs along preferential pathways.

Because the vadose zone is unsaturated, it has always been a great challenge to determine the intermittent flow and movement of water in such soils. In addition preferential flow and soil heterogeneity cause variable solute movement in the unsaturated zone, which is difficult to quantify (Rosner et al, 2001).

Methods for characterising dominant processes in the subsurface include vadose zone tracers. It has been shown that tracers are useful for understanding preferential flow in the unsaturated zone (Blume et al., 2009). Flury and Wai (2003) compiled a review on tracers, their application as well as analysis of results. They conclude that adsorption on soil surfaces is a major factor affecting tracer movement and that there is therefore no perfect dye tracer. Forrer et al. (2000) further looked at the image processing of the migration pathways of tracers in unsaturated media. They concluded that the formation of peds control the preferential flow of moisture in the subsurface (Figure 2.3).

Hogan et al. (2000) have shown the importance of understanding vadose zone processes, specifically in arid areas to determine recharge. Chloride profiles and soil moisture profiles are additional methods that have been employed to calculate recharge and they highlight the retention capacity of root bearing soils as well as the moisture movement through the lower vadose zone (Sami and Hughes 1996). Profiles are constructed by using sampling at various depths below the surface and then analysing the samples in the laboratory for gravimetric moisture content and chlorine, respectively.

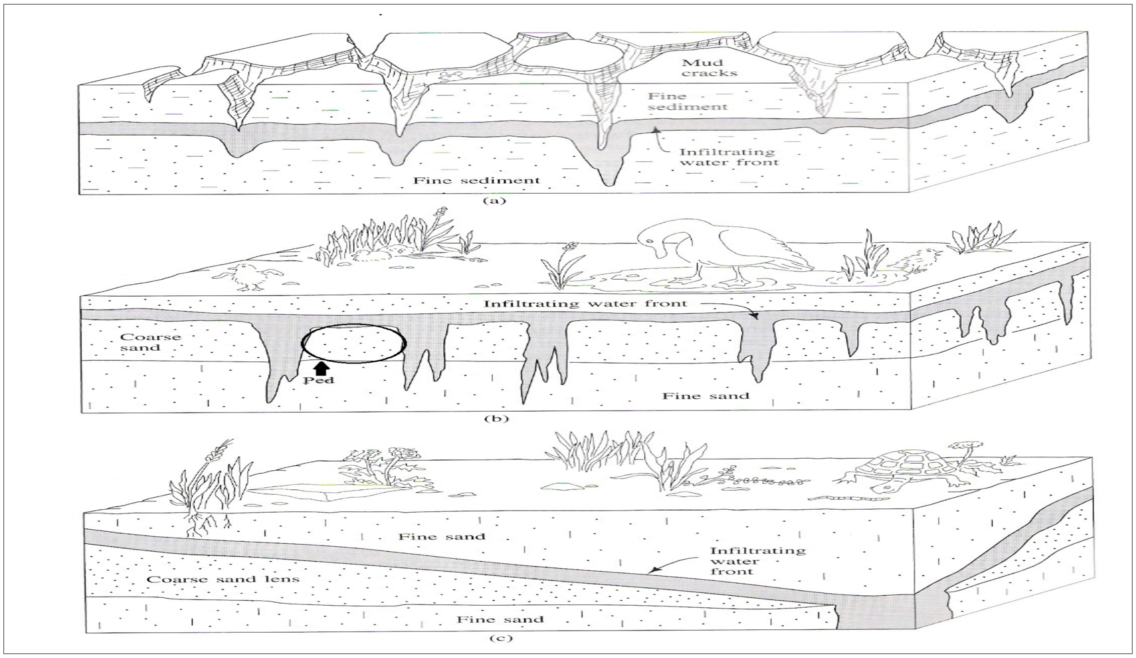

Figure 2.3: Schematic representing preferential flow of water within the vadose zone occurring in different forms; fingering (a), short circuiting (b) and funnelling (c) (modified after Fetter, 1999). Also it can be seen that the formation of peds between the "short circuits" in (b) controls the preferential flow (modified after Fetter, 2004)

In the past, Ward (1975) argued that the major force acting on soil moisture must be gravity, over and above cation exchange capacity (CEC) of the soils that plays a major role in adsorbing ions. Marshall and Holmes (1979) argue that suction also plays a major role in soil moisture movement. This is especially important where hysteresis occurs followed by the successive drying and wetting events. Such alternations can lead to alteration of the matric suction, thus greatly affecting the hydraulic conductivity of soils as well as the infiltration capacity. Hillel (1980) attributes the swelling and shrinking of clay and entrapped air tot he drying and wetting cycles. As the knowledge of soil water movement has increased and our understanding of the subject matter improved, soil scientists have developed multiple models related to soil hydrology.

Šimůnek and van Genuchten (2008) have summarised the dominating models controlling water movement in the unsaturated zone (Figure 2.4). Both physical and chemical processes have major a influence on selection of the specific type of numerical models, and also highlight the data required in order to run such models effectively. Scaling these processes increases model complexity (Šimůnek et al., 2008). Initially, most major models examined only the physical or chemical aspects of water movement through the soil. Subsequent work has coupled these chemical and physical processes in order to gain a better understanding of soil and its interactions with water (Šimůnek and van Genuchten, 2008).

Dual porosity, as well as dual permeability models are the most relevant when describing preferential flow in structured media (Šimůnek et al., 2003). The dual porosity model assumes that the preferential pathway, normally a fracture or macropore, interacts with the soil aggregate, or rock matrix (Cook, 2003). In the case of a variably saturated media, like soil, non equilibrium is the most important feature of preferential flow (Skopp, 1981). This unsteady state may be attributed to the fact that infiltrating water has not yet equilibrated with the water in the soil matrix (Šimůnek et al. 2003). This minimal interaction between the preferential pathway and the matrix assumes that water in the matrix is stagnant and is the underlying principle for dual porosity models.

By including molecular diffusion, dual permeability models are able to overcome the problem related to movement of water and solutes into the matrix (Šimůnek and van

Genuchten , 2008). This means that water flow in the matrix is accounted for, unlike in dual porosity models where it is assumed to be stagnant (Šimůnek et al. 2003). Dual permeability models are now more applicable to solute transport due to the fact that they are able to mimic solute migration in the field (Vogel et al., 2000) (Figure 2.4).

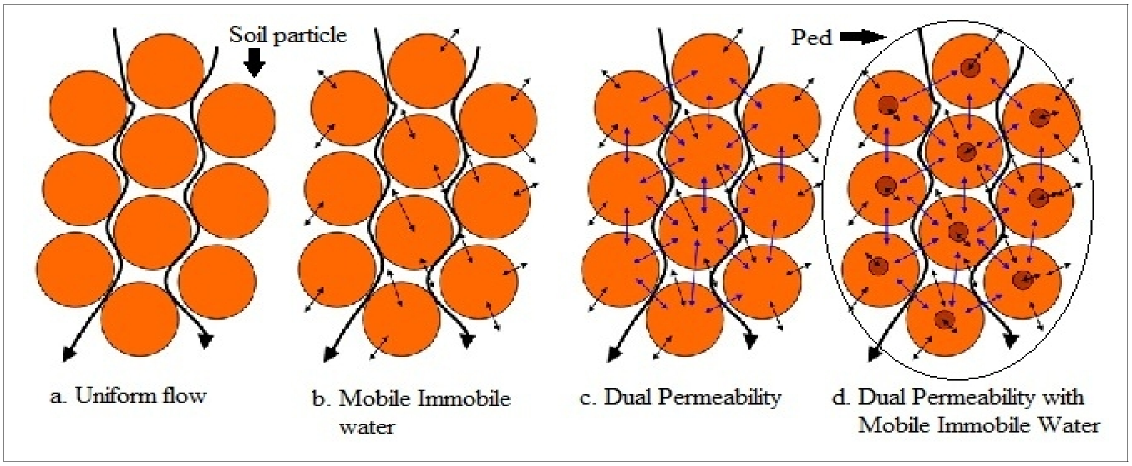

Figure 2.4 : Various conceptual models explaining the movement of water in soil : (a) Uniform flow under ideal situations with no preferential flow occurring (b). The Mobile-Immobile(MIM) water is able to move in the micropores but not out of peds in a dual porosity model that treats the finger, funnel or short circuit (outlined in Figure 11) as a preferential pathway with limited interaction to the matrix (c) . Dual permeability is whereby there is flow between peds (blue arrows) as well as movement of water in and out of the peds in to the matrix (black arrows). (d) Dual permeability coupled with MIM includes diffusion from within the soil particle (brown spot) along with (c) .This is a refinement of the initial permeability model (modified after Šimůnek and van Genuchten , 2008).

With recent advances in technology and computing power, extensive applications for hydrological monitoring are possible at larger scales. In the case of hydrogeology, for example satellite applications, as well as the increasing free availability of resources, such as Free Open Source Software (FOSS) and satellite images, we find that the ability to monitor water resources is becoming easier (Meijerink, 2007). This also applies to soil monitoring and soil moisture modelling on a river catchment scale (Western,1999).

Research on an even larger scale, for example complete river basins, is now also emerging. A good example is that of Duan et al. (2011) who recently outlined the spatio-temporal variations of a semi arid area across the inner Mongolian Plateau, Asia. An extensive monitoring network across the entire area was the major data generator over a period of seven years. Soil particle size and chemistry were measured in 2003, and rainfall and groundwater levels were measured between the period 2006 and 2009. Western et al. (1999) have shown the importance of measuring these ground based parameters intergrated with remote sensing applications adding significant improvement to regional projects. Duan et al. (2011) concluded that soil moisture in their location, on the Mongolian Plateau, was dependant upon topography, soil texture, vegetation density, as well as anthropogenic impacts. Seasonality, in general, is also a major role player in determining the available amount of soil moisture, due to the effect that rainfall has on available soil moisture (Western, 1999).

More recently the European Space agency (ESA) (www.esa.int) have launched a satellite, in 2009, which is able to detect soil moisture from space. The principles behind the Soil Moisture Ocean Salinity (SMOS) satellite and its application to various fields of science is outlined by Kerr et al. (2001). The interferometric radiometre, the first of its kind to be launched into space, is able to monitor soil moisture and ocean salinity by capturing images of emitted microwave radiation at the frequency of 1.4 Ghz (www.esa.int). Testing of the core model of the SMOS satellite has been completed in Australia using different vegetation types and terrains to calibrate the airborne data against ground measurement of soil moisture (Panciera et al., 2009). It was concluded however that in certain instances, specifically those with extensive vegetation cover and extreme surface roughness, the model did not fit ground based measurements well. This is likely because the spectral differences in land cover are masked by vegetation and limit the ability of satellites to detect variations beneath the vegetation (Meijerink, 2007). Moreover, surface roughness of soils, due to anthropogenic factors such as tillage, affects satellite readings due to backscatter (Thoma et al., 2006)

Despite all of this generated knowledge and an ever increasing understanding of the vadose zone there are still significant gaps in our ability to predict vadose zone hydrological properties, flow and water chemistry. Thus new research is still required before more robust methods and models become available. To achieve this NRC (2001) list the areas of future research required in fractured vadose zone hydrology as :

- Flow and transport processes in unsaturated fractures.
- Understand the spatial variability and develop upscaling methods.
- Comprehensive field experiments in fractured vadose zone of specefic geologic environments.
- Evaluation of current models for their adequacy for simulating flow and transport in the presence of fingering, flow instability, and funneling.
- Develop quantitative assessment and uncertainty analysis for models of flow and transport in fractures.
- Improved techniques for geochemical sampling.

Clearly our fundamental understanding of the fractured vadose zone is far from complete. Furthermore similarities exist in terms of the nature of the media in the vadose zone and groundwater (NRC, 2001). Governing equations for fluid flow in these saturated and unsaturated zones are similar. The Richard's equation (Richard, 1931), which explains flow in a variably saturated media, was derived from Darcy's law (Darcy, 1851), which is applied to flow in saturated media. Thus it can be seen that the relationships between the unsaturated and saturated zone are inextricably linked. Therefore research in these two realms needs to be carried out in a complimentary way.

2.4 Flow in fractured rock aquifers

Understanding the movement of water within fractured hosts is challenging, yet necessary if we are to understand fundamental water-related issues such as, according to Bodin et al. (2003):

- groundwater pollution in fractured reservoirs.
- The selection of safe repository sites for radioactive waste in deep geological formations, away from water infiltration.

Cook (2003) describes the nature of fractured aquifers and he states: "Fractured rock aquifers are comprised of a network of fractures that cut through a rock matrix" and that the "Characterisation of the fractured rock aquifers requires information on the nature of both the fractures and the rock matrix." (Cook, 2003 page 3). Thus it can be seen that the nature of fractured rock media is complex. Added to this is the fact that heterogeneity in the saturated media significantly affects hydraulic properties within a given volume of fractures (Fetter 2001) (Figure 2.5). In order to better understand these fractures an intricate examination of specific fracture dimensions such as length, width and aperture is required.

It is critical to understanding the dominant processes governing solute flow within fractured rocks is of the utmost importance. Smith et al. (2001) summarises the most obvious processes to be:

- advection and dispersion within the water conducting masses.
- retardation due to matrix diffusion into the rock matrix and sorption onto mineral surfaces.

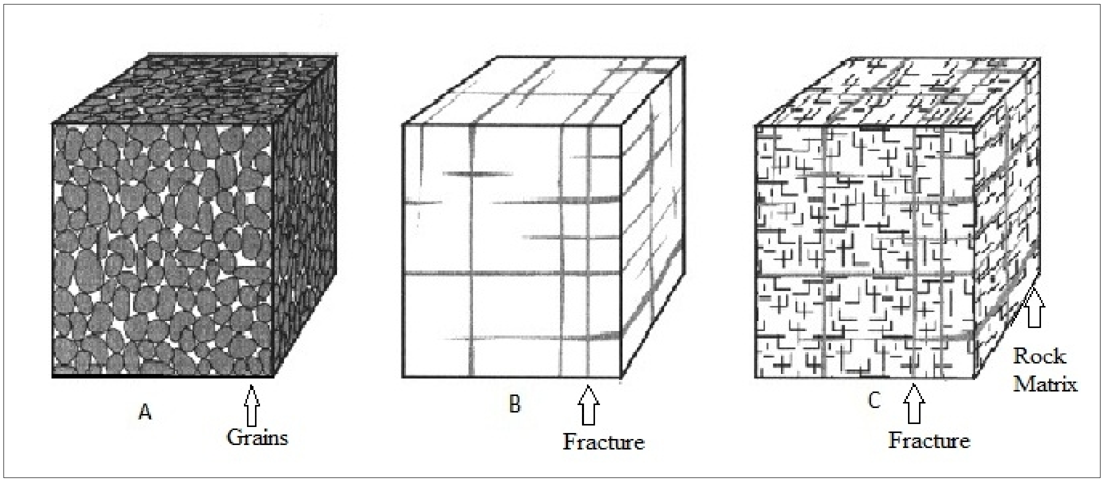

Figure 2.5 : Graphical examples of various types of aquifer media (A) Primary porosity media with water flow occurring between grains in unconsolidated sediments (B.) Secondary porosity media with water flow occurring in fractures of sedimentary rocks (C). . Dual porosity media with water flow occurring within fractures as well as the rock matrix of sedimentary rocks (modified after Kovalevsky et al., 2004).

Primary aquifers have water flow within them occurring between unconsolidated sediments. Whilst most secondary aquifers, which form during post depositional fracturing of a geological formation, are of the dual porosity type (Cook, 2003) . Thus as time progresses we find an apparent decrease in solute velocity, due to diffusion into the matrix (Cook, 2003). The double porosity concept regards fractured rock to consist of matrix blocks with a primary porosity and low hydraulic conductivity, separated by fractures with a low storage capacity but a high hydraulic conductivity (Kovalevsky et al., 2004). This has implications for understanding the movement of contaminants and pollution control (Figure 2.6).

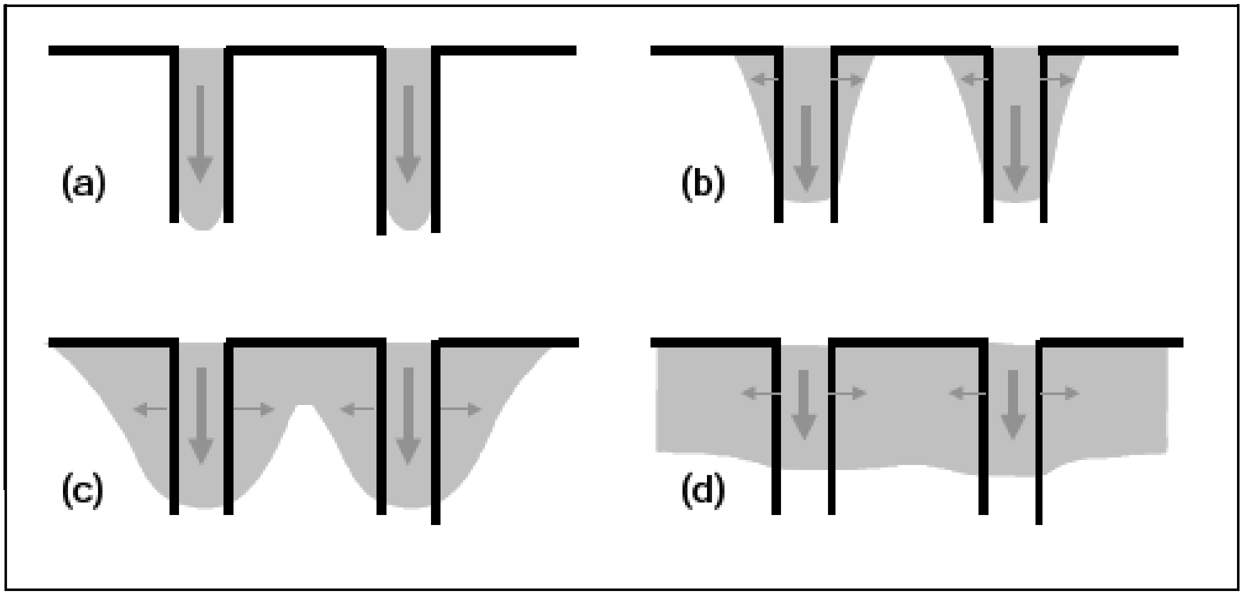

Figure 2.6: Schematic representation of tracer movement through fractured rocks (a), preferential flow in the fracture without diffusion into the rock matrix (b). Flow in fracture with partial diffusion into the surrounding rock matrix from the fracture (c). Partial exchange between the fracture and the rock matrix (d) complete equilibration between the fracture and the rock matrix (modified after Cook, 2003).

Smith et al. (2001) focus on modelling of radionuclide transport within vicinity of a nuclear testing facility. Their study involved the development and testing of a transport model using radioactive groundwater tracers in order to determine groundwater flow and related hydrogeological parameters. A critical conclusion from their work is that the dual porosity model is able to accurately describe the migration of tracers within the fractured media (Smith et al., 2001).

Flow through fractured rock aquifers has been extensively studied and the most common model for flow in a single fracture is the cubic law, based on the definition of a fracture as two parallel plates separated by a constant distance represent the fracture, commonly referred to as the parallel plate model for groundwater flow. This could be theoretically considered as a system of evenly spaced, identical, planar, parallel fractures in an impermeable rock matrix.(Cook, 2003).

Problems related to sampling and testing these fractured rocks has been reviewed by Witherspoon et al. (1980). They concluded that there is a definable relationship between fracture mechanics and fluid flow in the fracture. Cook (2003) further explores the mechanisms controlling flow in these secondary aquifers. Numerous case studies, as well as theoretical evaluations have been applied in order to account for spatial variations in conductivity, and to better understand the fracture flow behaviour mentioned by Witherspoon et al. (1980). Cook (2003) relates this uneven fracture distribution to spatial variations in 4 main properties:

- fracture aperture.
- fracture density.
- fracture length.
- fracture connectivity.

In South Africa, the study of the fractured rock aquifers has been extensively funded by the WRC (www.wrc.org.za). The geology and hydrogeology of the Karoo aquifers, for example, has been compiled by Woodford and Chevallier (2002). The numerical treatment of the physical parameters of these aquifers can be seen in Botha and Cloot (2004). Lastly the determination of Karoo aquifer parameters, like storativity and conductivity, has further been analysed by Bredenkamp et al. (1995) and Van Tonder et al. (2001), respectively.

2.5 Groundwater Recharge in arid regions

Bredenkamp et al. (1995) have developed a manual focused on the quantitative estimation of aquifer recharge specifically suited for South African conditions and in-situ tested. Cook (2003) has also scripted a similar guide for regional flow in fractured rock aquifers with a myriad of case studies from Australian aquifers. The latter text has many practical applications for characterising recharge, and also lists the short comings for transferring porous media assumptions and methods to hard rock aquifers.

Recharge of the southwestern United States desert also has been extensively studied (e.g Hogan et al. 2000). Factors such as vegetation, ephemeral streams, underlying geology as well as the close presence of mountains are found to be major controlling factors in the occurrence of recharge (Hogan et al. 2000). Wheater et al. (2008) affirm these facts, specifically for arid, areas and further highlight the variability and erratic nature of recharge in these water scarce zones. These factors are also important for hydrological modelling. Furthermore evaporation and evapotranspiration are critical in the water balance, specifically in these semi arid to arid areas.

De Vries & Simmers. (2002), in their review of methods and processes related to groundwater recharge, highlight that in many cases in arid and semi arid areas recharge is dependant upon the frequency and intensity of rainfall events. This erratic and episodic nature of recharge within arid zones has been further explored by Lewis and Walker (2002) as part of a study in southwestern Australia. However, very few studies have actually examined or quantified episodic recharge on a regional scale using relevant climatic data (Lewis and Walker, 2002).

More recently it has been realised that hydrochemistry, specifically using isotopes, is able to shed light on these episodic events, in conjunction with electrical conductivity measurements. Such work has identified pulses of recharge in a karstic aquifer in Turkey (Ozyurt and Bayari, 2007). Similarly, Bredekamp (2007) has developed a model, based on C14 fingerprinting content of groundwater in karstic aquifers in the central, northwestern and eastern regions of South Africa's gold mining hub in Gauteng. This application of isotopes proved that an exponential regression relationship is present between the C14 recharge estimates and rainfall. Furthermore this simple linear relationship provides a method to simulate the response of the groundwater levels from which the allocation of surplus water reserves could be derived for water management purposes (Bredenkamp, 2007). Unfortunately, neither of these studies were executed in a semi arid or arid area, and are not as relevant to the Karoo.

Hughes et al. (2008) employed a GIS 'modelling' approach in order to better understand episodic recharge processes in the more arid zone of the West Bank Aquifer of Palestine. Object orientated software was utilised in this spatial analysis to estimate recharge, and data inputs included:

- Distributed daily rainfall and distributed monthly potential evaporation.
- Landuse and associated values and slope aspect.
- Ephemeral stream flow and spring flow.
- Urban areas.
- Irrigated areas.

The requirements to complete this type of modelling are extensive compared to other methods of groundwater recharge estimation. Issues of scaling, data availability as well as data quality would play a major role in determining the reliability of the model output, specifically in arid areas (Thieken et al. 1999). Bredenkamp et al. (1995) advocate the use of multiple methods for recharge determination and then averaging those results in order to gain a representative value for recharge.

Titus et al. (2009) also utilised a GIS approach to determine recharge, but the major difference with most other studies is the fact that this was done in conjunction with spatial statistics analysis, incorporating the Chloride Mass Balance (CMB) and Saturated Volume Fluctiuation (SVF) to determine recharge. This GIS statistics approach is also more realistic than that of Hughes et al. (2008), due to fact that Titus et al. (2009) examined fracture features and lineaments, which are critical in fractured rock hydrogeology (Cook, 2003).

In summary, multiple methods are available to calculate groundwater recharge and care must be taken to choose an appropriate method to suit specific regions. Xu and Beekman (2003) have compiled an extensive collection of southern African case studies, to address this and in which all applicable recharge estimation methods are highlighted for Southern Africa, along with the underlying principles to simplify method selection.

2.6 Gravimetric applications to hydrologic monitoring

Gravimetry is defined by Allaby and Allaby (2003) as the science of measuring the gravitational acceleration at different sites. The investigation of subsurface geology can be carried out using variations in the earth's gravitational field generated by differences in density between subsurface rock and fluid masses (Milsom 2003).

Historically, Heiskanen and Vening Meinesz (1958) first examined the gravity field of the Earth in detail, and produced an all encompassing treatise evaluating mathematical as well as theoretical treatment of the subject matter. Major applications of gravimetric studies at the time were in the field of geodetics and isostacy.

Due to the evolution of technology more modern applications for gravimetric studies have since emerged. A prime example of this is shown by Milsom (2003) who describes applications using gravimetric studies that can can be applied at numerous scales in order to point out anomalies present in the subsurface, for example iron deposits with a relatively higher density (e.g Kovalevsky et al. 2004). These principles have only recently been extended to hydrogeological applications in order to aid in understanding subsurface processes without the extensive cost of drilling (Kirsch 2006). The theoretical basis for detecting variations in gravity applying it to hydrology is related to the temporal variations in the mass storage of water (Guntner et al., 2007). When water is added or removed from the subsurface, a change in the mass storage of moisture occurs, in turn creating a local change in the gravity signature (Kirsch 2006).

Howle et al. (2003) have suggested that the changes in gravity, caused by hydrology (e.g. Gravity anomalies), are mainly due to the recharge of groundwater. Creutzfeld et al. (2010) on the other hand have argued that the Total Water Storage (TWS), which includes the unsaturated zone, impacts gravity directly. In hydrology this is the reason for understanding the local hydrological regime of a site and then modelling it in order to correlate it to a gravity signal (Krause et al., 2007).

Using these principles, Neumeyer et al. (2006) compared the use of the Gravity Recovery and Climate Experiment (GRACE) satellites to Superconducting Gravimetre (SG) stations (Table 2.1) and its applicability to hydrological studies. Hydrological models are used to better understand the gravimetric signals at the major SG stations that form part of the Global Geodynamics Project (GGP). It has been shown that there is general agreement between the hydrological models and the ground data, although at certain stations there were significant deviations in the hydrological modelling from the hydrologic gravimetric signal. This deviation of the hydrological model from the gravimetric signal for hydrology could be attributed to a lack understanding of site specific conditions, and in turn the major driving forces for the local scale hydrology.

	GRACE		**Superconducting Gravimetres**
Gravity resolution	10 microgals	5 microgals	1 microgal
Spatial Resolution	500 km	2000 km	Point measurement
Spherical harmonic coefficients	L_{max}=40	L_{max}=10	Not applicable
Temporal resolution	1 month		10 seconds
Long term stability	No drift		3 microgals/year

Table 2.1: Comparison of resolution of gravity measurements between GRACE, with ranges, and Superconducting Gravimetres (modified after Neumeyer et al., 2006).

2.6.1 Gravimeters and their application to hydrology

The presence and occurrence of moisture in the vicinity of gravimeters has long been suspected to create background noise during gravity measurments (Heiskanen and Vening Meinesz, 1958). This led to early applications of ground based gravimetry for groundwater exploration purposes. Wallace and Spangler (1970), for example, utilised a gravimetric and seismic survey in order to characterise the extent of a hydrogeological basin in an arid area of southwest U.S.A. Bulk densities of subsurface material as well as porosity values were utilised in conjunction with the geophysical parameters to determine the storage capacity of the basin. This study proved that the coupling of non-intrusive geophysical methods is excellent for inferring specific hydrogeological parameters on a groundwater basin scale (Wallace and Spangler, 1970).

Llubes et al. (2004) compared three studies in the region of major SG stations across the European continent. An important categorisation was made with regards to classification of groundwater flow systems relative to their proximity to the SG stations, namely regional and continental flow (Llubes et al., 2004). Furthermore, importance of environmental data as well as an understanding of the geology and hydrogeology is critical for interpretation of SG data, as re-emphasized by Jacob et al. (2008). In this respect assumptions that neglect vertical flow on a local scale in soil must be re-examined, as this has shown to be critical in soil moisture movement (Fetter, 1999).

Damiata and Lee (2006) attempted to correlate the simulated drawdown in an unconfined aquifer to the potential gravimetric response. The modelled drawdown correlated well with the gravimetric response of the aquifer. The assumptions made are for an ideal situation as described by Neuman (1972). Unfortunately these are not realistic, due to classical assumptions like infinite aerial extent of the aquifer, homogeneity and isotropy of the aquifer material, and should just be considered as a showcase of the possibilities which gravimetry provides.

Harnisch and Harnisch (2006) examined seven SG stations throughout the world and the gravity and hydrological data stemming from these facilities. They concluded that great spatial and temporal variation occurs at every single site (Harnisch and Harnisch, 2006) This was attributed to the variable climatic conditions and thus in turn hydrological regime. Furthermore, the underlying geology also plays a critical role in determining soil type and characteristics (Fey, 2010). In line with understanding subsurface fluid flow, Kroner and Jahr (2006) showed that hydrologic variations in the subsurface can greatly aid in geohydrological modelling. Experiments in the vicinity of the SG at Moxa, Germany, for example, showed that anthropogenically induced interflow caused a marked difference in the gravity field and in turn allowed quantification of subsurface moisture differences.

Blainey et al. (2007), who followed up the work of Damiata and Lee (2006), explored the possibility of applying gravimetric data to estimate drawdown in an unconfined aquifer. Assumptions for the work were rooted in the classical assumptions of Darcy (1856), as well the work of Neuman (1972), as outlined above. Furthermore the same data set as used by Damiata and Lee (2006) was applied. It was concluded that the hypothetical case study should be applied in conjunction with direct methods, such as pump tests in order to aid in interpretation and determination of specific yield (Blainey et al., 2007). In other words gravity should be used as a complimentary tool in conjunction with other methods to characterise the hydrological regime (Christianson et al., 2011).

Naujoks et al. (2007) also examined the hydrological variations in the vicinity of the superconducting gravimeter in Moxa, Germany, using mobile gravimetres. 17 monitoring campaigns were completed between November 2004 to April 2007, using 9 Lacoste and Romberg relative gravimeters. The small scale, in the immediate vicinity of the SG, meant that the precision of the measurements was <1 microgal. The most important conclusion drawn is the fact that a greater understanding of the geohydrology is needed in order to fully appreciate the application of gravimetric data to hydrological studies. Naujoks et al. (2007) have shown that the standard deviations, in the vicinity of the Moxa SG station, could be as much as 14 nm/s^2 for a specific point. The spatial variation on the other hand was much greater and standard deviations measured up to 171 nm/s^2.

A dolomitic aquifer, in the south of France, formed the focus of a gravity study by Jacob et al. (2008). A simple conservation of mass energy could be applied to the scenario to ascertain inputs by precipitation and outputs as springflow (eg. Xu and Beekman, 2003). Three absolute gravimeters with rainfall stations at each location were utilised for data generation (Jacob et al., 2008). Gravity variation is considered to be a major factor for soil moisture at the local scale, and it was concluded, verifying observations by Cook (2003), that multiple parameter modelling is important for capturing greater uncertainty with regards to variables affecting groundwater flow. The frequency of gravity measurements, as also shown by Naujoks et al. (2007), aids in capturing the seasonal hydrological signal and thus the variation in subsurface moisture storage. This in turn aids with correlation of the gravity signal to the hydrological modelling.

Wziontek et al. (2009) examined the relationship between the distance from the SG and the cumulative gravity effect. They concluded that site specific studies are critical for understanding local hydrological effects and their relationship to gravity residuals. Boy and Hinderer (2006) validated this work, and emphasise further that greater understanding of every single aspect of the water balance and its relationship to the SG was needed in order to correctly quantify and remove the hydrological signal of the SG. A study of soil profiles, surface water, ground water, as well as mobile gravimetry highlighted the spatial and temporal variation within the vicinity of the SG at Moxa and emphasises the complex task of hydrological modelling in order to understand the gravimetric signal (Krause et al., 2009).

Whilst it can clearly be seen that the applications for gravity in the field of hydrology have great potential, problematic issues arise around scale, calibration and correlation with numerical modelling. Furthermore a good understanding of the geology and soils of the area is also critical. All of these issues are highlighted in the above listed studies. It can also be seen how the knowledge related to the relationship between hydrology and gravity has evolved over the past few years. Initially it was thought that only variations in groundwater levels could be detected (e.g Howle et al., 2003), but soil moisture as well as the spatial and temporal variations in gravity are now also being observed. This is due to the increased understanding of gravity applications in hydrology (Christianson et al., 2011) and the increase in precision of instruments like the SG (Creutzfeldt et al., 2010).

With all this said, one also has to take cognisance of the possible errors that can arise and how they might be mitigated (Table 2.2). Christiansen et al. (2011) have compiled many of the possible errors, the estimated amplitude for error, as well as mitigation measures which could be taken in order to reduce error. All of these were extracted from literature, including personal experience. These possible errors should be noted when attempting to complete any gravity survey as well as in the interpretation of the data in order to not adversely affect the results.

Error Source	**Estimated Amplitude**	**Mitigation**
Instrument casing temperature changes	Unknown	Shield against one sided heating. Avoid large changes in ambient temperature.
Unexplained non-linear background drift	Several microgals	Minimise time between station occupations in order to approximate linearity.
Uncertainty in air pressure data and correction coefficient	0.3 μ Gal h Pa^{-1}	Collect local air pressure data. Model remaining effects as linear drift.
Station instability and imprecise tilt correction	Several microgals	Reduce tilt to below 20 degrees for error less than 1 microgal. Tilt below 5 degrees is readily obtainable in field applications.
Calibration error	Depends on magnitude of gravity change	Minimize gravity span. Test calibration against calibration line with regular intervals.
Error on measured instrument height	<2 microgals	Use precise levelling and a stable height reference. Fix the height of one tripod leg.
Change in platform height	Up to tens of microgals	Use stable platforms e.g. concrete blocks, bedrock etc. In case of land rise/subsidence, use precise levelling and correct measured gravity value.
Vertical gradient not perfectly known	<1 microgal	Keep instrument height changes at a minimum. Fix the height of one tripod leg. Survey the local vertical gradient at each station.
Ocean loading effects	Several microgals	Correct using ocean tide models. Short term surveys: model as linear drift.
Instrument round off to nearest 1 μ Gal	< 0.5 microgals	Averaging of repeated measurements. Use raw 6 Hz data.
Spring hysteresis	Unknown	Keep instrument levelled when not in use. Use of the same station sequence for each survey. Independent of mode transport.
Insufficient rest after transport	Several microgals	Let the instrument rest for > 3 min after arrival at a station.

Table 2.2 : Potential error sources for gravity surveys (adapted and modfied from Christiansen et al., 2011).

2.6.2 GRACE satellite observation applications to hydrology

In the past the tedious task of hydrologic and hydrogeological monitoring was done only via on the ground point sources, and from which the the data then was extrapolated over larger areas, by means for example of kriging (e.g. Kovalevsky et al., 2004). The use of satellite applications has greatly stimulated the evolution of more rapid monitoring in recent times. Meijerink (2007) produced an all encompassing practical manual on remote sensing applications for every aspect of groundwater management, whilst Schultz and Engman (2000) summarised the theoretical aspects of remote sensing for hydrological applications, and also highlight the potential as well as limitations of these satellite based methods.

Between 2000 and 2002, a consortium of researchers, which included the GFZ, launched a number of satellites in order to monitor mass transport and mass distribution of fluids in the subsurface of the earth (Ilk et al., 2005). CHAMP and GRACE, launched in 2000 and 2002 respectively, are able to monitor spatial and temporal variations in the earth's gravity field with varying precision. The CHAMP satellite has a resolution of 350 km whereas the GRACE satellites have a resolution of 400 to 500 km, and an accuracy of 10 microgals (Neumeyer et al., 2006). Multiple applications for CHAMP has shown its efficacy for geosciences in general, and the earth's magnetic and gravimetric fields in particular (Reigber et al., 2005). The most recently launched gravity satellite, Gravity field and steady state Ocean Circulation Explorer (GOCE), is more precise still : 1 microgal to be exact,and has a spatial resolution of 100km with a vertical precision of 1 to 2 cm (www.esa.int/SPECIALS/GOCE/SEMDU2VHJCF_0.html).

The GRACE satellites, which is the first twin inter-satellite gravity mission, have an accuracy of 1cm, in terms of position, and 10 micrometres per second in terms of velocity. The theory as well as applications for GRACE have been outlined by Wahr et al. (1998). It is interesting to note that the applications as well as number of publications utilising GRACE is steadily increasing. This can be attributed to the improvement of geodetic models, as well available software products, to process data (Steffen et al., 2009). The International Centre for Global Gravity Field Models (ICGEM), based at the GFZ, is one of six global centres involved in the development of models and publishing of data related to CHAMP, GRACE and GOCE.

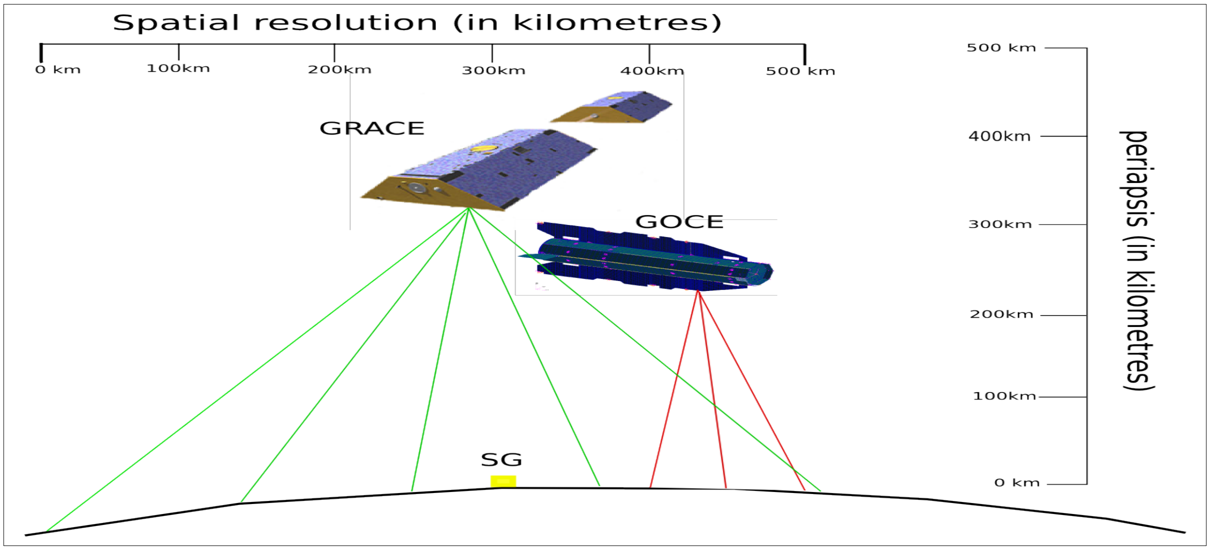

Figure 2.7: A comparison of the orbiting heights (periapsis) as well as spatial resolution of GRACE and GOCE. The Superconducting Gravimetre (SG) is ground based . The GOCE satellite orbits at 270 km (*www.esa.int*), whereas the GRACE satellite has been known to vary between 270km and 500km above the earth's surface (*http://www.csr.utexas.edu/grace/*). The spatial resolution of the GOCE satellite is 100km whereas GRACE covers an area of 500km. The SG is affected by factors such as polar drift, tides, ocean loading effects and atmospheric pressure, but 90 % of the hydrologic signal is detected within a 1km radius (modified after Creutzfeld et al., 2010).

The GOCE satellite is the first to use gradiometry. This allows for higher spatial resolution, due to the measurement of acceleration differences in all three spatial directions (Rummel et al., 2002). GRACE on the other hand uses the measured differences in distance between the twin satellites, stemming from the relative motion of the centres off mass of the two satellites (Tapley et al., 2004) (Figure 2.7).

Neumeyer et al. (2006) compared GRACE and SG data from the major SG stations, which form part of the GGP. The WaterGAP Global Hydrological Model (WGHM), the Leaky Bucket Model (H96) and the Land Dynamics Model (LaD) (Table 2.3), were then correlated to the GRACE and SG data at each station. Despite a few outliers at specific stations, there seems to be a general agreement between the GRACE, SG and hydrological model time series for the various SG stations. Correlation values as high as 0.75 and 0.72 were calculated between the SG and H96 as well as the GRACE and H96, respectively. Major differences in the models lie in the method used to calculate snow cover and the depth to groundwater (Neumeyer et al., 2006). Boy and Hinderer (2006) drew similar conclusions when comparing the GLDAS and LaD global hydrological models to the hydrological gravity residual of 20 SG stations all over the world. Suggestions were made that groundwater measurements, soil moisture as well as precipitation measurement instrumentation should installed at all the stations in order better understand the local hydrological effect on the SG readings (Neumeyer et al, 2006). This has shown to increase the understanding of the hydrological regime and thus in turn better model it and correlate to the gravity residual.

Model Name	**Meaning of Abbreviation**	**Developer**	**Spatial Resolution (cell grid size)**	**Temporal Resolution**	**Global Distribution maps**
WGHM	**W**aterGAP **G**lobal **H**ydrological **M**odel	Doll et al., (2003)	0.5ºx0.5º	24 hours (one day)	Soil (FAO, 1995) Drainage (Doll and Lerner, 2002)
LaD	**La**nd **D**ynamics Model	Milly and Shmakin (2002)	1ºx1º	Minutes to an hour	Soil (Zobler, 1986) Vegetation (Matthews, 1983)
GLDAS	**G**lobal **L**and **D**ata **A**ssimilation **S**ystem	Rodell et al. (2004)	0.25º; 0.5º ; 1.0º; 2.0ºx2.5º	Adjustable time step and output	Soil (Reynolds et al. 1999) ; Vegetation (Hansen et al. 2000)

Table 2.3 : Comparison of global hydrological models as well as their developers. The spatial and temporal resolution are also compared. Furthermore the global distribution maps used in each model for the vegetation and soil are the major differences between the models (sources : Doll et al. (2003), Milly and Shmakin (2002) and Rodell et al. (2004).

Werth and Güntner (2010) utilised GRACE data in order to calibrate a global hydrological model for 28 of the world's major river basins (Table 2.4). The major aim of the study was to calibrate the WGHM model with GRACE data and the groundwater, surface water, soil moisture and precipitation were the major model inputs. The study showed that hydrogeologic data was sorely lacking in hydrology models. Furthermore model calibration is critical specifically under certain climatic conditions due to the role of hydrological parameters being highly variable in differing environmental circumstances (Werth and Güntner 2010).

Longuevergne et al. (2010) examined the use of GRACE in understanding the water storage of the High Plains Aquifer in North America. It was shown that GRACE was able to detect the changes in terrestrial water storage across the entire area of the aquifer, which is approximately 450 000 km^2. Correlation values of 0.8 were calculated between GRACE and ground based water storage estimates. A similar conclusion was drawn by Andersen et al. (2005), who compared two ground based SG stations to GRACE for the extreme variability in water storage caused by a heatwave across Europe in 2003. Estimates were within 2cm in terms of total water storage volumes and proved the applicability of GRACE in terms of understanding inter-annual variations of water storage and climate change scenarios (Andersen et al., 2005). Furthermore GRACE has aided in visualisation of subsurface water storage on a continental scale (http://www.youtube.com/watch?v=jZKxVZt18ng&feature=related).

River Basin	Basin Area (Million km^2)	Period of discharge data	Discharge station
Amazon	5.93	2003-2007	Obidos
Amur	1.87	1975-2004	Bogorodskoye
Columbia	0.67	1977-2006	Dalles
Danube	0.8	1973-2002	Ceatal Izmail
Ganges	1.59	1973-2002	Farakka
Huang He	0.8	1973-2002	Huayuankou
Indus	0.85	1950-1979	Kotri
Lena	2.45	1973-2002	Stolb
Mackenzie	1.7	2003-2007	Arctic Red River
Mekong	0.8	1980-1991	Kompong Chan
Mississippi	3.24	2003-2007	Tarbert Landing
Murray	1.06	1965-1984	Lock 9
Nelson	1.2	1976-2005	Kelsey
Niger	1.8	1977-2006	Lokoja
Nile	2.91	1973-2002	El-Ekhsase
Ob	2.7	2003-2007	Salekhard
Orange	0.96	1972-2001	Vioolsdrif
Orinoco	0.97	1960-1989	Tunente Angostura
Parana	2.58	1965-1994	Timbues
St Lawrence	1.05	1973-2002	Cornwall
Tocantins	0.88	1978-1999	Tucurui
Volga	1.39	1973-2002	Volgograd
Volta	0.41	1955-1984	Senchi
Yangtze	1.93	1975-2004	Datong
Yenisei	2.54	2003-2007	Igarka
Yukon	0.83	1977-2006	Pilot Station
Congo (Zaire)	3.72	1954-1983	Kinshasa
Zambezi	1.39	1976-1979	Matundo-Cais

Table 2.4 : The river basins, their total surface area, the period of the data used as well as the station from which the instream flow (discharge) data was sampled from for the study calibrating the WGHM using GRACE data. (modified after Werth and Güntner 2010)

On the other hand Hinderer et al. (2009) argue that GRACE estimates for changes in terrestrial water storage are not comparable to ground based SG measurements. This is due to the fact that the GRACE measures across a large regional scale whereas the SG measurements are confined only to its immediate vicinity (Neumeyer et al., 2006). It has been argued therfore that the choice of hydrological model, model calibration and scale play a major role in determining the value of the results (Leavesley et al., 2002). More recently this has been re-examined by Krause et al. (2009), who concluded that the soil moisture model results correlated well with the gravity residual for the SG at Moxa, for a small catchment of approximately 2km^2. 77% of the variability stemming from the SG residual could be explained by changes in soil moisture. Niu et al. (2007) further illustrate that simple large scale hydrogeological modelling has had greater success with GRACE correlations. Neumeyer et al. (2006) have shown up to 75% correlation between large scale models and GRACE.

Fukuda et al. (2009) also compared GRACE and hydrological modelling. They raised the point that a groundwater component should be included in the hydrological modelling due to the increase in groundwater storage and therefore gravity variability. It was also emphasized again that GRACE is more applicable on a regional scale (e.g. Werth and Güntner, 2010). TWS from Global hydrological models as well as GRACE was compared and it can be clearly seen that the differences between the two methods is small. Thus, the resolution between the various hydrological modelling methods is steadily improving. This is especially true for larger hydrological basins with a definite seasonal pattern in terms of hydrology.

When comparing multiple studies using ground and satellite based gravity to hydrological models, it seems as if the SG stations in areas of relatively stable seasonal weather conditions have a stronger correlation to the GRACE signal than those in areas of erratic changes in climate. Examples of these are included in the studies of Harnisch and Harnsich (2006) as well as by Neumeyer et al. (2006). This also depends on the hydrological model used, model inputs and the manner in which it is calibrated. Thus, in conclusion, the hydrological regime of the semi arid Karoo should yield interesting results due to the minimal amounts of rainfall and limited surface water flow.

2.7 Hydrological modelling related to gravity studies

The number of available reliable hydrological models for various applications is large and creates problems when choosing an appropriate model, especially because objective information of the published models is limited (Leavesley et al., 2002). Furthermore the possibilities for coupling surface, unsaturated and saturated zone processes are possible due to to advances in computing and thus model integration (Sophocleous, 2002). Abe et al. (2006) show that close to 80% of the short term hydrological signals affecting the gravity measurements occur in the vadose zone. In line with this, and in order to filter the literature reviewed, an attempt is made here to examine relevant soil moisture models as well as hydrological models used in gravity studies.

In situ measurements are important for inputs into hydrological models since they give a actualistic representation of the environmental variables (Walker et al., 2004). The most direct method for obtaining *in situ* characteristics of soils would have to be the lysimeter (Meissner et al., 2008). This involves the installation of a steel or concrete cellar with the soil inserted into it and then weighing the column at regular intervals in order to determine the variability in soil moisture (e.g. Creutzfeld et al., 2010). Other indirect methods include the Time Domain Reflectometry (TDR) and soil moisture sensors; and it has been proven that the former yields better quantitative as well as qualitative *in situ* results (Walker et al., 2004). These measurements, in conjunction with environmental variables, such as precipitation and groundwater levels, aid in understanding the variability in soil moisture, and in turn improve hydrological models (e.g. Naujoks et al., 2007).

Numerous studies have attempted to compile and compare soil moisture models. One example is that of Scanlon et al. (2008) who examined multiple codes for soil water modelling. This was done by using the various models on two sites with loamy soil covered by a non vegetated engineered surface in a warm and cold desert region of North America. The models used in this study are presented in Table 2.5 , along with other models used in gravity studies.

It was concluded that major differences in results arise from the governing equations used in the models for flow, lower boundary conditions, and water retention functions (Scanlon et al., 2008). Despite these differences, in this specific study, the results from each model for surface runoff was estimated to be within 64% of measured runoff (Scanlon et al., 2008).

Model	Meaning of Abbreviation	PE Input	PE Calculation	Snow	Runoff	Boundary Condition	Water Retentio n	GUI
UNSAT -H		x	Penman*			UG	VG, BC	x
HYDR US-1D		x				UG, S	VG, BC	x
SHAW	**S**imultaneous **H**eat **A**nd **W**ater		Penman*	x		UG	BC	
Soil Cover		x						x
SWIM	**S**oil and **W**ater **I**ntergrated **M**odel	x				UG, S	VG, BC	
VS2DTI	**V**ariably **S**aturated **2** **D**imensional **T**ransport **I**nterface	x				UG, S	VG, BC	x
HELP	**H**ydrological **E**valuation of **L**andfill **P**erformance		Penman	x	SCS	UG	BC	x
J2000		x	PM	x	SWS	UG	VG	x
MIKE SHE	**S**ystem **H**ydrologique **E**uropean	x	PM	x	SWS	UG	VG	x

Table 2.5 : Some of the leading hydrological models used for soil and groundwater studies . Definitions of abbreviations are : PE= Potential Evapotranspiration, PM=Penman Monteith (1948),Penman*= modified Penman (Doorenbos and Pruitt, 1977) , SWS=Soil water saturation, SWS=Soil Water Saturation, UG= Unit Gradient, S=Seepage face, VG=Van Genuchten (1980) ,BC=Brooks and Corey (1964) ,BC*=Brooks and Corey with zero residual water content, SCS= Soil Conservation Service curve number GUI= Graphical User Interface, (Modified after Scanlon et al., 2008)

Ranatunga et al. (2008) examined 21 vadose zone models developed in Australia applied across different scales. Western (1999), for example, shows how the issue of scaling can have a major impact on model outputs, specifically in vadose zone applications. In order to classify these models better, three different classes of models were defined by Ranatunga et al. (1998) in the following order of complexity:

- Single layer models with tipping bucket approach.
- Multiple layer models with tipping bucket approach.
- Complex models (with or without groundwater component).

Emerman (1995) describes the tipping bucket as computationally simple due to its assumption that all water flows through the macropores. The inputs for such a model are few and include precipitation and the outputs are evaporation. No distinction is made between evaporation and transpiration, and once the soil bucket is filled surface runoff occurs (Ranatunga et al., 2008). The single layer assumes homogeneity throughout the soil, and oversimplifies the reality. A prime example of multiple layered soils, within the Karoo study area, is the duplex soil (Fey, 2010). This homogeneity and isotropy in the subsurface is a common assumption in hydrogeological modelling (Cook, 2003)

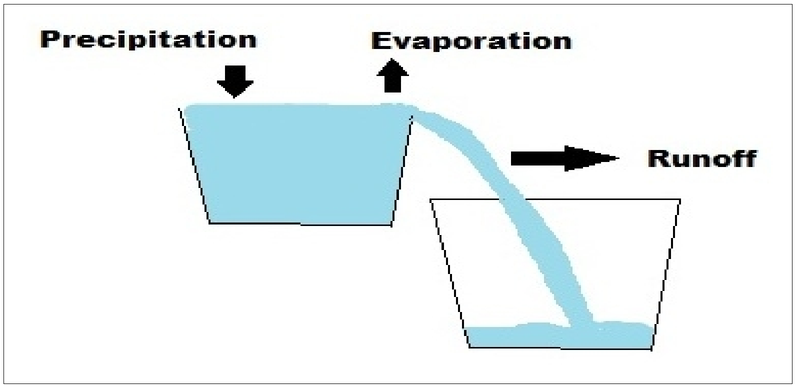

Figure 2.8: Simplified representation of a tipping bucket model. The major input is precipitation and the major output is evaporation. Once the bucket is filled the excess flow is calculated as runoff. The filling of the bucket relates to the saturation point of the soil.

Multiple layer models on the other hand are able to differentiate between the characteristics of various layers. The J2000 model, outlined by Krause (2002), shows that the differentiation within the soil is important in order to classify the various soil horizons and their properties. These multiple layer models also treat soil evaporation more realistically and thus demand more inputs than the single layer models (Ranatunga et al., 2008)

Complex models take into account numerical solutions instead of a tipping bucket approach, and also have one or two dimensional water flows (Ranatunga et al., 2008). Scanlon et al. (2008) compare the efficacy of multiple complex models and show that the data inputs are the most important aspect and many of the models yield comparable results, as previously shown.

Twarakavi et al. (2008) have shown how increasing model complexity does apparently produce more reliable outputs, but the complexity also demands greater computational efforts and data inputs. This is one of the issues which hydrological modellers struggle to overcome, along with scale (Western, 1999), in order to select an appropriate model choice (Leavesley et al., 2002).

Creutzfeld et al. (2010) and Christiansen et al. (2011) have shown that vadose zone modelling, as reviewed above, is able to contribute to a better understanding of the hydrological residual affecting the gravimetric signal. This in turn could either aid in removing this hydrological residual (Naujoks et al., 2007) or aid in calibrating unsaturated zone hydrological modelling (Christiansen et al., 2011).

Creutzfeld et al. (2010) further compared the results from the HYDRUS 1D hydrological software model to the hydrological gravity residual at Wetzell, Germany. Šimůnek et al. (2008) also compared this version of the HYDRUS software to other open source codes, and they have shown that HYDRUS 1D is able to model more processes controlling subsurface flow with an improved Graphical user interface. When comparing the modelling results from the HYDRUS 1D to lysimeter measurements, and then correlating this to the hydrological signal from the SG, it was shown that 95 to 97% of the gravity residual variations
in the SG signal could be explained using these high resolution data for hydrological modelling from the lysimeter, groundwater and atmospheric measurements (Creutzfeldt et al., 2010).

Naujoks et al. (2007) employed the J2000 hydrological model at the SG observatory in Moxa, and Krause (2002) has shown how this regional scale model is extremely flexible in terms of its object orientated approach. Bugan et al. (2000) have applied this model to a catchment in the Western Cape, South Africa, and they state that the model is centred around methods of runoff generation. This is important for surface water processes as well as subsurface flow, but not when groundwater is a major component. Naujoks (2007) however had great success when correlating the hydrological component of the gravity residual to the soil moisture results from the J2000 model, and obtained an excellent correlation between simulated and measured data.

Christiansen et al. (2011) utilised the MIKESHE software in an attempt to understand the gravity effect in the vadose zone. Liu et al. (2007) have shown the efficacy of this model as well as the possibility of coupling it with a a river model, called MIKE 11, thus further improving results for both surface and groundwater. In line with this Christiaens and Feyen (2001) have shown that the MIKESHE model is an excellent tool for determining soil hydraulic properties on the surface. Christiansen et al. (2011), however, argue that this specific model does not allow for inputs of preferential flow at depth, and therefore suggest using other geophysical tools in conjunction with gravity in order to aid in vadose zone model calibration.

2.8 Methods applied in this study:

All of the methods applied in this study are outlined in each individual chapter prior to the results. The work has been divided in this manner in order to understand the subject matter and allow the reader to easily assimilate the work.

The main methods applied in this study, specifically for the area of Sutherland, have also been tabulated in order to understand the applicability and context of the methodology in this study (Table 2.6). This also give the reader an understanding of the main objectives and outcomes of the methods used.

Objective	Methodology	Outcome
Geological mapping	Remote sensing with SPOT 5 imagery with GIS	Geological map of dolerite
	In Situ mapping of fractures with clinometre	Rose diagram
Aquifer characterisation	Pump test analysis	Determination of T and S values
	Water sampling and analysis for macro chemistry	Types of water present in study area and contamination of groundwater.
	Water sampling and analysis for stable isotopes	Sources and possible mechanisms of groundwater recharge
Soil mapping	Remote sensing with satellite imagery using GIS	Classification of soil according to hue (colour) and delineation of soil boundaries
	Digging of trenches in situ	Classification of soil type and duplex nature of soil
	In Situ plasticity tests	Determination of clay content with depth and duplex nature of soil
Soil hydraulics	In Situ infiltration tests	Infiltration capacity of soil types and possible recharge locations.
	Dye tracer test	Duplex nature of soil and preferential flow along rhizosphere
Understanding temporary water storage	Linear correlation between water level of SA BK 05 and gravity residual	SA BK 05 is a conduit and not a reservoir for groundwater.
Understanding episodic recharge	Time series analysis of soil moisture, groundwater and precipitation	Reaction of groundwater and soil moisture to rainfall differs
	Linear correlation between groundwater level and gravity residual	Episodic recharge occurs after rainfall events of specific intensity

Table 2.6 : The major objectives, methods and outcomes of the work undertaken in the immediate vicinity of the SAGOS.

2.9 Conclusions

With a background knowledge of fractured rock hydrogeology, the vadose zone as well as hydrological modelling applied to gravity we are able to contextualise the study area around Sutherland within the field of gravity applications to hydrology. The development and advancement of hydrology as well as gravimetry shows how these two fields of research are inextricably linked. From this it can clearly be seen that characterisation of the hydrological regime and hydrogeology of the area is critical for numerical modelling. This will then contribute to the correlation with the gravity residual in order to better understand the impact which the hydrology has on the SG in Sutherland as shown in chapters 5 and 6.

But first in the next chapter we will examine the hydrogeology of the area. This includes the water chemistry, hydraulic properties of the aquifer as well as geology of the area. The aforementioned are characterised in order to build a conceptual model and better understand the subsurface fluid flow of the area around the SAGOS.

CHAPTER 3
CONCEPTUAL GROUNDWATER MODEL FOR THE SAGOS

3.1 Overview

The aquifer in the vicinity of the Superconducting Gravimetre, Sutherland is examined. The secondary saturated geologic unit displays high fracture connectivity in the immediate vicinity of dolerite dykes, as is inferred from the rapid hydraulic recovery of wells in the immediate vicinity of this dolerite. Further evidence for preferential subsurface fluid flow lies in the regular orientation of joint and fractures, that were measured in the field. These NNE trending structures are likely conduits for flow and recharge. Hydrogeochemistry points towards possible localised water tables and isotopic data suggests preferential flow as the major mechanism for recharge, consistent with the previous work completed in the area. Signs of contamination are detected in one of the wells, possibly from anthropogenic activities. The source of groundwater seems to be stemming from numerous rainfall events.

3.2 Introduction:

Conceptual model development is important for understanding fluid flow as well as water-rock interaction, specifically in fractured media (NCR 2001). Such conceptual models also feed into numerical models to enhance better quantitative understanding of water resources. This requires the use of as many tools as possible in order to reduce uncertainty. Kovalevsky et al. (2004) have shown the use of various methods, specifically applicable to groundwater studies and highlight the advantages as well as shortcomings (Table 3.1).

Method	Advantages	Disadvantages
Geophysics	• Non-invasive method to characterise subsurface	• Open to interpretation • Indirect measurement related to groundwater (eg resistivity) • Equipment can be costly • Special skills required for interpretation
Groundwater sampling	• Water quality can be determined	• Only point source • Contamination of sample in field or laboratory could lead to bad results • Sample analysis can be costly (depending on type of analyses)
Remote sensing	• Able to identify structural features in fracture rock for drilling • Cut costs by limiting extensive field visits	• Reflectance could affect image interpretation • Image quality and resolution • Specialised software and skills required
Numerical modelling	• Able to predict future scenarios • Ability to determine aquifer parameters	• Parameters for model inputs costly • Specialised software and skills required
Data mining	• Able to determine patterns in data without being in the field • Cut costs by limiting extensive field visits	• Data quality • Data availability • Specialised skills and software

Table 3.1: Comparative methods used in hydrogeology (Modfied after Weaver et al., 2007 and Kovalevsky et al., 2004)

Characterising the groundwater regime of an area plays a major role in understanding the processes governing the flow of water in the subsurface (Cook, 2003). This understanding in turn has an impact on the development and choice of numerical model to be used for determining aquifer parameters (Kovalevsky et al., 2004). Numerical modelling has been shown to be an important tool for the understanding of hydrogeology and thus the management of this subsurface water resource (Chiang and Kinzelbach, 2000)

For southern Africa, Xu and Beekman (2003) have made a compilation of multiple methods to determine recharge, and outline those most applicable to certain situations. Recharge is one of the most important inputs into the groundwater system as it determines the amount of water that can be sustainably extracted (Weight and Sonderegger 2001). Bredenkamp et al. (1995) have also produced a similar manual for examining storativity within a South African context. Van Tonder et al. (2001) on the other hand, examined storativity and explored the concept of sustainable yield from an aquifer using pump tests. Many local works have led to the creation of Microsoft Excel® based software, such as the Windows Interpretation Software for Hydrogeologists (WISH), which has been developed in South Africa and applied locally. Open source tools have also found application in data mining and analysis (Janert, 2011).

3.3 BACKGROUND:

3.3.1 Study Area:

The study area is located around the South African Geodynamic Observatory Sutherland (SAGOS). Here, a Superconducting Gravimetre (SG), installed in 2000, has recently become important for hydrogeodetic research because of its ability to measure subsurface hydrological changes in its immediate vicinity (Creutzfeldt et al., 2010). This has been proven to be useful for modelling water reservoirs. The study area is located at 1759 metres above sea level and is approximately 15 km^2 in size.

Sutherland is located in the Northern Cape Province of South Africa (Figure 3.1). The locale is a semi-arid area with a mean annual rainfall of 300-400mm and evaporation rates of 1800-2000mm per annum (Mukheibir and Sparks, 2005). The Karoo and Karroid bushes dominate, with some stunted shrubs also scattering the area (Acocks, 1988). Rivers draining the area are mainly non-perennial and flow during periods of peak rainfall, these rivers are also responsible for recharge in the area. Runoff values for the area are in the region of 10-20mm per annum (Midgeley et al., 1994)

3.3.2 General Geology:

The Karoo Basin extends over a large area of South Africa The basin came into existence during the early Carboniferous period (Smith 1990) and its formation, and subsequent evolution, was controlled by four major geodynamic events:

- Deposition of the Karoo Supergroup sediments in a foreland basin during the uplift of the Cape Fold Belt (~260 Ma to 190 Ma).
- The break-up of Gondwana with the intrusion of the Karoo dolerite and extrusion of the Drakensburg basalts (~190 to 180 Ma).
- Intra-plate mantle activity with emplacement of kimberlite pipes and fissures accompanied by the intrusion of carbonatite plugs and major epierogenic uplift and formation of the Kalahari plateau (~170 to 60 Ma).
- Weak tectonic activity associated with uplifting, geomorphological, changes, erosion, modern river system and joint development (~30 Ma to present time).

These major events, as well as the methods used to quantify and understand them, have been extensively documented by Woodford and Chevallier (2002), Tinker et al (2008), de Wit (2007), Tankard et al. (2009) and Lindeque et al. (2007)

The first depositional event was glacial, this formed the Dwyka Group, and as the ice sheets disappeared we find the fluvio-deltaic sands accumulated in the northern part of the basin. At the same time muds, which formed the Ecca and Beaufort Groups, followed by turbidite sands and silts were deposited in the deeper trough in the south because of the increasing influence of orogenic activity (Smith 1990). The Beaufort Group forms the backbone of the geology in the area around the SAGOS, with the Abrahamskraal Formation dominating.

The most interesting local magmatic feature is the Saltpetrekop volcanic structure. This extrusion is located south east of the SAAO and has caused brittle and ductile deformation with its upwelling (Boctor and Yoder, 1983). There is also extensive carbonatite intrusives with olivine, pyroxene and amphibole minerals occurring within the immediate vicinity of the historic volcano. Newton (1987) examined the fracturing network in the environs of the previously mentioned structure by means of remote sensing. This post depositional structure has caused a clear concentric fracture pattern that extends radially outwards in all directions from the centre of the structure (Newton, 1987). Viola et al (2005) also examined neotectonic stresses and concluded that ten distinct episodes of deformation occurred on the west coast of South Africa, in close proximity to the study area. This has major implications for brittle deformation, joint systems and features similar to the Salpetrekop, and structural reactivitation on a larger scale.

3.3.3 General Hydrogeology:

Pump tests have been shown to be useful as tools for determining aquifer parameters. Fetter (2001) describes the technical aspects of this methodology and outline the important assumptions for different methods. The calculation of aquifer parameters in fractured rock on the other hand is complicated due to the fact that many of the assumptions applicable are only valid in porous media (Kirchner and Van Tonder , 1995). Furthermore in-situ complications for pump tests are numerous and could occur at any time (Weight and Sonderegger, 2001). Therefore the greatest care should be taken when completing a pump test and examining the data stemming from it, specifically in fractured media (Van Tonder et al., 2002).

Chemical and isotopic methods for groundwater studies are gaining popularity due to their broad applicability (Mazor 2004). Bredenkamp et al.(1995) have compiled a manual for the application of many of these methods and advocated the use of multiple methods, specifically in the fractured rocks of the Karoo. Sami and Hughes (1996) compared the Chloride Mass Balance method to a physical based method, known as the variable time interval (VTI), in a catchment of the Karoo similar to this study area. The results yielded were comparable between the CMB and VTI methods, but Bredenakamp et al. (1995) have clearly shown that the latter method is much simpler and more applicable.

With regards to the estimation of recharge in Southern Africa, Xu and Beekman (2003) have outlined multiple physical and chemical methods for the calculation of the addition of moisture to the saturated zone. Subyani (2005) has shown that recharge events are able to flush salts into the groundwater system by means of preferential flow. Sami (1992) attributes the salinity in groundwater to five possible mechanisms, these include:

- Marine water intrusion.
- The mixing of meteoric water with connate water trapped during the deposition of sediments in a marine environment.
- The concentration of dissolved salts by evaporating or transpiration near the soil surface during slow diffuse recharge.
- Leaching of evaporate salt deposits by water percolating rapidly through preferential pathways.
- Chemical dissolution of the aquifer material.

There are definite methods to identify these 5 different sources of salinity. Abid et al. (2010) show that by examining the relationships between elements in the groundwater, in conjunction with stable and radioactive isotope hydrogeochemistry, the sources of salinity can be identified. This should be done in conjunction with an understanding of the geology and environmental processes such as climate and land use (Subyani, 2005).NCR (2001) suggests that the use of stable isotope data, like deuterium and Oxygen 18, could aid in understanding the temporal and spatial variation of water storage within fractured media. Stable isotopes were sampled in order to better understand the inputs as well as interaction within the hydrological system.

3.3.4 The role of dolerite in hydrogeology:

Dykes are propogated due to the pressure from magmas and subsequent movement of magma through the pre-existing structures such as joints (Delaney and Pollard, 1981). Sills are formed in a similar manner, but as the magma migrates it encounters stresses until it reaches a level of neutral buoyancy (Ruben, 1995).

In the fractured rock aquifers of the Karoo it has been proven that dolertie dykes have caused a substantial amount of secondary porosity (Woodford and Chevallier, 2002). Van Zijl (2006) has shown how weaknesses in bedding planes as well as changes in stratigraphy can play a major role in dyke and sill emplacement in the Karoo. Cook (2003) has extensively reviewed the nature of fractured rock aquifers and shown that sills act as barriers to water infiltration and flow. Woodford and Chevallier (2002) have further shown, in the vicinity of Beaufort West, South Africa, how dolerites are able to compartmentalise groundwater flow and thus completely separate small systems. A similar scenario has been documented in the goldfields of the Witwatersrand (Cook, 2003), as well as in the ring complexes of the Eastern Cape (Chevallier et al., 2004). It appears that the doleritic sills act as impermeable barriers for groundwater flow, whereas the dykes are able to compartmentalise the flow. The general trend for the dykes in the Sutherland region is NW. Contact metamorphism along the dykes is evident up to 1m away (Woodford and Chevallier 2002).

Fracturing occasionally extends several tens of metre away from the dyke into the country rock, but is only visible near surface where an advanced stage of weathering has taken place and not in the deeper seated transgressive, sub-horizontal open fractures (Woodford and Chevallier, 2002). This high fracture connectivity is consistent with borehole yields which increases with depth when drilled alongside dolerite intrusions in the Karoo (Sami, 1996). Thus dyke emplacement has caused secondary fracturing in the sandstones, and these fractures facilitate water movement, but not at depths greater than 50m (Sami, 1996). Botha and Cloot (2004) has looked at the geology, geometry and deformation within these Karoo aquifers. An interesting hypothesis implies that the major conduits of water flow being horizontal fractures (Botha and Cloot, 2004). This statement is site specific and dependant on the fracture aperture, width, surface roughness and density of the fractures amongst other factors

(Cook, 2003). Van Tonder et al. (2001) further extrapolate the argument of Botha and Cloot (2004) adding that in South Africa hard rock groundwater flow occurs within vertical and horizontal fractures, in a dual porosity medium as shown by Cook (2003) and Kovalevsky et al. (2004), and by means of radial flow along these fractures into the well.

3.4 Methodology:

3.4.1 Hydrogeochemistry:

Groundwater samples were taken at five wells (SA BK01 SA BK04, SA BK05, SA BK06 and SA BK07), across the study area during two periods of sampling. During the first field visit (11th to the 20th of May, 2010) all the wells were sampled. During the second sampling event (15th to the 22nd of September, 2010) SA BK01 was omitted as it was thought to be a perched water table. Temperature and conductivity of all water samples were measured in situ.

Samples were filtered in the field through 0.45 micron filter into HDPE sampling bottles. Cation samples were slightly acidified with 10% HNO3, while the anions were left unacidified in the field. For isotope studies, samples were left unfiltered and poured into 50 ml plastic vials in the field and tightly sealed in order to limit interaction between the atmosphere and the water. This is all in line with lab requirements and the protocol outlined by Weaver et al. (2007) for field sampling of major element chemistry in groundwater.

Rainwater and fog samples were collected at the end of the gutter at the hostel, in the immediate vicinity of SA BK 06 (Figure 3.4). These were first rinsed with sample water and then placed at the outlet pipe. In total three rain and two fog samples were collected in this manner over a period of a few hours.

Rainfall samplers were also constructed in the field using PET bottles. The upper parts were cut off and duct taped to the end of a bottle in order to act as a funnel. These two samplers were placed in close proximity to one another in the immediate vicinity of SA BK 06. Enough rainfall was captured in order to fill one 100ml HDPE bottle, which was returned to the laboratory for analysis

For chloride analysis, in the BEM laborotary , samples were titrated with silver nitrate. The carbonate and bicarbonate were titrated with hydrochloric acid. Nitrate was examined by using an auto-analyzer instrument using a cadmium reduction method and then determined spectrofotometrically. Sulphate, sodium, calcium and magnesium were all analysed by means of Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). The method makes use of the fact that excited electrons emit energy at a given wavelength and each element operates at a unique wavelength (Walsh, 1992).

Results from the BEM laboratory in Stellenbosch were then converted into milli-equivalents and statistically analysed in order to calculate error balances, following Hem (1986). Groundwater sample results with an error balance of less than 10% are selected. These were then plotted on a piper diagram.

Analytical methods for the stable isotopes analysis are outlined in Harris et al. (1999). Firstly the closed tube reduction method of Coleman et al. (1982) was used to reduce the water to H2. The CO2 equilibration method of Socki et al. (1992) was applied for the oxygen isotopes. Thereafter the measurement of the isotopes was done with a Finnegan MAT252 mass spectrometer. The resulting deterium and Oxygen 18 values were plotted alongside the global as well as Western Cape Local Meteoric Water Line, as recommended by Craig (1961) and Diamond & Harris (1997), respectively. Reported analytical error for the stable isotopes was ± 0.1 for the Oxygen 18 and ± 1.0 for the Deterium, respectively.

The chloride values were used in order to determine the recharge in the local vicinity. A method, known as the Chloride Mass Balance, was deemed as the most applicable to the fractured rock aquifers (Cook, 2003). Data from the DWA, from January 1983 to October 2009, for local rainfall was used and the average annual rainfall were calculated. Chloride for rainfall was determined by taking the harmonic mean from the rainfall samples taken from the first sampling run. Dry deposition of local chlorides assumed to be 0.1 mg/l as suggested by Van Tonder. (2002). The chloride values at late times were used for wells that had multiple samples extracted. For wells with single samples these Chloride values were utilised. The methodology employed is described in detail by Xu and Beekman. (2003)

3.4.2 Geology:

The geological map for Sutherland (CGS, 1983) was studied in order to better understand the subsurface and its relationship with hydrogeology and pedology (Figure 3.1). Mapping of the dolerites in the area was aided by SPOT 5 imagery. Images were uploaded into Quantum version GIS 1.5. and then rendered as a three band colour image. Bands 1, 2 and 3 were chosen for the Red, Blue and Green bands, respectively. The dolerites could be clearly seen and digitised in a distinct grey (Figure 3.2). A completed map was compared with the existing geological map of the area. Previously drilled logs of wells SABK01, SABK 04 and SABK05 were examined in order to better understand the subsurface geology. The drill chips from various depths were closely inspected in order to document the geology at various depths. Further *in situ* measurements of the strata were completed with a clinometre. Fracture sets were studied and outcrops were examined. The orientation and number of fractures were plotted on a rose diagram.

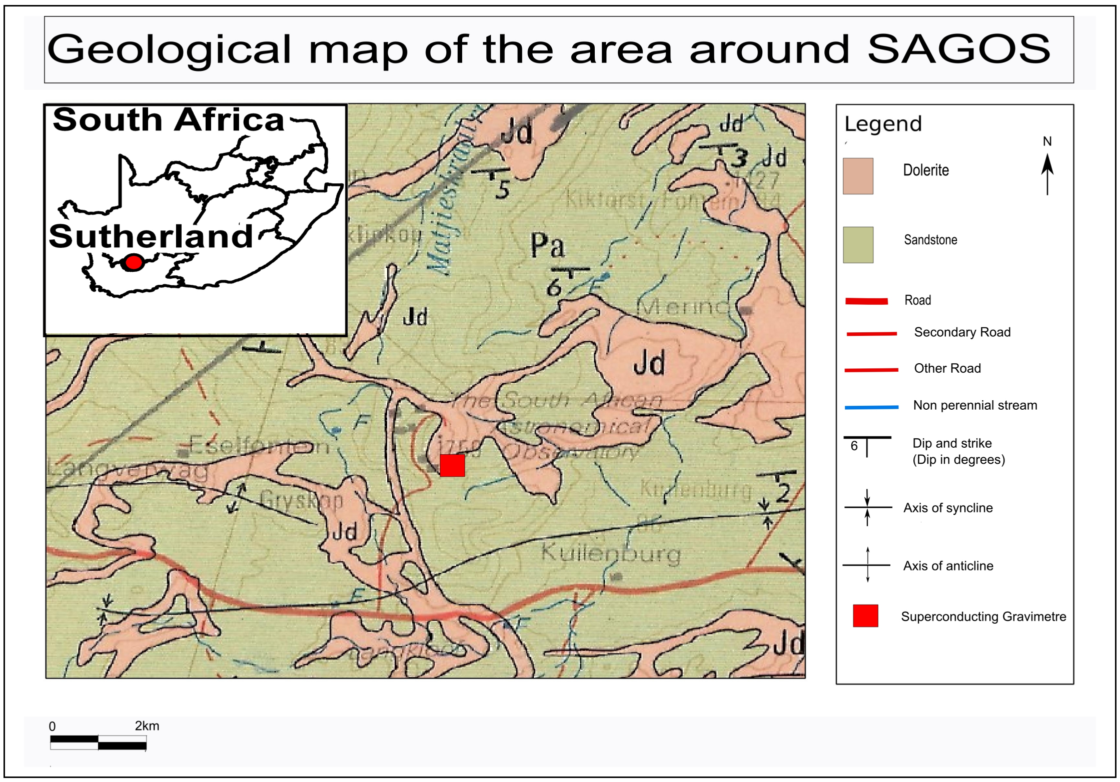

Figure 3.1: Geology around the SAGOS. Dolerite sills and dykes intrude the sandstone of the Beaufort Group, that dominates the area (Abrahamskraal Formation) (Council for Geoscience, 1983)

3.4.3 Hydrogeology:

The differing pump test methods for the various wells was undertaken due to the type of tests conducted in the well as well as due to the time frames of these tests. The pump test methods have the following general assumptions:

- The aquifer is confined
- The aquifer has a seemingly infinite areal extent
- The aquifer is homogenous, isotropic and of uniform thickness over the area influenced by the test
- Prior to pumping the piezometric surface is horizontal (or nearly so) over the area influenced by the test
- The aquifer is pumped at a constant discharge rate
- The well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow

Furthermore the following assumptions are included for the Cooper Jacob method:

- The flow to the well is in an unsteady state
- the well radius is small and time is sufficiently large

The Birsoy Summers method on the other hand excludes the assumption of a constant discharge rate and instead replaces this with an assumption that the aquifer is pumped step wise or intermittently at a variable discharge rate or is intermittently pumped at a constant discharge rate.

Measurements of the groundwater levels were taken at continuous time intervals within the well during the pump test, in order to determine drawdown. After pumping, the wells were then monitored for recovery, and in the case of SABK04 and SABK05 multiple tests were completed (Table 3.2). In the case of the latter the entire well was emptied leaving little or no water after the pumping phase. By contrast SA BK 06 was only pumped once for a short while and then monitored for recovery. The use of pump tests to characterise aquifer parameters has been outlined by Fetter (2001) as well as Weight and Sonderegger (2001). Advice for conducting and interpreting pump tests in fractured rock have been documented by Cook (2003). A manual for pump test analysis for Karoo aquifers has also been developed by Van Tonder et al. (2002) and this manual was consulted for the pump test design and the interpretation of data.

Well Number	Average Discharge rates (l/s)			Time (in minutes)		
	1st step	2nd step	3rd step	1st step	2nd step	3rd step
SA BK 04	0.42	0.43	-	6	32	-
SA BK 05	0.23	1.3	0.84	12.75	6.5	24.41
SA BK 06	0.26	-	-	13.24	-	-

Table 3.2: Average discharge rates and time taken for steps of pump tests conducted

Results from the pump tests were graphed and compared (Figure 3.10). The data for SABK06 was analysed using the FC method Microsoft Excel® based macro (Van Tonder et al., 2001). The Cooper Jacob method, as shown by Kruseman and De Ridder (1990), as well as the Advanced and Basic FC method were implemented for the well. The data is plotted on a semi log and a straight line is drawn through the data until a point on the x axis (Fetter, 2001). Early and late times are ignored and the straight line is drawn mainly through the majority of the data. The initial time is taken from the intersection point on the x axis. Transmissivity and Storativity are calculated from the formulae below:

$$T = \frac{2.3Q}{4\pi\Delta(h0-h)}$$

$$S = \frac{2.25Tt0}{r^2}$$

where:

T	is the transmissivity ()
Q	is the pumping rate (litres per second)
∆ (h0-h)	is the drawdown per log cycle of time (minutes)
S	is the storativity (dimensionless)
r	is the radial distance to the well (metres)
t0	is the time where the straight line intersects the X axis (minutes)

Results were tabulated and interpreted (Table 3.2). The storativity, and transmissivity values were computed in the same Microsoft Excel® based software using the methodology of Birsoy and Summers (1980) for SABK04 and SABK05 as outlined in Kruseman and De Ridder (2000). The methodology is similar to that of Cooper and Jacob, as outlined before.

3.5 Results:

3.5.1 Geology:

In the immediate vicinity of the SAGOS site, a doleritic sill occurs below the SG, which is located on a hill. Drill logs reveal that the uppermost layer is comprised of red soil, which is clayey, and regolith of unconsolidated doleritic gravels overlies the dolerite cap rock. The uppermost five metres of dolerite varies in terms of weathering grade and fracture intensity with indications of sub-vertical jointing. SA BK 01, which is one of the drilled boreholes, reveals that the dolerite layer has a maximum thickness of 20 metres (Appendix A). Borehole depth varies considerably due to the altitude of the well and the amount of consolidated material overlying the fractured zone and thus the depth to the water strike. (Table 3.3)

Borehole	Latitude	Longitude	Altitude of well (mamsl)	Total depth of well (mbgl)	Water strikes (mbgl)
SA BK 01	-32.3816	20.8105	1794.25	131	122
SA BK 04	-32.3859	20.8084	1686.17	120	117
SA BK 05	-32.3868	20.7981	1583.30	19	7 and 11

Table 3.3: Location of drilled wells and water strikes within these wells

The dip of the beds is 6° South. Two locations reveal distinct sets of cross cutting fractures. The major fractures are aligned in a NE-SW direction. The secondary fractures are W-E. (Figure 3.2). These geological features, as well as riverbeds, could act as preferential pathways for infiltration and ultimately recharge (Adams et al., 2001). The fracture measurements were taken in the immediate vicinity of the soil cross profiles (Figure 4.1).

Latitude	Longitude	Fracture orientation	Number of Fractures
32.3696	20.8041	40°	7
32.3696	20.8041	82°	4
32.3696	20.8041	159°	3
32.3733	20.7937	38°	2
32.3733	20.7937	79°	1

Table 3.4 : Location of fracture sets, their orientation as well as number of fractures in the study area. These fracture sets were used to construct the rose diagram.

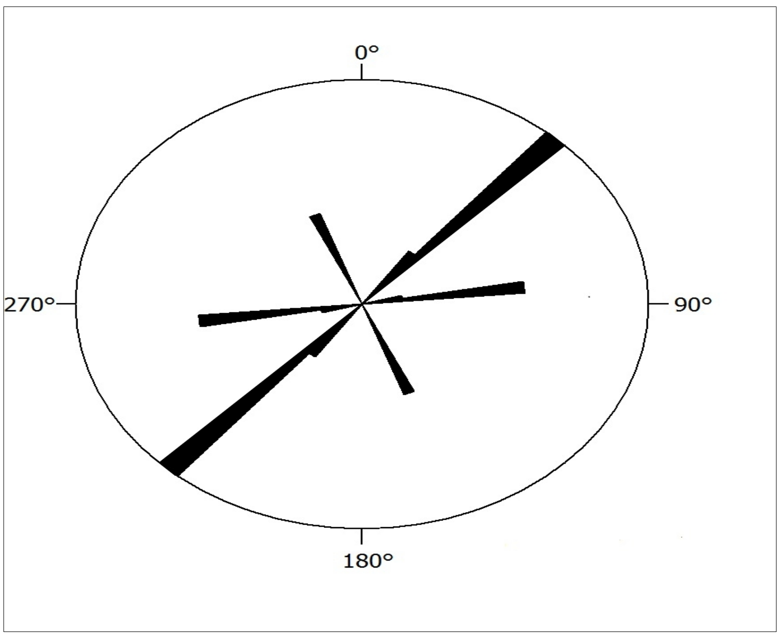

Figure 3.2: Rose diagram of the major fracture orientation in the study area. The NE-SW trending fractures dominate, whereas the W-E fractures are minor.

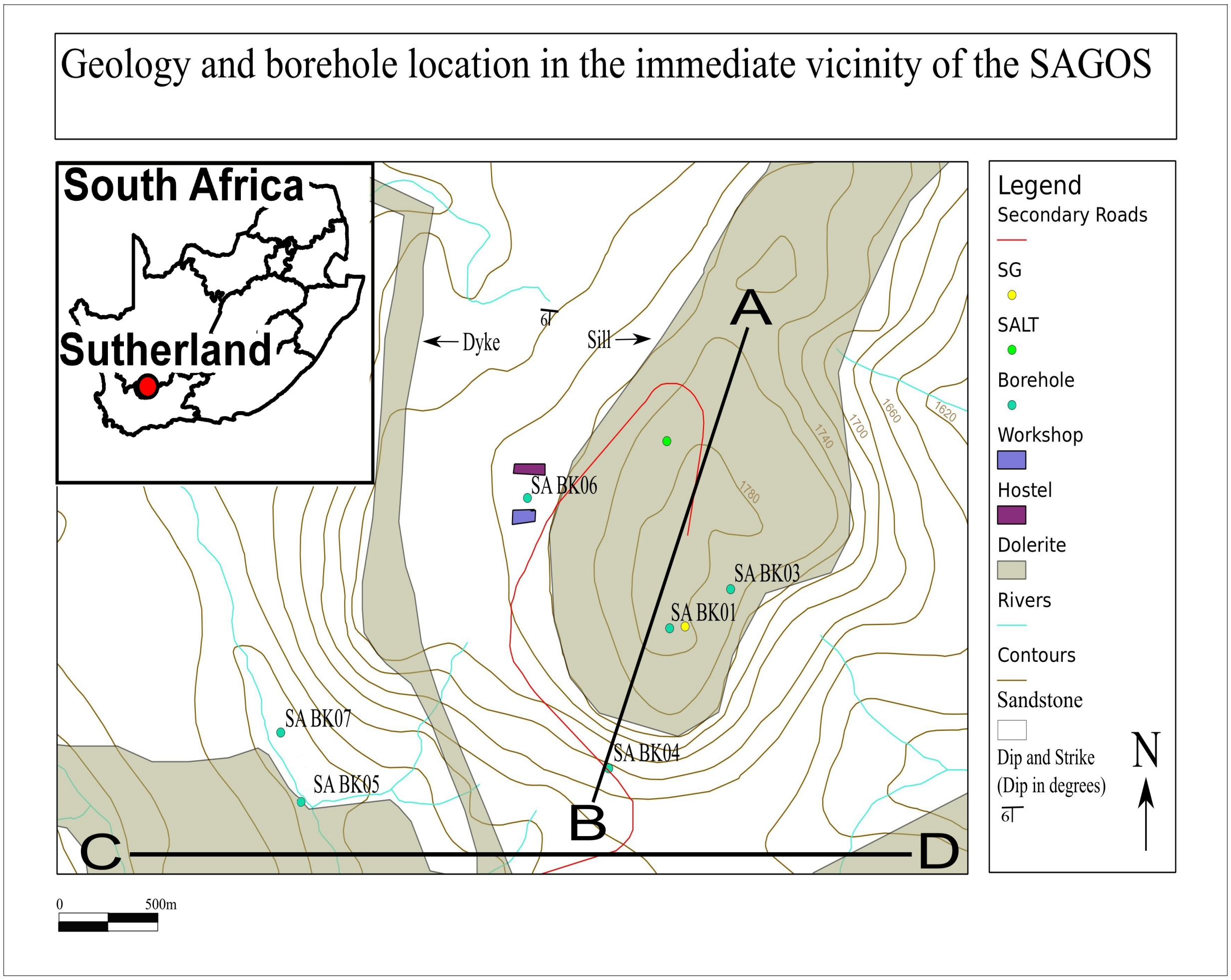

Figure 3.3: Dolerite map of the study area indicating a dyke and sill in the immediate vicnity of the SG. Furthermore the Sandstone in the area forms part of the Beaufort Group and has been classified as the Abrahamskraal formation. The site also houses the South African Large Telescope (SALT).

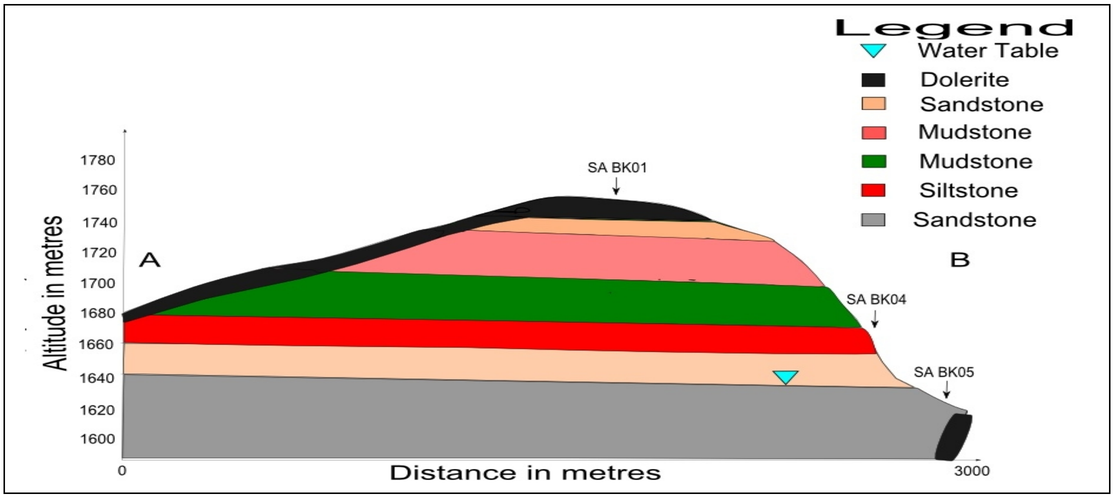

Figure 3.4: Geological cross section of the line A-B indicated on figure 3.3. A 6 degree dip in a southerly direction occurs from A to B. Intercalated mudstone and sandstone beds dominate the geology. The water table is based on the water level in SA BK 04.

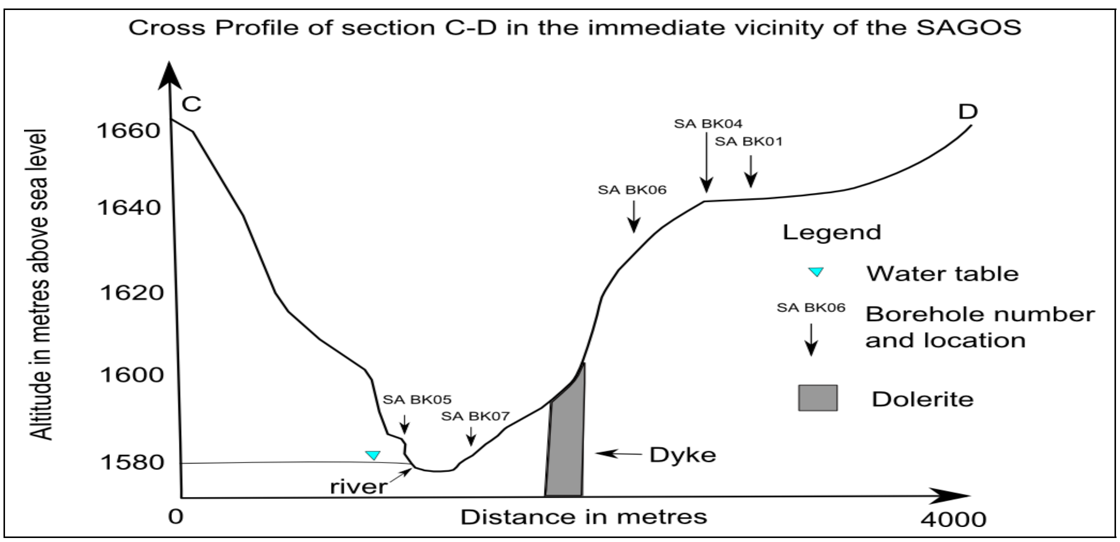

Figure 3.5: Cross profile of section B-D indicated on Figure 3.3 with the N-S trending dyke dividing the area. Note the water table west of the river. The location of the wells is also shown. The water table is based on the water level in SA BK 05.

3.5.2 Hydrogeochemistry:

The geochemical characteristics of the groundwater in the basin is shown in Figure 3.6. There are no distinct trends. Groundwater from SA BK 7 is an outlier when compared to the other wells and displays a signature of Na-HCO_3 type water. This is generally typical of deeper fresher water, but in this case the stench of sulphides was notable in the field, suggesting that the water is sourced from an anoxic environment. Thus the water is likely stagnant and possibly represents a perched water table. Waters from SA BK 4 on the other hand are typical Ca- HCO^- type waters, reflecting freshly recharged water. SA BK 1 as well as SA BK 5 reveal no real dominant water type, but trend towards the Ca (Mg)- HCO_3 type water. These samples show higher levels of salinity than SA BK 4 and SA BK 7. The waters stemming from SA BK 6 shows a trend towards Ca-Cl- SO4 type water. The higher concentration of salinity is evident from the elevated TDS values.

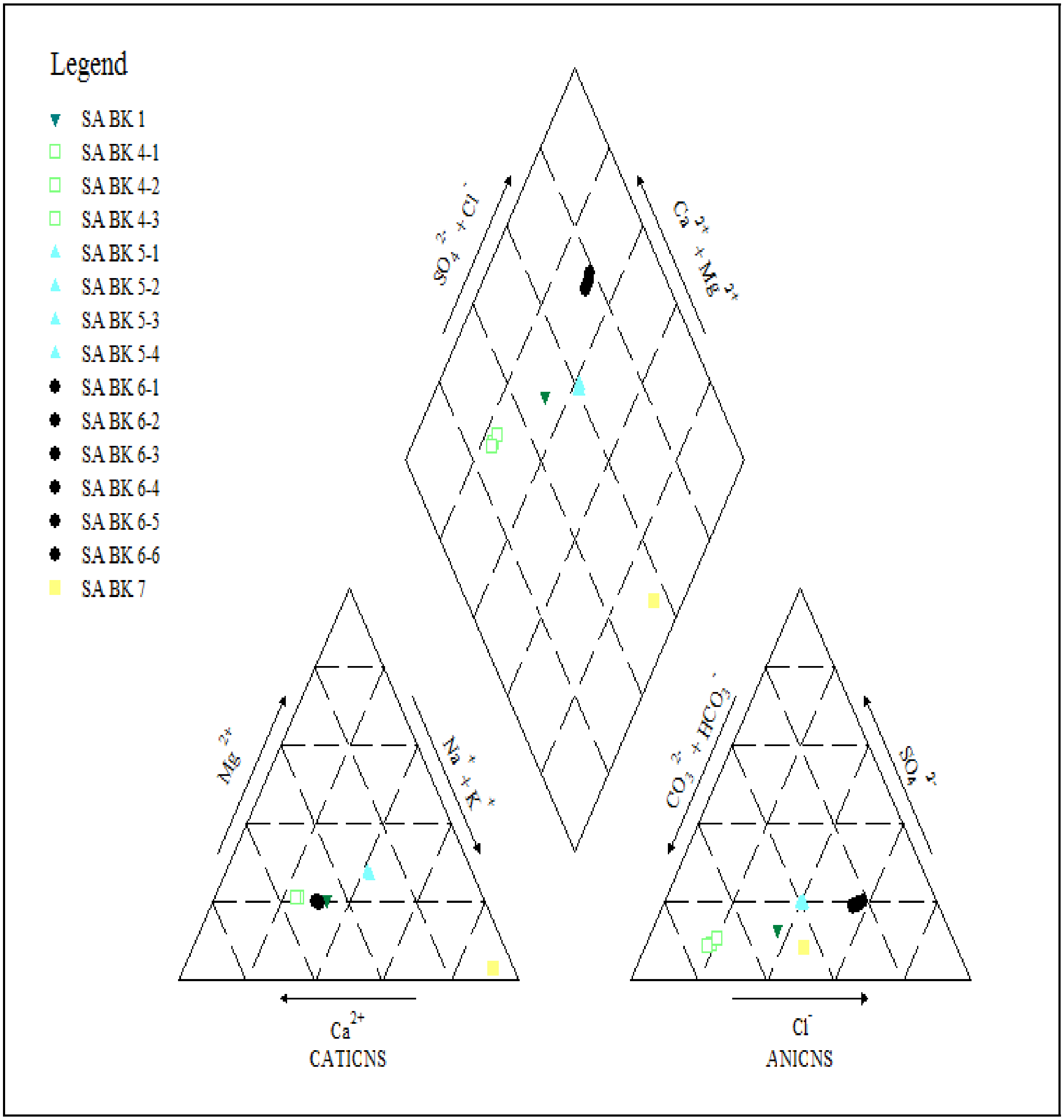

Figure 3.6: Piper plot for groundwater samples taken in the vicinity of the SAGOS

Sample Number	Date	pH	Temperature	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	CO_2^-	SO_4^{2-}	Cl^-	δO18	δH2	Error Balance	EC μ S/cm
SA BK 1	19/04/2010	8	15.4	70.53	2.36	86.44	23.01	260.29	15.06	57.81	123.36	-3.39	-29.44	2.11	959
SA BK 04-01	17/04/2010	7.81	16.4	31.10	1.01	62.46	14.55	244.98	12.05	26.63	42.29	-6.26	-38.85	-0.61	556
SA BK 04-02	17/04/2010	7.81	17.3	32.31	0.9	62.94	14.88	211.29	9.04	27.04	38.77			6.17	555
SA BK 04-03	17/04/2010	7.64	17.6	29.85	0.34	59.77	13.74	244.98	15.06	25.64	40.53	-6.41	-34.06	-2.45	557
SA BK 04-04	17/04/2010											-6.39	-37.27		
SA BK 05-01	14/04/2010	7.79	16.3	206.46	1.17	133.25	72.03	505.26	60.24	247.63	387.70	-4.51	-28.75	-6.06	224
SA BK 05-02	14/04/2010	7.34	18.4	191.62	1.12	116.82	63.22	471.58	57.23	221.42	354.21	-4.68	-30.13	-7.04	213
SA BK 05-03	14/04/2010	7.68	18.4	196.55	1.06	125.14	66.71	489.95	45.18	234.91	348.93	-4.72	-30.73	-5.70	217
SA BK 05-04	14/04/2010	7.68	18.4	200.23	1.23	127.57	67.86	486.89	69.28	237.51	361.26	-4.61	-29.29	-5.54	217
SA BK 06-01	13/04/2010	8.25	13.8	237.25	1.22	324.82	79.23	428.71	60.24	348.84	773.63	-5.19	-33.72	-4.38	
SA BK 06-02	13/04/2010	7.60	18.9	256.36	0.52	342.84	84.47	425.65	87.35	364.76	796.54			-2.51	3400
SA BK 06-03	13/04/2010	7.92	17.5	255.45	0.56	339.80	82.75	431.77	60.24	362.96	805.35	-5.22	-31.75	-3.40	3400
SA BK 06-04	13/04/2010	7.89	18	240.66	0.49	341.17	83.81	419.52	45.18	366.32	785.96	-5.24	-32.04	-3.19	3440
SA BK 06-05	13/04/2010	7.86	18.5	253.48	0.62	343.10	84.37	428.71	72.29	378.67	810.64	-5.12	-32.70	-3.66	3460
SA BK 06-06	13/04/2010	7.87	18.6	246.92	0.54	335.59	82.45	422.58	105.42	368.61	817.68	-5.11	-29.51	-4.70	3450
SA BK 07	19/04/2010	8.72	15.6	157.17	0	8.71	2.49	214.35	30.12	38.59	167.41	-6.08	-37.98	-9.45	874
Stream	17/04/2010	7.08	13.5	7.41	0.67	10.79	2.57	27.56	0	6.69	17.62	1.18	26.33		14
Rainfall 1	17/04/2010	8.31	15	0.18	0	0.2	0	19.9	0	0.60	2.64	2.15	28.60		11.2
Rainfall 2	17/04/2010	7.49	14.4	0.15	0	0.52	0	22.97	0	0.69	3.52	3.63	35.74		12.8
Rainfall 3	17/04/2010	7.24	14.7	0.07	0	0.31	0	6.12	0	0.54	2.64	4.33	40.85		15
Rainfall 4	17/04/2010			0.02	0	0.26	0	15.31	0	0.51	3.52	4.55	41.24		
Rainfall 5	17/04/2010			0.55	0	0.84	0.06	30.62	0	2.14	7.05	2.02	26.64		
Fog 1	16/04/2010	7.13	9.8	1.1	0	5.97	0.72	45.93	0	1.77	3.52				79.5
Fog 2	16/04/2010	7.20	9.3	0.8	0	8.10	0.84	59.7	0	1.82	4.41	0.26	16.88	-	75.3
SA BK 04	22/09/2010	7.22	16.8	28.9	0.9	62.1	14.40	0	0	26	48.50	-6.44	-33.33	48.9	560
SA BK 05	22/09/2010	5.5	14.6	191.10	1.2	145.80	75.1	0	0	262	357.80	-4.15	-26.8	16.74	2.64
SA BK 06	22/09/2010	7.23	17.7	224	0.7	331.4	74.3	0	0	318	788.70	-4.94	-27.9	5.79	410
SA BK 07	22/09/2010	6.01	12.9	144.8	0.3	10	2.7	0	0	181	163.90	-6.06	-35.3	-8.84	890
Stream	21/09/2010	7.68	84.5	22	3.6	47.2	12	0	0	53	96.90	-4.39	-29.1	6.75	84.5
Rainfall 1	21/09/2010	7.30	4.8									-9.01	-53.1		34.3
Rainfall 2	21/09/2010	6.31	5.8									-5.06	-25.7		16.4
Rainfall 3	21/09/2010	7.17	6.1									-11.04	-74.1		27

Table 3.5: Chemical composition of water samples taken in the immediate vicinity of the SAGOS site.

The plotting of Na+K-Cl versus [(Ca+Mg)-(HCO3 +SO4)] gives greater insight into the dominant processes contributing to hydrogeochemical evolution. It can be seen in Figure 3.7 that two distinct groups of samples are present. Extensive increase in salinity resulting from an imbalance can be seen in Figures 3.7 and 3.8 specifically for samples stemming from SA BK 6.

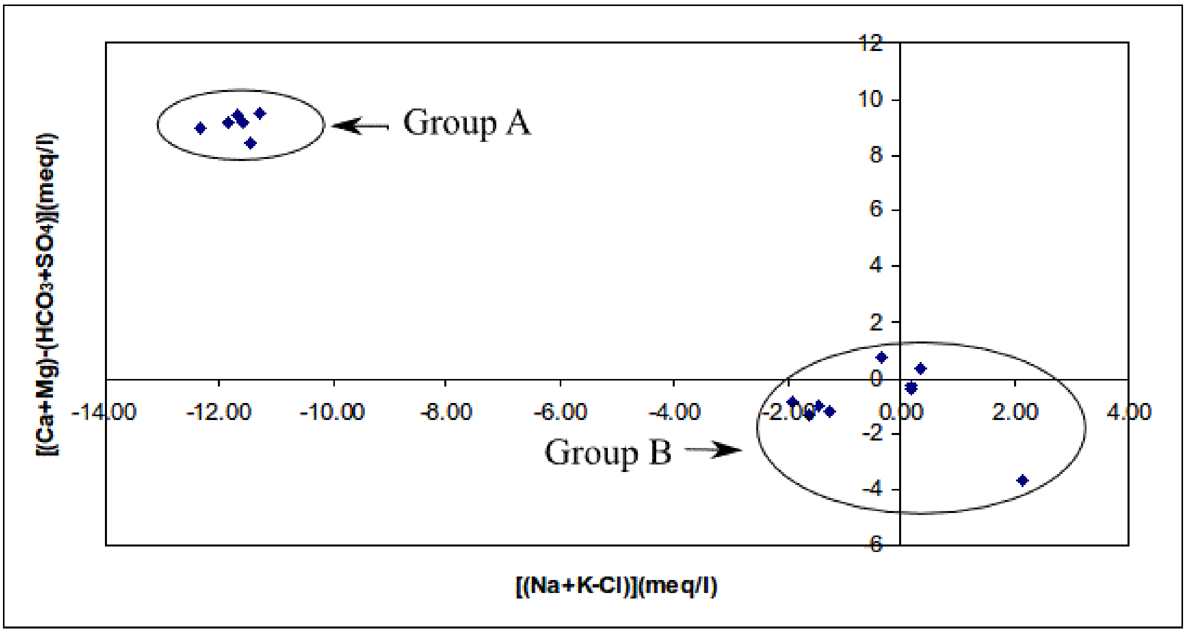

Figure 3.7: Relationship between [Na+K-Cl] and [(Ca+Mg)-(HCO3 +SO4)] in groundwater. Samples plotting around the axis are indicative of a balanced between the cations and anions and most likely stem from natural sources (Group B). Group A on the other hand, which is sampled solely from SABK06, plots at a distance from the axis and indicates contamination

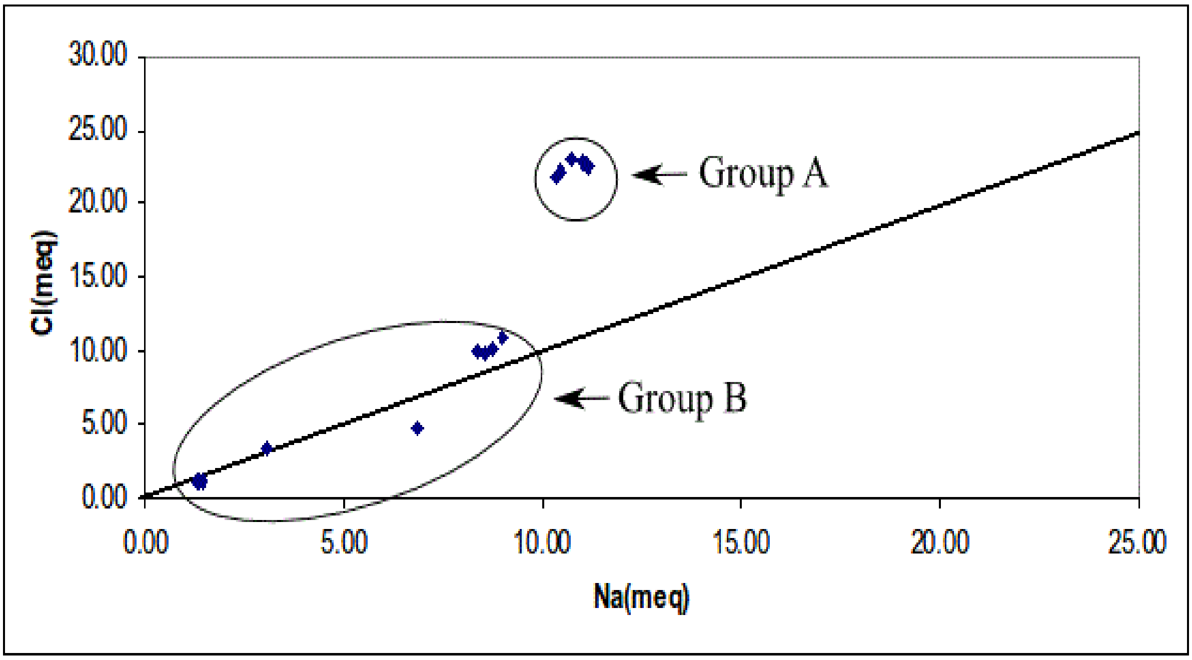

Figure 3.8: Relationship between Na and Cl in the groundwater samples with a halite dissolution line. Values plotting at a greater distance from the line indicate external sources of Na and Cl. Group A, which stems from SABK06, indicates an imbalance in Na and Cl values. Group B on the other hand, which represents the remaining wells in the area, indicates a more balanced relationship between Na and Cl with data plotting closer ot the halite dissolution line.

Newly sampled stable isotope data is similar to that of Adams et al. (2001). All groundwater sample data plots are in close vicinity to the meteoric water line. This source of groundwater has thus not been significantly affected by evaporation. This can be seen from the close proximity of the samples to the meteoric water line and not an extreme trend towards the y axis as shown in other arid regions (Kendall & McDonnell, 1998). Groundwater samples plot in close proximity to each other (Figure 3.9). The surface water grab sample, which was taken in the immediate vicinity of the soil cross section (Figure 4.1), plots in close proximity to the fog as well as precipitation rainfall samples in the positive quadrant.

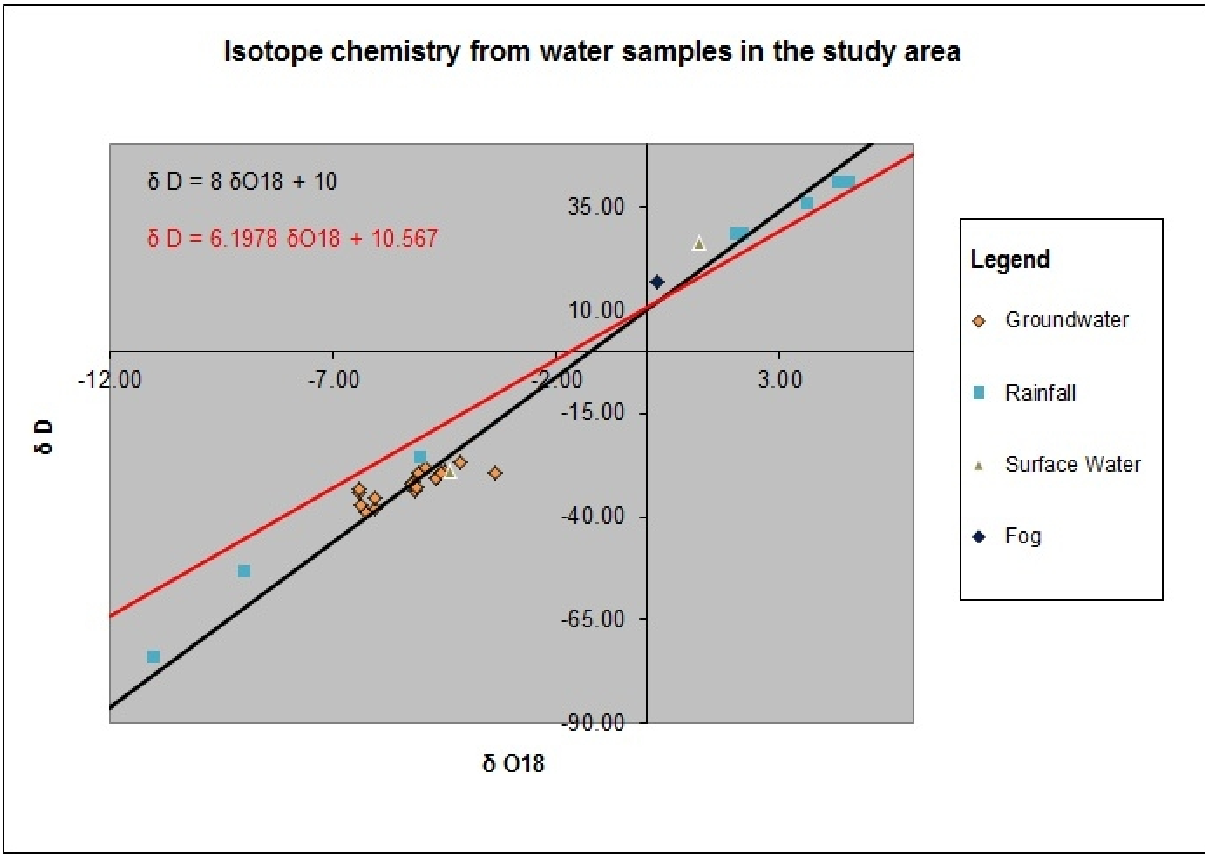

Figure 3.9: Isotopic data for water samples taken in the vicinity of the SAGOS. Local and global meteoric water line are shown in red and black, respectively. Groundwater data plots between the rainfall data indicates a mixture of rainfall events contributing to recharge.

3.5.3 Hydrogeology:

Hydraulic head measurements in the study area indicate lower water tables to the south (Table 3.6). This in turn suggests flow in a southerly direction. Major fracture orientation in the area trends are NE-SW, with a southerly dip of 6 degrees.

Borehole	*Latitude*	*Longitude*	*Altitude*	*Water level (mbcl)*	*Casing height*	Hydraulic head (mamsl)
SA BK 01	-32.3816	20.8105	1794.25	78.8	0.16	1715.29
SA BK 04	-32.3859	20.8084	1686.17	34.39	0.35	1650.84
SA BK 05	-32.3868	20.7981	1583.30	4.83	0.25	1578.22
SA BK 06	-32.3776	20.8056	1737.74	10.85	0.1	1726.79
SA BK 07	-32.3848	20.7971	1588.04	0.7	0.42	1586.92

Table 3.6: Location of boreholes and their respective water levels taken on the same date as the first sampling event for each well in Table 3.5 for the respective wells.

In the study area a dyke trending in a NW direction apparently acts as a seperator between the boreholes to its east and to the west of this intrusion. An extensive drilling programme in the vicinity of the SG has shown a fairly well consolidated dolerite at depth below the subsurface. Further drilling revealed that the 20 metre thick dolerite cap on top of the hill overlies a saturated geologic unit. There is also a distinct relationship between aquifer response and borehole proximity to the dolerite. This can be seen from the recovery in the pump test analysis whereby SA BK 05 recovers faster than SA BK 04 (Figure 3.10). The latter borehole is located farther away from the dolerite intrusion in the area.

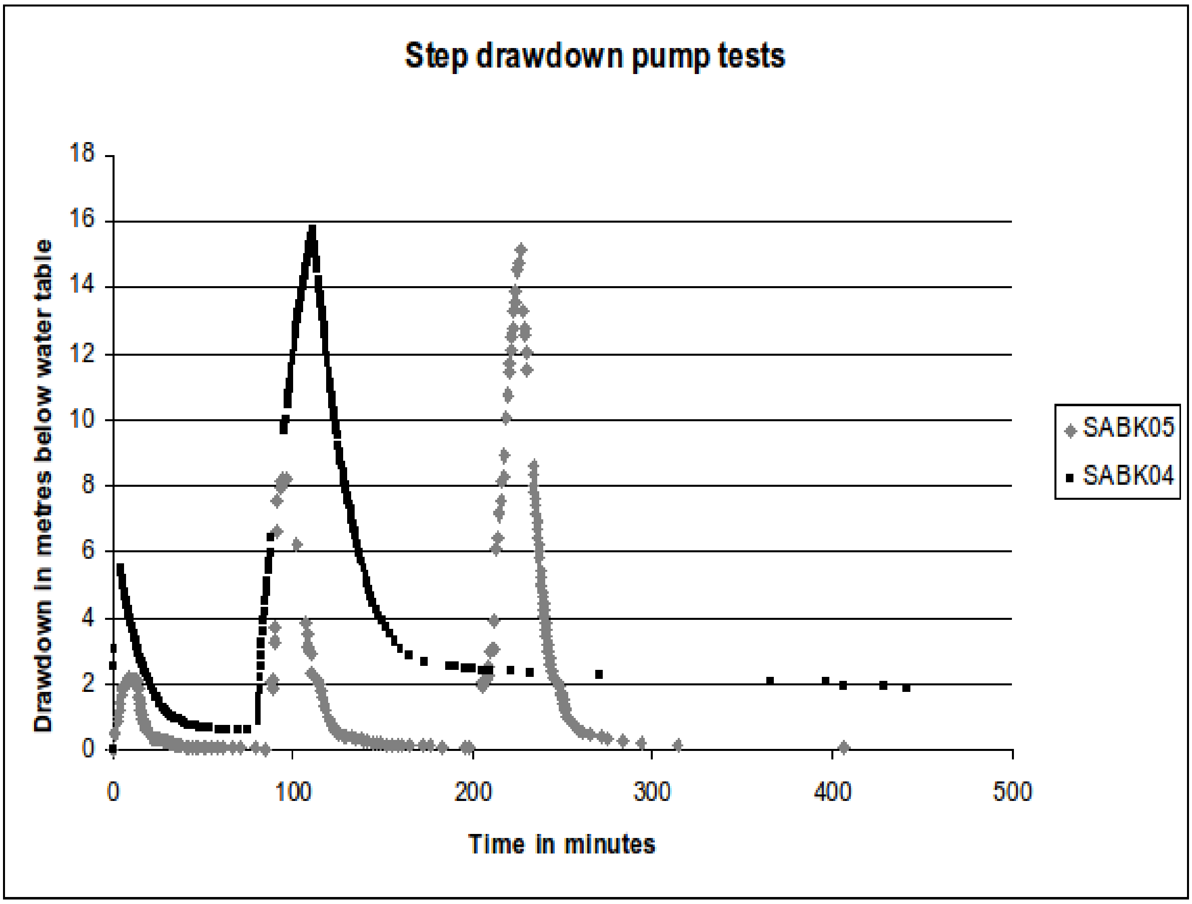

Figure 3.10: Hydraulic response to pumping and recovery in wells SABK05 and SABK04. The slow recovery rate of SABK04, when compared to SABK05, could possibly be attributed to the distance from the dyke.

SABK06 pump test results yielded transmissivity values of 0.1 m^2/day for both the basic and advanced FC. The Cooper Jacob value on the other hand was 0.3 m^2/day. These values are close to one another and much smaller than the transmissivity values for the other two wells. This relationship between proximity to the dyke and increase in transmissivity can be seen from SABK04 and SABK05, which are located much closer to the dolerite extrusion in the area as compared to SABK06. Drill logs for SABK05 reveal contact with the dyke due to a mineralised or baked zone being drilled through. Also two water strikes were penetrated implying higher hydraulic conductivity in this well. No observations of this nature were made in the other drilled wells.

Problems arose during the pump tests due to the limited amount of water in all the wells as well as the slow recovery rates, which did not allow the pump tests to be carried out for extensive periods or at high discharge rates. This is clearly evident from the complete emptying of SABK05 during the pump test. Time frames and discharge rates for the various pump tests are given in Table 3.2. The methodology of (Birsoy & Summers 1980), which was the most applicable for SABK04 and SABK05, did not have all the assumptions fulfilled as outlined in Kruseman and De Ridder (2000). Weight & Sonderegger (2001) have shown that the complications, assumptions and applications of pump tests.

Borehole Number	Aquifer parameter	
	Transmissivity (m^2/day)	Storativity
SABK04	2	1.00E-04
SABK05	10	1.00E-05

Table 3.7: Aquifer parameters determined from pump tests for SABK04 and SABK05

Storativity values are also all in the same order of magnitude with the basic FC and Cooper Jacob method being 0.005. The advance FC on the other hand was 0.001. These results as well as those of SABK04 and SABK05 fall within reasonable estimates outlined by (Kirchner and Van Tonder, 1991). This dimensionless value has captured the attention of Bredenkamp et al . (1995) who compared multiple methods, besides pump tests, for more accurately determining storativity in the fractured rocks of the Karoo aquifers.

3.6 Discussions and Interpretation:

3.6.1 Geology:

The dip of the beds, lower water tables in the south, as well as orientation of fractures, which are all in a southerly direction, further aids the argument of the regional groundwater flow being in a southerly direction. The conceptual model of Adams et al. (2001) states that these preferential pathways, as well as the riverbeds, are the main locations for water infiltration and subsequently recharge. This is consistent with stable isotope data for the water samples.

3.5.2 Hydrogeochemistry:

With regards to the Group A from Figure 3.8, which stems solely from SABK06, we see an indication for external inputs or contamination. This is because values at great distances from the origin points towards the enrichment of certain ions (Abid et al., 2010). In the study area Na, K and Cl are elevated in the groundwater of SABK06. The increased salinity in SA BK06 possibly represents a longer residence time or anthropogenic inputs. The well is in the immediate vicinity of a workshop, and the surface outside of the workshop is slopes in the direction of the well with runoff containing detergents as well as petroleum products.

The anomalously positive precipitation values of the stable isotopes may possibly be due to the migration of fog and the subsequent mixing with atmospheric moisture. Kendall and McDonnell (1998) have shown in numerous case studies how such vapour, which normally originates from terrestrial evaporation, can be forced to migrate to higher altitudes and mix there with local moisture and be further isotopically enriched, like the study area. This could be due to the evaporation of surface water bodies and the subsequent migration of moisture filled air up the South African escarpment.

With regards to the depleted precipitation values, which have low values in deterium and Oxygen 18, it has been shown that these are typical of cold fronts and thunderstorms (Gat, 1996). This is to be expected in the area of Sutherland as the source of precipitation on the escarpment varies throughout the year and cold fronts and thunderstorms are not uncommon (Tyson and Preston-Whyte, 2000). It can also clearly be seen that the groundwater isotopes plot in between all these precipitation values (Figure 3.9). This suggests that the inputs from these rainfall events are the cause of the recharge and have mixed with the groundwater as shown in many other cases by Kendall and McDonnell (1998).

Evaporation values in the area are two to three times as much as than rainfall (Mukheibir and Sparks, 2006). This suggests that if ponded waters were to recharge groundwater it would be evident in the stable isotope data, due to the fractionation of the recharged water, as well as an increase in salinity as shown in other arid areas (Subyani, 2005). It can thus be concluded that riverbeds and fractures are preferential pathways for infiltration due to their ability to cumulatively absorb greater amounts of water in short periods of time.

3.5.3 Hydrogeology:

The lower flow in SABK06 must be attributed to distance from the dyke and thus fracture density related tot he intrusions. Woodford and Chevallier (2002) have shown also how borehole yield increases with proximity to the dyke and attribute it to fracture density. Cook (2003) has pointed to the fact that fracture density and transmissivity are inextricably linked in fractured rock aquifers. This must also be the reason for higher hydraulic conductivity and recovery in SA BK05 as it is closer to the dyke in the south then SA BK04 and SA BK06.

3.6 Conclusions:

The data in the area collected indicates flow is in a south westerly direction. This is likely due to the decreasing head as well as the NE- SW orientation of fractures. These preferential pathways also act as conduits for recharge. Dolerite sills seem to limit infiltration and also dictate flow directions. Proximity to the dyke intrusions is directly linked to fracture connectivity and therefore hydraulic conductivity within the subsurface. Pump test data affirms this when comparing SA BK 5, which is closer to the dolerite, to SA BK 4. This is due to the fact that pump test recovery rates are much slower further away from the dyke.

Hydrogeochemical data also suggests localised water tables with little interaction between wells. This difference is greater than 100m when comparing static water levels of certain well. This ties in well with a model of fracture connectivity that is higher close to dykes and that tightly packed sandstones limit flow at greater distances away from the dykes. Furthermore major ion chemistry has shown that an increase in salinity occurs in well SABK06 due to possible contaminant inputs from a workshop in the immediate vicinity of the well.

Isotope data shows little or no evaporation effect. This likely suggests that the preferential pathways are conduits for recharge, as also proposed by Adams et al (2001). Furthermore the plotting of groundwater data between rainfall samples suggest that this external water source (e.g. precipitation) is the major contributor to the saturated zone.

This study has shown that the use of multiple methods for characterisation of the hydrogeological regime is an excellent tool for the understanding of inputs and dominant flow mechanisms. Geology, geochemistry and aquifer hydraulics are inextricably linked and need to be examined alongside one another in order to aid in conceptual model development. This will in turn help determine the selection of numerical models and improve the understanding and ultimately management of groundwater resources.

CHAPTER 4
IN SITU HYDRAULIC PROPERTIES OF SOILS SURROUNDING THE SAGOS

4.1 Overview

The soils surrounding the South African Geodynamic Observatory, Sutherland, are examined. This was done in order to characterise their properties and in turn to evaluate the dominant processes controlling the local hydrological regime. The initial visit included the application of brilliant blue dye tracer to 1m^2 vegetated and 1m^2 unvegetated plot of soil. The plots were then dug up and the movement of tracer in a cross section of the subsurface was noted by means of measuring flow paths and photos of each cross section removed. Soil mapping was undertaken through the use of satellite imagery followed by field verification. In conjunction with the ground mapping, soil profiles were exposed in order to examine the subsurface characteristics of the soil. The red duplex soils have an average thickness of 40cm. Thereafter infiltration tests were conducted randomly across the terrain in order to determine the in-situ properties of the soils in the region. Laboratory tests indicate a low clay content at the surface. This could be attributed to high wind velocity. Column seperation and seiving results correlate well for the samples taken in the field. It is shown that the infiltration capacity of the multi-layered soils surrounding the gravimeter decreases with depth. These results are all consistent with great spatial variability, laterally as well as vertically, within the soils of the study area. Finally it is shown that local rivers beds are hydraulically conductive due to the coarse nature of the underlying gravel.

4.2 Introduction:

Soils hydraulics is of major importance in hydrological studies (Xu and Beekman, 2003). Christiansen et al. (2011) have shown, by means of gravity studies, how this interface between the surface water and groundwater is able to act as a storage facility, due to the adsorption capacity of the particles as well as the overall water retention capacity of the soil type (Marshall and Holmes, 1979). Furthermore, unsaturated media has been known to form preferential flowpaths like fingering, funnelling and short circuiting (Fetter 1999). Characterisation of these processes plays a major role in numerical modelling of flow occurring in macropores and storage occurring throughout the matrix (Šimůnek and van Genuchten, 2008).

Sami and Hughes (1996) have done extensive work in terms of characterising the hydrological and hydrogeological regime of Karoo catchments. Hughes and Sami (1992) have also shown how the riverbed is able to act as a conduit and thus preferentially drain water, specifically in ephemeral channels occurring in arid areas. Adams et al. (2001) have validated this with the use of isotopic data and suggest that these river beds are conduits for groundwater recharge in the study area.

NCR (2001) have shown the importance of furthering an understanding of dominant processes within the vadose zone, specifically those related to preferential flow. These have all been previously outlined in Section 2.3. There are multiple methods available to test for the dominating flow mechanisms within the subsurface. Flury and Wai (2003) advocate the use of tracers. The brilliant blue tracer known as Brilliant Blue FCF or more commonly known as CI Food Blue, is one of the most commonly used dye tracers in vadose zone hydrology (Flury and Wai, 2003).

Wang et al. (2006) similarly advocate the use of these tracers in mapping heterogeneities in the vadose zone. Forrer et al. (2000) have shown how image processing of the dye tracer tests allows one examine the migration of moisture in the subsurface. This is completed by means of analysing the cross section photograph of an excavated section of soil where the tracer has been applied to. The photograph is then uploaded into an image processing software and analysed in in order to determine the spatial distribution of the dye tracer quantitatively (Forrer et al., 2000).

Blume et al. (2009) have also used dye tracer experiments, in conjunction with other applications, like groundwater monitoring, surface water monitoring and soil moisture monitoring. This method of using multiple methods to understand subsurface flow gives greater insight and understanding for fluid movement in the unsaturated media. In turn, understanding these vadose zone processes aids in conceptual model development and the determination of dominant migration mechanisms, which then highlights the most pertinent factors to be used in subsequent numerical modelling, such as preferential flow (Šimůnek and van Genuchten 2008).

Soil classification is important for understanding the hydrology as well as the in-situ characteristics of the subsurface (van Schaik 2009). Fetter (1999) has also shown the that soil water flow could vary at depth due to preferential flow. This is why it is important to complete laboratory tests, in conjunction with in-situ applications, for the determination of soil type and characteristics.

Konert and Vandenberghe (1997) have shown that seive analysis is an important tool for better understanding the distribution of sediment size within a sample. This method further gives insight into dominant class of sediment and has also been shown to have a direct relationship with hydraulic conductivity (Alyamani and Sen 1993). The soil type also has implications for determining runoff, recharge and infiltration in a catchment (Van Tol et al., 2010).

The use of aerial photography in order to understand, manage and mitigate anthropogenic impacts on the environment has been advocated by Aber et al. (2010). Pellikka et al. (2005) has shown that the use of aerial photography could significantly aid soil erosion mapping. Kampouraki et al. (2008) have applied aerial photography to differentiate between soils, as well as landcover, and thus map them. This makes it the perfect tool for the shrub infested Karoo and eases the process of ground truthing and mapping in some regards.

4.3 Methodology

4.3.1 Field Infiltration tests and sampling:

The Decagon mini disk infiltrometer® was used in order to determine the infiltration rates in the area. A known volume of water was recorded and then allowed to infiltrate into the soil. During this process measurements were taken at constant time intervals for each test. Soil samples were then taken in the immediate vicinity of these infiltration tests. Two cross profiles of the stream in the area were also completed. Infiltration measurements were taken at various points across the stream in close vicinity to each other.

The initial and end infiltration rate was calculated using the formula:

$$q(h) = It/(\pi r^2)$$

where :

q = one dimensional steady state infiltration rate (cm/s)

h = tension, selected on the infiltrometer (cm)

It = infiltration rate at time t (mL/s)

R = radius of infiltrometer disk (cm)

Surface samples were taken at various locations across the entire catchment, as previously mentioned (Figure 4.1). They were allocated a sample number and abbreviation, based on location. Certain locations were examined at the subsurface and at depth. Thereafter sample locations, along with the rivers and contour lines of the study area, were plotted on a digital map using Quantum GIS 1.7. This point data highlights the spread of the samples across the area.

The samples were then grouped according the soil type classification methodology outlined by Fey (2010). This eliminative key has recently been proposed as a method to classify soils in South Africa (Table 4.1). Thereafter boxplots were created in order to examine the statistical significance of each sample and its relationship to other sample groups (Helsel and Hirsch, 2002).

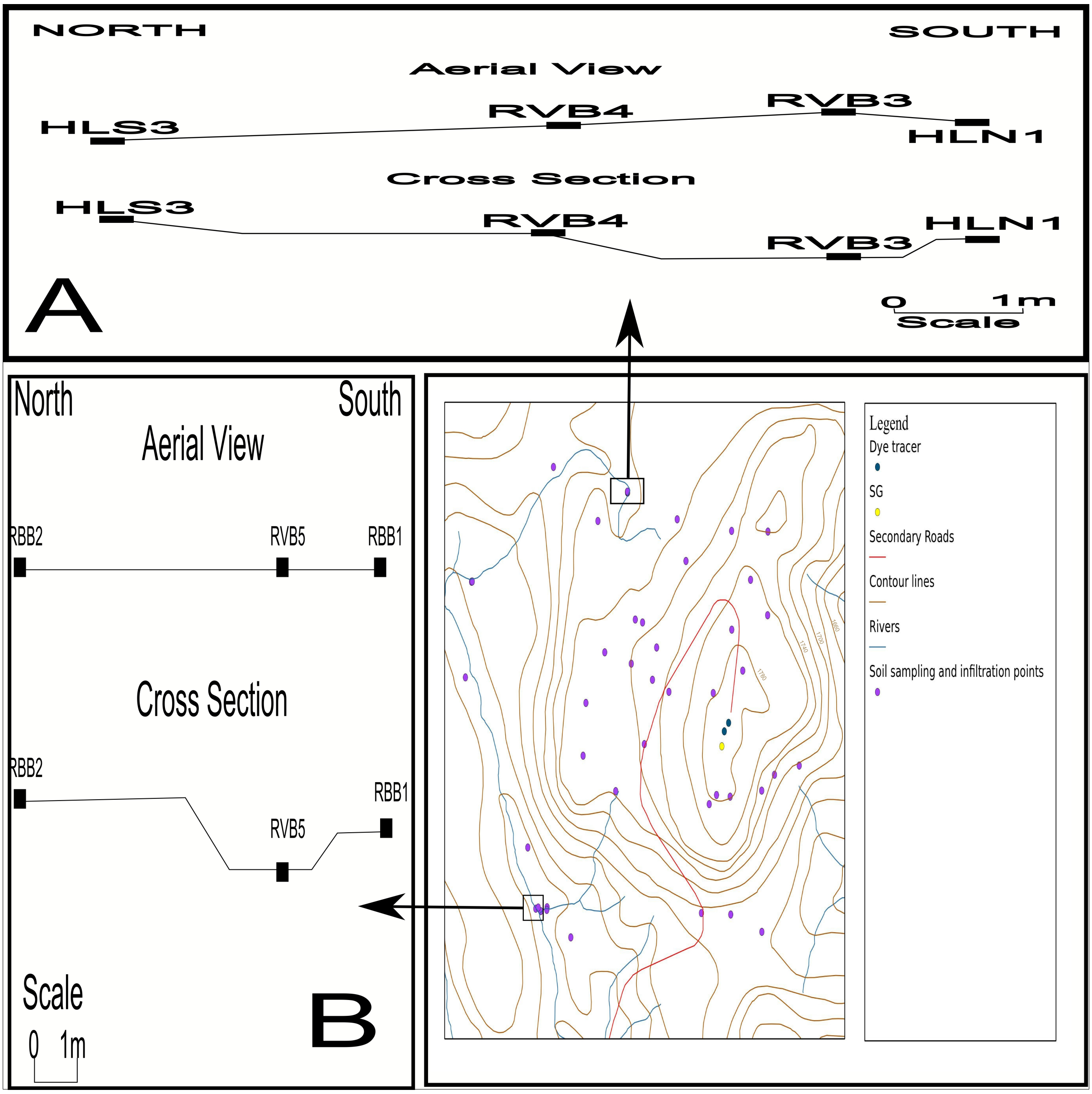

Figure 4.1: Map of soil sampling points and infiltration points in the immediate vicinity of the SG. The dye tracer tests are highlighted and a cross section shown (top left corner). Cross sections of infiltration tests done in the river at points in the study area are also shown (to the left and above the map)

Soil Group		Concept	Identification	Soil form
1	Organic	Wetland Peat	Organic O	Champagne
2	Humic	Humic enrichment	Humic A	Kranskop Magwa Inanda Lusiki Sweetwater Nomanci
3	Vertic	Swelling, cracking clay	Vertic A	Rensburg Arcadia
4	Melanic	Black Clay, high base status	Melanic A	Willowbrook Bonheim Steendal Immerpan Mayo Milkwood Inhoek
5	Silicic	Silica enrichment ; arid	Dorbank	Garies Oudtshoorn Trawal Knersvlakte
6	Calcic	Carbonate or gypsum enrichment	Soft or Hardpan carbonate or gypsic horizon	Molopo Askham Kimberly Plooysburg Etosha Gamoep Addo Prieska Brandvlei Coega
7	Duplex	Marked clay enrichment	Pedocutanic or prismacutanic B	Estcourt Klapmuts Sterkspruit Sepane Valsrivier Swartland
8	Podzolic	Metal Humate enrichment	Podzol B	Tstsikamma Lamotte Concordia Houhoek Jonkersberg Witfontein Pinegrove Groenkop
9	Plinthic	Iron enrichment (absolute); mottling or cementation	Soft or hard Plinthic B	Longlands Westleigh Avalon Lichtenburg Bainsvlei Wasbank Glencoe Dresden
10	Oxidic	Iron enrichment (residual); uniform colour	Red apedal, yellow brown apedal or red structured B	Pinedene Griffin Clovelly Bloemdal Hutton Shortlands Constantia
11	Gleyic	Reduction (aquic subsoil or wetland)	G	Kroonstad Katspruit
12	Cumulic	Young soil in unconsolidated sediment (colluvial, alluvial, aeolian)	Neocutanic or neocarbonate B, regic sand, deep E or stratified alluvium	Tukula OakleafMontagu Augrabies Namib Vilafontes Kinkelbos Fernwood Dundee
13	Lithic	Young soil on weathered rock	Lithocutanic B or hard rock	Glenrosa Mispah Cartref
14	Anthropic	Human disturbance	Disturbed material	Witbank

Table 4.1: Grouping of soils according to an eliminative key. Identification is based on specific characteristics related to horizons or materials. Sample identification begins at number 1 and moves down the table until a distinguishing feature is found (modified after Fey, 2010).

4.3.2 Laboratory tests:

4.3.2.1 Column separation:

Soil samples were tested in the laboratory in order separate the sediments and classify them. Initially samples were passed through 2000 micron and 63 micron sieve. Using methods outlined by Assaad et al. (2003). Dry and wet methods for determining the volumes of sand, silt and clay of a soil sample were applied. Particles larger than 2000 microns were weighed and classified gravel. Those less than 2000 microns but greater than 63 microns were classified as sand particles (e.g. Boggs, 1995). The component of the samples which passed through the 63 micron sieve was poured into 1 litre containers with de-ionised water and vigorously shaken. After twenty minutes the container was decanted and the residue at the base classified as silt and was placed in a separate container. The decanted water was then allowed to settle for 24 hours and then again decanted. The final accumulated material was considered as clay. The clay and silt components of the samples were dried at 50 degrees celcius for 24 hours. Each component was weighed and a percentage of the total weight was calculated. This wet method allowed the overall classification of the soil type.

4.3.2.2 Seive analysis:

Following Assaad et al. (2003), seives of various sizes were utilised in order to seperate the particles of different sizes. Each sample was weighed and then placed in the upper seive of 2000 microns. The sample was then placed in a shaker for two hours and allowed to pass through seives underlying the upper previously mentioned one. This was done to enable comparison of the results to the column seperation method.

4.3.3 Tracer tests:

Flury and Wai (2003) completed an extensive review related to the use of dyes tracers in vadose zone hydrology. It was concluded by the aforementioned authors that the brilliant blue dye, used in this study, was the most common tracer used. Flury et al. (1994) further advocate the use of the brilliant blue dye due to its non-toxic nature and minimal adsorption capacity to soil surfaces. This dye tracer was chosen for application in the study area.

Nobles et al. (2010) have shown in arid areas, like the study area, that the brilliant blue dye tracer highlights areas of preferential flow within the subsurface. Carminati et al. (2010) attributes this preferential flow in the vicinity of the rhizosphere to the expansion and contraction of roots. This in turn leads to the roots losing contact with the soil and creates the previously mentioned preferential pathways. This methodology of observing subsurface dye tracer flow was applied.

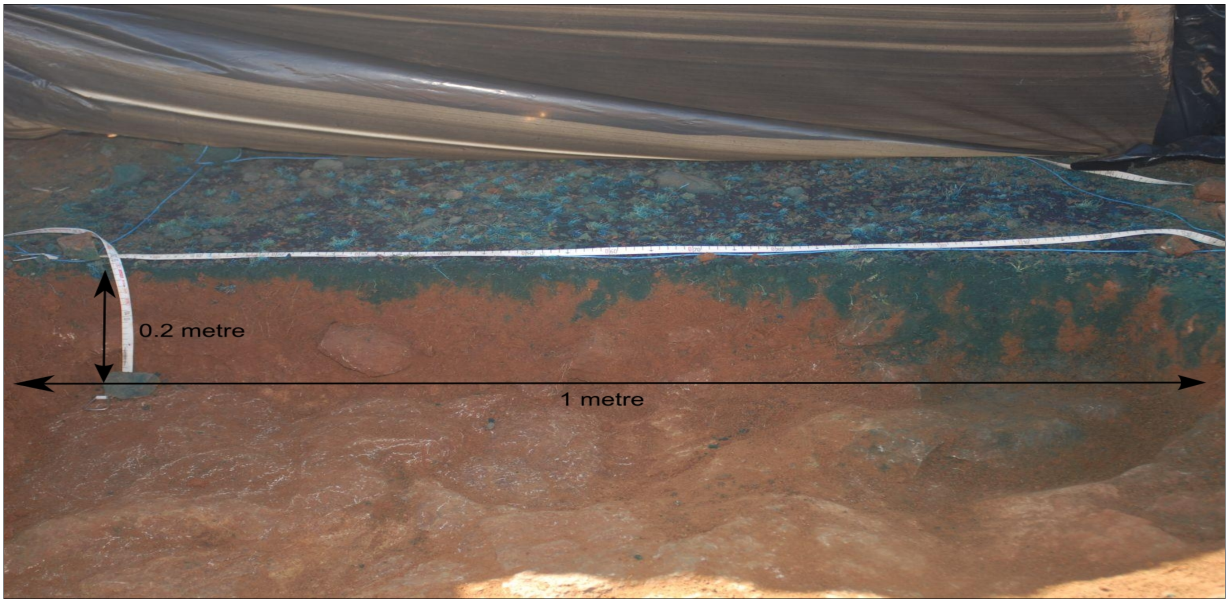

Figure 4.2: Cross section of dye tracer on unvegetated plot. It can clearly be seen that the dye tracer is limited in terms of its ability to penetrate the lower layers on the left of the profile. This is due to enrichment of clay.

These dye tracer tests were carried out on two plots of $1m^2$ in area (Figure 4.2). The first site was vegetated and the second one barren. These soil sites were sprayed with 25 litres of brilliant blue dye tracer which equates to 2.5 mm of rainfall for one plot. The concentration of the dye in water was 4g/l. Application of the dye was completed with a pesticide sprayer in order to simulate rainfall (Blume et al., 2009). Thereafter the soil was removed in sections of 20cm in order to observe, as well as captured by digital photos, of the migration of the dyed water through the subsurface. Measurements were made of some of the longest pathways travelled by the dye in the subsurface. Migration patterns were also observed on the respective plots by measuring the length of the preferential pathways.

4.3.4 Soil mapping:

A Google© earth image of the study area was examined to map variations in soil hue. Areas of differing soil colours were outlined and mapped from the aerial images. Upon completion field verification was carried out to ground-truth the map. This was completed by digging trenches in the various mapped areas and carrying out in-situ plasticity tests. Corrections to the initial map were made in the field according to observations. Trenches were dug in order to properly classify the soil according to the eliminative methodology for soil classification (Fey, 2010) (Figure 4.3). Thereafter the map was scanned and georeferenced. The latter exercise was completed in Quantum GIS version 1.7.0. Then the digitisation of the map was also done in the aforementioned software. Upon completion of the map the image was exported as a JPEG (Figure 4.7).

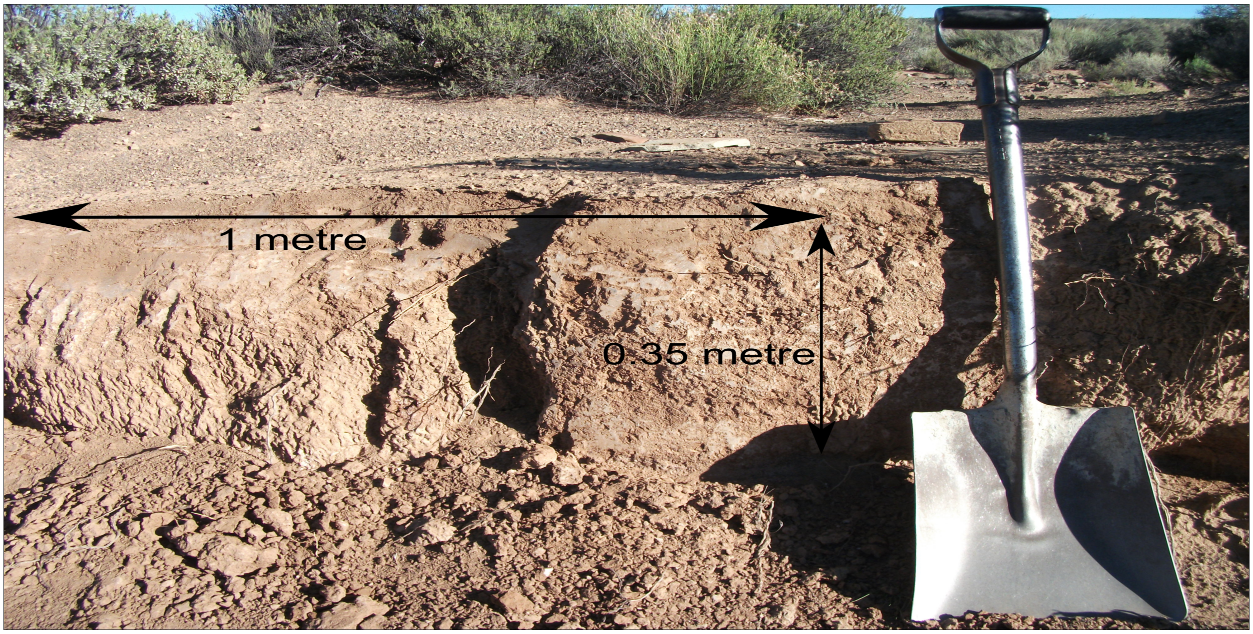

Figure 4.3: Trench dug in brown duplex soil in close proximity to the stream west of the SG station.

4.4. Results:

4.4.1 Infiltration tests

Initial infiltration rates within the basin are much greater in the riverbeds (Figure 4.4). Also on average this cumulic soil is the location for the highest initial infiltration. This preferentially higher flow can clearly be seen from Figure 4.4, whereby the median value of the cumulic soils exceeds the 75^{th} percentile value of all the other soil types. It is also evident that the variability within these cumulic soils is greater than others. The only outlier present is above the 75^{th} percentile within the lithic soil type. This sample is HLS2 and occurs within the head waters of a tributary to the stream west of the SG at cross section A.

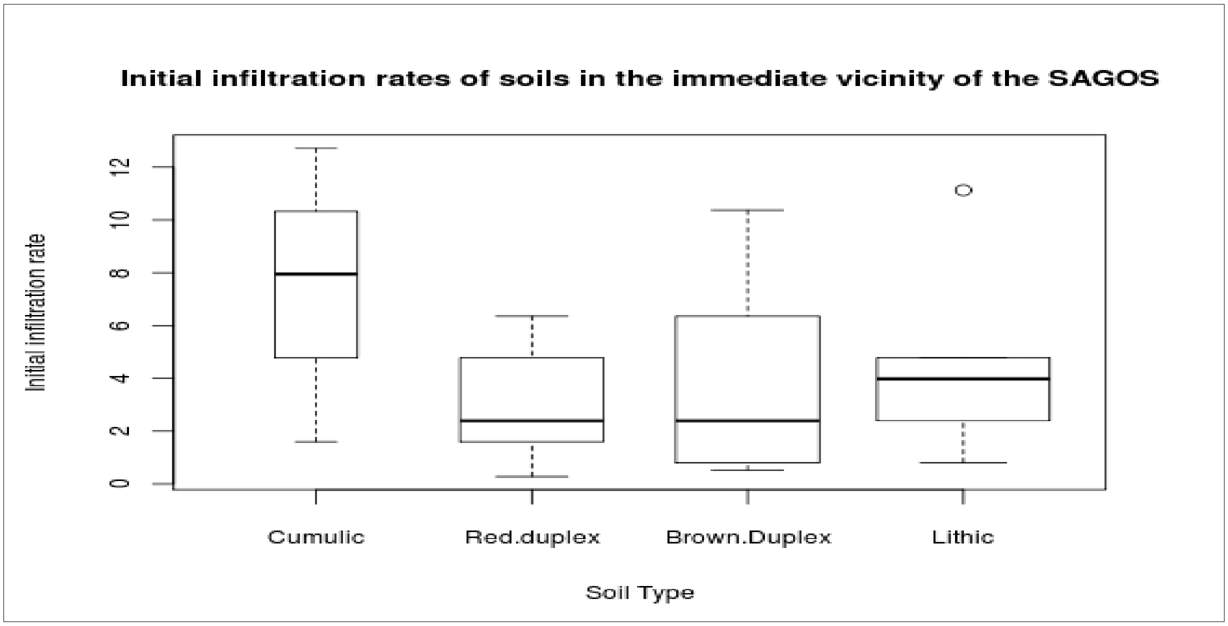

Figure 4.4: A comparison between the various soil types and their initial infiltration rates for all the sampled points. It is evident that the initial infiltration rates of the cumulic soils, which occur in the rivers, is much higher than all of the other samples. The thick line in the middle of the box is the median. The line above the median is the 75th percentile, whereas the line below it is the 25th percentile. The sample spread is indicated by the length of the box.

Attempts were made to spread the samples across the entire study area in order to gain a representative idea of the hydraulic properties of the soil. A total of 34 samples was taken (Table 4.2) with 13 Lithic, 3 Cumulic, 8 Brown duplex and 9 Red duplex samples. In only 4 cases were the initial and end infiltration rates of the infiltrometer tests the same. Two of these samples were in the river, and the remaining two on south facing slopes. In all the other cases the initial infiltration rates were greater than the end infiltration rate.

Sample Number	Latitude	Longitude	Altitude (mamsl)	Initial Infiltration Rate(cm/s)	End infiltration rate (cm/s)	Soil type
RVB3	-32.3696	20.8041	1656	1.59	1.59	Cumulic
RVB5	-32.3733	20.7937	1582	7.95	7.95	Cumulic
RVB4	-32.3696	20.8041	1656	12.72	2.39	Cumulic
HLE4	-32.3810	20.8157	1678	4.77	1.59	Lithic
FLT13	-32.3879	20.8132	1628	7.16	1.59	Brown Duplex
HLN2	-32.3733	20.8124	1749	4.77	0.80	Lithic
FLT8	-32.3763	20.8026	1700	0.53	0.27	Brown Duplex
FLT6	-32.3871	20.8111	1637	0.80	0.40	Brown Duplex
HLT2	-32.3822	20.8101	1764	6.36	1.59	Red Duplex
HLS6	-32.3686	20.7991	1624	0.27	0.27	Red Duplex
RBB1	-32.3733	20.7936	1584	3.18	0.80	Lithic
HLN1	-32.3696	20.8041	1656	4.77	1.59	Lithic
HLW5	-32.3844	20.7974	1566	4.77	0.80	Lithic
HLT4	-32.3770	20.8119	1761	0.80	0.27	Red Duplex
HLW4	-32.3712	20.8112	1714	0.80	0.27	Brown Duplex
HLT6	-32.3747	20.8136	1755	4.77	2.39	Red Duplex
HLS5	-32.3871	20.8091	1636	10.38	3.98	Brown Duplex
FLT5	-32.3823	20.8111	1764	1.59	0.13	Red Duplex
FLT10	-32.3806	20.8011	1710	3.98	0.80	Red Duplex
HLS2	-32.3820	20.8033	1690	11.13	3.18	Lithic
HLS1	-32.3826	20.8097	1756	0.8	0.8	Lithic
HLS4	-32.3713	20.8136	1737	4.77	0.80	Lithic
HLE3	-32.3813	20.8141	1707	2.39	0.80	Lithic
FLT9	-32.3784	20.8013	1705	2.39	0.80	Lithic
RBB2	-32.3733	20.7937	1629	3.98	0.80	Lithic
HLT6	-32.3747	20.8136	1755	4.77	2.39	Red Duplex
HLW2	-32.7790	20.8069	1739	2.39	0.80	Red Duplex
FLT11	-32.3801	20.8053	1712	4.77	0.80	Brown Duplex
HLT3	-32.3780	20.8099	1762	2.39	1.59	Red Duplex
HLE6	-32.3773	20.7932	1571	6.36	1.59	Brown duplex
FLT12	-32.3707	20.8075	1683	2.39	0.80	Brown Duplex
FLT7	-32.3767	20.8044	1707	0.80	0.13	Brown Duplex
HLS3	-32.3696	20.8041		0.80	0.00	Lithic
HLE2	-32.3820	20.8132	1716	3.98	0.40	Lithic

Table 4.2: Results for in-situ Initial and end infiltration rates of sampling points across the study area

Sample Name	Depth	Latitude	Longitude	Intiial inifltration rate (cm/s)	End infiltration rate (cm/s)	Soil type
HLT	surface	-32.3820	20.81	0	0.13	Red duplex
	10 cm below			0.27	0.27	Red duplex
HLS	surface	-32.3804	20.8056	5.57	3.98	Lithic
	7 cm below			1.59	0.8	Lithic
RVB	surface	-32.3767	20.7938	0	0.13	Brown duplex
	7 cm below			0.13	0.13	Brown duplex
HLE	surface	-32.3790	20.8053	1.06	0.27	Brown duplex
	6 cm below			0	0	Brown duplex

Table 4.3: Infiltration tests on the surface and at depth across the study area

Chittleborough (1992) has shown how duplex soils, similar to those in the study area, have the greatest variability in terms of texture and depth. Fey (2010) defines these duplex soils as a layered soil with marked enrichment of clay in the lower layer. It can clearly be seen that the infiltration rates at depth are more consistent, whereas we find greater differences occurring at the surface, especially in the duplex soils (Table 4.3). Fey (2010) suggests that the extensive illuviation in lower layers of duplex soils is due to the removal of finer particles by wind. This is the major reason for the clay accumulation in the subsurface, which is responsible for lower infiltration rates at depth. On the other hand in the lithic soil the infiltration rates are far greater than in the duplex soils, on the surface and at depth. These variations can also be seen from the surface infiltration tests in Table 4.3 with a decrease in infiltration rate over time. This is to be expected as the soil becomes saturated and the wetting front meets with the lower clay layer that possesses the ability to retard the flow of water (Marshall and Holmes, 1979).

The cross sections traversing the riverbeds have shown a higher initial and end infiltration rate than the locations on the riverbed. This can clearly be seen in Figure 4.5 as well as Figure 4.6. The initial infiltration rate in RVB4, Figure 4.6, is 3 to 4 times as much as any of the other locations in the same cross section. The initial and end infiltration rates in the sample RVB5 are the same.

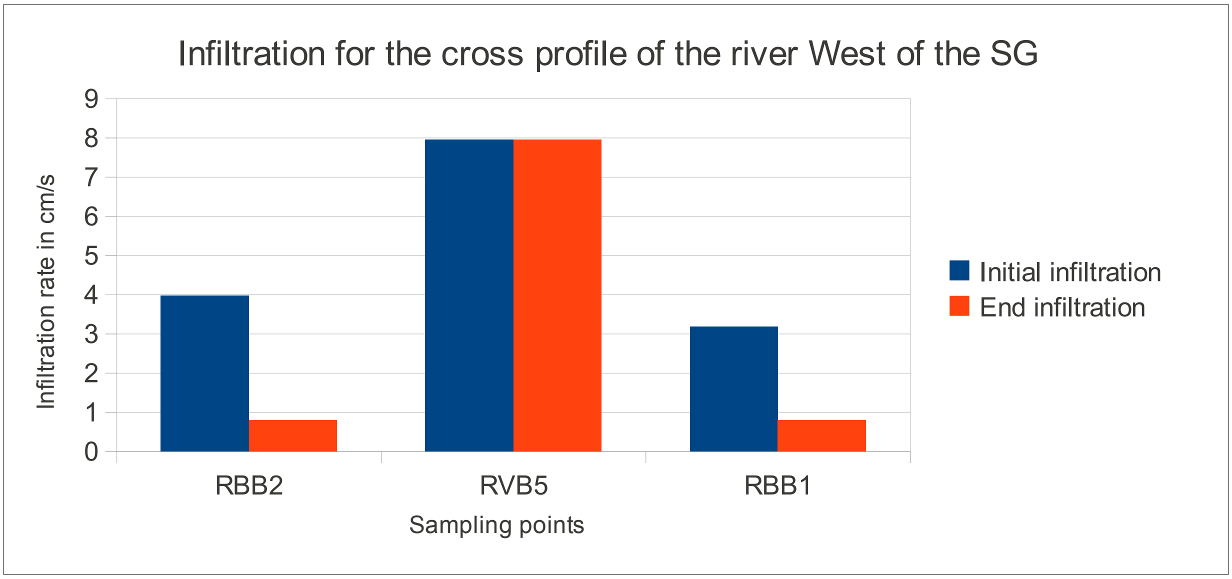

Figure 4.5: Infiltration values for the cross section measured across the river located west of the SG. Infiltration in the river (RVB5) is double at other closely located points.

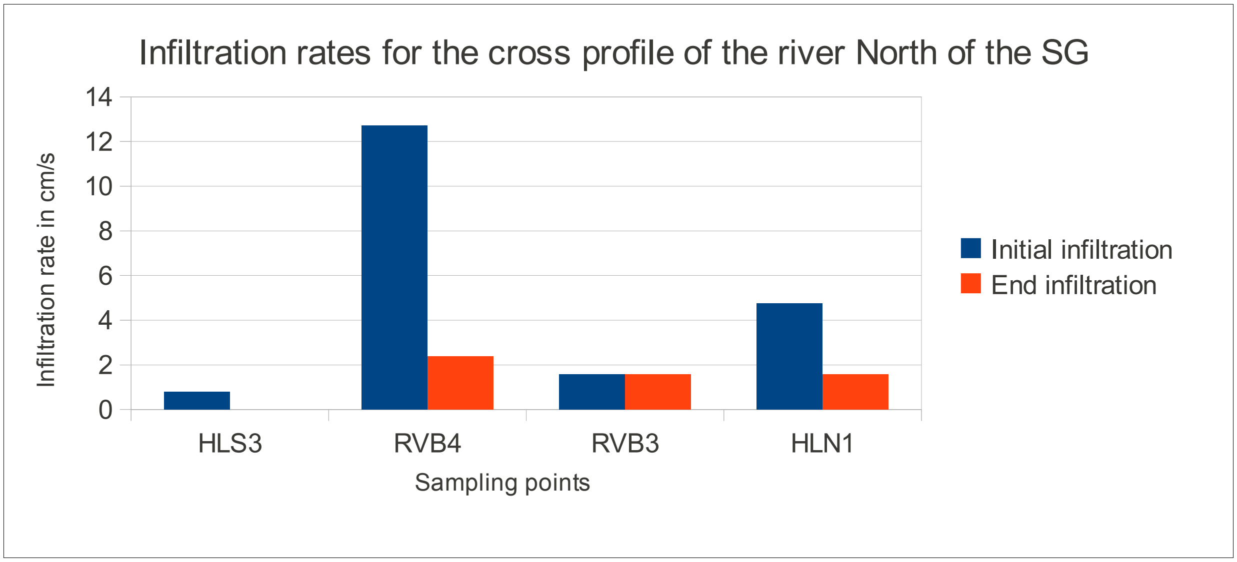

Figure 4.6: Infiltration values for the cross section measured across the river located northwest of the SG. It can clearly be seen that initial infiltration in the river (RVB4) is three times greater than HLN1. Furthermore the end infiltration rate in the river is 1 cm/s greater in than at any other sample point.

4.4.2 Tracer tests:

The soils of the area can be classified as mainly duplex (Fey, 2010). This soil type is normally derived from dolerite, which is abundant in this area. Field observations indicate and average thickness of about 30 cm. Tracer tests conducted in the vadose zone above these dolerites show that preferential flow in these clays predominates. Observations show further that a substantial amount of infiltration occurs in the vicinity of the rhizosphere. This leads one to believe that the ideas of Carminati et al. (2010), with regards to expansion and contraction in the vadose zone, have a substantial amount of weight. These infiltration tests have also proven that the underlying consolidated dolerite acts as a barrier for infiltration. This is shown by the fact that the tainted water was halted at the bedrock.

Cross section	10cm	20cm	40cm	60cm	80cm	100cm
Longest flowpath on vegetated plot	15cm	18cm	21cm	25cm	22cm	27cm
Longest flowpath on Bare plot	-	20cm	22cm	20cm	-	9cm

Table 4.4: Measurements of longest flowpaths on irrigation plot

On average the longest flow paths occurred within the vegetated plot in the study area (Table 4.4). Furthermore it was also noted that multiple preferential pathways occurred on this vegetated plot whereas preferential flow was limited on the non-vegetated plot. Also the flow on the non-vegetated plot was mainly confined to the upper layer, possibly due to the nature of the duplex soils and the illuviated lower layer with its ability to restrict infiltration (Marshall and Holmes, 1979)

Extensive ponding was noticed during the application of the brilliant blue dye tracer on the vegetated plot. This ponding occurred between rocks and not in the vicinity of the vegetation itself. Blume et al. (2009) attribute this ponding phenomena to capillary barriers or impeding layers. The latter scenario seems plausable due to the extensive preferential flow occurring in the vicinity of the vegetation along the rhizosphere. On the other hand there seems to be a barrier seperating the illuviated lower horizon from the sandy upper layer on certain cross sections on the unvegetated plot. This could be attributed to one of the major differences between the properties of sand and clay, which is the lower hydraulic conductivity of the latter soil type (Assaad et al., 2003). This means that the illuviated horizon of this duplex soil would limit the vertical movement of moisture and ultimately groundwater recharge (Xu & Beekman 2003).

4.4.3 Laboratory tests:

4.4.3.1 Column separation:

It can clearly be seen that most of the samples were classified as either sandy or loamy sand (Table 4.5). It should be noted that these samples are reflective of the surface characteristics of the study area and not at greater depth. Problems with the classification lie in the fact that particles larger than 2000 micron are classified as gravel and thus do not form part of the soil classification system (or triangle) which only considers sand, silt and clay components.

Samples from the riverbed, especially RVB3 and RVB5, display a large percentage of coarse gravel material. Other riverbed samples also have a substantial amount of gravel, but a greater sand content, such as RVB4. This method of classification completely differs to the in-situ eliminative key as outlined be Fey (2010). The samples RVB3 and RVB5 had a mud content, which is a combination of clay and silt, of 0.00126 and 0.00208 grams respectively. This volume is negligible when compared to the total volume of the sample and the amount of gravel stemming from these samples.

Sample Number	Initial weight(g)	Gravel weight(g)	Sand weight(g)	Silt Weight(g)	Clay weight(g)	Sand %	Silt %	Clay %	Soil Class
RVB3	11.1	5.6	5.5						Gravel
RVB5	10.4	6	4.4						Gravel
RVB4	10.7	2.2	8.2	0.2	0.00	96.93	2.84	0.23	Sand
HLE4	11.4	2.3	8.2	0.5	0.1	93.41	5.42	1.17	Sand
FLT13	10.6	1.5	0.77	0.9	0.3	86.52	9.77	3.71	Sand
HLN2	10.7	1.8	0.82	0.1	0.6	93.36	0.24	6.40	Sand
FLT8	10.5	3.2	0.69	0.3	0.1	95.81	3.49	0.70	Sand
FLT6	10.5	4.7	0.54	0.3	0.00	94.78	4.94	0.28	Sand
HLT2	10.1	2	0.72	0.7	0.00	90.43	9.28	0.29	Loamy Sand
HLS6	10.5	3.4	0.68	0.2	0.00	96.41	3.32	0.27	Sand
RBB1	10.1	2.3	0.58	0.14	0.1	85.30	14.09	0.61	Loamy Sand
HLN1	11.2	8.2	2.7	0.1	0.00	98.09	1.84	0.07	Sand
HLW5	12.2	3.9	7.9	0.3	0.00	96.23	3.61	0.16	Sand
HLT4	10.3	0.8	9.1	0.3	0.00	96.24	3.52	0.24	Sand
HLW4	10.5	2.2	7.1	0.9	0.1	87.67	11.49	0.84	Sand
HLT6	10.7	0.05	9.9	0.2	0.00	97.92	2.05	0.03	Sand
HLS5	9.2	1.7	6.7	0.6	0.00	91.70	7.90	0.40	Sand
FLT5	6.8	0.3	5.6	0.7	0.00	87.97	11.74	0.29	Loamy Sand
FLT10	9	0.2	7.9	0.7	0.1	91.38	7.86	0.77	Sand
HLS2	10.5	5	5.4	0.1	0.00	98.73	1.21	0.05	Sand
HLS1	10.2	3.9	5.4	0.5	0.1	89.78	8.98	1.24	Loamy Sand
HLS4	10.1	1.1	8.1	0.6	0.00	93.38	6.47	0.15	Sand
HLE3	10.3	2.4	6.4	1.31	0.00	84.17	15.21	0.62	Loamy Sand
FLT9	10.2	1.7	7.2	0.8	0.2	87.95	9.57	2.48	Sand
RBB2	10.3	3.2	6.2	0.7	0.00	89.26	10.32	0.42	Loamy Sand
HLT6	10.2	2	7.5	0.7	0.00	90.74	8.96	0.30	Sand
HLW2	10.4	2.9	6.9	0.4	0.00	94.25	5.47	0.28	Sand
FLT11	9.2	1.7	6.7	0.6	0.1	90.59	8.64	0.76	Sand
HLT3	10.6	0.5	9.8	0.3	0.00	97.38	2.53	0.09	Sand
HLE6	10.9	4.5	5.1	1.1	0.3	78.01	17.02	4.97	Sand
FLT12	101	1.4	7.3	1.1	0.4	83.52	12.44	4.04	Sand
FLT7	10.2	0.4	9.1	0.6	0.00	93.39	6.27	0.34	Sand
HLS3	10.5	8.4	1.7	0.3	0	81.95	16.24	1.81	Loamy Sand
HLE2		8.8	4.3	0.5	0.00	89.91	9.49	0.61	Sand

Table 4.5: Classification of soil type of samples in the study area by column seperation

Problems with the methodology arose in the laboratory due to the spillage of samples. The minimum amount of sample lost for for seive analysis was 0.05%, which is much less than for the 0.27% column seperation. The scenario for maximum losses on the other hand is the complete opposite with 13.89% of RVB4 lost via seive analysis and only 5.37% of HLE4 lost through the process of column separation. What was surprising was the fact that with the column seperation for HLT6 had a minor gain of 0.5%. This was the only anomaly, whereas for the seive analysis the samples HLT3 and HLE2 had gains of 0.3% and 0.01%, respectively.

4.4.3.2 Seive analyses :

It can clearly be seen from the data that the samples taken in the riverbeds have a substantial amount of gravel. This coarse material has been shown to have a greater hydraulic conductivity (Weight and Sonderegger 2001). Therefore the infiltration rates from the tests in the cumulic soils was also substantially higher.

Correlations between the gravel, sand and mud components of the laboratory methods yields values of 0.68, 0.67 and 0.71 respectively. Statistically the two methods are in strong agreement in terms of the results (Helsel and Hirsch 2002). By comparing methods, in conjunction with mapping, it also shows that the upper layer of soil has a major sandy component. Fey (2010) explains this and states that illuviation occurs in the lower layers. This could be attributed to the windy conditions which remove the finer particles from the surface.

4.4.4 Soil mapping

The eliminative methodology for soil classification as outlined by Fey (2010) was employed. The results yielded an extensive area underlain by duplex soil. The red and brown duplex soils, as they were further classified, dominate the hills and flatter areas, respectively. The lithic soils on the other hand seem to be more prevelant on the hillslopes and can be defined by their underdeveloped soil profile due to the extensive exposure of the parent rock material (Fey, 2010). The last major soil type occurs mainly within the riverbeds. This cumulic soil has extensive amounts of gravel, as shown in the soil classification.

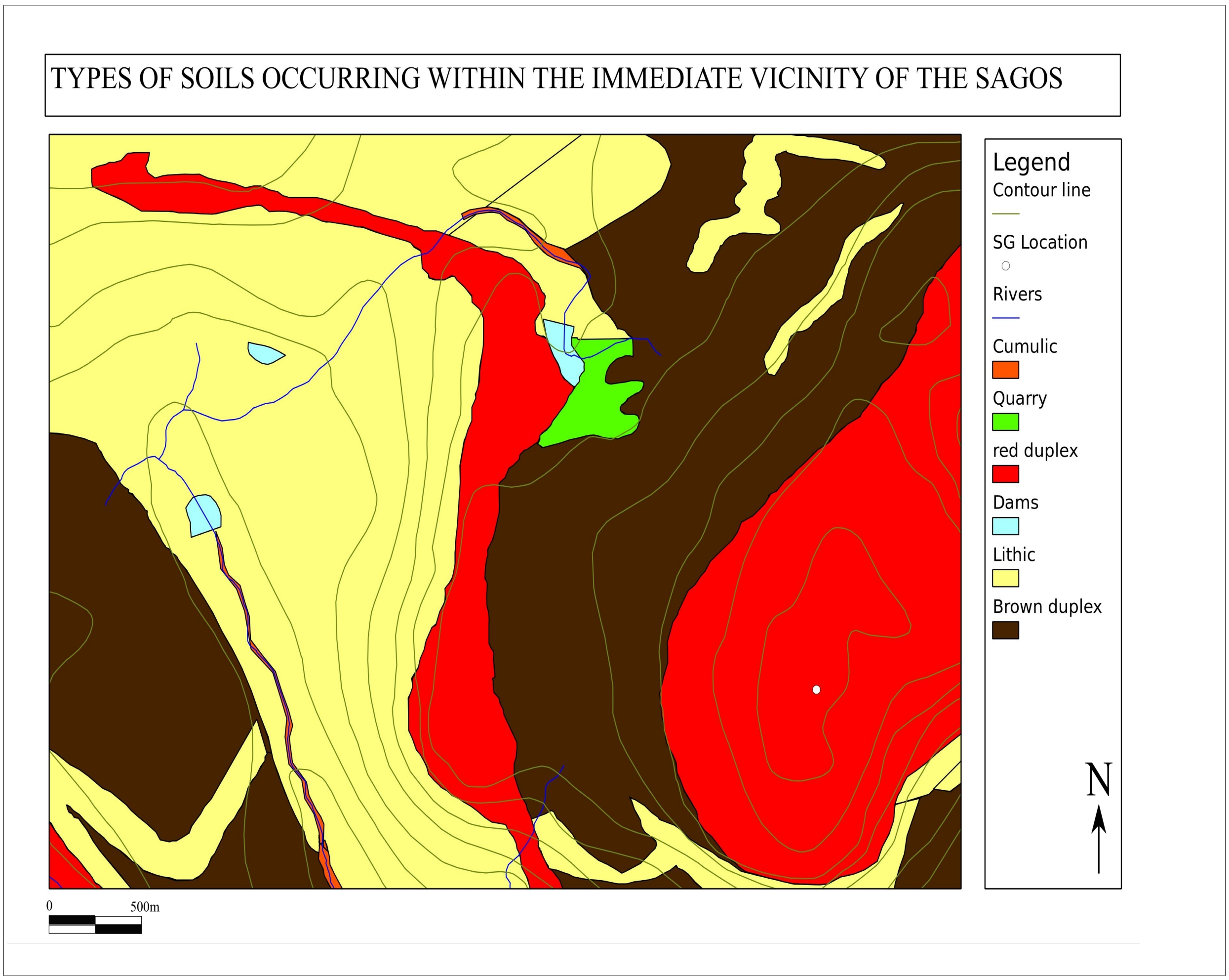

Figure 4.7: The various soil types in the study area mapped by satellite imagery.

Problems with the methodology lie in the simplified classification. This creates some confusion in the field as to the exact soil type, specifically in distinguishing between the lithic and cumulic soil types. Soil heterogeneity also plays a role in adversely affecting the accuracy of mapping. This has a definite relationship to issues of scaling as well as soil moisture variability (Western, 1999). Furthermore it was noted that in some instances patches of certain soil types would occur within masses of other types. This cannot always be seen from aerial photography and thus the importance of ground truthing for mapping exercises cannot be over-emphasized.

Field observations of this lithic soil point out extensive fracturing and jointing of the parent material. This can also be seen in the vicinity of HLS2, which is in the headwaters of ine of the tributaries in the study area. Vegetation has been noted to be more dense as well. Further in-situ observations highlight the protrusions of bedrock in the river, and in the region of HLS2, as well as the gravel nature of the cumulic soils present in the seasonal streams.

4.5 Discussion:

The analysis of all of the results are described in this section of work in order to better understand the relationship between the geology, hydrogeology, major water chemistry and isotope hydrology.

The box and whisker plot (Figure 4.4) reflects the variability within a sampled set. Its also a clear graphical comparison between different samples. In this specific case the thickness of the box, which is the square root of the number of observations within the group, also aids in interpreting the diagram. The sample number, as well as variance, plays a significant role in affecting the length of the box and whisker plot (Crawley, 2007). This is important as the Cumulic soils is based on only 3 samples, whereas the Lithic soils sample set has 13 samples. It is important to mention this because in many scenarios the results are entirely interpreted on the graphical outputs, and not the data inputs.

The elevated infiltration rates in the stream leads one to believe that these ephemeral streams are preferential pathways for infiltration and ultimately groundwater recharge (Adams et al., 2001). It is also evident that the variability within these cumulic soils is greater than others. This could be attributed to the amount of clay and silt present, as shown in the seive analysis and column seperation of the soil. Fey (2010) has stated that these cumulic soils are normally poorly sorted, not well defined in structure and typical of alluvial deposits.

In the immediate vicinity of HLS2 it could also be seen that the parent rock material protruded from the subsurface quite extensively, as is typical of this lithic soil type (Fey, 2010). The higher rate of initial infiltration could be attributed to the extreme spatial variability, specifically in arid and semi arid regions like the study area (NCR, 2001). With this variability we find the occurrence of macropores and preferential flow occurring in the subsurface. The preferential flow along these fractures has to be the reason for an increase in the infiltration rates at certain locations, like HLS2 in the study area. Farmer (2003) has also shown how the sensitive interaction between vegetation, climate and soil can have an impact on permeability of the soil.

More recently observations have been focussed on unsaturated zone fracture flow have due to their possible importance for streamflow contribution (Hughes 2010). These macropores in the lithic soils could also be possible contributors to a delayed streamflow response . Similarly it should also be mentioned that the understanding of these vadose zone fractures is also important for groundwater recharge (NCR, 2001). Adams et al (2001) also argue for the possibility that these conduits are preferential pathways for recharge in the Sutherland area and prove it by means of hydrogeochemical data. This is in line with observations for the fractured bedrock in river channels as well as the highly conductive nature of the cumulic soils in these river beds.

4.6 Conclusions:

Extreme spatial variability of soil types is evident in the study area. This can be seen from the mapping and could be attributed to aspect, which is the angle of the slope. This is because the north facing slopes differ somewhat to the south facing ones in terms of the microclimate. Other generic factors for soil formation applicable in this scenario would have to be vegetation and the parent material (Jenny 1941).

The two laboratory based methods (eg, column seperation and seive analysis) yield similar results for soil classification at the surface. This is however not indicative of the deeper subsurface environment where clay dominates. Moreover mapping and infiltration tests show that the subsurface soil characteristics also vary significantly with depth.

Tracer tests indicate that the rhizosphere has aided in preferential flow and that these conduits are possible migration pathways in the red duplex soil of the study area. In addition those areas with little or no vegetation indicate preferential flow to a lesser extent. In the latter scenario the duplex nature of the soil seems to be the major limiting factor for infiltration once contact has been made with the lower illuviated layer. The lower hydraulic conductivity of the clay retards infiltration over time, as is evident from the infiltrometer tests as well. This is consistent with the conclusions of Marshall and

Holmes (1979).

Illuviation in the lower layers means that the water retention capacity of soil at depth is greater due to the enrichment of clay and the properties of this soil type. This is evident from the infiltration data at the surface, which decrease over time. The infiltration tests at depth, and their consistently lower flow rates , also point to the multi layered nature of the soil. The dye tracer tests also point towards two distinct layers in the soil. The effect of evaporation should be noted in the upper layers of the soil due to the higher hydraulic conductivity of the coarser sandy material. This is an important factor when considering water storage changes as well as for numerical modelling (Creutzfeldt et al., 2010)

CHAPTER 5
TIME SERIES ANALYSIS OF RAINFALL EVENTS AND THE GRAVITY RESPONSE AT THE SOUTHERN AFRICAN GEODYNAMIC OBSERVATORY, SUTHERLAND

5.1 Overview

Individual rainfall events are closely examined for their significance and relation to residual gravity data. The subsurface water level at one well in conjunction with precipitation and the gravity residual data are highlighted in order to determine possible patterns and relationships. In some instances strong correlations are found between the water level data and the gravity residual for the events having multiple instances of precipitation. With regards to the individual rainfall events strong correlations were also found between the water level in SABK07 and the gravity residual. This sheds some light on the variability of the hydrological regime. In both cases weak and inverse correlations were also found. Furthermore the fact that one reservoir is not the only contributor to the mass storage in the subsurface is also highlighted. Lastly the possibility that this well could merely be a conduit for throughflow due to the instantaneous response to precipitation and the subsequent drop in water level is another possibility.

5.2 Introduction:

Time series analysis of data has applicability in multiple fields (El Adlouni et al., 2008). In many cases the application of the time series has been for forecasting and thus determining future scenarios. This forward modelling poses many problems especially where they do not necessarily account for external factors and possible randomness within a system (Taleb, 2004). Furthermore the omission of anomalies, smoothing of data, that is the removal of noise, and forced calibration of models further obscures results (Taleb, 2009).

An event-based approach to understanding anomalies has been employed in fields like engineering (Nafday, 2011). Treatment of this data finds it origins in statistics and the nature of rare events, known as “black swans”, and has been thoroughly examined by Chichilnisky (2010). In the field of hydrology we find the study of anomalous events applied for example to flood prediction. Case studies utilising stochastic modelling, such as those of Chua and Wong (2010) as well as Cameron et al. (2000), show the ability of statistical methods to account for multiple possibilities and outcomes. Similar statistical methods applied to water resources have also been outlined by Helsel and Hirsch (2002). It is ultimately this mathematical treatment of data, like modelling, which leads to tangible outputs for management decision, specifically as for this treatise in water resources (e.g. Chiang and Kinzelbach, 2000).

In arid and semi-arid areas rainfall events have extremely high spatial and temporal variability (Wheater et al., 2008). Despite this variability, rainfall is an important driver for infiltration and thus groundwater recharge, specifically in fractured rock aquifers (Xu and Beekman, 2003). This is the reason for attempting to understand single rainfall events and the effect that they might have on local gravity variations. This has been examined by Abe et al. (2006) to some extent at the Superconducting Gravimetre (SG) in Bandung, Indonesia. It was found that 80% of the observed gravity decrease, within the time frame of specific rainfall events, was caused by precipitation and the subsequent adsorption of soil moisture at the Bandung SG station (Abe et al., 2006).

5.3 Background

5.3.1 Hydrology and Gravity

Neumeyer et al. (2006) studied multiple Superconducting Gravimetre (SG) stations all over the world. Regional scale GRACE data was compared to the local gravity readings of the SG stations. Estimates for hydrology model derived gravity variations were compared to the GRACE and SA results. Major conclusions from this work highlighted the limited understanding of the local hydrological regime in the immediate vicinity of SG stations (Neumeyer et al., 2006).

Boy and Hinderer (2006) conducted similar work to that of Neumeyer et al. (2006) on 20 of the global SG stations. Large scale hydrological models, such as the GLDAS and Lad, as developed by Rodell et al. (2004) and Milly and Shmakin (2002) respectively, were compared to the hydrological residual derived at the SG stations. In most cases there was a strong seasonal variation in the SG signal was observed. Snow as well as soil moisture were the major contributors to this biannual variation (Boy and Hinderer, 2006). Zhou et al. (2009) further verified this work by examining GRACE results over a slightly longer time frame.

Harnisch and Harnisch (2006) examined the hydrological influences on long term gravity data at seven SG stations all over the world. The precipitation data as well as groundwater levels, in some cases the soil moisture, was compared to the residual gravity signal in order to evaluate the effect the local scale hydrology has on gravity. A similar methodology was applied by Abe et al. (2006), but only focused on the vadose zone. Significant variation in terms of local hydrological regime at the seven SG stations was clearly evident from the results displayed by Harnisch and Harnsich (2006) and further confirmed by hydrological modelling completed by Naujoks et al. (2007) and Creutzfeldt et al. (2009) at the Jena and Moxa stations, respectively.

Krause et al. (2009) have used the J2000 model in order to understand the local hydrology within the vicinity of the Moxa SG station. The application, as well as functionality of this model has previously been reviewed by Krause (2002). Observed and simulated soil moisture measurements strongly correlate with one another and it was also shown how important the moisture variations are because of their impact on gravity measurements (Krause et al., 2009). Naujoks et al. (2007)have also shown, at the same SG station, the great heterogeneity of gravity measurements possibly due to subsurface fluid storage and movement. From a hydrological perspective this variability could possibly be attributed to factors such as slope, initial moisture content of the soil, insolation,aspect, and soil texture amongst others (Hébrard et al., 2006).

It can clearly be appreciated then that multiple approaches contribute towards a better understanding of the hydrological gravity residual at any SG station . Neumeyer et al. (2006) suggested therefore that each station should be equipped with environmental monitoring instruments in order to better understand the local changes in water storage. Results from small scale hydrological modelling at the SG stations in Jena and Moxa, as shown by Naujoks et al. (2007) and Creutzfeldt et al. (2009), respectively, are consistent with the interpretations that hydrology on the local scale is the major contributor to the residual signal affecting the SG.

Leirião et al. (2009) have taken a slightly more theoretical approach. They examined the possibility of utilising gravity measurements to aid in determination of parameters estimated during a pump test. This idea builds on the work of Montgomery (1971) as well as that of Damiata and Lee (2006). The data stemming from the synthetic aquifer pump test was shown to better understand possible applications for gravity signals for hydrological model calibration (Leirião et al., 2009). Subsequent field applications related to hydrology and gravity, like those of Creutzfeld et al. (2010) as well as Christiansen et al. (2011), have shown that there is a strong correlation between soil moisture and gravity. This in turn could either aid in removing this hydrological residual (Naujoks et al., 2007) or aid in calibrating unsaturated zone hydrological modelling (Christiansen et al., 2011). The latter concept must be performed in conjunction with other tools in order to fully understand the relationship between moisture storage and movement in the vadose zone (Creutzfeldt et al., 2010)

Many of the studies related to the impact of hydrology on gravity have only been recently completed (Naujoks et al., 2007). The assumptions for the subsurface hydrological components of the work are based on early works of, for example by Damiata and Lee (2006). These assumptions, some outlined by Neuman (1972), are unfortunately only applicable in primary porous media and they lose their efficacy when transferred to fractured rock aquifers (Cook, 2003). Furthermore many of the early studies have merely examined time series data and then attempted to model the local hydrology (Creutzfeld et al., 2010) or large scale hydrology (Boy and Hinderer, 2006) based on this simple smoothed analysis. Abe et al. (2006) on the other hand have attempted to look at local scale single rainfall events and Kroner and Jahr (2006) have also emphasized the importance of this event-based approach to better understanding the impact of hydrology on gravity.

An event-based approach to understanding hydrology in arid areas, has been advocated by Knighton and Nanson (2001). With regards to the application of this in the vicinity of a SG, Kroner and Jahr (2006) used significantly induced subsurface fluid flow at the Moxa SG station Germany, to study the impact on gravity. Naujoks et al.

(2007) have also completed multiple gravity measurement campaigns across the same catchment at Moxa and conclude that hydrological variations occur temporally and spatially. This event-based approach could highlight some major increases in the subsurface moisture due to the measured impact on the gravity (Abe et al., 2006). Christiansen et al. (2011) has examined an event-based infiltration experiment and its impact on gravity measurements on an aquifer in Denmark. The approach was effective in understanding the mass movement of moisture through the subsurface, specifically in the vadose zone and aided in hydrological modelling calibration (Christiansen et al., 2011)

Evaporation values are normally two to three times higher than precipitation for the study area (Mukheiber and Sparks, 2005). This high evaporation has a direct impact on other aspects of the hydrological cycle such as runoff, which has been estimated at 10-20mm per annum (Midgley et al., 1994). It has also been noted that rivers draining the study area are mainly non-perennial and flow during periods of peak rainfall, these rivers are also able to act as conduits for groundwater recharge in the area (Adams et al., 2001). Multiple groundwater wells drilled across the area reveal sandstones dominating the subsurface with higher hydraulic conductivity in the fractured rock close to doleritic dykes (Woodford and Chevallier 2002).

5.3.2 Correlating hydrology and gravity

The application of correlation between variables as well as the numerous types of correlations has been extensively outlined by Helsel and Hirsch (2002). Furthermore the advantages and disadvantages of utilising the Mann Kendal and Spearman rho tests in hydrological time series has been closely examined (Yue et al., 2002).The application of such correlation tests, specifically to understand the links between gravity and hydrology, has been employed by Naujoks et al. (2007) in the vicinity of the Moxa Observatory, Germany. Creutzfeldt et al. (2010) studied the residual from the Wetzell SG station and could explain up to 97% of the variation in the residual gravity signal by utilising multiple methods and then correlating the results to the gravity residual. This methodology of using more than one tool for understanding the subsurface moisture movement has also been advocated by Christiansen et al. (2011).

The targeting of single rainfall events, specifically in arid areas, is of the utmost importance due to their contribution to the hydrological regime of the area (Wheater et al., 2008). Rainfall runoff modelling has been applied in areas with typically low rainfall and the results have shed light on the subject matter and lead to a greater understanding of hydrological processes (Al-Qurashi et al., 2008). Furthermore hydrological modelling has also recently aided in understanding the relationship between gravity and the hydrological residual (Guntner and Bronstert, 2004). The correlation and explanation of the hydrological residual has been outlined by Naujoks et al. (2007) as well as Creutzfeld et al. (2010). This method of understanding the linear relationship between two variables has been shown by Helsel and Hirsch (2002). The correlation method is able to shed light on the direct linear relationship between two variables. This should however be interpreted with caution as the direct linear relationship between two variables could relate to externalities (Taleb, 2004).

The correlations between residual SG have been compared to GRACE as well as large scale hydrological models. Neumeyer et al. (2006) have shown that the model derived gravity for the Sutherland station, has a strong correlation to the SG signal. The three large scale hydrological models, namely the Watergap Global Hydrological Model-WGHM (Döll et al., 2003), Leaky bucket model (H96) (Huang et al., 1996) and the Land

Dynamics model (LaD) (Milly and Shmakin, 2002), were utilised in order to better understand the effect hydrology has on gravity. Unfortunately the water level in the well SABK07 poorly correlated to the gravity residual for the time period of April 2002 to November 2003 (Neumeyer et al., 2006).

Zhou et al. (2009) completed similar work to Neumeyer et al. (2006), but used the Global Land Data Assimilation System (GLDAS) developed by Rodell et al. (2004) . The other large scale hydrological model which they implemented was the LaD, as previously mentioned. Results from the hydrological models for both Zhou et al (2009) as well as Neumeyer et al (2006) were in strong agreement with the SG signal at the Sutherland station, but there was a weak correlation with the GRACE signal. This is surprising due to the fact that the spatial and sampling resolution of the models is on a much larger scale than that of the SG (Boy and Hinderer, 2006)

Boy and Hinderer (2006) examined 20 SG stations globally, including the Sutherland station. The results for the long term time series data from the Sutherland SG shows weak correlations to the hydrological models, possibly due to the weak resolution of the models when compared to the high precision of the SG (Boy and Hinderer 2006). A weak correlation was detected between the groundwater level and and the gravity residual and an even weaker relationship was found between the latter component and modelled gravity effect of rainfall (Harnisch and Harnisch, 2006)

More recently work on the area has shown that the correlation between the local groundwater level change and the gravity residual has been calculated to be 0.6865 (Abe, personal communication, 2010). This is a significant increase on the -0.22 calculated by Harnisch and Harnisch (2006). When comparing the time frames for the analysed data the period examined by Harnisch and Harnisch (2006) is earlier to that of Abe (correspondence) and differs somewhat. This must be the major reason for the difference in their reported results.

5.4 Methodology

5.4.1 Environmental Data:

The environmental data in the study area for this aspect of the study was extracted from the evaporation and precipitation data sets from the Department of Water Affairs and Forestry (DWAF). This data database contains daily readings, but not hourly, like the well data at SABK07. This environmental data, in conjunction with the environmental data from the weather station located at the SG, which is outlined below, was then analysed.

5.4.2 Evaporation data:

To the west of the SG, approximately ten metres west of SA BK6, a typical type A evaporation pan is located. The use and potential misuse of type A evaporation pans, is outlined in detail by Jacobs et al., (1998). Daily measurements are made onsite and these are recorded and sent to a central database. This data is then made available online at www.dwaf.gov.za/hydrology. The (DWAF station number is D5E008 for the Sutherland pan). The data was downloaded and processed in order to calculate the average monthly evaporation. The available data from the evaporation pan
is from April 1982 to October 2008.

5.4.3 Precipitation data:

A rain gauge is situated at the same site as the A pan. Daily measurements are made and also uploaded to the same central database as the evaporation data and can be downloaded. Monthly precipitation values were plotted from the period of April 1982 to October 2008. Dates when the total precipitation exceeded evaporation were highlighted. These dates were then extracted and earmarked for closer time series analysis and correlation. This formed the basis for the investigation. Above the SG station is another weather station installed to monitor the environmental variables affecting the SG. These variables include the air pressure, precipitation wind speed as well as wind direction. The rainfall data stemming from this sensor was also examined.

Unfortunately the precipitation data for the sensor located above the SG also had problems with the data. Upon closer inspection it was seen that multiple recordings were made for a single event. This was due to the fact that the sensor readings were taken in close proximity to one another. The sensor installed close to the SG for the soil moisture readings was programmed for every hour and the data examined for this specific monitoring station seems more reasonable, but is only available from December 2008.

Furthermore one is unable to pinpoint the exact time of the precipitation event due to the aforementioned problems related to multiple entries of the monitoring station located at the SG and the daily resolution of the weather station located at SA BK06

5.4.4 Hydrological data:

The long term time series of a well beside the seasonal stream in the valley west of the SG station was examined. SABK07 (Figure 3.3), as the well is known, is monitored on an hourly basis by means of a diver for water level and water temperature. Data related to individual rainfall events was extracted from the day of the precipitation events. The groundwater level data was then correlated with the gravity residual, by means of the linear correlation as outlined in Helsel and Hirsch (2002).

Changes in groundwater level were plotted alongside the gravity residual for the rainfall events lasting multiple days. This was completed for the number of days the event lasted, in one set of graphical plots, as well as for a period of ten days after the last rainfall event, including the days of the event on another set of plots.

The missing values for groundwater levels during the final rainfall event, which was on the 22nd August 2006, were the only missing values that affected this study.

5.4.5 Gravity data

Major sources of temporal gravity variations are tides of the solid earth, ocean tide loading, changes in the atmosphere and polar motion (Creutzfeldt et al., 2010). Removal of these variations is done traditionally using models (Krause et al., 2009). The effect from polar motion is removed using data from the International Earth Rotation Service (IERS). Tidal effect is removed using the ETERNA software package (Wenzel, 1996). The barometric pressure was reduced using the data stemming from the meteorological station located at the SG. The elastic response of the solid earth is completed by examining monthly tides and applying a simple barometric admittance function (Creutzfeldt et al., 2010). Due to the spatial and temporal variability in hydrology it is difficult to determine the gravity residual related to hydrology and remove it (Krause et al., 2009). This could then be considered the major signal after removing all the other aspects affecting the SG (Imanishi et al., 2006).

5.4.6 Correlation:

Helsel and Hirsch (2002) suggest the use of correlation between two variables in order to measure the strength of the relationship between aforementioned variables. Pearsons “r” or linear correlation is one of the most widely used tools for determining the direct linear relationship between two variables in scientific research (Taylor, 1990).

$$r=\frac{1}{n-1}\left(\frac{x_i-\bar{x}}{s_x}\right)\left(\frac{y_i-\bar{y}}{s_y}\right)$$

Where

r = correlation coefficient

n = number of samples

x_i = first sample of first variable

y_i = first sample of second variable

s_x and s_y = standard deviation of samples

x and y = the mean values of the sample

The formula shown above is used to determine the dimensionless value of “r”. This is completed by dividing the distance from the mean by the sample standard deviation (Helsel and Hirsch, 2002). The closer this “r” value tends towards ±1, irrespective of the direction, the stronger the linear relationship between the two variables (Taylor, 1990).

5.5 Results:

20 rainfall events were identified (Table 5.1). From these events a further 5 rainfall events spanned a period of more than one day (Table 5.2). The last of the latter set of events unfortunately had no gravity residual readings and thus no correlation is present in Table 5.1 and 5.2.

Rainfall Event	Date of rainfall event	Evaporation(mm)	Precipitation(mm)	Precipitation – Evaporation(mm)	Correlation between gravity residual and chane in groundwater level
1	20021220	12.9	16.9	4	0.63
2	20021221	5.5	11	5.5	-0.42
3	20030822	2	10.2	8.2	0.51
4	20030916	3.9	4.3	0.4	0.71
5	20031123	6.1	6.6	0.5	0.9
6	20040401	5.8	13.8	8	0.43
7	20040402	5	7	2	-0.46
8	20040415	6.4	17.2	10.8	0.1
9	20040416	6.4	10.6	4.2	-0.37
10	20040807	0.9	1.4	0.5	0.46
11	20041020	5.2	12.2	7	0.05
12	20041222	3.2	5.2	2	-0.63
13	20041224	7	16	9	0.42
14	20050118	7.7	8.2	0.5	0.26
15	20050119	0.9	11.4	10.5	0.58
16	20050120	5	12	7	0.23
17	20050220	3.8	7.8	4	-0.79
18	20050503	4.6	13.6	9	0.01
19	20060822	1.8	29.3	27.5	-
20	20060823	4.2	14.2	10	-

Table 5.1 : Single rainfall events at the Sutherland Geodynamic Observatory with correlations between groundwater level in SABK07, on an hourly basis, and the gravity residual

	Rainfall event	Start Date	End date	Cumulative precipitation(mm)	Correlation
A	1 and 2	20021220	20021221	27.9	0.63
B	6 and 7	20040401	20040402	20.8	-0.01
C	8 and 9	20040415	20040416	27.8	0.68
D	14,15 and 16	20050118	20050120	31.6	0.32
E	20 and 21	20060822	20060823	37.5	-

Table 5.2: Rainfall events lasting multiple days at the Sutherland Geodynamic Observatory with correlations between groundwater level in SABK07 and gravity residual

Graphical examination of the longer term data displays a weaker relationship between the water level and gravity residual in the order of one magnitude. The data examined for ten days after the end of the final rainfall event, for each of the four long term rainfall events, shows little or no relation between the aforementioned variables. This is further substantiated by the weak correlations calculated for these events. (-0.169 for the event “C” and -0.08 for the event “D”). On the other hand a weak positive correlation of 0.11 for the event “A” was determined. Unfortunately the final two entries for event “D” are missing from the gravity residual and these were omitted.

The initial change in water level for the event “A” is the greatest at 0.1 metres (Figure 5.1), whereas the two events of 2004 show a change in groundwater level of one order of magnitude smaller, in the region of 0.01 metres (Figure 5.2 and 5.3). A regular diurnal pattern is present in the event (Figure 5.1). This is, however, not very evident in the events occurring during 2004, but once again this daily pattern can be seen in the event of 2005 (Figure 6). This could possible be attributed to evapotranspiration and soil moisture, which directly affect the gravity residual as shown by Creutzfeld et al. (2010) at the SG situated at Wetzell, Germany.

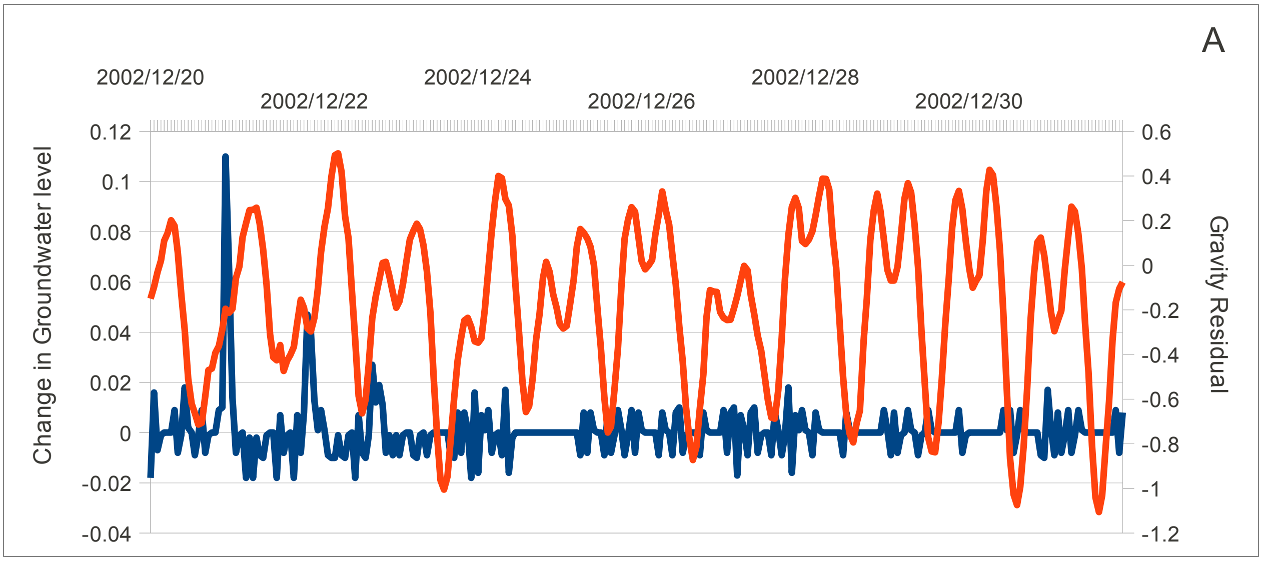

Figure 5.1 : Change in Groundwater level in metres (blue) and gravity residual (orange) for ten days after the precipitation event “A”

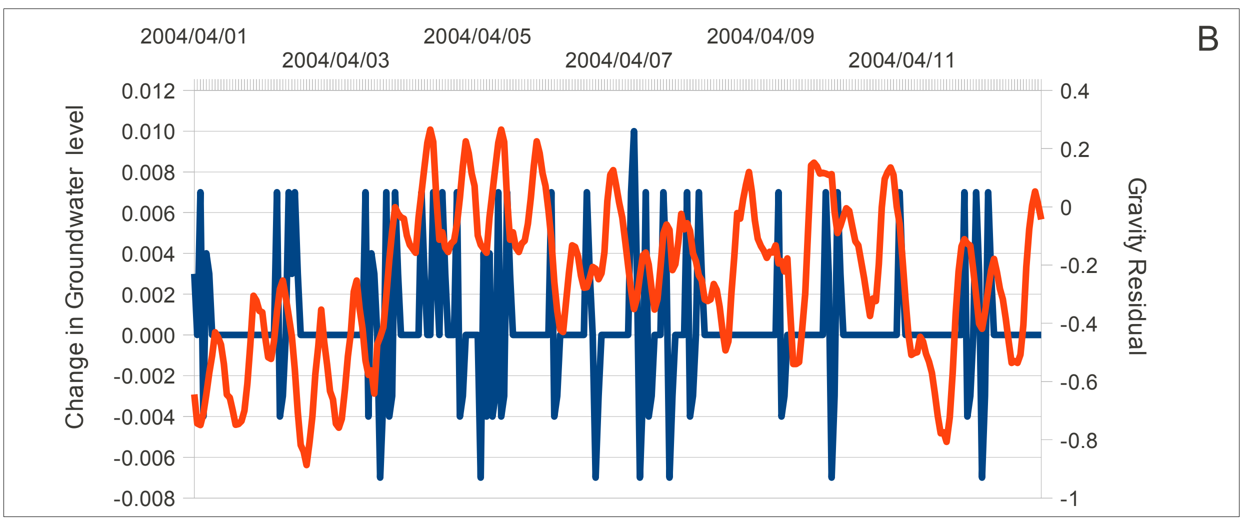

Figure 5.3: Change in Groundwater level in metres (blue) and gravity residual (orange) for ten days after the precipitation event “B”

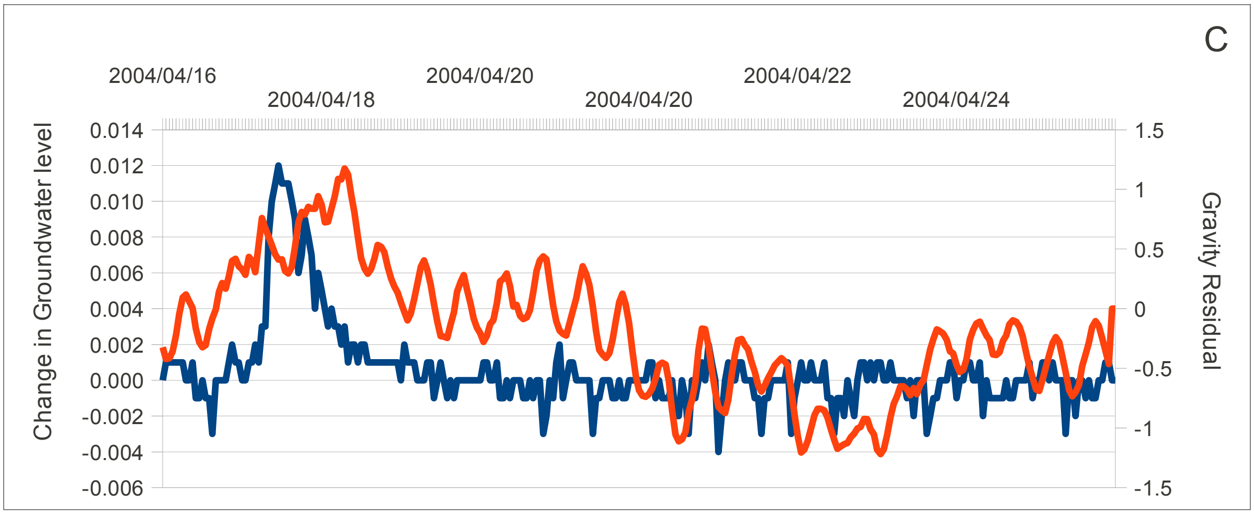

Figure 5.2 : Change in Groundwater level in metres (blue) and gravity residual (orange) for ten days after the precipitation event “C”

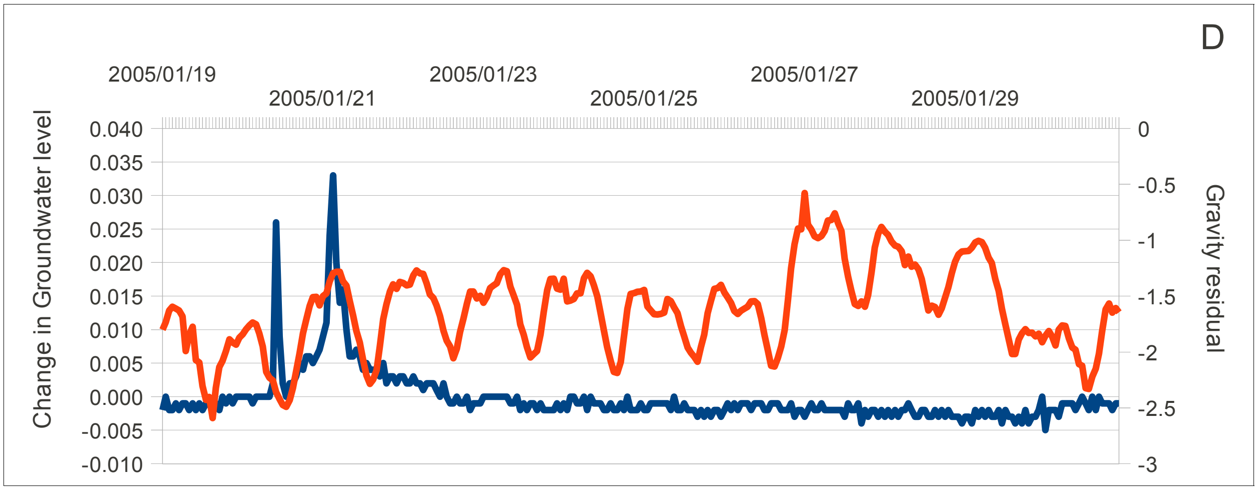

Figure 5.4 : Change in Groundwater level in metres (blue) and gravity residual (orange) for ten days after the precipitation event “D”

Type of data	Source of data	Period of missing data
Precipitation	Department of Water Affairs	June 2004, June 2007-May 2008, August 2008, September 2008
Evaporation	Department of Water Affairs	August 1997-December 1997, December 2000, May 2001, July 2004, August 2004, June 2007-November 2008, March 2009, April 2009, June 2009, July 2009, September 2009, October 2009, November 2009

Table 5.3: The types of missing data, the source of the data, as well as the period of the missing data used in this study from the Sutherland site.

The four rainfall events show differences in terms of the correlation between the groundwater level and the gravity residual for two days after the vent. Two of the events have a strong correlation, 0.63 and 0.68 respectively. Whereas combined events number 6 and 7 combined have an inverse correlation, yet seperately the former yields a positive correlation. The weakest positive correlation can be seen from event numbers 14, 15 and 16 with the middle event having a stronger link to the groundwater level when compared to the other days.

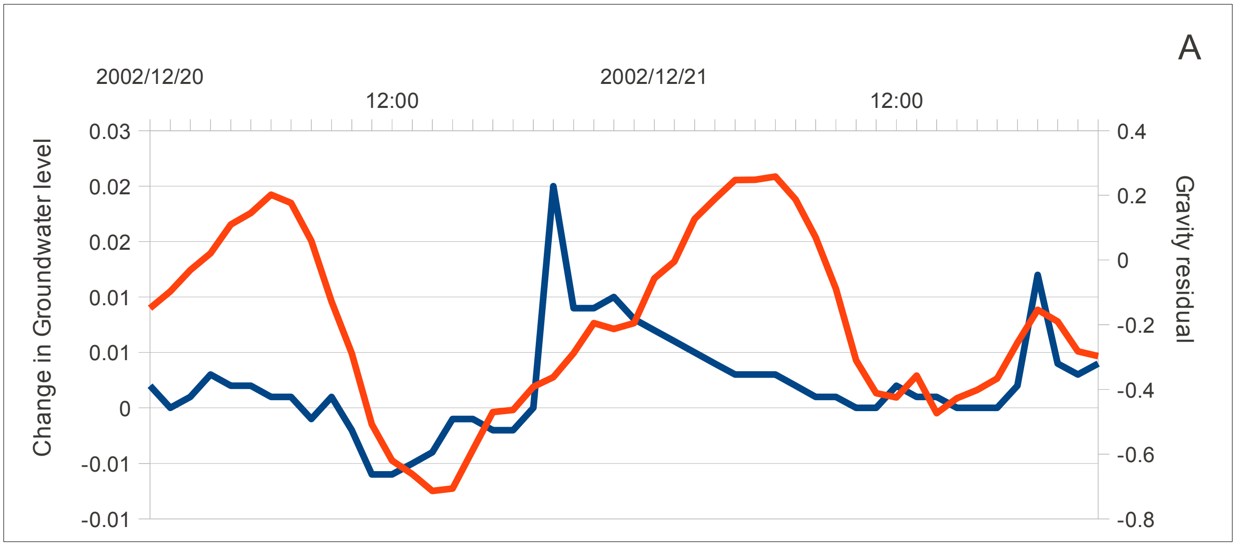

Figure 5.5 : Change in Groundwater level in metres (blue) and gravity residual (orange) for the precipitation event “A”

From the graphical presentation of the data for the duration of the rainfall events, it can clearly be seen that a lag time response is present for the gravity data and its relationship to the well. In Figure 5.5 it is clear that the lag of the gravity residual is delayed in relation to the water level, whereas in figure 6 the lag effect is not as evident. The interchanging of variables lagging is difficult to explain with a limited amount of data. Similar studies in the vicinity of SG's suggest that the soil moisture component is the major contributor to the SG residual (Naujoks et al., 2007). The fact that the SG is located in a bunker with soil above it could be the reason for the decrease in gravity shown in Figure 5.6.

The inversely correlated event “B” shows a different effect to A, which has a lag response, when comparing the gravity residual to the change in water level of the well. A decrease in gravity could be attributed to an increase in soil moisture above the SG (Abe et al., 2006). A variation in terms of the daily pattern can clearly be seen in all of these short terms events with a climbing limb evident in the gravity residual of Figure 5.6 as well as a definite inversely correlated graphical relationship between the change in groundwater level and gravity residual for hydrology.

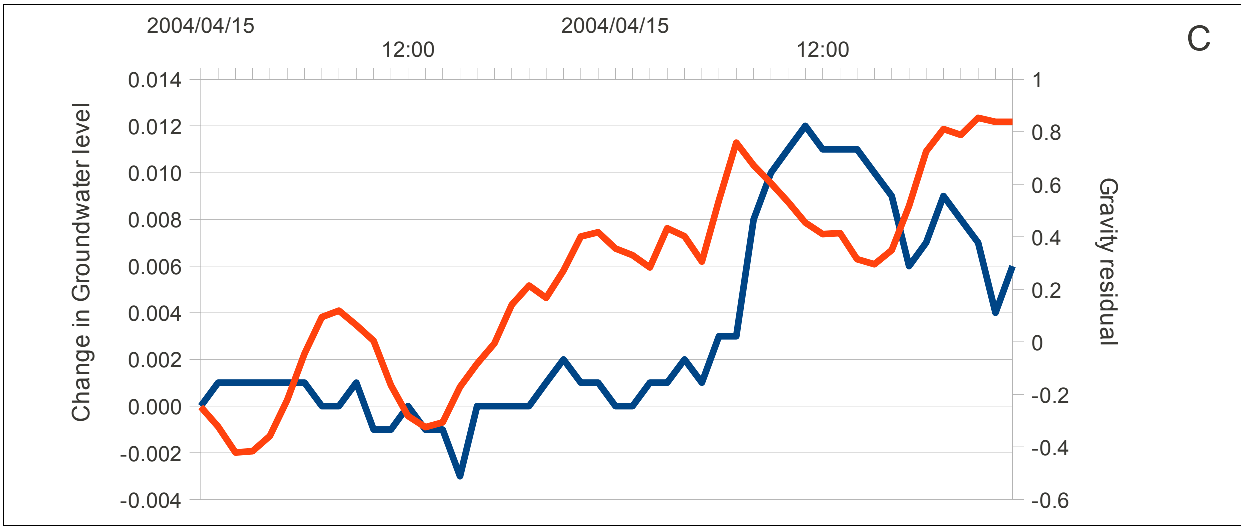

Figure 5.6: Change in Groundwater level in metres (blue) and gravity residual (orange) for the precipitation event “C”

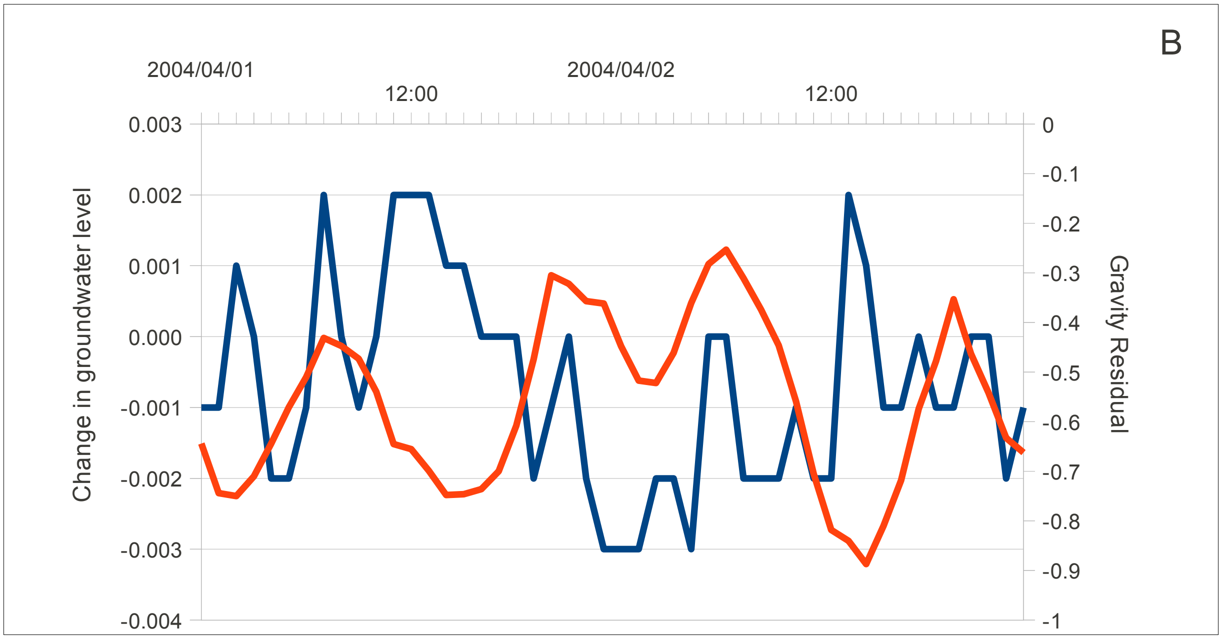

Figure 5.7 : Change in Groundwater level in metres (blue) and gravity residual (orange) for the precipitation event "B"

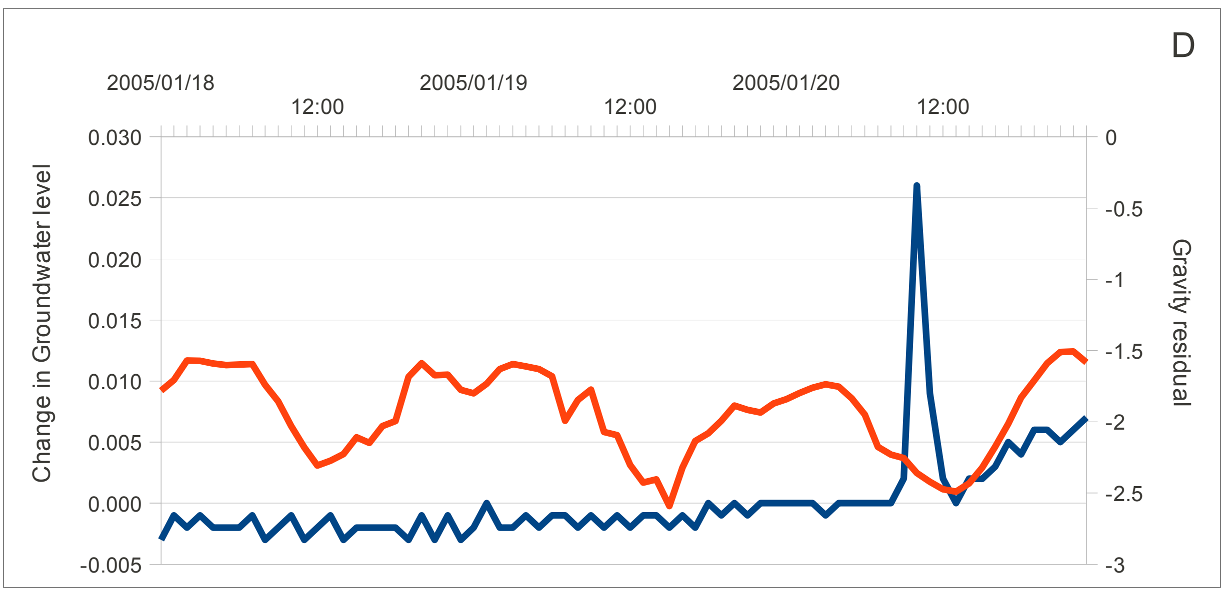

Figure 5.8 : Change in Groundwater level in metres (blue) and gravity residual (orange) for the precipitation event "D"

5.6 Conclusions:

It can be seen clearly that direct correlations are not necessarily reflective of relationships between measured parameters . Also direct correlations could also be misleading in the sense that they do not take into account other external factors such as initial soil moisture, intensity of the precipitation, ponding as well as duration of precipitation event. In my specific case study I found that at times the correlation between a groundwater level and the gravity residual was as high as 0.98 and at other times as low as -0.79.These results differ to the long term time series analysis of Harnisch and Harnisch (2006).

In some cases the graphs of the precipitation events show a significant lag time with respect to the gravity residual and its relationship to the water level in the well. In many cases a spiked increase or decrease occured in the water level. This could mean that the well is merely a throughflow pathway and not actually part of the groundwater system. This idea has been further examined by Hughes (2010) and plays a major role in the streamflow contribution for arid regions in South Africa.

The lag response could possibly also be attributed to the fact that the SG measures changes in mass. The increase in mass over the entire area would obviously take some time due to the infiltration of soil moisture into the subsurface. Therefore the measurement in one location cannot be reflective of the total measured mass examined by the SG. Furthermore the measured increase or decrease in gravity is dependant upon the the point of infiltration occurring above or below the station (Imanishi et al., 2006). Also up to 90% of the hydrological signal affecting the SG occurs at a radius of around 1000m (Creutzfeld et al., 2010).

This suggests that the perceived understanding of the impact which hydrology has on interpreting the gravity residual should be examined more closely. Many cases in the past have only attempted to understand and model the effect that hydrology has on gravity. Naujoks et al.(2007) explained 77% of the variability in the hydrological residual by means of soil moisture modelling. Creutzfeldt et al. (2010) had greater success and could could explain 95 to 97 % of the variation in the SG residual using hydrological modelling, soil moisture data as well as a lysimeter. In line with this it is therefore envisaged that soil moisture modelling should be undertaken to better understand the hydrological regime affecting the SG at Sutherland. The study leads one to believe that the lag time response in the gravity residual is related to the addition of moisture to the subsurface storage component. This could be groundwater and or soil moisture as highlighted by Hinderer (2000), but it seems as if the response in the well SABK07 is only one component of this gravity residual (Harnisch and Harnisch, 2006).

It is important to note also which method is used when correlating the gravity residual to the hydrological model. Helsel and Hirsch (2002) highlight the various methods for correlating, and prove that linear correlation could yield the exact same result for completely different data sets. It is therefore envisaged that other methods should be compared with linear correlation in order to examine variations and determine the best fit for this specific application. Yue et al. (2002) have explored this possibility, but specifically for monotonic trends in hydrology.

Variability in the SG hydrological residual could also be due to the variability in the soil and   factors such as slope, initial moisture content of the soil, insolation, aspect and soil texture amongst others (Hébrard et al., 2006). This will be have to be factored when modelling and examining the long term time series data for correlation with the gravity residual.

CHAPTER 6
UNDERSTANDING EPISODIC RECHARGE EVENTS BY USING HYDROLOGICAL TIME SERIES ANALYSIS AND GRAVITY RESIDUALS IN THE IMMEDIATE VICINITY OF THE SAGOS

6.1 Overview:

The long term time series of the soil moisture as well as groundwater in the immediate vicinity of the Superconducting Gravimetre (SG) is examined. Strong correlations between the groundwater levels in the wells and the gravity residual are documented. SA BK05, which occurs directly alongside the river, shows the greatest correlation between its water level and gravity residual. Decreases in the water levels of the wells correlated to negative gravity residuals. Recharge for two wells in the area was calculated for each precipitation event with a correlation of greater than 0.7 between the water level in the well and the gravity residual. This has shed light on the nature of episodic recharge events within the immediate vicinity of the SAGOS. The variability in soil moisture and groundwater could be attributed to the erratic rainfall in the area. Soil moisture data seems to have little or no effect on the gravity residual in the immediate vicinity of the SAGOS. This is believed to be due to the variability of soil moisture, which is directly affected by evaporation as well as infiltration.

6.2 Introduction:

Groundwater recharge is an important parameter for understanding the hydrogeological regime of an area. Xu and Beekman (2003) have compiled an extensive manual of the various methods for determining recharge based on case studies from the SADC region. Healy and Cook (2002) further reviewed groundwater fluctuation methods as tools for determining recharge. The most promising factor is the ability of water table fluctuation methods to estimate recharge based on linking specific information from the atmosphere, unsaturated and saturated zones (Xu and Beekman, 2003). This is especially important for preferential flow in arid zones as contribution of rainfall to groundwater can be measured more distinctly (e.g Van Wyk et al., 2012). Time series related to the parameters affecting groundwater are just as important for understanding the processes and mechanisms for recharge (Healy and Cook, 2002).

Studies related to the correlation of the hydrological signal to gravity has been researched at the catchment scale (Christianson., 2011), at basin scale (Werth et al., 2009), as well as continental scale (Longuervergne et al., 2010). This has also been outlined extensively in the Literature review and in chapter 5. Creutzfeldt et al. (2010) argue that 90% of the hydrological signal affecting the Superconducting Gravimetre (SG) occurs within a 1 kilometre radius. Abe et al. (2006) have also shown that 80% of the hydrological signal affecting the SG in Bandung, Indonesia stems from the soil moisture immediately above the SG. Furthermore Imanishi et al. (2006) also argue that the majority of the hydrological signal affecting the SG, at Matsushiro, Japan, could be attributed to precipitation events. This shows the importance of catchment scale hydrological parameters related to precipitation events in the immediate vicinity of the SG. This is even more important in arid zones as precipitation events, in conjunction with alluvial stream beds and hard rock terrain, dominate the hydrological regime in such zones (Lange et al., 2000).

Episodic recharge within the semi-arid Niger areas has been extensively studied by Massuel et al. (2006). The application of vadose zone chemistry, electrical conductivity and hydrological modelling lead to the conclusion that episodic recharge might occur during periods of extensive rainfall via sandy mid slope fans.

Van Wyk et al (2012) recently examined long term time series of rainfall in the Northern Cape of South Africa and concluded that the soil moisture should be monitored in conjunction with groundwater levels. Furthermore, Van Wyk et al (2012) stated that the episodic recharge events, which contribute the greatest volume of groundwater in the region occur only once every 4 to 9 years in the semi-arid Northern Cape.

It has been recommended elsewhere therefore that future studies related to episodic recharge in semi-arid areas should examine time series of soil moisture in conjunction with precipitation and groundwater levels (Van Wyk et al., 2012). In line with this the SAGOS has data sets for the aforementioned parameters as well as gravity residual. The gravity residual signal is indicative of the addition of mass to the water budget of the area. This is an excellent tool therefore to aid in understanding episodic recharge in the semi-arid area surrounding the SAGOS. This was tested further in this study, as described below.

6.3 Methodology:

6.3.1 Gravity data:

The gravity residual calculation follows the description given in section 5.4.6. The gravity data for all the major precipitation events in table 6.1 were extracted for the same period as outlined in the meteorological data. These data sets were then correlated with soil moisture as well as groundwater level data as described in section 5.4.6

6.3.2Meteorological data:

An environmental station was setup alongside the soil moisture sensors approximately 10 metres northeast of the SG. Precipitation, wind speed, wind direction, as well as relative humidity and radiation were measured and recorded on an hourly basis.

The hourly data was examined and all precipitation events were separated. A total of 46 precipitation events were identified from the period of 05/12/2008 to 29/03/2010 (Table 6.1). The data from the end of the precipitation event for and to 24 hours after the event was extracted. If another precipitation event occurred within this time frame then this event was included as part of the initial event and data for 24 hours after the ending of the latter event was extracted.

Event	Start of event	End of event	Length of event	Volume of precipitation
1st	05/12/2008 (14:00)	17:00	4 hours	12.2mm
2nd	28/12/2008 (18:00)	20:00	3 hours	3.8 mm
3rd	11/1/2009 (14:00)	16:00	3 hours	1.3 mm
4th*	06/02/2009 (16:00)	0/02/2009 (22:00)	9 hours (intermittently)	14.5 mm
5th	12/02/2009 (19:00)		1 hour	0.9 mm
6th	12/02/2009 (04:00)	06:00	3 hours	0.2 mm
7th	24/02/2009 (00:00)	10:00	10 hours	7.3 mm
8th	25/02/2009 (13:00)		1 hour	4.7 mm
9th*	04/03/2009 (16:00)	08/03/2009(17:00)	98hours (intermittently)	11.8 mm
10th*	12/03/2009 (14:00)	12/03/2009(23:00)	10 hours (intermittently)	13.4 mm
11th*	02/04/2009 (14:00)	06/04/2009 (00:00)	82 hours (intermittently)	23.7 mm
12th*	16/04/2009 (14:00)	17/04/2009 (19:00)	29 hours (intermittently)	19.9 mm
13th*	22/04/2009 (15:00)	24/04/2009 (18:00)	51 hours (intermittently)	66.1 mm
14th*	29/04/2009 (20:00)	30/04/2009 (08:00)	12 hours (intermittently)	3.4 mm
15th *	15/05/2009 (17:00)	17/05/2009 (01:00)	32 hours (intermittently)	9 mm
16th	24/05/2009 (17:00)		1 hour	0.1 mm
17th*	29/05/2009 (03:00)	29/05/2009 (12:00)	10 hours (intermittently)	2.1 mm
18th	30/05/2009 (22:00)		1 hour	0.1 mm
19th*	06/06/2009 (18:00)	07/06/2009(18:00)	24 hours (intermittently)	0.6 mm
20th	11/06/2009 01:00	11/06/2009 02:00	2 hours	0.3 mm
21st*	13/06/2009 (16:00)	13/06/2009 (02:00)	10 hours	5.8 mm
22nd	16/06/2009 (16:00)	16/06/2009 (22:00)	8 hours (intermittently)	0.7 mm
23rd*	19/06/2009 (19:00)	20/06/2009 (21:00)	28 hours (intermittently)	11.1mm
24th*	22/06/2009 (14:00)	25/06/2009 (18:00)	76 hours (intermittently)	19.4 mm
25th	11/07/2009 (02:00)	11/07/2009 (09:00)	7 hours	6 mm
26th*	13/07/2009 (18:00)	14/07/2009 (16:00)	22 hours (intermittently)	5.1 mm
27th	18/08/2009 (18:00)	18/08/2009 (19:00)	2 hours	0.5 mm
28th*	14/09/2009 (09:00)	14/09/2009 (13:00)	5 hours (intermittently)	0.4 mm
29th	27/09/2009 (13:00)		1 hour	0.1 mm
30th	04/10/2009 (13:00)	04/10/2009 (15:00)	3 hours	7.3
31st	09/10/2009 (18:00)		1 hour	0.1 mm
32nd	11/10/2009 (18:00)		1 hour	0.1 mm
33rd*	26/10/2009 (04:00)	26/10/2009 (12:00)	9 hours (intermittently)	1.7 mm
34 th	04/11/2009 (13:00)		1 hour	0.6 mm
35 th*	09/11/2009 (04:00)	09/11/2009 (19:00)	15 hours (intermittently)	2.3 mm
36 th*	11/11/2009 (07:00)	12/11/2009 (04:00)	21 hours (intermittently)	1.4 mm
37 th*	07/12/2009 (07:00)	07/12/2009 (15:00)	8 hours (intermittently)	18.2 mm
38 th*	02/01/2010 (06:00)	02/01/2010 (14:00)	9 hours (intermittently)	4.3 mm
39 th	10/02/2010 (10:00)	10/02/2010 (11:00)	2 hours	2.7 mm
40 th	22/02/2010 (19:00)	23/02/2010 (06:00)	12 hours	32.8mm
41 st*	24/02/2010 (12:00)	24/02/2010 (18:00)	7 hours (intermittently)	2 mm
42 nd	04/03/2010 (19:00)	04/03/2010 (20:00)	2 hours	2.1 mm
43 rd*	06/03/2010 (16:00)	08/03/2010 (20:00)	52 hours (intermittently)	39.5 mm
44 th	10/03/2010 (00:00)	10/03/2010 (03:00)	4 hours (intermittently)	0.5 mm
45 th	11/03/2010		1 Hour	2.2 mm
46 th	16/03/2010		1 Hour	5.2 mm

Table 6.1: Precipitation events occurring in the immediate vicinity of the SAGOS

*indicates a rainfall event composed of more than one event occurring within a 24 period of the next event

6.3.3 Soil moisture time series:

Time Domain Reflectrometry (TDR) sensors were implanted in the subsurface, in the immediate vicinity of the SG, following a similar setup as installed by Creutzfeld et al. (2010) at the SG observatory in Wetzell, Germany. These sensors were used to measure the soil moisture. The moisture content of the soil is determined by a relationship between the velocity of an electromagnetic wave , that is passed along the length of the TDR, and the time of travel (Walker et al., 2004). The number of probes, their distribution and depth are outlined in Table 6.2. All TDR probes were connected to the TDR100 time domain reflectometer, and data was logged every 15 minutes by a CR1000 System. Another TDR probe, BG-Veld1-PR1, was located at a depth of 0.4 metres. Soil tensiometers were also implanted in order to measure the soil temperature and infer soil moisture. Take and Bolton (2003)   have carefully outlined the principles, applications and use of these instruments. The six tensiometers, two located at 0.2m, two at 0.4 and another two at 0.6m below the surface, measured temperature and pressure head.

Number	Name	Depth	Number of sensors	Description
SA-MUX 54	TDR array	0-15 cm	9	Surficial TDR sensors shortened to 15 cm
SA-MUX 55	TDR array	15-30 cm	9	Surficial TDR sensors shortened to 15 cm
SA-MUX 51	BG-Veld1-PR1	0-40cm	4	Soil pit with sensors at depths of 0.1m, 0.2m,0.3m and 0.5m
SA-MUX 51	BG-Veld1-PR2	0-40cm	4	Soil pit with sensors at depths of 0.1m, 0.2m,0.3m and 0.5m
SA-MUX 52	BG-Veld2-PR1	0-40cm	4	Soil pit with sensors at depths of 0.1m, 0.2m,0.3m and 0.4m
SA-MUX 52	BG-Veld2-PR2	0-40cm	3	Soil pit with sensors at depths of 0.1m, 0.2m and 0.4m
SA-MUX 53	BG-SA-SG	0-100cm	5	Soil pit beside the roof of the SG, with sensors at depth: 0.2m, 0.4m, 0.6m, 0.8m, 1.0m
SA-MUX 53	BG-Roof	0-40cm	3	Soil pit on the roof of the SG, with sensors at depth: 0.1m, 0.25m and 0.4m

Table 6.2: TDR probes and their distribution in the immediate vicinity of the SG

Data from the soil moisture sensor SA_Mux52 was extracted for each precipitation event. Missing values for the short term time series were linearly interpolated in order to graph specific events more clearly.

6.3.4 Groundwater Time Series:

The average monthly groundwater level for the well SA BK07 was plotted alongside the monthly precipitation for the period of March 2000 to March 2007. The groundwater data, as well as gaps in the data, from the wells SA BK04, SA BK05 and SA BK06 are highlighted in table 6.3. The data from these wells was plotted prior to the installation of new sensors.

Well number	Data	Period of data
SA BK01	Groundwater level and groundwater temperature	7/12/2008-12/24/2009
SA BK05	Groundwater level and groundwater temperature	7/12/2008-12/24/2009
SA BK04	Groundwater level and groundwater temperature	7/12/2008-12/24/2009
SA BK07	Groundwater level and groundwater temperature	07/05/2007-12/28/2009

Table 6.3: The data used for long term time series analysis as well s the well number and period of the data.

The groundwater recharge was calculated using the Water Table Fluctuation method as outlined by Healy and Cook (2002). Recharge is determined by the formula:

$$R = S_y \, (dh/dt)$$

Where:

R= groundwater recharge in volume (mm or m over time)

S_y= Specific yield (which is a dimensionless value)

dh = change in groundwater level (in metres)

dt = change in time (in hours)

The S_y value, which can be defined as the ability of an aquifer to release groundwater, for the wells SA BK 04 and SABK 05 was calculated in chapter 3. The results yielded values of 0.0001 and 0.00001 for the wells SA BK04 and SA BK05, respectively. These values were substituted into the above equation, along with the data from the water levels for each precipitation event yielding a correlation value of greater than 0.7 between the groundwater level and the gravity residual.

The events having the strongest correlation between the water level and gravity residual for one, two and three wells were further studied. Also the event with the highest amount of rainfall was examined.

6.4 Results

6.4.1 Soil moisture time series

The results from the TDR sensor clusters Mux_51 and Mux_52 both display a higher volumetric moisture content at the greatest depth of 0.45m and 0.4 metres respectively. This ranges from 0.25 to 0.42 in the former case and from 0.25 to 0.6 in the latter. The higher water retention capacity at depth could possibly be attributed to the enrichment of clay below 0.2 m as shown in chapter 3.

There is also a substantial amount variability in upper layer at 0.1m in both sensor locations. At times the volumetric soil moisture content was the lowest value and other times, especially after rainfall events an increase in soil moisture content occured. The only other location of great variability is at 0.3 metres in sensor Mux_51. The readings span the entire range of the recorded volumetric soil moisture, from less than 0.1 to more than 0.4. Furthermore when comparing the correlations with gravity between the soil moisture at various depths with the groundwater these soil moisture correlations are much weaker (Table 6.4).

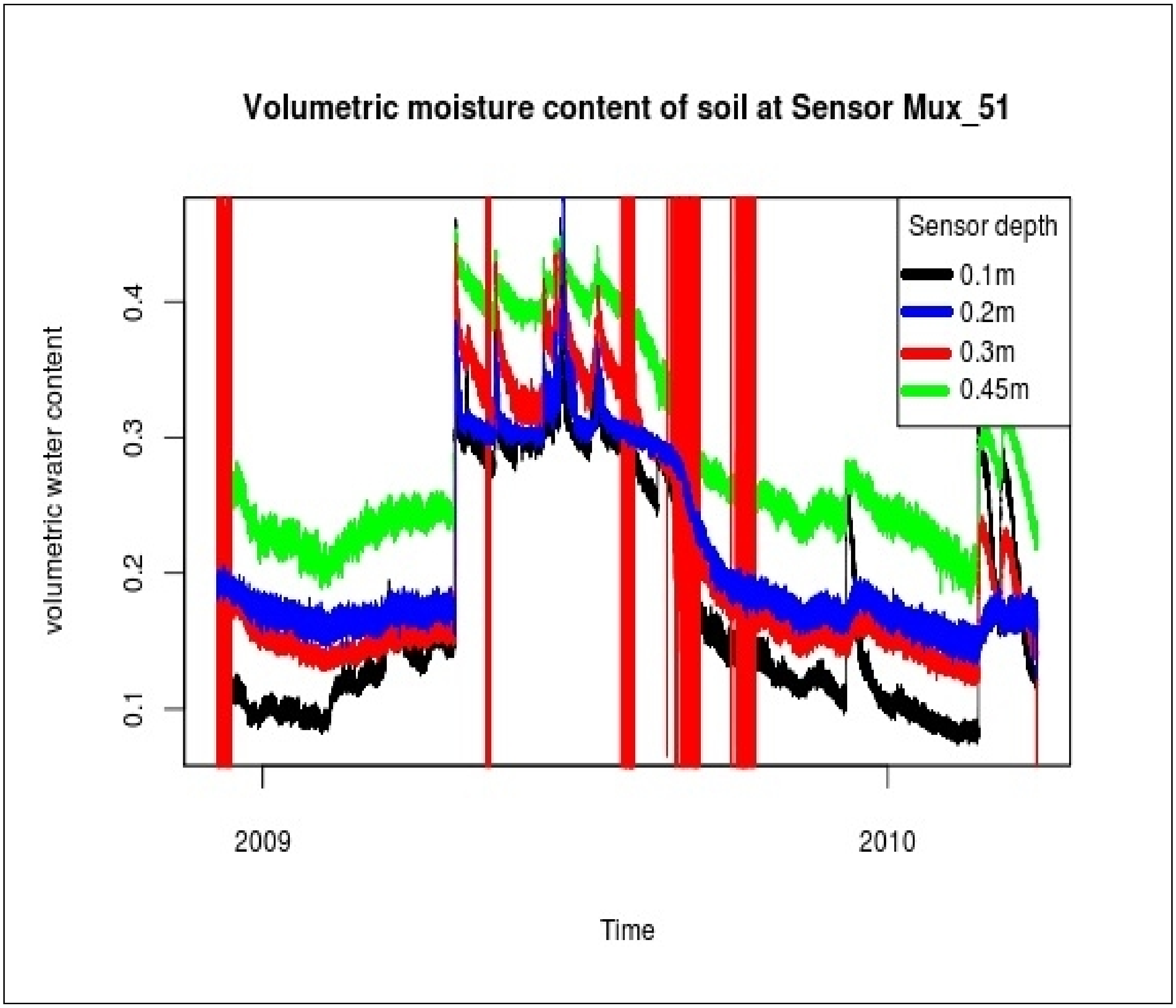

Figure 6.1: Time series of soil moisture from SA Mux 51. The red bands appear to be noise at the depth of 0.3m. This is normally due to environmental conditions.

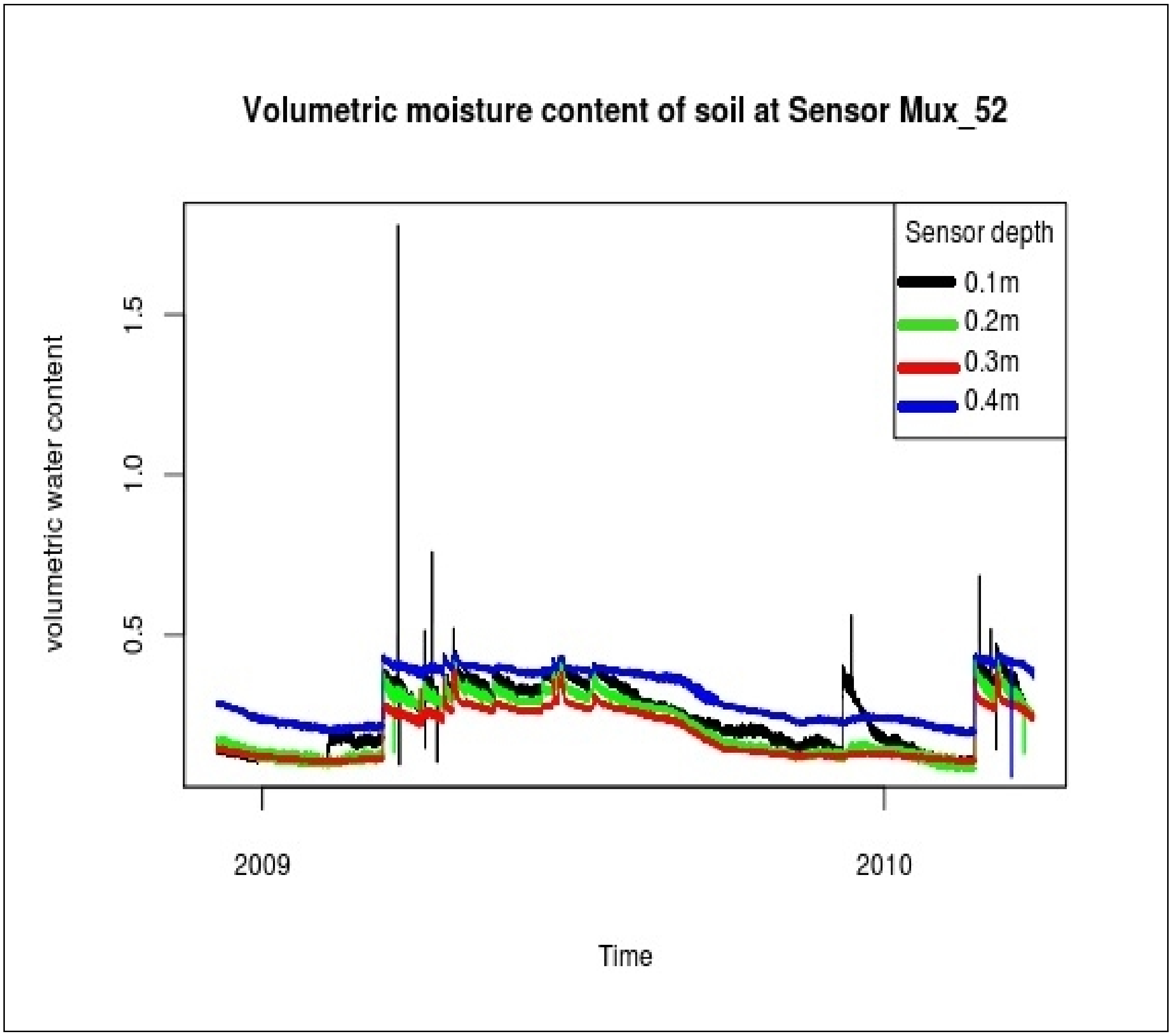

Figure 6.2: Time series of soil moisture from SA Mux 52. The variation in the upper 0.1 m could be attributed to errors in the sensor.

	Correlation coefficient at SA Mux 52 between soil moisture and the gravity residual			
Event	**0.1 m**	**0.2m**	**0.3m**	**0.4m**
1st	-	-	-	-
2nd	-	-	-	-
3rd	-0.299	-0.101	-0.189	0.016
4th*	-0.860	0.141	0.191	0.165
5th	-0.147	-0.221	0.235	0.233
6th	0.282	0.209	0.527	0.076
7th	-0.677	-0.104	-0.08	-0.09
8th	-0.631	-0.445	-0.344	-0.332
9th*	-0.191	-0.106	-0.022	-0.031
10th*	-0.324	-0.366	-0.257	-0.341
11th*	-0.159	-0.218	-0.068	-0.143
12th*	-0.510	-0.597	-0.648	-0.412
13th*	-0.079	-0.242	-0.280	0.010
14th*	-0.418	-0.640	-0.205	-0.543
15th *	0.473	0.449	0.314	0.180
16th	-0.798	-0.647	-0.010	-0.124
17th*	0.586	-0.359	-0.126	-0.034
18th	-0.424	-0.068	0.390	-0.283
19th*	-	-	-	-
20th	-	-	-	-
21st*	-	-	-	-
22nd	-0.291	-0.560	-0.210	0.131
23rd*	-0.148	-0.080	-0.158	-0.160
24th*	0.026	0.047	0.196	0.226
25th	-0.252	0.018	0.024	0.452
26th*	-0.044	0.559	0.712	0.716
27th	-0.327	-0.349	-0.319	-0.299
28th*	-0.617	-0.388	-0.359	-0.440
29th	-0.400	-0.536	-0.149	-0.130
30th	-0.626	-0.463	-0.104	0.128
31st	-0.780	-0.588	-0.291	-0.404
32nd	-0.266	-0.210	-0.150	-0.118
33rd*	-0.539	-0.343	0.154	-0.387
34 th	-0.092	0.243	-0.119	0.555
35 th*	-0.485	-0.133	0.098	-0.334
36 th*	-0.551	-0.009	0.232	-0.333
37 th*	0.624	-0.285	0.094	-0.115
38 th*	-0.393	-0.297	-0.100	0.168
39 th	0.001	-0.175	-0.057	0.215
40 th	0.366	0.164	0.072	0.201
41 st*	0.144	-0.08	-0.267	-0.020
42 nd	-0.334	-0.499	-0.544	0.218
43 rd*	-0.311	-0.324	-0.336	-0.130
44 th	-0.181	-0.203	0.042	0.325

Table 6.4 : Correlation values between volumetric soil moisture content and the gravity residual at soil sensor SA Mux 52 for precipitation events.

6.4.2 Groundwater

The well SA BK07 has a longer time series than recorded at the other wells in the area. Furthermore the response of the well SA BK07 to precipitation is more evident than the other wells in the area. This could possibly be attributed to the proximity of the well to the surface and river. This has been shown in the previous chapter with correlations between the groundwater level and gravity.

The results from SA BK01 show in a drastic drop in the water level of 40 metres. This is due to the lowering of the sensor in the well. Also we find that in SABK 01 data is missing for event 1. Upon closer inspection the values for events 2,3,4,5, specifically in SA BK 01, were found to be too low. Lastly data for precipitation events 38 to 46 are absent in the groundwater recordings for all the wells.

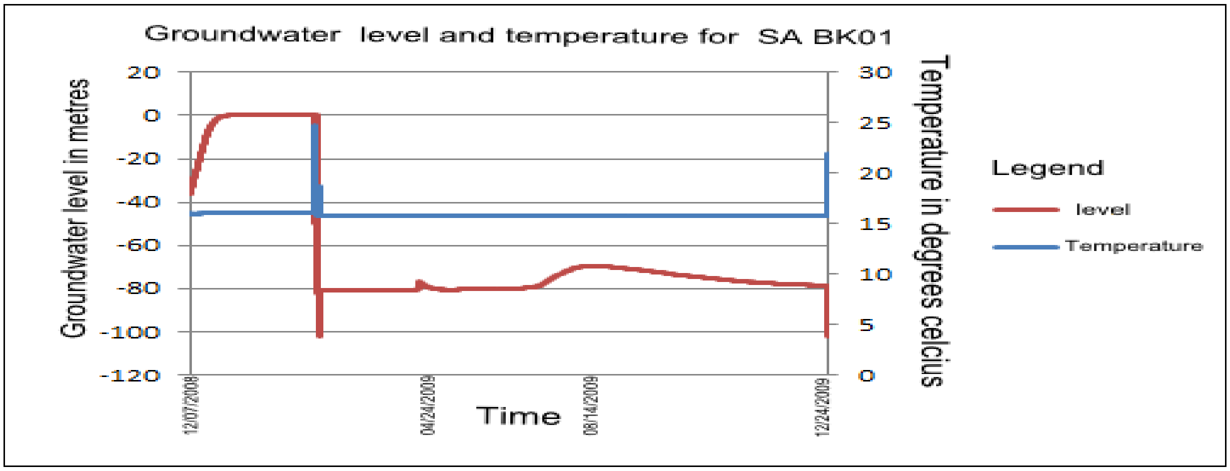

Figure 6.3: The groundwater level and temperature in the well SA BK01. Time is in the format dd/mm/yyyy. Furthermore the spike in water level could be attributed to the relocation of the sensor in the well.

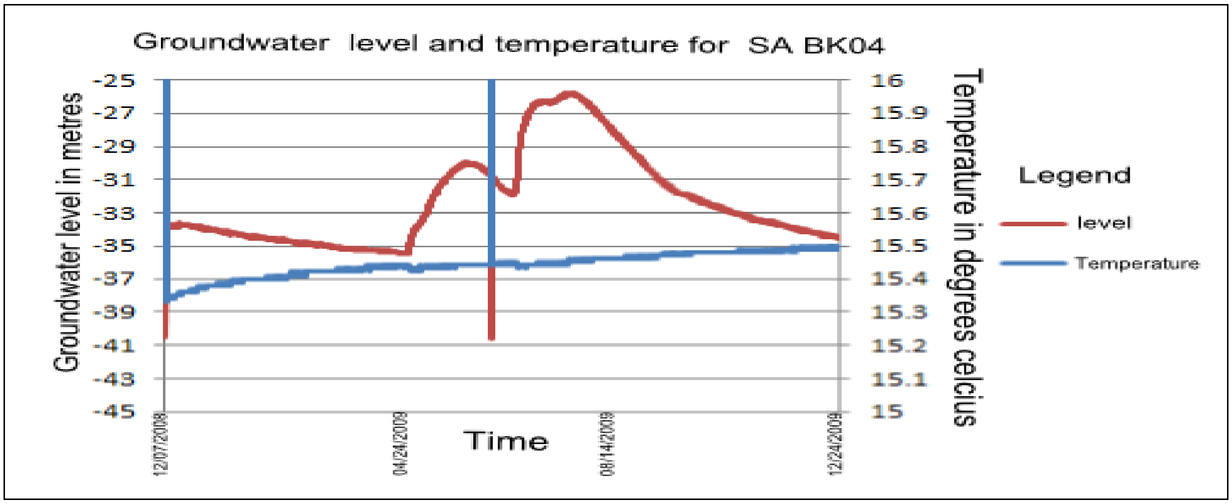

Figure 6.4: The groundwater level and temperature in the well SA BK04. Time is in the format dd/mm/yyyy on the x axis. The vertical variation could be attributed to the movement of the sensor in the well or sensor error.

An increase in groundwater level also directly relates to an increase in groundwater temperature in wells SA BK 04 and SA BK05. The groundwater level in SA BK05 was raised by 1.6 metres due to rainfall inputs. The groundwater level in the well SA BK04 on the other hand was 1m. The variation of 0.8 metres in SA BK07 occurs as a cyclical event with a direct correlation between the water level and water temperature (Figure 6.6).

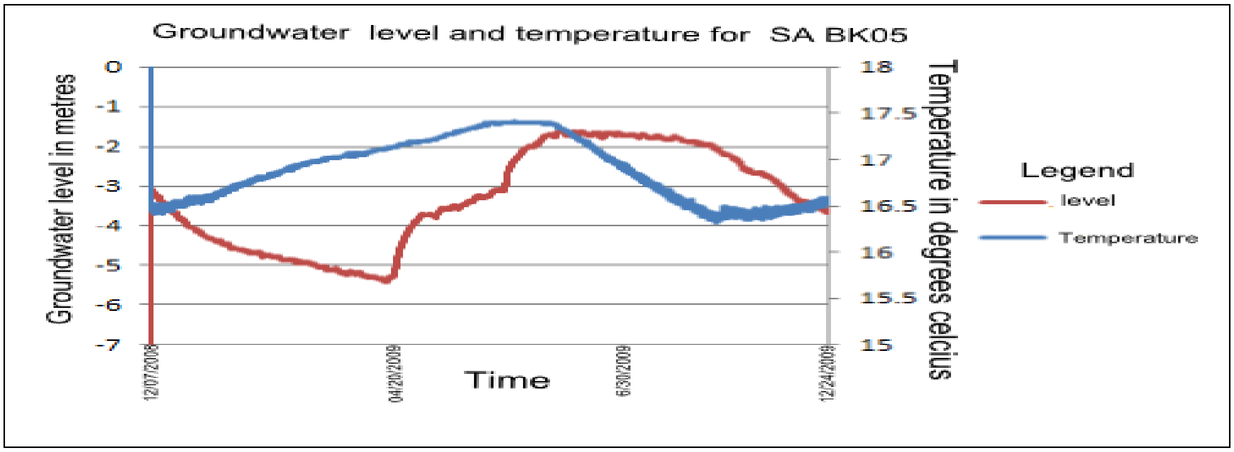

Figure 6.5: The groundwater level and temperature in the well SA BK05. Time is in the format dd/mm/yyyy on the x axis. An increase in groundwater level correlates to an increase in water temperature owing to an inflow of water in the well.

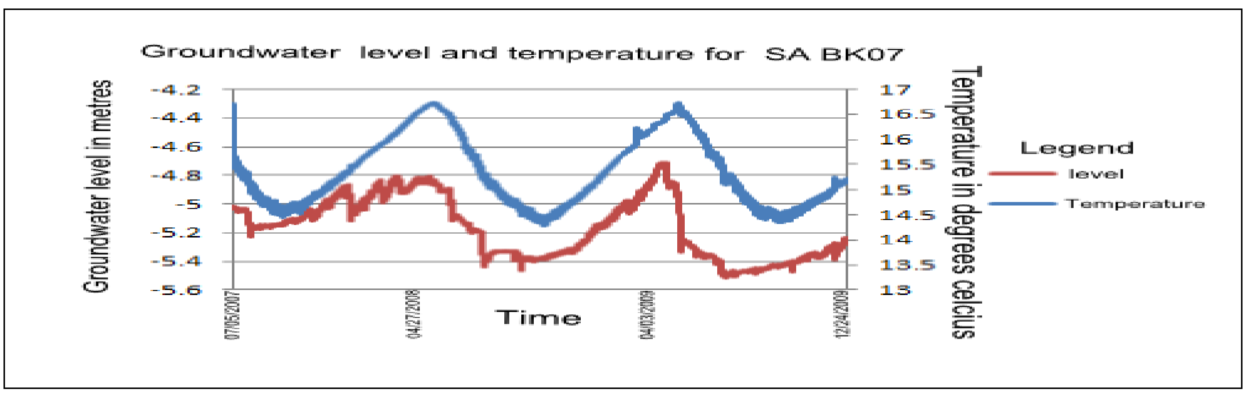

Figure 6.6: The groundwater level and temperature in the well SA BK07. Time is in the format dd/mm/yyyy on the x axis. A seasonal variation occurs within the well, indicating it is merely a conduit.

In 17 cases of correlation values exceeding 0.7, between groundwater levels and the gravity residual, were documented in three wells for 11 rainfall events. 9 of these 17 events occur in well SA BK05. Furthermore 3 rainfall events at 2 wells had a correlation of greater than 0.7 (e.g. 12, 13 and 15) Only one event with all three wells having the aforementioned correlation occur during event 24.

The missing correlation values for events 1, 2, 19, 20 and 21 are due to the gaps in gravity residual data. Missing data for correlation values for events 38 to 46 on the other hand could be attributed to missing groundwater data.

	Correlation coefficient between groundwater level and the gravity residual					
Event	**SA BK01**	**Δ SA BK01**	**SA BK04**	**Δ SA BK04**	**SA BK05**	**Δ SA BK05**
1st	-	-	-	-	-	-
2nd	-	-	-	-	-	-
3rd	-	-	0.321	-0.456	0.389	0.251
4th*	-	-	0.321	-0.010	0.907	-0.064
5th	-	-	0.657	0.339	0.569	0.059
6th	-	-	0.008	-0.678	0.581	0.151
7th	0.032	-0.163	-0.183	0.1629	-0.527	0.014
8th	0.620	-0.057	0.375	0.212	0.894	0.166
9th*	0.140	0.010	-0.228	-0.058	-0.059	0.214
10th*	0.265	0.036	0.320	0.033	0.187	-0.113
11th*	0.480	-0.193	-0.141	0.056	0.123	-0.236
12th*	0.738	0.097	0.467	-0.339	0.723	-0.134
13th*	0.638	-0.177	0.896	-0.082	0.885	-0.037
14^{th}*	-0.164	-0.252	-0.220	-0.035	-0.031	-0.288
15th *	0.909	0.262	0.678	-0.129	0.902	-0.341
16th	0.477	0.290	0.127	-0.055	0.711	-0.040
17th*	0.111	-0.046	-0.366	-0.529	-0.010	0.058
18^{th}	-0.613	-0.288	0.057	-0.504	-0.501	0.058
19^{th}*	-	-	-	-	-	-
20^{th}	-	-	-	-	-	-
21^{st}*	-	-	-	-	-	-
22nd	-0.542	0.144	0.632	-0.290	-0.541	0.495
23rd*	0.581	0.019	0.480	-0.363	0.347	0.271
24^{th}*	0.932	0.0003	0.865	-0.195	0.893	-0.149
25th	-0.225	0.073	-0.674	0.101	-0.238	-0.030
26th*	0.768	0.123	0.158	-0.043	0.774	0.224
27th	-0.313	0.018	-0.042	-0.179	-0.645	-0.003
28th*	-0.466	0.429	-0.324	-0.153	0.540	0.313
29th	-0.819	0.012	0.344	0.060	0.623	-0.087
30th	-0.521	-0.051	-0.1167	0.470	0.470	-0.306
31st	0.614	0.159	0.727	-0.170	0.723	0.059
32nd	-0.616	-0.170	0.347	0.457	0.591	-0.047
33rd*	-0.124	0.057	0.295	0.154	0.404	0.069
34 th	0.407	-0.113	0.204	0.036	0.589	-0.053
35 th*	0.428	-0.004	0.449	0.015	0.690	0.042
36 th*	-0.807	-0.002	0.151	-0.006	0.486	-0.001
37 th*	-0.567	-0.281	-0.248	0.3690	-0.697	-0.318

Table 6.5 : Correlation between groundwater levels after rainfall events and gravity residual for the wells in the immediate vicinity of the SAGOS. The Δ indicates a correlation done with the change in water level.

6.4.3 Recharge events:

6.4.3.1 Soil moisture:

The change in soil moisture over the duration of the precipitation events is very limited. We find a maximum volumetric change of 0.1 in the upper layer of soil. A quarter of all recorded values are negative, with the remaining 75% displaying values varying over four orders of magnitude. (Table 6.6).

Event Number	Change in volumetric soil moisture content			
	0.1 metres	0.2 metres	0.3 metres	0.4 metres
4	0.05	-0.01	-0.04	0
8	0.1	-0.07	0.02	-0.1
12	0.065	0.043	0.049	0.027
13	0.049	0.052	0.035	0.008
15	0.054	0.033	0.029	0.005
16	-0.001	-0.013	-0.005	0.008
24	0.013	0.020	0.035	0.012
26	0.009	0.027	0.019	0.011
29	-0.005	-0.006	-0.002	0.001
31	-0.005	0.001	-0.009	0.002
36	-0.01	-0.014	0.001	-0.007

Table 6.6 : Change in soil moisture at various depths for precipitation events

It can clearly be seen from figure 6.8 that the initial rainfall volume of 0.1 at the start of the precipitation event has little or no impact on the volumetric soil moisture content. Furthermore the soil moisture in the upper 0.1 metres is affected by the precipitation event, whereas the lower layers of soil show little or no variation in the soil moisture for event 4.

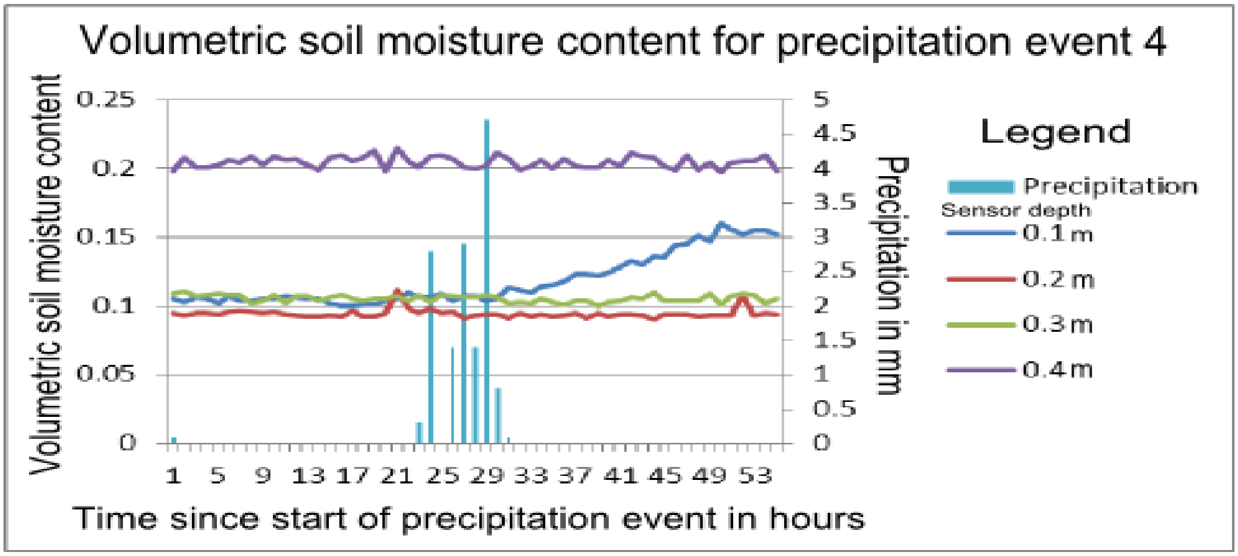

Figure 6.7: Precipitation and volumetric soil moisture content at various depths for event 4. It is evident that the soil in the upper 0.1m responds to precipitation with little or no variation at depth.

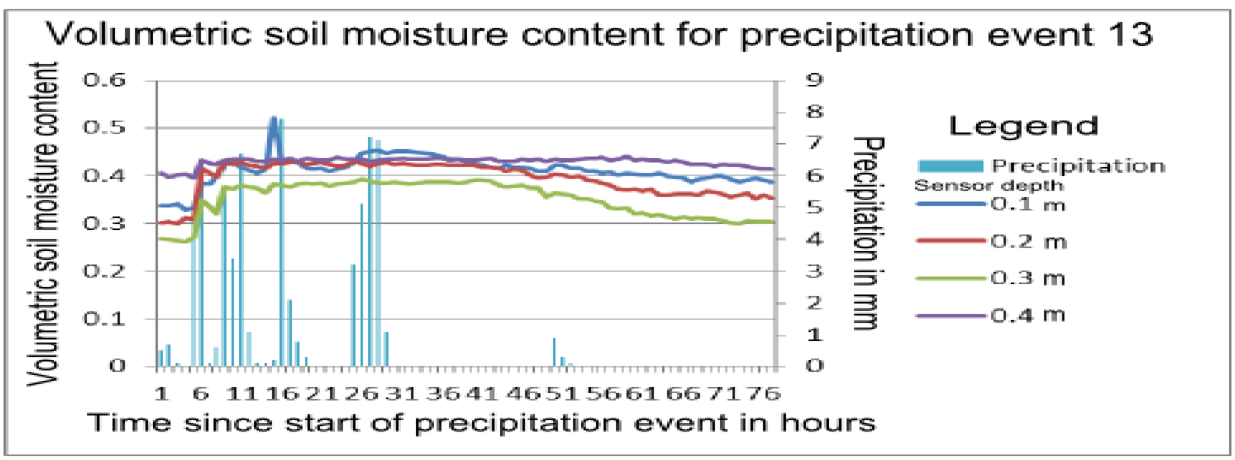

Figure 6.8: Precipitation and volumetric soil moisture content at various depths for event 13. An overall increase in the soil moisture at all depths occurs after the initial precipitation events. Subsequent precipitation events only affect the upper 0.1 with an overall decrease in soil moisture over time.

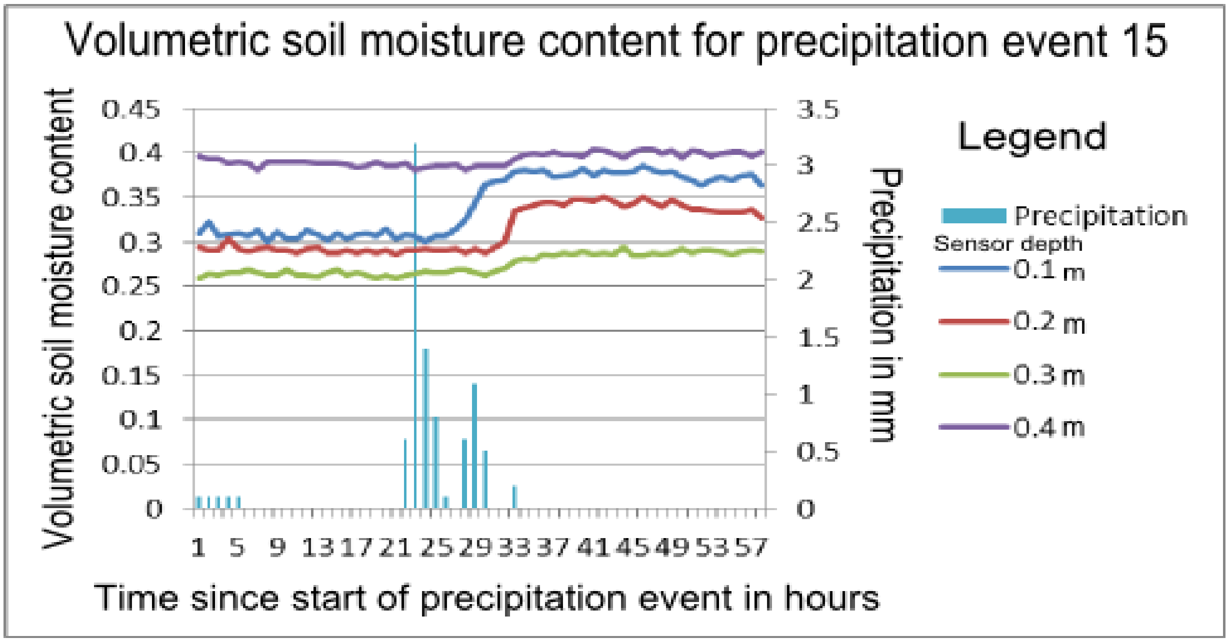

Figure 6.9: Precipitation and volumetric soil moisture content at various depths for event 15. A lag time response to the rainfall occurs at the various depths. The impact the rainfall has on soil moisture volume also decreases with depth.

Event 13 showed the highest volume of precipitation as well as the greatest intensity for the precipitation event. Initial spikes in the volumetric soil moisture content are evident, yet soil moisture decreases by almost 0.1 at 0.3 metres and to a lesser degree in the layers above. This sharp decrease is not present in response to the other precipitation events that have been more closely studied. Event 15 on the other hand shows a similar response to event 13, except a notable lag time response in the lower layers from the second pulse of rainfall can be seen. Furthermore the soil moisture storage is slightly more prolonged.

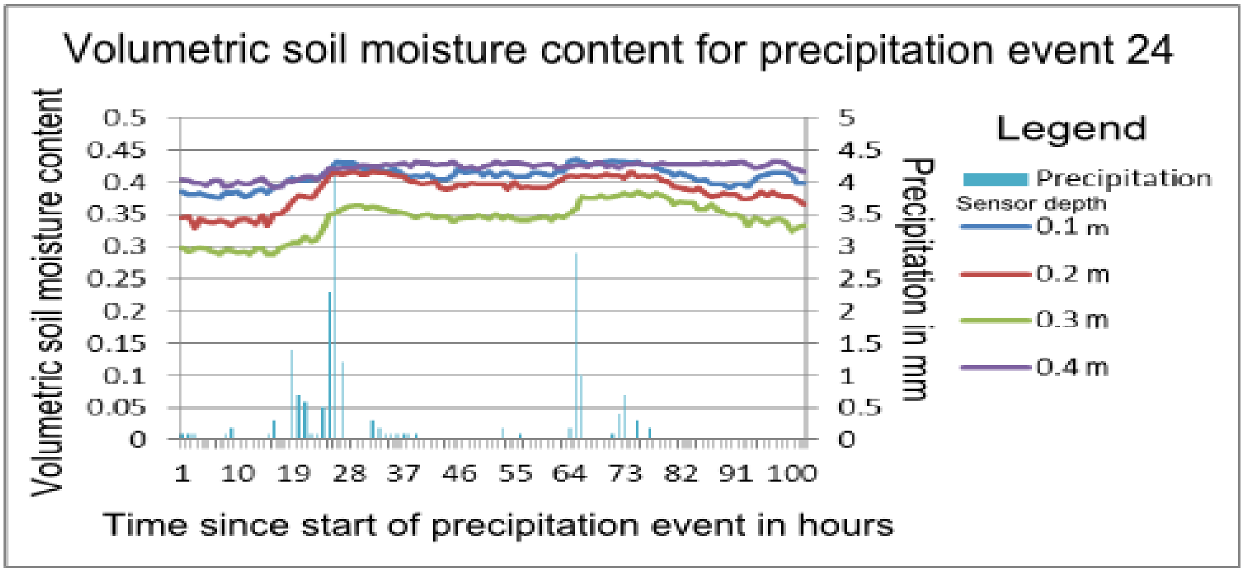

Figure 6.10: Precipitation and volumetric soil moisture content at various depths for event 24. Soil moisture content responses occur only after rainfall events with a total volume of greater than 1mm. The variation in between rainfall events could be attributed to evaporation.

The initial rainfall for precipitation event 24 has no effect on the soil moisture content. The third pulse of rainfall, however increase the volumetric soil moisture at levels 0.1, 0.2 and 0.3 by 0.05. Thereafter a slight drop occurred until approximately 64 hours after the start of the rainfall event, after which another rainfall event occurs that increases the volumetric soil moisture content once again.

6.4.3.2 Groundwater levels:

The long term time series shows an increase in groundwater levels by 1.6 metres in SA BK05 and approximately 1 metre in SA BK 04. These cumulative gains are in response to numerous smaller recharge events occurring due to rainfall inputs as shown in table

6.6. For some instances a strong correlation of up to 0.9 was found, yet no recharge was recorded in the wells in the area. Upon closer inspection the change in gravity residual for these events was negative. This can clearly be seen in events 4 and 8 (Table 6.7).

Event Number	Total volume of precipitation in mm	Rainfall intensity in mm/h	Recharge in well in metres/hour		Change in gravity residual
			SA BK 04	SA BK 05	
4	14.5	1.6	-	-	-0.6748
8	4.7	4.7	-	-	-0.2055
12	19.9	2.2	-	1.1E-08	-0.4978
13	66.1	2.54	1.378E-6	7.39E-08	0.4814
15	9	0.64	9.062E-07	1.625E-08	0.8419
16	0.1	0.1	2.72E-07	2.48E-08	0.1429
24	19.4	0.58	3.46E-06	5.049E-08	1.2666
26	5.1	0.39	2.12E-08	2.97E-08	0.1267
29	0.1	0.1	5.2E-08	1.76E-08	0.361
31	0.1	0.1	-	-	-0.2194
36	1.4	0.14	5E-08	6.52E-10	0.588

Table 6.7 : Calculated recharge for each precipitation event in wells SA BK04 and SA BK05 as well as the change in gravity residual recorded.

“-” Denotes a drop in water level over the time period and thus no recharge

Cases of high rainfall intensity, such as event 13, contributed less water to groundwater recharge than events with lower rainfall intensity, like event 24. Furthermore even though each precipitation event was studied, not all of them contributed equally to groundwater recharge. This is probably due to the decrease recorded in the water table. The WTF method applied in this scenario for the short term events show minimal gains in the total recharge for precipitation events.

6.5 Discussions

6.5.1 Soil moisture data

The lower volumetric moisture is most likely due to content as well as variability shown in the sensor at 0.1 m for the cluster Mux_52 could possibly be attributed to evaporation. Furthermore the increases in moisture content in this upper layer are due to rainfall occurring. Sandy soil, like the type present in the upper layer of the soil, is normally more porous and thus has a higher hydraulic conductivity. The higher water retention capacity of the soil at depth is most likely due to the enriched clay content. These clay soils are able to hold water for longer periods of time due to lower permeability (Marshall and Holmes, 1979). The anomalous values indicated by extreme spikes in the time series analysis of cluster Mux_51 and cluster Mux_51 could be attributed to errors. These residual random errors are normally related to the environmental and operating conditions of the TDR probes (Walker et al., 2004). The vertical noise shown in figures 6.1 and 6.2 may be caused by the instrument itself (Cataldo et al., 2009). This intrinsic error is common and could also be related to installation problems (eg Creutzfeldt et al., 2010). It has been shown that incorrect installation could lead to lower than actual in-situ readings by up to 10% (Walker et al., 2004).

The fact that only 4 instances of correlation were recorded that exceeded 0.7 could be attributed to the storage capacity of the soil. The maximum recorded depth from dug trenches of the red duplex soil in the immediate vicinity of the SAGOS was 0.5 metres. Studies understanding episodic recharge in semi-arid areas have documented vadose zones of 30 metres thick, with water storage capabilities (Massuel et al., 2006). This extensive thickness has aided in understanding flow in the unsaturated zone as well as its effect on episodic recharge. Christiansen et al. (2011) have also shown that a highly porous media, such as the sand of their study area in Denmark, is needed to better understand the relationship between gravity and the vadose zone. The limited depth of the soil in the vicinity of the SAGOS, coupled with the fact that the underlying dolerite is impermeable, leads one to believe that the storage capacity of the soil in this area would not have a great impact on the gravity residual. Massuel et al. (2006) have examined the links between the vadose zone and saturated zone and have shown the effect on episodic recharge and geophysical measurements. The fact that the soil in the measured area of the SAGOS is not directly linked to the groundwater table means that the effect of this vadose zone on the gravity residual will be minimal (e.g. Christianson et al., 2011).

6.5.2 Groundwater data

The variation from well to well in groundwater level could be attributed to the nature of the fractured rock aquifer and the well location (Cook, 2003). Woodford and Chevallier (2002) have also shown that wells sunk in close proximity to dykes in the Karoo have higher yields due to greater fracture connectivity in the immediate vicinity of the dykes. This can clearly be seen when comparing the variation in water levels between SA BK 04 and SA BK05. The latter well has been sunk closer to the dyke and drill logs indicate intersection with two water strikes as well as the baked zone. SA BK01 on the other hand has been drilled well away from the dyke, but instead penetrates a sill. The great variation in water level is clearly not due to recharge, but instead is likely linked to the physical movement of the diver lowered into SA BK01. The missing values for the events 1 to 5 are due to the recorded values being too low on closer inspection, possibly due to sensor error or lack of contact with the water level (Cataldo et al., 2009). Furthermore the missing data for events 38 to 46 could be due to the sensor memory being exceeded and thus hampering available storage to record the data. The diurnal pattern present in SA BK04 could possibly be attributed to tidal effects as suggested by Gribovskie et al. (2010). This is because of the fact that the change in water levels is spaced over a shorter period of time. Anomalous values for groundwater levels could be attributed to instrument error, or in the case of SA BK01, human error due to the movement of the diver.

Precipitation events 4, 12 and 24 had rainfall volumes of 14.5, 19.9 and 19.5 mm respectively. The final event recorded the greatest increase in gravity residual as well a groundwater level in SA BK04. The only event which had a greater impact on the change in water level in SA BK05 was number 13. This specific precipitation event had a total volume of precipitation of 66mm, yet its impact on the gravity signal was merely a third of event 24. This could be attributed to an excess amount of precipitation which would have lead to hortonian overland flow and greater volumes of runoff. This has been shown in arid areas elsewhere due to the occurrence of flash floods (Wheater and Al-Weshah, 2002). It is also typical in arid zones due to the nature of the hard rock at surface (Lange et al., 2000). This is also the case in the immediate vicinity of the SAGOS as the limited soil cover on slopes Also the rainfall intensity of events 12 and 24 was lower than 0.7mm/hour. The rainfall intensity of event 13 on the other hand exceeded 2.5mm/hour. This rainfall intensity coupled with the high infiltration rates in the alluvial beds of the ephemeral streams have been shown to be the major dominating factor in arid zone hydrology all over the world (Lange et al., 2000). Hughes and Sami (1992) have also shown how hydrological losses in alluvium lined ephemeral streams in a catchment in South Africa play a major role in hydrology. The same material lines the stream in the immediate vicinity of the SAGOS and these have been earmarked as conduits for preferential groundwater recharge (Adams et al., 2001).

The decrease in water level in the wells correlates to a decrease in gravity residual for the same time period as shown in precipitation events 4, 8, 12 and 31. This loss in water mass could possibly be due to evaporation as it is localised and not more than 0.16, except for one case in SABK5. This anomalous case is also the lowest recorded recharge value and is negligible when compared to other events, some having recharge volumes of two orders of magnitude greater.

6.6 Conclusions

The analysis of rainfall events in the immediate vicinity of the SAGOS, in conjunction with soil moisture data and groundwater levels, has shed light on the understanding of episodic recharge. It is evident that factors such as the amount of rainfall, intensity of the rainfall, duration of the rainfall event, as well as antecedent soil moisture conditions determine the volume of recharge contributing to groundwater. This can be seen by the fact that a rainfall event of 66.1 mm had a lesser impact on recharge than an event of 19.4mm and it can be concluded therefore that the initial soil moisture as well as runoff regime need to be understood in order to properly quantify recharge and understand the mechanisms responsible (see also Chapter 3) for the area around the SAGOS. This work further advocates the ideas of preferential flow as a mechanism for groundwater recharge in the semi-arid area surrounding the SAGOS. This is also evident from the data for the well SABK05, which has an immediate response and a rise in water level. This well response differs to that of SABK07, which rises and falls immediately after a rainfall event (see chapter 5). This indicates that SABK05 stores groundwater whereas SABK07 is likely a conduit or throughflow. The higher correlations between groundwater levels and the gravity residual occurring after rainfall events. This is despite the fact that the calculated recharge, using the Water Table Fluctuation method, was in the region of 1E-08 for SA BK 05. Furthermore the fact that recharge in SA BK04 was 2 orders of magnitude greater than SA BK 04, for some of the events, alludes to preferential flow playing a role in the recharge process. The gravity residual data also indicates a loss in water with a decrease in groundwater level, as correlated to a decrease in the gravity residual over time. Furthermore weaker correlations between the soil moisture and gravity residual occur after the precipitation events. Also the interaction of the soil with the atmosphere and its rapid response to precipitation and evapotranspiration seems to have little or no effect on the gravity residual. The SG residual data has added value and increased our understanding on the episodic recharge in the immediate vicinity of the SAGOS.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Water resource management and in turn potable water supply are a major issue in the semi-arid Karoo. Most of the towns rely on groundwater for their drinking supply. Therefore understanding this subsurface water reservoir is of the utmost importance. It is also critical that the recharge mechanisms, rates of flow, as well as volumes, are understood for sustainable groundwater extraction.

The major conclusions of this study have been summarized after each chapter. These are merges below in order to examine the relationships between them.

Foremost this study has shown and emphasized that remotely sensed data will greatly aid future management of groundwater resources. This is due to the fact that a greater area is covered and more data is captured than at a single sample point. This has been shown with the use of SPOT 5 imagery for mapping the geology as well as aerial photography to aid in mapping the soils around the SAGOS. Furthermore the verification of this satellite data with ground based measurements is critical important for understanding and improving the precision of the remote sensing tools.

This study also confirms the importance of water chemistry in understanding the subsurface and to determine sources of recharge and in-situ water chemistry. This has been verified in this study through the use of macro chemistry, as well as stable isotopes. Major conclusions related to the distinct water chemistry results within each well show that isolated water tables occur due to the distinct water chemistry within the study area. In addition the stable isotope chemistry points to a mixing relationship between precipitation events, and that precipitation preferentially flows into the groundwater. Evidence for this lies in the fact that groundwater samples plot in between rainfall samples on the stable isotope plot. Finally, all the samples plot in close proximity to the meteoric line and were not greatly affected by evaporation. The knowledge of aquifer hydraulics also aided in understanding the impact of the dykes on fracture connectivity and in turn the hydraulic conductivity of the sandstones. This secondary porosity is greatest closer to the dykes, as was proven with pump tests. These doleritic intrusions also compartmentalize the groundwater flow as is evident from the water chemistry.

In-situ infiltration tests and soil mapping revealed a high hydraulic conductivity in the river beds. These river were therefore identified as the preferential pathways for infiltration and groundwater recharge, as shown by the similarity of the isotopic signature of the rainfall and groundwater. Red duplex soils on the other hand display higher infiltration rates in their upper layers, whilst the enriched clay layer at depth limits flow, as shown by dye tracer tests. These duplex soils are on average 0.5 metres thick. Field observations indicate salinization at the surface, also limiting infiltration in the brown duplex soils. The major difference between these two duplex soils is the colour. Furthermore the red duplex stems from dolerite whereas the brown duplex lies on sandstone. Laboratory tests, which included sieve analysis and column separation, classified the soil in the area as sand or loamy sand. Soil mapping and the use of the eliminative key, as outlined by Fey (2010), indicate that the soils of the area are multi layered in nature with sand in the upper layer and clay at lower depth.

Precipitation events from 2002 until 2006 were earmarked for further examination. The change in water level in SA BK07 and the corresponding gravity residual were correlated in order to understand the relationship between subsurface fluid storage and its effect on gravity. It was concluded that the well SA BK 07 seems to be a conduit, possibly a perched water table, due to its proximity to the surface and the water chemistry data. In field observations indicate an anoxic environment due to the stench of sulphides. Correlations as strong as 0.9 were observed in certain instances, when comparing the gravity and change in water level. Inverse correlations of -0.79 were also observed. It was deduced that no definite pattern or relationship could be deduced from the statistical data. Graphical representation of the data on the other hand indicates an inverse relationship between gravity and the change in water level. A lag time response is also evident and this could be due to the delayed time response of infiltrating recharge. The addition of mass, by means of recharge, is the major factor affecting the change in gravity residual

17 instances of correlations, between the groundwater levels in the various wells and the gravity residual, exceeding 0.7 were determined for precipitation events. Only 4 instances were calculated between the soil moisture and gravity residual on the other hand. This has lead to the conclusion that the groundwater recharge is the major contributor to change in gravity residual. This is due to the change in groundwater level and the gravity residual correlating in excess of 0.7.

In summary, stemming from the idea of comparing soil moisture and short term groundwater levels to understand recharge in the semi-arid Karoo, this work has shown that gravity is an excellent tool for understanding episodic recharge of water reservoirs in the vicinity of the SAGOS.

7.2 Recommendations for future work

Major recommendations are summarized in line with the future research required to further characterize the hydrological regime.

Stable isotopes in such as carbon, hydrogen, chlorine as well as oxygen concentrations of bulk samples should be conducted in order to determine the source of contamination in environmental geochemistry. This is due to the unique signatures of certain constituents of the specific compounds, like for example fertilizers. This will definitely play a role in understanding the sources of contaminants in the Karoo and beyond. Possible applications include, Acid Mine Drainage, Agriculture as well as industrial effluent. Monitoring the movement of BTEX chemicals as well as other organic solvents must also be examined using of stable isotopes. This will be of particular interest for example for future studies related to monitoring water contamination effects during planned hydraulic fracturing in the Karoo.

Spatial examination of gravity signals with mobile gravimeters will aid in understanding the varying spatial and temporal gravity signal and clarify the uncertainties embedded in these signals. Other geophysical tools, such as GPR, seismics, resistivity and ground based magnetics, are useful for better characterising subsurface hydrogeology, provided they are complimented with drilling.

The SG station at Sutherland has one SG installed and another SG in storage, which was initially meant for an SG station in South America. It is proposed that the inactive SG be installed at the newly built geodetic station at Maatjiesfontein. The ground based SG will complement the space geodetic instruments proposed for installation at the site (Combrinck et al., 2007). In this manner the measurements of two SG's could be directly compared to one another. The effect of local hydrology at various locations could be compared at a higher resolution and in both cases in fractured rock environments. Another possibility is the use of a new mobile SG in conjunction with Lacoste and Romberg gravimeters at various locations across the entire catchment. This has been done by Naujoks et al. (2007) at Moxa and highlighted the variability in gravity residual spatially as well as temporally.

The temporal and spatial resolutions for gravity are extremely variable and dependant on the manner in which the gravity signal is processed as well as the total water storage. The local measurements for SG and GPS are highly precise at a site scale. GRACE on the other hand has a resolution in the region of 250 km. The gap in between these two scales from a hydrological perspective lies in the catchment and regional scale.

Episodic and preferential recharge need to be better understood for the Karoo. The relationship between rainfall and recharge in arid areas of the Northern Cape, show that recharge is not necessarily an annual event. Similarly it has been shown in this study that not each and every rainfall event contributes to the mass change in gravity residual correlated to groundwater levels. This is important to note and the threshold in terms of volumes of rainfall as well as intensity needs to be examined in future studies in order to better quantify recharge.

Such quantification of recharge as well as the flow of moisture in the unsaturated fractured zone will have a great impact on groundwater protection zoning and management (Nel et al., 2009). This issue must take precedence as the possibility for fracking has arisen in the Karoo following the lifting of the moratorium on exploration for shale gas. Therefore the numerical modeling as well as fracture delineation for the unsaturated zone is of the utmost importance.

Another site specific study that should be undertaken is the close geophysical examination of streams. Fnais (2010) has shown how the use of resistivity profiles, in conjunction with seismic profiles and vertical electrical sounding, can delineate areas of preferential flow within an arid area. Ground Penetrating Radar is another tool which could potentially aid in characterizing the sub-surface. Another new application to sub- surface geophysics is Magnetic Resonance Imaging. A special issue on the applications for exploring and assessing groundwater using Magnetic Resonance Imaging has been published by the European Association of geoscientists and engineers (Legchenko et al., 2011). These tools should all be applied in conjunction with down well geophysical logging as shown by Cook (2003). Once again the combination of multiple tools is important for understanding the subsurface. The profiles should be done across the stream channel as well as along the channel itself. This would highlight the depth to groundwater table, as well as the zones of recharge within the channel.

Generation of copious amounts of data requires skilled programmers and data scientists to manage, process and present this data (Janeart, 2011). Furthermore this data must feed into numerical models, which should be completed at site, catchment and regional scale in the immediate vicinity of the SAGOS for future studies.
Monte Carlo simulations and Principle component analysis of the various models should be completed. This will add value to the study due to their ability to examine multiple variables as well as uncertainty. Smidts and Devooght (1998) have shown that the increasing computational power and space, along with data, allows for more intensive examination of variables and therefore more possible solutions. These applications could all be done with the use of open source tools and scripting languages, such as those highlighted by Janeart (2010) as well as Duncan and Hull (2001). Other FOSS languages for data analysis include, but are not limited to :

- R statistical programming.
- Bash Shell or command line in Linux.
- Standard Query Language (SQL).
- Python.

The above mentioned tools are all currently being applied in the field of data mining for the purposes of data manipulation, analysis and graphical presentation (Janeart, 2010).

Once the data has been mined, specifically from the NGDB in a South African context, data quality control should be implemented. Statistical methods, specifically for water resources, such as error balances and interpolation have been outlined by Helsel and Hirsch (2002). The gaps in data could then be examined and hopefully filled by future groundwater projects. This will add value to the current database and aid in groundwater resource management. Furthermore this previous knowledge, in conjunction with modern trends will aid in the direction for future research needs.

In line with this, the International Groundwater Resource Assessment Centre (IGRAC), in the Netherlands, has compiled an online database on all the available software for analyzing groundwater related information. The online interface allows one to search through the plethora of software by selecting a country or even organization. One such organization leading the FOSS drive related to geology is the USGS. The code for most of the software is freely available and can be modified by the user.
One such tool (e.g.HYDRUS 1D package), as developed by Simunek and van Genuchten (2008), for simulating soil moisture and water transport in the vadose zone. The highly porous alluvium lining the riverbeds is the most important area as it dictates the hydrological regime in arid zones (Lange et al., 2000). Multiple codes for soil water

modeling have been compared by Scanlon et al. (2008) and are highlighted in Table 2.5. This has to be done in conjunction with groundwater modeling for the area surrounding the SAGOS. MODFLOW is the major modeling tool used in industry today (Chiang and Kinzelbach, 2003). The available open source GUI's for this finite difference model can be found on the USGS website. More recently a version of PMWIN, as developed by Chaing and Kinzelbach (2003), has also been made freely available. In South Africa the SPATSIM model should be applied for surface water in arid zones , like the immediate vicinity of the SAGOS.

From a policy perspective the need arises for the stakeholders, resource managers, researchers' and politicians to speak to one another. This has been shown by Braune et al. (2008) with the inclusion of the AMCOW in the development of a SADC wide groundwater management policy. This could be achieved by hydrologists speaking to geodetecists in order to refine and develop the models and estimation tools linking the two scientific fields.

Aspects of the work were undertaken and it was found that the model could not provide a realistic representation. However, the uncertainty related to the analysis of numerical modeling, specifically in fractured rock aquifers, extends beyond the scope of this work. The data mining and analysis will tie in well with the numerical modeling for future work and to better correlate total water storage with the gravity residual. These modeling projects are normally works on their own and require extensive computing power and knowledge of the software.

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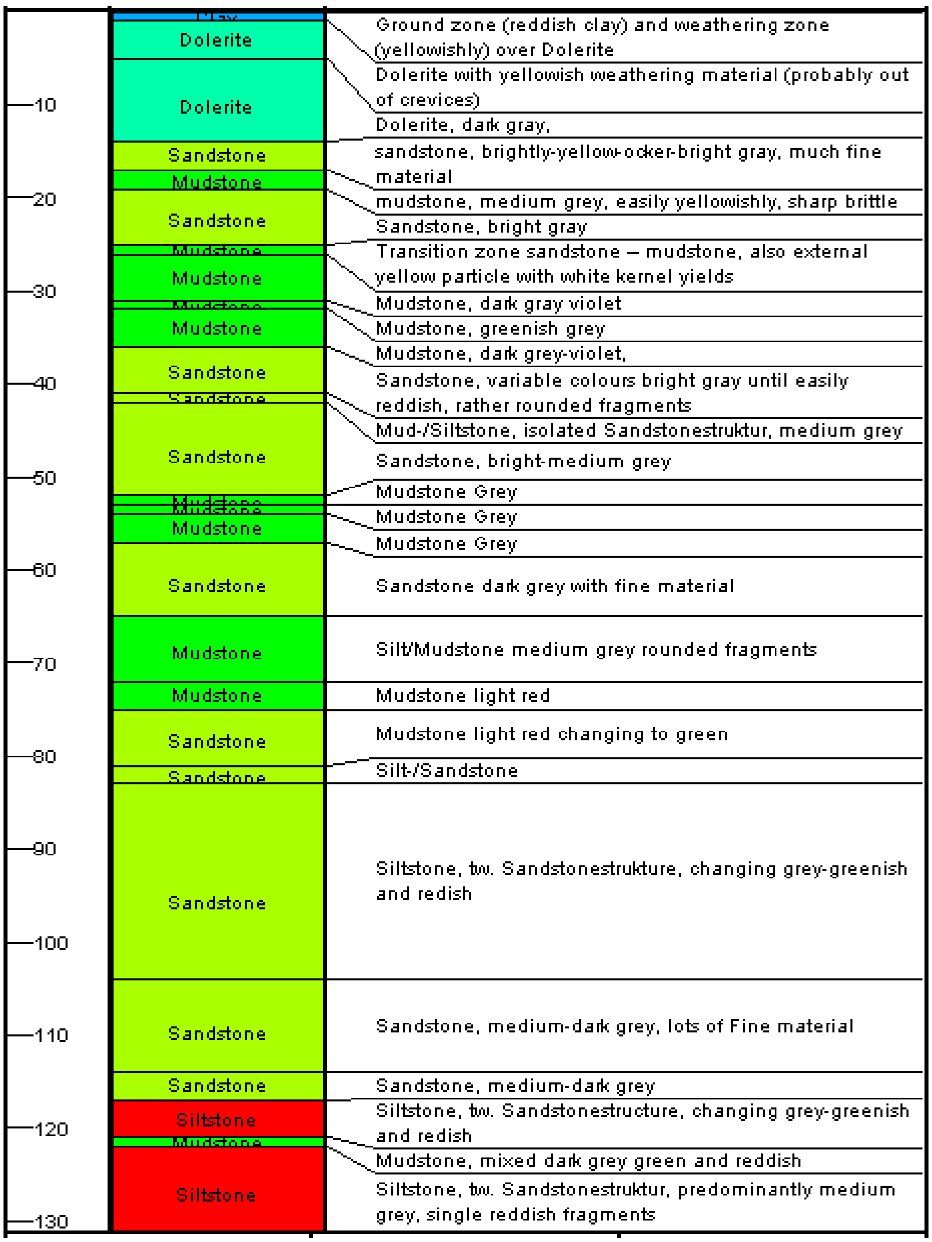
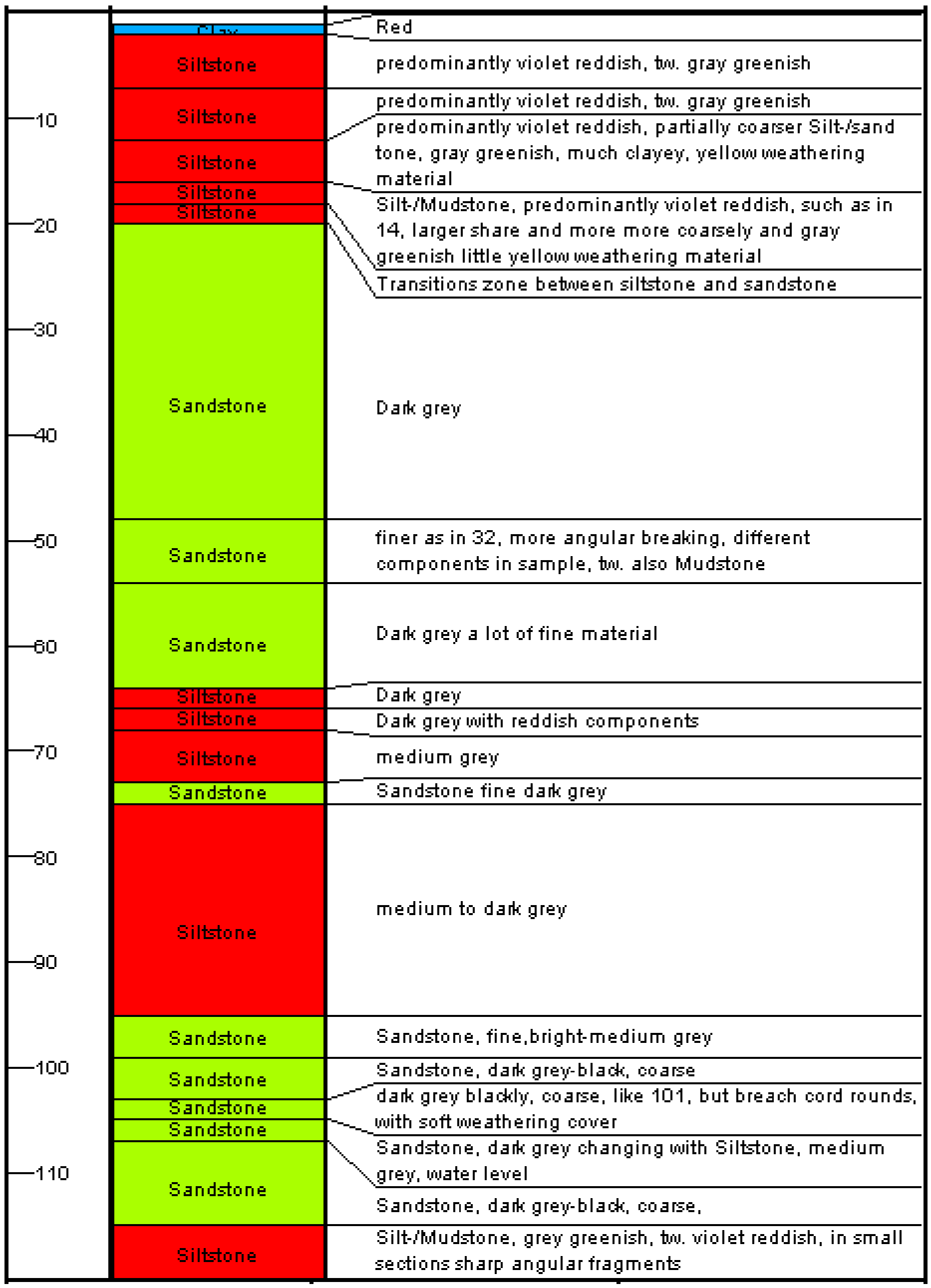
APPENDIX A
DRILL LOGS

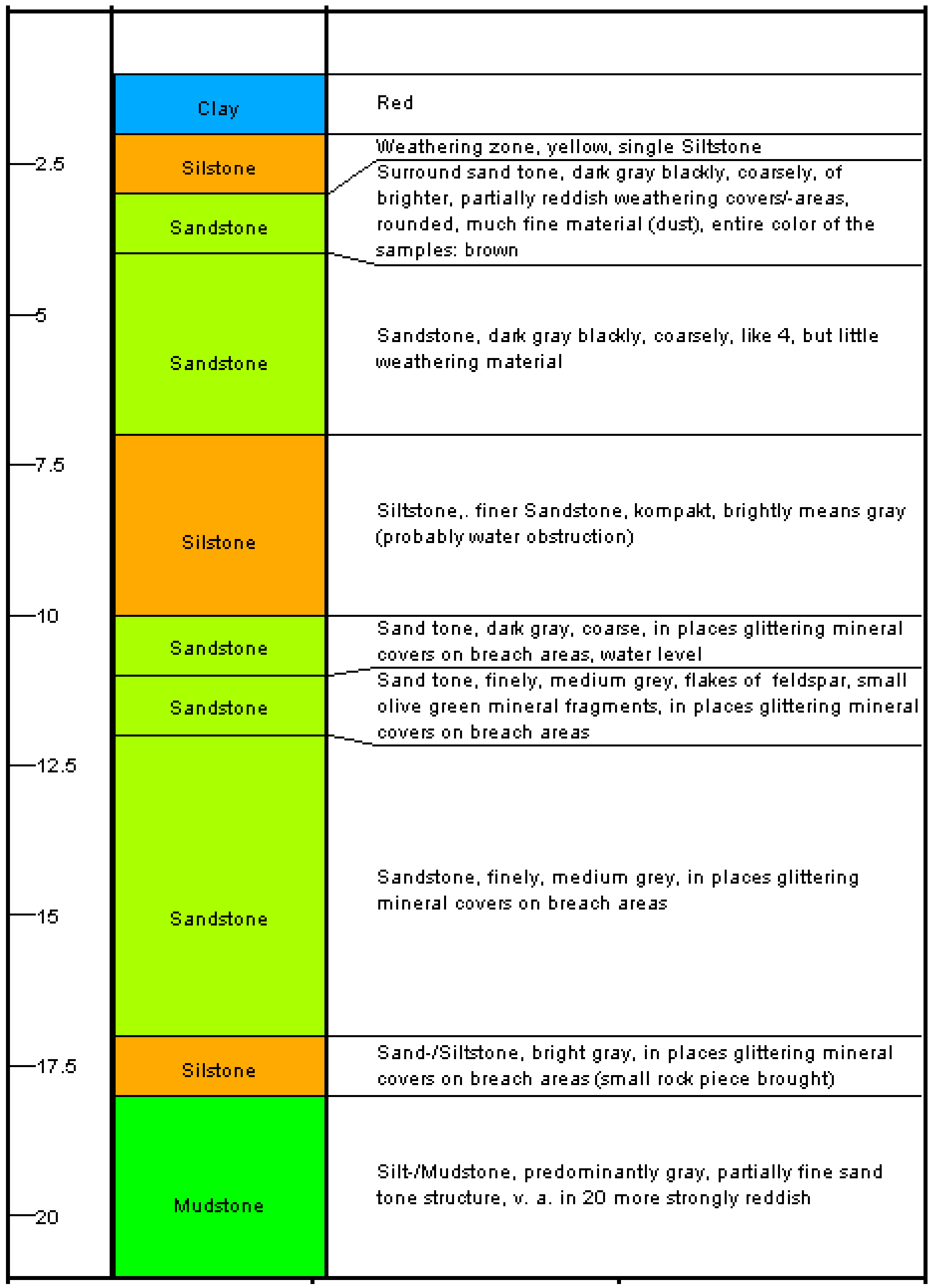
SA BK 01



SA BK 04


10
20
30
40
50
60
70
80
90
100
110
Clay
Siltstone
Sandstone
Red
predominantly violet reddish, tw. gray greenish
predominantly violet reddish, tw. gray greenish
predominantly violet reddish, partially coarser Silt-/sand tone, gray greenish, much clayey, yellow weathering material
Silt-/Mudstone, predominantly violet reddish, such as in 14, larger share and more more coarsely and gray greenish little yellow weathering material
Transitions zone between siltstone and sandstone
Dark grey
finer as in 32, more angular breaking, different components in sample, tw. also Mudstone
Dark grey a lot of fine material
Dark grey
Dark grey with reddish components
medium grey
Sandstone fine dark grey
medium to dark grey
Sandstone, fine,bright-medium grey
Sandstone, dark grey-black, coarse
dark grey blackly, coarse, like 101, but breach cord rounds, with soft weathering cover
Sandstone, dark grey changing with Siltstone, medium grey, water level
Sandstone, dark grey-black, coarse,
Silt-/Mudstone, grey greenish, tw. violet reddish, in small sections sharp angular fragments

SA BK 05


2.5
5
7.5
10
12.5
15
17.5
20
Clay
Silstone
Sandstone
Sandstone
Silstone
Sandstone
Sandstone
Sandstone
Silstone
Mudstone
Red
Weathering zone, yellow, single Siltstone
Surround sand tone, dark gray blackly, coarsely, of brighter, partially reddish weathering covers/-areas, rounded, much fine material (dust), entire color of the samples: brown
Sandstone, dark gray blackly, coarsely, like 4, but little weathering material
Siltstone,. finer Sandstone, kompakt, brightly means gray (probably water obstruction)
Sand tone, dark gray, coarse, in places glittering mineral covers on breach areas, water level
Sand tone, finely, medium grey, flakes of feldspar, small olive green mineral fragments, in places glittering mineral covers on breach areas
Sandstone, finely, medium grey, in places glittering mineral covers on breach areas
Sand-/Siltstone, bright gray, in places glittering mineral covers on breach areas (small rock piece brought)
Silt-/Mudstone, predominantly gray, partially fine sand tone structure, v. a. in 20 more strongly reddish

APPENDIX B
LIST OF PUBLICATIONS

Analysis of temporal and spatial variations in water storage for the area of SAGOS and the Western Karoo[1]

Mahed, G[1], Gunter, A[2], Docoure, M[3] and De Wit, M[3]

1)AEON-Africa Earth Observatory Network, University of Cape Town, South Africa
2) Helmholtz Centre for Geosciences, GFZ, Potsdam, Germany
3) AEON, Faculty of Science, Nelson Mandela Metropolitan University, South Africa

ABSTRACT

Spatial and temporal variations in water storage can be attributed to the heterogeneous nature of the subsurface. In this paper, the properties of soil and fractured rock aquifers are examined for the example of the South African Gravimetric Observation Station (SAGOS) in Sutherland. Also, aspects of groundwater recharge and their implications for gravimetric observations are reviewed. First results obtained from a hydro-meteorological monitoring system that was installed about one and a half years ago in Sutherland, measuring climate variables, soil moisture and groundwater levels, are evaluated. The results will aid in the development of a local 3-D subsurface model and in interpreting the gravity residuals of the superconducting gravimeter in Sutherland.

[1] This poster presentation was delivered at the European Geophysical Union Conference in Vienna, Austria, 02-07 May 2010

In-situ hydraulic properties of soils surrounding the South African Geodynamic Observatory, Sutherland[2]

Mahed, G[1], Gunter, A[2], Blume, T[2], Kreutzfeld, B[2] and De Wit, M[3]

1)AEON-Africa Earth Observatory Network, University of Cape Town, South Africa
2) Helmholtz Centre for Geosciences, GFZ, Potsdam, Germany
3) AEON, Faculty of Science, Nelson Mandela Metropolitan University, South Africa

ABSTRACT

The soil surrounding the South African Geodynamic Observatory, Sutherland, is examined. Mapping, by means of satellite imagery, and thereafter field verification, was undertaken. In conjunction with the mapping, trenches were dug in order to examine the subsurface characteristics of the soil. Thereafter infiltration tests were scattered across the terrain in order to ascertain the in-situ hydraulic properties. Furthermore time series analysis of the volumetric soil content was examined at various depths close to the Superconducting Gravimeter at Sutherland. Laboratory tests prove that the low clay content of the soil could be attributed to illuviation. This was confirmed by utilising two different methods.(name these methods here) It was also shown that the water retention capacity of the duplex soils surrounding the gravimeter increase with depth. These investigations are all consistent with great spatial variability, laterally as well as vertically, within the soil. Furthermore we found that the rivers are preferentially more hydraulically conductive due to the coarse nature of the underlying material.

[2] This paper was presented at the Inkaba Workshop at the Geosynthesis Conference in Cape Town, 28 August- 02 September, 2011

Characterisation of the Groundwater regime in the immediate vicinity of the SAGOS[3]

G.Mahed[1], M.De Wit[2], A.Gunter[3] and Blume, T[3]

1) AEON-Africa Earth Observatory Network, University of Cape Town, South Africa
2) AEON, Faculty of Science, Nelson Mandela Metropolitan University, South Africa
3) Helmholtz Centre for Geosciences, GFZ, Potsdam, Germany

ABSTRACT

The aquifer in the vicinity of the Superconducting Gravimetre, Sutherland is examined. The secondary saturated geologic unit seems to display high fracture connectivity in the immediate vicinity of post dolerite dykes. This has been inferred from the rapid hydraulic recovery of wells in the immediate vicinity of these dolerite intrusives. Further evidence lies in the orientation of fractures, which were measured in-situ, as well as hydraulic head measurements. Hydrogeochemistry on the other hand points towards possible perched water tables with, the isotopic data suggestive of preferential flow as the major mechanism for recharge.

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[3] This paper was presented at the Biennial Groundwater Conference of the Groundwater division of the Geological Society of South Africa, Pretoria, 19th-21st September 2011

Time series analysis of rainfall events and the gravity response at the Southern African Geodynamic Observatory, Sutherland[4]

G.Mahed[1,2], M, de Wit[2] , A.Gunter[3] and Blume, T[3]

1) Nelson Mandela Metropolitan University, Department of Geoscience, Port Elizabeth, South Africa
2) AEON, Faculty of Science, Nelson Mandela Metropolitan University, South Africa
3) Helmholtz Centre for Geosciences, GFZ, Potsdam, Germany

ABSTRACT

Individual rainfall events are closely examined for their significance and relation to residual gravity data. The subsurface water level at one well in conjunction with precipitation and the gravity residual data are highlighted in order to determine possible patterns and relationships. In some instances strong correlations are found between the water level data and the gravity residual for the events having multiple instances of precipitation. With regards to the individual rainfall events strong correlations were also found between the water level in SABK07 and the gravity residual. This sheds some light on the variability of the hydrological regime. In both cases weak and inverse correlations were also found. Furthermore the fact that one reservoir is not the only contributor to the mass storage in the subsurface is also highlighted. Lastly the possibility that this well could merely be a conduit for throughflow due to the instantaneous response to precipitation and the subsequent drop in water level is another possibility.

[4] This paper was presented at the UNESCO and International Union for Geological Sciences Project 564, Final meeting in Johannesburg, October 31- 02 November 2012. It is also envisaged that the paper will be published in a special edition of the Journal of Physics and Chemistry of the Earth