RESPICE PROSPICE

UNIVERSITY *of the*
WESTERN CAPE

SUSTAINABLE UTILISATION OF TABLE MOUNTAIN GROUP AQUIFERS

Dissertation submitted to the University of the Western Cape in the fulfillment of the requirements for the degree of

Doctor of Philosophy

By

Anthony A. Duah

In the

Department of Earth Sciences
Faculty of Natural Sciences
University of the Western Cape
Cape Town

Supervisor: Prof. Yongxin Xu

July, 2010

DECLARATION

I declare that SUSTAINABLE UTILISATION OF TABLE MOUNTAIN GROUP AQUIFERS is my own work, that it has not been submitted for any degree or examination in any other University, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full Name: Anthony Appiah Duah Date: July, 2010

Signed…………………………………..

ABSTRACT

Sustainable Utilisation of Table Mountain Group Aquifers

A. Duah

PhD Thesis

Department of Earth Sciences

Key words: Sustainability, sustainable yield, safe yield, aquifer, Climate Change, Climate Variability, trend analysis, recharge, discharge, adaptive management, dependent ecosystem, hydrostratigraphic unit, precipitation index.

The Table Mountain Group (TMG) Formation is the lowest member of the Cape Supergroup which consists of sediments deposited from early Ordovician to early Carboniferous times, approximately between 500 and 340 million years ago. The Table Mountain Group (TMG) aquifer system is exposed along the west and south coasts of South Africa. It is a regional fractured rock aquifer that has become a major source of bulk water supply to meet the agricultural and urban water requirements of the Western and Eastern Cape Provinces of South Africa. The TMG aquifer system comprises of an approximately 4000 m thick sequence of quartz arenite and minor shale layers deposited in a shallow, but extensive, predominantly east-west striking basin, changing to a northwest orientation at the west coast. The medium to coarse grain size and relative purity of some of the quartz arenites, together with their well indurated nature and fracturing due to folding and faulting in the fold belt, enhance both the quality of the groundwater and its exploitation potential for agricultural and domestic water supply purposes and its hot springs for recreation. The region is also home to some unique and indigenous floral species (fynbos) of worldwide importance. These and other groundwater dependent vegetation are found on the series of mountains, mountain slopes and valleys in the Cape Peninsula. The hydrogeology of the TMG consists of intermontane and coastal domains which have different properties but are interconnected. The former is characterized by direct recharge from rain and snow melt, deep groundwater circulation with hot springs and low conductivity groundwater. The coastal domain is characterized by shallow groundwater occurrence usually with moderate to poor quality, indirect recharge from rainfall of shallow circulation and where springs occur they are usually cold.

The sustainable utilization of the TMG aquifer addressed the issues of the groundwater flow dynamics, recharge and discharge to and from the aquifer; challenges of climate change and climate variability and their potential impact on the aquifer system. The concept of safe yield, recharge and the capture principle and the integration of sustainable yield provided the basis for sustainable utilization with the adaptive management approach. Methodology used included the evaluation of recharge methods and estimates in the TMG aquifer and a GIS based water balance recharge estimation. The evaluation of natural discharges and artificial abstractions from the TMG aquifer system as well as its potential for future development. The Mann-Kendal trend analysis was used to test historical and present records of temperature and rainfall for significant trends as indication for climate variability and change. The determination of variability index of rainfall and standard precipitation index were additional analyses to investigate variability. The use of a case study from the Klein (Little) Karoo Rural Water Supply Scheme (KKRWSS) within the TMG study area was a test case to assess the sustainable utilization of TMG aquifers.

Results show that recharge varies in time and space between 1% and 55% of MAP as a result of different hydrostratigraphic units of the TMG based on geology, hydrology, climate, soil, vegetation and landuse patterns however, the average recharge is from 1% to 5% of MAP. The TMG receives recharge mainly through its 37,000 km^2 of outcrop largely exposed on mountainous terrain. Natural discharges from the TMG include 11 thermal and numerous cold spring discharges, baseflow to streams and reservoirs, and seepage to the ocean. Results from this study also show increasing temperature trend over the years while rainfall trend generally remain unchanged in the study area. Rainfall variability persists hence the potential for floods and droughts in the region remain. Global and Regional Models predict about 10% to 25% reduction in rainfall and increase in variability in future. Impacts of this change in climate will affect the different types of aquifers in various ways. Increase in temperature and reduction in rainfall will increase evapotranspiration, reduce surface flows and eventually reduce shallow aquifer resources. Coastal aquifers risk upsurge in salinisation from sea level rise and increase in abstractions from dwindling surface water resources. While floods increase the risk of contamination to shallow aquifers droughts put pressure on all aquifers especially deep aquifers which are considered to be more reliable due to the fact that they are far removed from surface conditions. Future population growth and increase in freshwater demand will put more pressure on groundwater.

Recharge to groundwater have been over-estimated in certain areas in the past leading to high abstraction rates from boreholes causing extensive groundwater storage depletion evident by high decline in groundwater levels in these areas and hampering sustainable management of the aquifer resources. Over-abstraction have resulted in loss of stream flow and baseflow reduction to streams during summer, complete loss of springs and reduction of flow to others. Flow to wetlands, riparian vegetation, and sometimes loss and shifts in dependent ecosystems have also resulted from over-abstraction. Sustainability has spatial and temporal implications due to changing climate and demand.

The study recommends adaptive management practices in which several factors are considered in managing groundwater together with surface water resources in order to maintain ecological and environmental integrity. The KKRWSS and other groundwater supply schemes in the Western and Eastern Cape Provinces demonstrate the huge potential of the TMG to provide freshwater supply for domestic and irrigation water needs however, the huge decline in groundwater levels due to over-abstraction in the KKRWSS and other groundwater schemes underscores the need for sustainable utilization of the TMG groundwater resources for present and future generations with minimal impacts on the quality, dependent hydrological and ecosystems as well as the environment.

ACKNOWLEDGEMENTS

This work has been as a result of the help and cooperation of many individuals and institutions. The author would like to express his heart-felt gratitude to the following persons who contributed in no small way to the successful completion of this thesis. Those who need special mention include:

- Professor Yongxin Xu who gave me the opportunity to undertake this exercise and guided me throughout the period of the study with direction and useful advice.
- Professors Niko Verhoest, Luc Brendonck, Lincoln Rait and Eberhard Braune for your pieces of advice and help.
- The VLIR (Flemish Inter University Council) programme of the University of the Western Cape for granting me the scholarship during the first three years of this study.
- The staff of the Department of Earth Sciences of UWC especially Caroline Barnard who was my first call and Wasielah Davids for the help in assisting me throughout the study.
- Professor Jonathan Levy for his invaluable assistance during his time at UWC.
- The Department of Water Affairs in Bellville and Pretoria, Mike Smart, Henry De Haast, Roseeda Peters, Chaka Shouneez and Arul Uz-Zaman for providing me with lots of data for this study.
- The Water Research Commission for all the reports you freely provided.
- All the friends and colleagues I met at the Department during my time of studies including Jaco Nel, Humberto Saeze, Riyaz Nakhwa, Segun Adelana, Lixiang Lin, Haili Jia, Wisemen Chingombe, James Ayuk, Opuwari Mimonitu, Solomon Adekola, Thokozani Kanyerere, Josue Bahati, Zayed Brown, Innocent Muchingani and all the many MSc and honors students who shared friendship with me during my stay in UWC.
- Special posthumous thanks to Patrick Ackon (RIP) for his assistance in helping me find my way around in and out of campus during my first few months in South Africa. Also to Professor Francis Benyah, Yaw Nkansah-Gyekye, Samuel Kwofie, Francis Adu-Poku (RIP), colleagues from Ghana who were always there to help and offer friendship.
- CSIR Water Research Institute, Ghana (my employers), who gave me the time and assistance to pursue this degree.
- My family for the patience, support and encouragement all the time I was away from home pursuing this degree.

May the Lord bless and multiply back to you what you gave me. I am grateful to you all.

Anthony A. Duah.

Cape Town.

Table of Content

Page

Table of Content.. v
List of Figures.. x
List of Tables xii
List of Appendices... xiii
CHAPTER 1 INTRODUCTION... 1
1.1 Background of study 1
1.2 Objectives of the study... 3
1.3 Literature Review... 3
1.3.1 The Concept of Sustainability and Safe Yield 3
1.3.2 Recharge, Sustainability and the Capture Principle.. 4
1.3.3 Sustainability and Sustainable Pumping Rates 9
1.3.4 Sources of water to pumping wells and basin sustainable yield 11
CHAPTER 2 DEFINITION AND APPROACH TO GROUNDWATER SUSTAINABLE YIELD ……………………………………………………………………………..15
2.1 The American Concept of Groundwater Sustainable Yield.. 15
2.1.1 The spatial and temporal aspects of sustainable yield 15
2.1.2 Understanding the boundaries of the system and water needs 16
2.1.3 Adaptive management 16
2.2 The Australian Concept of Sustainable Yield 17
2.2.1 Extraction regime... 18
2.2.2 Acceptable levels of stress.. 18
2.2.3 Storage depletion 19
2.2.4 Protecting dependent economic, social and environmental values......................... 19
2.3 The South African Approach to Sustainable Yield... 20
2.3.1 Resource Directed Measures (RDM)... 20
2.3.2 Groundwater use and adaptive management 22
2.3.3 The TMG Aquifer System and Sustainable Yields.. 23
2.4 Methodology 27
2.4.1 Methodology in determining sustainability 27

2.4.2 Data Requirements 28
2.4.2.1 Precipitation data 30
2.4.2.2 Water levels and borehole information data 30
2.4.2.3 Temperature data 30
2.4.2.4 Other data and information 30
2.5 Summary 31
CHAPTER 3 HYDROGEOLOGICAL SETTING OF THE TMG 32
3.1 History and Lithostratigraphy 32
3.2 Structure 35
3.3 Geomorphology and Drainage 37
3.4 Hydrogeological Domains 38
3.5 Aquifer types and characteristics 39
3.6 Occurrence of Springs 41
3.7 Porosity, Storativity and Transmissivity 43
3.7.1 Porosity 43
3.7.2 Storativity 45
3.7.3 Transmissivity 46
3.8 Groundwater Quality in the TMG 47
3.8.1 Hydrochemical characteristics 47
3.8.2 Isotope analysis of deep borehole and hot springs 50
3.8.3 Problems associated with TMG groundwater 51
CHAPTER 4 GROUNDWATER FLOW DYNAMICS IN THE TMG 52
4.1 Aquifer Recharge to the TMG 52
4.1.1 The Conceptual recharge model 52
4.1.2 Recharge Mechanisms 53
4.1.3 Spatial and temporal variability of recharge 54
4.1.4 Selection of Recharge methods 55
4.1.4.1 Hydrostratigraphic regions of the TMG 56
4.1.4.2 Commonly used recharge methods in Southern Africa 57

4.1.4.3 Recharge forecasting 59

4.1.5 Recharge Estimation in the TMG 59
4.1.6 Regional Water Balance in the TMG 61
4.1.6.1 Components of the water balance model 63

4.2 Aquifer Discharges from the TMG 69

4.2.1 Natural discharges from the TMG aquifer 70
4.2.1.1 Baseflow in the TMG 70

4.2.1.2 Spring flow in the TMG 71

4.2.1.3 Discharge to other water bodies 71

4.2.2 Artificial discharges from TMG 72
4.2.2.1 Borehole abstractions from TMG 72

4.2.3 Groundwater Dependent Ecosystems 74
4.2.3.1 Level of Dependency and Threats to GDEs 76

4.2.3.2 The Presence of GDEs in the TMG 77

4.3 Summary 78

CHAPTER 5 CLIMATE VARIABILITY AND ITS IMPACT ON GROUNDWATER 80
5.1 Introduction 80

5.2 Historical Climate Trends in Southern Africa 81

5.2.1 Climate patterns in the South Western Cape 82
5.2.2 Global temperature changes 83
5.3 Trend Analysis 85

5.3.1 The Mann-Kendall (M-K) trend test 85
5.3.2 Temperature trends in South Africa 87
5.3.3 Current temperature trends in the Western Cape 88
5.3.4 Precipitation trends 89
5.3.4.1 Basic statistics 90

5.3.4.2 Autocorrelation function 92

5.3.5 Current precipitation trends in the Western Cape 92
5.3.6 Rainfall Variability 95

5.4 The Standard Precipitation Index 98
5.4.1 SPI and groundwater fluctuations 104
5.4.2 Time Lag between Rainfall and Recharge 111
5.5 The Response of Groundwater Flow Dynamics to Climate Change and Variability .. 113
5.5.1 Impacts on Shallow Aquifers 115
5.5.2 Impacts on Coastal Aquifers 116
5.5.3 Impacts on Deep Aquifers 117
5.5.4 Timing of Recharge and Aquifer Properties 117
5.6 Summary 118
CHAPTER 6 SUSTAINABLE UTILISATION OF GROUNDWATER RESOURCES – A CASE STUDY OF THE KLEIN KAROO RURAL WATER SUPPLY SCHEME (KKRWSS). 121
6.1 Introduction 121
6.2 Background of the KKRWSS Study Area 122
6.2.1 Topography and Drainage 122
6.2.1.1 Spring flows 124
6.2.2 Climate 124
6.2.3 Geology and hydrogeological setting of the Kammanassie Mountain area 125
6.2.4 Wellfields 126
6.2.5 Properties of the TMG aquifer in the KKRWSS 128
6.2.6 Recharge Estimates of the Vermaaks River wellfield 129
6.3 Problems Associated with the KKRWSS Project 129
6.3.1 Decline of water levels 130
6.3.1.1 Abstraction management of the Vermaaks wellfield 134
6.3.2 Iron clogging and changes in water quality 135
6.3.3 Drying up of springs and impact on vegetation and ecosystems. 137
6.4 Sustainable management approach to Scheme problems 138
6.4.1 Stabilization of water levels 138
6.4.2 Managing Iron clogging and water quality problems 139
6.4.3 Management of spring losses 140
6.5 Summary 141

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS 143
7.1 Conclusions 143
7.1.1 Groundwater resources potential of the TMG 143
7.1.2 From Safe yield to Sustainable yield 144
7.1.3 TMG Recharge and Aquifer properties 145
7.1.4 Climate Change impact on aquifers 146
7.1.5 TMG Aquifer discharges 146
7.1.6 TMG sustainability 147
7.2 Recommendations 148
CHAPTER 8 REFERENCES 150

List of Figures

Page

Figure 1.1 Schematic cross section of an aquifer situated on a circular island in a fresh water lake that is being developed by pumping. 5
Figure 2.1: Sequential process of GRDM studies 21
Figure 3.1: Distribution of Table Mountain Group 33
Figure 3.2: Structural sections of the TMG 36
Figure 3.3:A horizontal terrain aquifer in the Table Mountain, Cape Town (Xu et al, 2007) 39
Figure 3.4:Types of aquifers occurring in the TMG 41
Figure 3.5: TMG hot springs are a major source of domestic water supply and recreation 43
Figure 3.6: BH1 at Gevonden (High Fe conc) 48
Figure 3.7: Drilling of BH1 (right) and BH2 (left) 48
Figure 3.8: Piper diagram of TMG boreholes and hot springs (2005) 49
Figure 3.9: Piper diagram of TMG Hot Springs (2008) 51
Figure 4.1: The various processes involved in recharge 53
Figure 4.2: Interflow in fractured rocks 55
Figure 4.3: Interflow in bedding planes 55
Figure 4.4: Hydrostratigraphic units of the TMG area 56
Figure 4.5: Distribution of precipitation in the TMG area 64
Figure 4.6: Distribution of mean annual runoff (MAR) within the TMG area. 65
Figure 4.7: Mean annual evaporation (A-pan) in the study area 66
Figure 4.8: Vegetation types in the study area 67
Figure 4.9: Mean annual recharge in the study area 69
Figure 4.10: Baseflow in the TMG 71
Figure 4.11: Location of KKRWSS and CAGE Project areas in the TMG 73
Figure 4.12: Artesian flow from deep well (DAGEOS Project) at Oudtshoorn 74
Figure 5.1: Mean annual precipitation within study area (Data: WRC WR2005) 83
Figure 5.2: Locations of selected rainfall stations in the study area. 91
Figure 5.3: Autocorrelation plots for rainfall time series within the study area. 93
Figure 5.4: Rainfall variability (Annual) map of the study area 96
Figure 5.5: 12-Month SPI plots for some rainfall stations in the Olifants and Breede Catchments 102
Figure 5.6: Comparative variations of 6-, 12- and 24-month SPIs for rainfall stations in the KKRWSS project area. 103

Figure 5.7: Water level vs 6, 12 and 24-Month SPI for De Doorns Rain Station....................................105
Figure 5.8: Linear regression between Water Level and SPIs from De Doorns station 106
Figure 5.9: Water level vs 6-M, 12-M and 24-M SPIs for the Hermanus station....................................108
Figure 5.10: Linear regression between Water Level and SPIs from Hermanus station 109
Figure 5.11:A conceptual model of the different aquifers in the TMG 113
Figure 6.1: Location of KKRWSS area and Kammanassie Mountains 123
Figure 6.2: Geology map of the Kammanassie Mountain area..125
Figure 6.3: The locations of different purpose boreholes in the Kammanassie area. 127
Figure 6.4: Decline of water levels in the production boreholes in the Vermaaks Wellfield 131
Figure 6.5: Water levels in production boreholes in the Western Wellfield..132
Figure 6.6: Water levels of Varkieskloof Wellfield in the Eastern Section...133
Figure 6.7: Water levels of Bokkraal Wellfield in the Eastern Section 133
Figure 6.8:Abstraction vs Water level (VR11) 135
Figure 6.9:Abstraction vs Water level (VR6) 135
Figure 6.10:Abstraction vs Water level (VR7) 135
Figure 6.11:Abstraction vs Water level (VR8) 135

List of Tables

Page

Table 3.1: Stratigraphical succession of the Table Mountain Group 34

Table 3.2: Important information on TMG hotsprings (After Meyer, 2002) 42

Table 3.3: Porosity derived from core samples, aquifer tests, field measurements and density logging. ... 44

Table 3.4: Recommended storativity values for TMG aquifers (Jia, 2007) 46

Table 3.5: Results of water quality analysis from boreholes in Gevonden, (2006-2007). 48

Table 3.6: Results of isotope analysis of TMG hot springs and boreholes 50

Table 4.1: Recharge estimation methods commonly used in (semi-) arid Southern Africa (modified from Xu and Beekman, 2003) 58

Table 4.2: Pan factors for open water evaporation and catchment evapotranspiration in TMG area. 66

Table 4.3: Crop factors for vegetation types found in the TMG area (Acocks classification). 67

Table 5.1: Average Temperature and Precipitation values for Cape Town (1961 -1990) 82

Table 5.2: Results of M-K trend tests for max and min temperatures in study area 88

Table 5.3: Basic Statistics of Rainfall Data 90

Table 5.4: Summary of results of trend tests on precipitation time series 94

Table 5.5: Index of variability of some rainfall stations in the study area. 97

Table 5.6: The SPI indices and description 101

Table 5.7: Results of Correlations between Water Level and SPIs for De Doorns 107

Table 5.8: Results of Correlations between Water Level and SPIs for Hermanus 110

Table 5.9: Summary output for 8 month time lag between Rainfall and Water Level for De Doorns 112

Table 5.10: Summary output for 9 month time lag between Rainfall and Water Level for Hermanus 112

Table 6.1: Sumamary of data on production boreholes in the Eastern Section of KKRWSS 128

Table 6.2: Ranges of transmissivity (T) and storativity (S) in the Vermaaks River wellfield. 129

Table 6.3: Readjustment of recommended abstraction rates for some KKRWSS boreholes 134

List of Appendices

Page

Appendix I: Results of hydrochemical analysis of hot springs in the TMG ………………………….…158

Appendix IIA: Results of maximum temperature trends in study area ………………………………….159

Appendix IIB: Results of minimum temperature trends in study area ………………………………….160

Appendix IIIA: Results of annual rainfall trends (1950 - 1979) ……………………………………… .161

Appendix IIIB: Results of annual rainfall trends (1980 - 2007) ……………………………………….. 162

Appendix IIIC: Results of annual rainfall trends (1950 - 2007) ……………………………………….. 163

Appendix IV Table of information on monitoring boreholes in the KKRWSS area ……………………164

CHAPTER 1 INTRODUCTION

1.1 Background of study

A sustainable water service delivery is the thrust of the Millennium Development Goals on water for African governments. With between 60 and 90 percent of communities in Africa served by groundwater, not only will a sustainable management of the groundwater resources benefit countless populations but also provide hope for improved quality of life. There has been reported decline of groundwater levels in the TMG aquifer system since 1984 as a result of pumping from production wells in the Vermaaks River Catchment (Jolly & Kotze, 2002; Wu, 2005). This led to the reduction of pumping rates in an attempt to halt the decline in water levels but the levels continued to decline. Subsequent reduction in abstraction rates could not arrest the situation because it is believed that there has been an over-estimation of the recharge rates in the TMG and for that matter the catchment area. An understanding of the flow characteristics and the review of the recharge rates was expected to address the situation. Jolly (2002) reported that some shallow TMG boreholes have been pumped at rates in excess of 30 *l*/s. Many schemes have failed as a result of abstractions exceeding recharge leading to water levels falling to the depths of the pumps. Recharge is generally low and sporadic resulting in aquifer storage decline between recharge events. TMG aquifers have generally low storativity as a result Jolly (2002) recommended that water level decline must be carefully managed to make certain water levels do not drop below the top water strikes in the boreholes otherwise the risks of microbial induced biofouling which causes clogging of pumps and screens exist. Other reported abstraction schemes within the TMG included the Arabella Country Estate, near Botrivier where 4 production wells supply about 30 *l*/s of groundwater to the estate (Parsons, 2002); Botrivier water supply project with 6 wells supplying about 20 *l*/s (Weaver, 2002); Ceres Municipality wellfields where 7 boreholes from the TMG supply 48 l/s and 3 boreholes from the Bokkeveld supply 50 *l*/s (Rosewarne, 2002); the Hex River valley project and the CAGE project at Citrusdal are also documented. Some of these drilling projects have little or no management plans while others are well managed even though ecological and environmental concerns are hardly integrated in the management programmes. The impact of these groundwater projects on the surface water regimes i.e. the baseflow into rivers, wetlands and estuaries which also control the availability of water for plant use are hardly evaluated or monitored. It is envisaged that a comprehensive approach into the study of these and other related factors of groundwater and surface water interactions in the TMG will provide more understanding and the development of a concept for sustainable management for current and future abstraction programmes for the local catchment regimes of the TMG aquifer.

There have been several research programmes into the understanding of fractured rock aquifer system such as the TMG aquifer which poses a great challenge to hydrogeologists. Most of Africa's aquifers are contained in fractured basement rocks with limited primary porosity but with considerable secondary porosity that must be exploited to provide water for millions of its people living mostly in rural communities. A study such as this current one will in no doubt generate a lot of interest in the hydrogeological and ecological communities in Africa and for that matter South Africa and will be useful for future studies in many parts of Africa with similar interests.

The importance of this research also derives its basis from the current and future focus of African governments' Millennium Development Goals on Water Supply. The declaration of the historic United Nations Conference on Environment and Development (UNCED), Earth Summit on 3-14 June 1992 in Rio de Janeiro also known as Agenda 21 is on Sustainable Development. It is an international blueprint that outlines actions that governments, international organisations, industries and the community can take to achieve sustainability. The formation and meetings of the UN Commission on Sustainable Development (CSD) from 1993 to 1996 was to monitor and implement Agenda 21. The World Summit on Sustainable Development (WSSD) in Johannesburg, South Africa on 26 August to 4 September 2002 focused on the future direction of a global sustainable development agenda and pursuing effective means for its implementation. These and many other international conferences are directed to harness all natural resources in a sustainable manner in order to protect resources and the environment for future generations.

1.2 Objectives of the study

The aim of this research is in line with the Africa Water Vision of utilizing groundwater resources sustainably as outlined below:

- To assess the factors and variables determining the sustainable utilization of the TMG regional aquifer, i.e. to determine the balance between recharge to and discharges from the regional aquifer that will ensure a reasonable sustainability with minimum or no adverse impacts on the environment. This will be done in the context of climate change and climate variability.

In order to achieve the above objective the following broader objectives are put forward.

- Evaluation of Recharge estimates in the TMG over the past decade;
- Analysis of the long-term rainfall trends on the backdrop of climate change and potential impact on groundwater resources of the TMG;
- Assessment of the major components of natural discharge such as baseflow, spring flow and environmental flows that sustain ecosystems and the environment within the TMG;
- Assessment of major abstractions and groundwater use within the TMG area and their long-term sustainable management.
- A case study of the sustainable utilization of the TMG aquifers at the Klein Karoo Rural Water Supply Scheme in the Little Karoo area.

1.3 Literature Review

1.3.1 The Concept of Sustainability and Safe Yield

The world is now focusing on sustainable development of all natural resources including groundwater resources. The question that has been asked before is how this new concept of sustainability relates to safe yield, and to what extent do the controversies surrounding safe yield carry over to sustainability (Alley & Leake, 2004). The concept of safe yield has evolved over the century. Alley *et al* (2004) quotes Lee (1915) as first defining safe yield as the quantity of water that can be pumped "regularly and permanently without dangerous depletion of the storage reserve." They also refer to Meinzer’s (1923) later definition of safe yield as "the rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is no longer economically feasible." It is relevant that both definitions focused on depletion of ground water reserves. Alley *et al* (2004) observed that over time, the concept expanded to include degradation of water quality (Conkling, 1946), the contravention of existing water rights (Banks, 1953), and other factors. We also note Todd's (1959) broad definition of safe yield of a groundwater basin as "the amount of water which can be withdrawn from it annually without producing an undesired result." On the other hand "optimum yield" within the current socio-economic framework will involve selecting an optimal management scheme from a number of possible available schemes. Such a decision will in no doubt consider the present and future costs and benefits that may even lead to optimal yields that involve mining the groundwater.

Alley and Leake (2004) further states that a common misperception has been that the development of a groundwater system is "safe" if the average annual rate of groundwater withdrawal does not exceed the average annual rate of natural recharge. Bredehoeft *et al* (1982) and Bredehoeft (2002) give examples of how safe development depends instead on how much of the pumpage can be captured from increased recharge and decreased discharge.

Custodio (2005) however refers sustainability to the use of natural resources without jeopardizing their use by future generations. According to him it goes along with the concept of human beings living in peace and harmony with the environment, both now and in the future. He strongly believes that in reality, scientific, technical, and social as well as space and time frameworks, under which sustainability is evaluated, are continuously changing and that what may be sustainable now may not be in the future, and what may appear unsustainable today may be sustainable in the future. Present-day decisions must therefore take the future into consideration but the influence given to the future, however, will depend on the credibility of scenarios considered and the weight given by society and politicians.

1.3.2 Recharge, Sustainability and the Capture Principle

There has been long term debate in hydrogeological circles on whether recharge needs to be known in order to determine sustainability. Theis (1940) raised the idea that it was not necessarily true to know recharge in order to determine sustainability. This idea has been supported by others over time; Lohman (1972), Alley *et al*. (1999), Bredehoeft (2002) and Seward *et al*. (2006), to name just a few. According to Bredehoeft (2002) the size of a sustainable groundwater development usually depends on how much of the discharge from the system can be "captured" by the development. He, in particular, emphasizes that capture is independent of the recharge; it rather depends on the dynamic response of the aquifer system to the development which could be solved by groundwater models. To confirm the above principle Bredehoeft (2002) provided the following illustration:

If one considers a simple aquifer system, a permeable alluvial aquifer underlying a circular island in a fresh water lake. The intent is to develop a well on the island. The island aquifer is shown schematically in various stages of development in Figure 1.1 below.

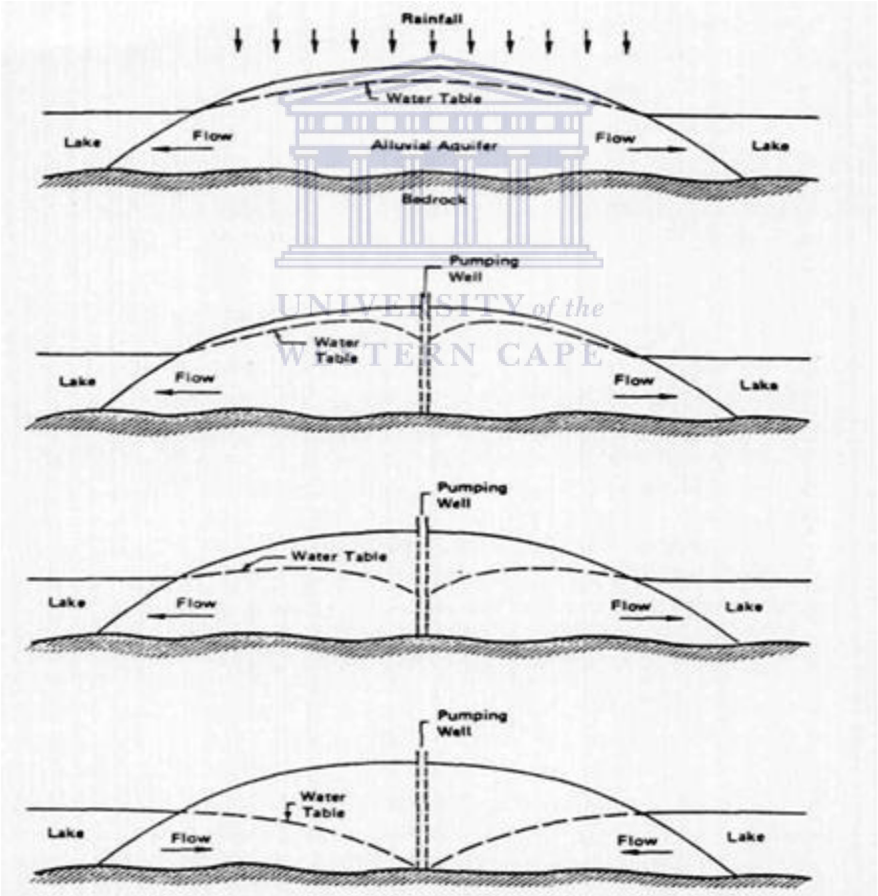

Figure 1.1 Schematic cross section of an aquifer situated on a circular island in a fresh water lake that is being developed by pumping.

(After *Scientific Basis of Water-Resource Management.* Copyright 1982 by the National Academy of Sciences. Courtesy of the National Academy Press, Washington, D.C)

Before development, the system is in long-term equilibrium, recharge over the island is balanced by discharge from the permeable aquifer directly to the lake (figure 1.1-top cross section). We have the following water balance for virgin conditions on the island:

$$R_o = D_o \qquad \text{or} \qquad R_o - D_o = 0 \qquad \text{………………………}\mathit{(1.1)}$$

where R_o is the virgin recharge and D_o is the virgin discharge. A water table develops on the island in response to the distribution of recharge and discharge and the transmissivity of the alluvial aquifer. The discharge can be obtained at any point along the shore by Darcy's law:

$$d = T\,(dh/dl) \qquad \text{……………………… …}\mathit{(1.2)}$$

where *d* is the discharge through the aquifer at any point along the shore: *T* is the transmissivity at the same point: *dh/dl* is the gradient in the water table at that point. If we integrate the point discharge along the entire shoreline of the island we obtain the total discharge from the island:

$$\int T(dh/dl)ds = Do \qquad \text{…………………………}\mathit{(1.3)}$$

We then install a well in the middle of the island and initiate abstraction (Figure 1.1- second cross section). At any given time, the new water balance for the island would be:

$$(R_o + \Delta R_o) - (D_o + \Delta D_o) - P + dV/dt = 0 \qquad \text{…………………………}\mathit{(1.4)}$$

where ΔR_o is the change in the virgin rate of recharge caused by the abstraction: ΔD_o is the virgin rate of discharge caused by the abstraction: P is the rate of abstraction; and dV/dt is the rate at which water is being removed from groundwater storage on the island. We know that the virgin rate of recharge, R_o, is equal to the virgin rate of discharge, D_o, so the water budget equation following the beginning of abstraction reduces to:

$$\Delta R_o - \Delta D_o - P + dV/dt = 0 \qquad \text{or} \qquad \Delta R_o - \Delta D_o - P = dV/dt \qquad \text{………………………}\mathit{(1.5)}$$

For sustainability, the rate of water taken from storage is zero; thus, we define sustainability as:

$$dV/dt = 0 \qquad \text{………………………}\mathit{(1.6)}$$

Now the water budget for sustainability is

$$\Delta R_o - \Delta D_o = P \qquad \text{………………………(1.7)}$$

We are now stating that, to achieve sustainability, the abstraction must be balanced by the change in recharge, ΔR_o, and/or the change in discharge, ΔD_o, caused by the abstraction. Traditionally, the sum of the change in recharge and change in discharge caused by the abstraction, the quantity ($\Delta R_o - \Delta D_o$), is defined as the "capture" attributable to the abstraction. For sustainability, the rate of abstraction must equal the rate of "capture." We notice that to determine sustainability we do not need to know the recharge. The recharge may be of interest, as are all the facets of the hydrologic budget, but it is not a determining factor in our analysis. Recharge is often a function of external conditions such as rainfall, vegetation, and soil permeability. In many, if not most, groundwater situations, the rate of recharge cannot be impacted by the abstraction; in other words, in terms of the water budget.

$$\Delta R_o = 0 \qquad \text{………………………(1.8)}$$

In most situations, sustainability of a groundwater development occurs when the pumping captures an equal amount of virgin discharge:

$$P = \Delta D_o \qquad \text{………………………(1.9)}$$

We return to the island aquifer and see how the capture occurs conceptually. When abstraction begins, a cone of depression is created. Figure 1.1 (second cross section) shows the cone of depression at an early stage in the development of our island aquifer. The natural discharge from the island does not start to change until the cone of depression changes the slope in the water table at the shore of the island; Darcy's law controls the discharge at the shoreline. Until the slope of the water table at the shoreline is changed by the abstraction, the natural discharge continues at its virgin rate. Until the point in time that the cone reaches the shore and changes the water table gradient significantly, all water pumped from the well is supplied totally from storage in the aquifer. In other words, the cone of depression must reach the shoreline before the natural discharge is impacted (Figure 1.1- third cross section). The rate at which the cone of depression develops, reaches the shoreline, and then changes the slope of the water table there depends on the dynamics of the aquifer system. Capture has nothing to do with the virgin rate of recharge; the recharge is irrelevant in determining the rate of capture.

Figure 1.1 (third cross section) shows the water table in the island aquifer at a point in time when the natural discharge is almost eliminated; the slope of the water table is almost flat at the shoreline. This is a deliberately created aquifer system in which one can induce water to flow from the lake into the aquifer (Figure 1.1- fourth cross section). In this instance, the sustainable development can exceed the virgin recharge (or the virgin discharge). This again suggests that the recharge is not a relevant input in determining the magnitude of a sustainable development. Often the geometry of the aquifer restricts the capture. For example, were the aquifer on the island to be thin, we might run out of water at the pump long before we could capture any fraction of the discharge. In this case all water abstracted would come from storage. It would be "mined." In the island example, with a thin aquifer, the well could run dry before it could impact the discharge at the shoreline. The aquifer geometry and diffusivity limit the potential drawdown at the well. This again points out that the dynamic response of the aquifer system is all-important to determining the impacts of development. It is for these reasons that hydrogeologists are concerned with the dynamics of aquifer system response. Hydrogeologists model aquifers in an attempt to understand their dynamics. Clearly, the circular island aquifer is a simple system. Even so, the principles explained in terms of this simple aquifer apply to all groundwater systems. It is the dynamics of how capture takes place in an aquifer that ultimately determines how large a sustainable groundwater development can be (Bredehoeft, 2002).

The most important implication of the capture principle is that virgin recharge does not determine sustainability. Sustainability is determined rather by how much induced recharge can be created, and by how much of the existing discharges, natural or otherwise, can be taken up by the abstraction. This is partly a technical problem; Bredehoeft (2002) raised the issue of aquifer geometry but another issue of equal importance is the positioning of boreholes close to discharge zones so as to capture as much of the existing losses as possible. The issue is also partly political as noted by Seward *et al* (2006), what reduction in existing discharges is permissible. Regulations may restrict reduction in discharges to rivers/streams and springs as is the case in many countries such as South Africa.

1.3.3 Sustainability and Sustainable Pumping Rates

Devlin and Sophocleous (2005) differentiate between sustainability and sustainable pumping rates as two different concepts that are often misunderstood and therefore used interchangeably. They argued that the latter term refers to a pumping rate that can be maintained indefinitely without mining an aquifer, whereas the former term is broader and concerns such issues as ecology and water quality, among others, in addition to sustainable pumping. Another important difference between the two concepts according to Devlin and Sophocleous (2005) is that recharge can be very important to consider when assessing sustainability, but it is not necessary to estimate sustainable pumping rates. Sophocleous (2000) had reported that, in the past, the volume of recharge to an aquifer was accepted as the quantity of water that could be removed from the aquifer on a sustainable basis, the so-called safe yield, but it is now understood that the sustainable yield of an aquifer must be considerably less than recharge, if adequate amounts of water are to be available to sustain both the quantity and quality of streams, springs, wetlands, and groundwater-dependent ecosystems. Sustainable resource management demands the managing of groundwater for both present and future generations, and providing adequate quantities of water for the environment and thus quantifying what these environmental provisions are is presently an urgent research need. Sophocleous (2005) again affirms that sustainable use of groundwater must ensure not only that the future resource is not threatened by overuse and depletion, but also that the natural environment that depend on the resource are protected. One agrees with his opinion that there will always be trade-offs between groundwater use and potential environmental impacts, and therefore a balanced approach to water use between developmental and environmental requirements needs to be advocated. However, to properly manage groundwater resources, managers need accurate information about the inputs (recharge) and outputs (pumpage and natural discharge) within each groundwater basin, so that the long-term behavior of the aquifer and its sustainable yield can be estimated or reassessed. Thus, without a good estimate of recharge, the impacts of withdrawing groundwater from an aquifer cannot be properly assessed, and the long-term behavior of an aquifer under various management schemes cannot be reliably estimated.

Zhou (2009) however showed that if one introduces the residual discharge (D_R) as being the natural discharge minus the decreased discharge:

$D_R = D_o - \Delta D_o$ ………………… *(1.10)*

Then, if we substitute Eq. (1.10) into Eq. (1.4) one obtains a new equation for calculating the sustainable pumping rate:

$P = R_0 + \Delta R_0 - D_R$ ………………… *(1.11)*

Eq. (1.11) implies that the sustainable pumping rate and residual discharge are balanced by natural discharge and induced recharge and in circumstances where there is no induced recharge, the sustainable pumping rate and residual discharge are balanced only by natural recharge:

$P = R_0 - D_R$ ………………… *(1.12)*

It is therefore obvious that natural recharge is a very important factor in determining the sustainable pumping rate. The principle is very simple; natural discharge originates from natural recharge. There will be no discharge if there was no recharge. It is also clear that the maximum sustainable pumping rate will be achieved when the residual discharge becomes zero in which case the maximum sustainable pumping rate will be equal to the total groundwater recharge. Therefore any pumping rate larger than the total groundwater recharge will cause groundwater storage depletion (Zhou, 2009).

It is important for water managers to also know that the sustainable yield of aquifers, and thus the environmental impact of groundwater extraction, depends not only upon the volume extracted, but also on the location of pumping wells relative to recharge and discharge areas, and sometimes also on the timing of the extraction (Sophocleous, 2000, 2005). Prediction of environmental impacts of groundwater extraction will require detailed investigation of natural groundwater recharge and discharge processes. The task of groundwater managers is to determine what limits of environmental impact are acceptable to the community and to manage extraction to maintain impacts within those limits. In recent times environmental laws have been enacted for managers to operate within the confines of the law. In regions with high demand of groundwater for irrigation, Kendy (2003) points out that to arrest water-table declines, evapotranspiration has to decrease, thus, sustainability (defined as stabilizing groundwater levels) begins not with reducing irrigation pumping per acre, but rather with reducing the total acreage of irrigated land (Kendy, 2003).

1.3.4 Sources of water to pumping wells and basin sustainable yield

Theis (1940) stated that under natural conditions before groundwater development, aquifers are in a state of approximate dynamic equilibrium. The new discharge by wells must be balanced by an increase in recharge of the aquifer, or by a decrease in the natural discharge, or by loss of storage in the aquifer, or by a combination of these. These are in fact the explanation of the water balance equation (Eq. 1.5). Theis (1940) further elaborated on situations where pumping can induce additional recharge such as in areas where water table is shallow and there is sufficient recharge water (humid climate areas), lowering of water table by pumping can induce recharge. Pumping can also induce recharge from surface water bodies. Possibilities for decreasing discharge include the decrease of groundwater discharge to surface water bodies, the decrease of spring discharges and the decrease of evapotranspiration. Thus, in order to induce more recharge or decrease natural discharge (capture), water must be initially removed from storage to create a favourable hydraulic gradient. Therefore, the dynamic response of an aquifer to pumping depends on (1) distance of the pumping well to the source of recharge and the nature of the recharge; (2) the distance of the pumping well to the area of natural discharge; and (3) the character of the cone of depression. In Bredehoeft's illustration above, he showed that groundwater must be removed from storage before it reaches a new state of equilibrium. When the pumping rate is set to be equal to the recharge, pumping eventually captures all evapotranspiration losses by phreatophytes. However, it takes between 400 and 1000 years before the system is brought to a new state of equilibrium. The induced recharge may have caused the depletion of streamflow and residual discharge may not be sufficient to maintain groundwater dependent ecosystems. Furthermore, pumping always creates a cone of depression, which may cause intrusion of bad quality water and land subsidence. Today, it is widely recognized that pumping can affect not only surface water supply for human consumption, but also the maintenance of streamflow requirements for fish and other aquatic species, the health of riparian and wetland ecosystems, and other environmental needs. How much groundwater is available for use depends on how changes in recharge and discharge affect the surrounding environment and the acceptable trade-off between groundwater use and these changes.

Achieving this trade-off in the long-term is a central theme in the evolving concept of sustainability (Alley *et al*., 2005; Zhou, 2009).

Kalf and Woolley (2005) used the basin water balance (Eq. 1.11) to define the basin sustainable yield. If the total basin inflow, I_s, is defined as the sum of natural recharge and induced recharge by pumping, Eq. 1.11 can be rewritten as:

$$P_s = I_s - D_R \qquad \text{…………………………………………}(1.13)$$

They defined P_s as the basin sustainable yield and P_d as the maximum basin sustainable yield in the situation when the residual discharge, D_R, is equal to zero and $P_d = I_d$. The basin sustainable yield as defined here is similar to safe yield discussed earlier and therefore caution should be taken to avoid the pumping causing unacceptable consequences. The basin sustainable yield should therefore be a compromised pumping rate which can be sustained by groundwater recharge and will not cause unacceptable environmental, economic and social consequences. Zhou (2009) outlines the following conditions to be satisfied by the basin sustainable yield:

- The water balance equation (Eq. 1.11) is only a necessary condition, not an absolute condition. Other constraints must be satisfied
- Environmental constraints require considering groundwater as a part of an integral water and ecological system. Pumping capture should not cause the excessive depletion of surface water and excessive reduction of groundwater discharge to springs, rivers and wetlands. The cone of depression induced by pumping should not cause the intrusion of undesirable quality water, land subsidence and the damage of groundwater dependent terrestrial ecosystems.
- Economic constraints require maximizing groundwater development to fulfill water demand for irrigation and industrial use. Meanwhile, the cone of depression should not go too deep so that wells will not run dry and costs of pumping are economically feasible.
- Social constraints require safe access of good quality groundwater for drinking water supply and equitable distribution of shared groundwater resources by all. Downstream users should have an equal water right as the upstream users; rural communities should have the same water right as the urban dwellers. Pumping should not damage the existing water user rights of spring and surface water.

It is clear that the basin sustainable yield cannot be simply calculated as a single value using the water balance equation. It requires assessing the dynamic response of the basin to the introduced pumping regime and how this response affects the environment and society. Because of conflicts of interests, all stakeholders should participate in discussing the trade-offs among impacts. A compromised groundwater development plan could be reached among the stakeholders. The hydrogeologists' role is to use numerical groundwater models to generate various groundwater development scenarios and to access the impacts of those scenarios. The scenarios should be clearly presented to stakeholders and used as a basis for reaching a compromised development plan.

The determination of the sustainable use of groundwater is not solely a scientific, engineering, or a managerial question. Rather, it is a complex interactive process that considers societal, economic, and developmental values, and the respective consequences of different decisions. Another argument for sustainable pumping is based on managing groundwater storage. This management strategy adjusts withdrawal (pumping) rates to take advantage of natural recharge cycles. For example, during periods of high demand, some water may be withdrawn from the storage by greatly increasing pumping rates and lowering the hydraulic heads. During periods of low demand and high natural recharge, this depleted storage would then be replenished. However, the same question of the sustainability of this approach remains. Any portion of the natural recharge that does not contribute to the natural discharge will have some consequences for the water users and water uses which rely on it. Depending on the volumes and rates of the denied groundwater discharge, the affected users may or may not be able to adapt to the new reality. In order to sustain valued ecosystems and endangered species, segments of societies worldwide expect water to be made available, in volumes not easily quantified, to meet key habitat requirements. This relatively recent trend is accompanied by actions of environmental groups, which include legal challenges and lawsuits against various government agencies in charge of water governance (Kresic, 2009).

From the above discussions, it is increasingly clear that every abstraction programme should be evaluated using criteria pertaining to the location and its water needs. In certain areas groundwater is the only reasonable and affordable source of water for the human population as in many rural communities in Africa. In such communities, little or no consideration is given to ecological and environmental concerns as it becomes a matter of human survival. In situations like this it is still important that adaptive management programmes are put in place to ensure the sustainability of the abstraction programme for current and future populations with minimum impact on the environment since the environment becomes an integral part of human survival in any society as in the cases of spring flow, river baseflow, groundwater flow to wetlands and estuaries. Ecological importance must be investigated by specialists and where they are threatened by groundwater abstractions, recommendations for buffer zones and reserves made to preserve their survival and integrity. Trade-offs must always be agreed upon by all stake holders to ensure successful implementation of management goals. Management measures will always differ from one hydrologically different location to the other such as a forest zone and a semi-arid or arid zone. This requires the services of experts who can determine the requirements to ensure sustainability but formulation and implementation of policies must always be discussed with all stake holders to ensure reasonable success.

CHAPTER 2 DEFINITION AND APPROACH TO GROUNDWATER SUSTAINABLE YIELD

The history and background of sustainable groundwater yield from an aquifer was discussed in the previous chapter. The difference between an aquifer yield and sustainable yield was outlined. An aquifer yield is simply how much water could be extracted from an aquifer based on the hydraulic properties of the aquifer itself. To achieve a sustainable yield on the other hand, there must be sufficient inflows to sustain the rate of pumping and more importantly, the pumping should not cause unacceptable environmental, economic and social consequences.

2.1 The American Concept of Groundwater Sustainable Yield

The American Society of Civil Engineers (ASCE) Task Committee for Sustainability Criteria in 1998 proposed an inclusive definition of sustainability as: "*sustainable water resource systems are those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity*" (Loucks *et al*., 2000). This and similar definitions recognise the fact that sustainable yield is not a fixed figure but could vary over time as environmental conditions vary. Maimone (2004) provided some guidance in developing and a practical, working definition of sustainable yield. These are the spatial and temporal aspects of sustainable yield, understanding the boundaries of the system, understanding the water needs, developing a conceptual water budget and implementation of an adaptive management concept together with all stakeholders. Other considerations include uncertainties in the system and effects of changing technology. Some of these considerations are discussed in detail below.

2.1.1 The spatial and temporal aspects of sustainable yield

The spatial scale of the problem must be understood and defined according (Maimone, 2004). Defining sustainable yield over a relatively large area, for example, may result in seemingly low rates of withdrawal per square kilometer. The total use of groundwater compared to total recharge and discharge may suggest a sustainable situation but may ignore local effects of pumping that might heavily influence an important ecosystem like a wetland or a first order stream or degrade a sensitive plant community that is dependent on a certain water table depth. The critical considerations are to select areas where withdrawals can best be made and identifying areas where impacts are to be minimized. Define sustainable yield on a small scale enough to address important local impacts, but large enough to recognize the ability of aquifer system to adjust to pumping stress. There is also the issue of time. Pumping, recharge, discharge, and ecological response are all time dependent, changing over varying periods (days, seasons, multi-year trends, etc.). Sustainable yield must therefore be defined over a specific time period. Withdrawals could be varied over water availability or seasons for example.

2.1.2 Understanding the boundaries of the system and water needs

The boundaries of the system usually determine the amount of water lost or gained, the areas of direct recharge and discharge to wetlands, streams or coastal areas. Boundaries are therefore critical in defining the water budget and sustainable yield of the system. Deep confined aquifers may have almost impervious boundaries with limited recharge and such systems may have non-renewable resources. In such situations, sustainable yield may be undetermined. In defining sustainable yield one also needs to understand the trend of present and future water needs. Groundwater must be treated as part of the water cycle. Aquifer recharge and discharge to surface water, the extent, timing and growth of future water needs must be understood. Demand management will require trade-offs and risk, hence sustainability in Howard’s (2002) opinion must be considered within a framework of probability. His view is that sustainable yield as measured by risk has three main components; probability of water supply shortages, the costs when shortages occur, and the level of acceptability of the risks. Thus, sustainable yield also must consider reliability and cost of failure. This makes it dependent on the probability of certain occurrences, and a consensus on the acceptability of risk of failure. According to Howard, sustainability must be defined as “*a system that maintains acceptable risk over an indefinite time horizon*.” The risk is a function of uncertainty in both supply and demand, as well as their interaction in time and space.

2.1.3 Adaptive management

Recent trends in resource management focus on the concept of adaptive management. Adaptive management, according to Maimone (2004), treats management policies and actions as experiments, not fixed policies. Management must continually improve by learning from experiences. Changing technology and increasing knowledge and understanding can change our perception of risk and our priorities with regard to the acceptability of trade-offs, hence water resource management must be adaptive and flexible. Adaptive management links science, values, and the experience of stakeholders and managers to the art of making management decisions. Adaptive management concept appears to be the only viable approach in dealing with the uncertainties in knowledge and the variability of societal attitudes toward the resource. It also presents some challenges because defining sustainable yield implies some form of control of water use, usually resulting in the requirement for withdrawal permits for water suppliers and other users. Permit holders require some form of consistency and stability in making long-term planning and capital investments. Such guarantees from permit holders and probabilities in demand and supply, balanced with environmental requirements require a collaborative and consensus-seeking approach to adaptive management.

2.2 The Australian Concept of Sustainable Yield

The National Groundwater Committee (NGC, 2004) of the Department of Environment and Heritage of Australia similarly defined sustainable groundwater yield as: "*the groundwater extraction regime, measured over a specified planning timeframe that allows acceptable levels of stress and protects dependent economic, social and environmental values*." This definition of sustainable yield has not been adopted by all states and territories although it has been agreed upon by the committee. The definition is based on adopting a certain approach in its implementation. In considering groundwater sustainability, the assessment considers whether the sustainable yield of the resource has been determined for each groundwater management unit and compares the sustainable yield to:

- the cap that has been set within that management area
- the level of water entitlements

Non-renewable groundwater aquifers are treated differently. Non-renewable aquifers have no current recharge mechanism and policy on use of these waters differs across the country as to how or if at all these resources should be utilized. The National Water Commission of Australia has a key role in implementing the requirements of the *National Water Commission Act 2004*, and the Intergovernmental Agreement on a National Water Initiative, signed by the Australian

Government and all state and territory governments to better manage Australia’s scarce and valuable water resources (AWR, 2005). The definition of groundwater sustainable yield is based on adopting the following approach to its implementation.

2.2.1 Extraction regime

It is recognized that sustainable groundwater yield should be expressed in the form of an extraction regime, not just an extraction volume. The concept is that a regime is a set of management practices that are defined within a specified time (or planning period) and space. Extraction limits may be expressed in volumetric quantity terms and may further specify the extraction or withdrawal regime by way of accounting rules and/or rates of extraction over a given period and/or impact, water level or quality trigger rules. The limits may be probabilistic and/or conditional. The extraction regime may often be defined by a maximum volume that may be taken in any single year. In cases where draw beyond the rate of recharge may be acceptable, it may be only for a specified period, after which time the rate may be less than the rate of recharge to compensate. In some cases and under specified circumstances (for example, high or low rainfall years) the amount of water that may be taken may be greater or less than the longer-term value and the conditions for this can be specified.

2.2.2 Acceptable levels of stress

The approach recognizes that any extraction of groundwater will result in some level of stress or impact on the total system, including groundwater dependent ecosystems. The concept of acceptable levels of stress as the determining factor for sustainable yield embodies recognition of the need for trade-offs to determine what is acceptable. How trade-offs are made is a case and site-specific issue and a matter for the individual authority to administer. The trade-offs will often involve balancing between environmental, social and economic needs. In some cases, the stress may be temporary as the system adjusts to a new equilibrium. The definition should be applied in recognition of the total system. That is, it should recognise the interactions between aquifers and between surface and groundwater systems and associated water dependent ecosystems. The definition implies that integrated management decisions must be taken to fully satisfy its spirit.

In calculating sustainable yield, a precautionary approach must be taken with estimates being lower where there is limited knowledge. Application of the calculated sustainable yield as the limit on extractions must be applied through a process of adaptive management involving monitoring impacts of extraction. Sustainable yields should be regularly reassessed and may be adjusted in accordance with a specified planning framework to take account of any new information, including improved valuations of dependent ecosystems.

2.2.3 Storage depletion

The approach recognizes that extraction of groundwater over any timeframe will result in some depletion of groundwater storage (reflected in a lowering of water levels or potentiometric head). It also recognizes that extracting groundwater in a way that results in any unacceptable depletion of storage lies outside the definition of sustainable groundwater yield.

Where depletion is expected to continue beyond the specified planning timeframe, an assessment needs to be made of the likely acceptability of that continuation and whether intervention action might be necessary to reduce extraction. If intervention is likely to be necessary, then planning for that action should be undertaken so that it can be implemented at the end of the specified timeframe. Major considerations in determining the acceptability of any specific level of storage depletion should be “inter-generational equity”, and a balance between environmental matters, social and economic values.

2.2.4 Protecting dependent economic, social and environmental values

The definition recognises that groundwater resources have multiple values, some of which are extractive while others are *in-situ* (e.g. associated water-dependent ecosystems) and all have a legitimate claim on the water resource. In considering trade-offs in resource values, due recognition should be given to environmental dependencies, the risk of irreversible impacts and any decisions shall be made in accordance with the principles of ecological sustainable development (NGC, 2004).

2.3 The South African Approach to Sustainable Yield

The South Africa National Water Act (NWA) of 1998 provides all the tenets of sustainability of water resources including groundwater. The thrusts of the Act are sustainability, equity and efficiency, one of the few in the world that has measures in place to ensure water resources are protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner, for the benefit of all. The Act emphasizes on the setting up of a Reserve as the only right to water. This is the provision of water of sufficient quantity and quality for basic human needs (Basic Human Needs Reserve) and water for ecosystems to maintain ecological integrity (Ecological Reserve). The Act promotes the management of water resources at the lowest possible level through the establishment of Catchment Management Agencies (CMAs) at the local community level. All water resources including surface water and groundwater are recognized as a common resource that should be managed together in an integrated manner.

2.3.1 Resource Directed Measures (RDM)

Sustainability is not defined in the NWA per se but it is still one of the main goals of the Act. It is addressed in the contexts of sustainable water use, ecological sustainability and institutional sustainability. The approach to sustainability is outlined in a process called Resource Directed Measures (RDM) which comprises three main interrelated components, namely:

- Classification
- Reserve
- Resource Quality Objectives

In Classification water resources are broadly classified using their present and intended future state. The Reserve is defined as the quantity and quality of water required (a) to satisfy basic human needs by securing a basic water supply for people to be supplied with water from that resource, and (b) to protect aquatic ecosystems in order to secure ecologically sustainable development and use of water resources. A set of resource quality objectives (RQOs) are then established for each resource depending on their classification which will also set up the Reserve as explained earlier. Part of the groundwater system may be included in the Reserve. Where groundwater contributes to or supports basic human needs or aquatic ecosystems, groundwater forms part of the Reserve and hence has to be considered. However, groundwater also occurs in areas away from aquatic ecosystems and supports other components of the environment that may not form part of the Reserve. In such instances, groundwater protection is mainly affected through Classification and Resource Quality Objectives. The sequential steps to be followed when assessing these three components are illustrated in figure 2.1.

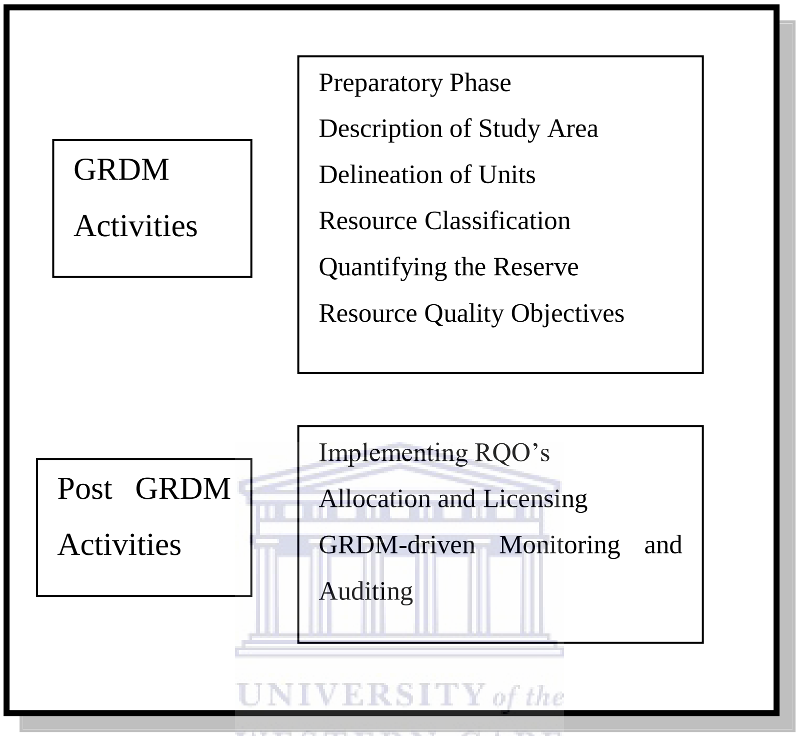

Figure 2.1: Sequential process of GRDM studies

The RDM is a strategy developed by the Department of Water Affairs (DWA) to ensure protection of water resources as outlined in the NWA. The measures are developed progressively within the context of a national water resources strategy and catchment management strategies. One of the major challenges of sustainable water resources management is to assess as accurately as possible how much water can be taken out of the system before its ability to meet social, ecological and economic needs is reduced. The classification system and the determination of the resource quality objectives are two mechanisms that can be used to try and balance protection and development. For example, setting up RQOs might imply limitations on the use of a particular groundwater resource so as to avoid undesirable reductions to base flow, reduction in spring flow, damage to aquatic ecosystems, damage to terrestrial ecosystems, ingress of sea water, development of subsidence, etc.

2.3.2 Groundwater use and adaptive management

Water use is broadly defined as: "*doing something that has an impact on the water resource*." This means any activity that has an impact on the *quantity*, *quality* or the *environment* surrounding the resource like obstructing or diverting the flow of water in a watercourse is seen as water use. In the case of groundwater, the abstraction of water from an aquifer, or the dumping of wastes in an abandoned shaft that could seep or leach into the groundwater reservoir will be regarded as groundwater use. Groundwater use, like all other water uses, is regulated by different types of water use authorizations. These are:

- Schedule 1 use – activities that are considered to have minimal or no risk impact on the water resource like use of water for domestic and subsistence farming and fire fighting. No registration is required and is applicable to all catchments.
- General authorizations – activities considered to have low risk impact on water resources like abstracting limited amount of water from certain rivers or groundwater sources. No license is required but registration is required in most cases. It is applicable to certain catchments only.
- Licensing – activities considered as high risk to water resources. Registration and licensing is used to control water use that exceeds the limits outlined in Schedule 1 and allowed for under general authorizations.
- Continuation of existing lawful use – persons already using water legally before the NWA came into existence may register and continue to use the water without applying for a license. This is a transitional measure until the water use is formally licensed.

These authorizations are based on the assumption that water use will have no risk, low risk or high risk on sustainability. If the classification process has been completed, then the RQOs are binding on water use authorizations. However, if the classification is not completed, then the only thing that is required before a license can be approved is preliminary Reserve determination. For each license application, the DWA national office makes an estimate of the recharge and the Reserve. The ecological component of the groundwater Reserve is normally based on estimates of in-stream flow requirements (IFR) needed to maintain aquatic ecosystems, using the assumption that maintenance low flow component of IFR can be met by base flow from groundwater. The amount of groundwater set aside for maintaining ecological Reserve is therefore reduced to a certain percentage of base flow. This means that in parts of the country where there is no base flow, no ecological Reserve from groundwater can be determined. The Reserve may not also be used to protect terrestrial ecosystems, since it only applies to aquatic ecosystems (Seward et al, 2006). The DWAF regional office will then decide to recommend the license application or not and what conditions to apply based on recharge, the Reserve, the quantity required by the license application, existing use and any other relevant factors. The normal procedure is to apply a simple water balance procedure. The Reserve and the existing lawful use are subtracted from recharge and if the remainder exceeds the license application then it is assumed that there is enough water available to recommend the license application. This could however, cause serious implications such as capture of water from nearby streams, reduced yields from boreholes on adjacent properties, reduction of flows in nearby springs or reduced soil moisture to groundwater dependent vegetation. Even though it may be difficult to determine these impacts from the onset, continual monitoring could establish the extent of some of these impacts if not all and adaptive management requires that measures be taken to review the conditions of the license agreement when it comes up for renewal.

There is no doubt about the increasing awareness of the partial or total dependence of certain ecosystems on groundwater and the fact that past management practices made no provision for the supply of water to maintain priority ecosystem. Current water reforms which aim at an Integrated Water Resource Management (IWRM) is strengthened by legislation in the National Water Act (NWA) and the National Environmental Management Act (NEMA). It requires that environmental water requirements (ecological reserve and resource quality objectives) need to be taken into account when assessing the sustainability of water resource (including groundwater) development.

2.3.3 The TMG Aquifer System and Sustainable Yields

From a geohydrological point of view, the TMG rocks represent a multi-porous medium that essentially consist of two major components, namely (i) fractures and (ii) inter-fracture 'blocks' or rock matrix. In general, the fractures serve as the more permeable conduits for the rapid movement of groundwater, whilst the matrix blocks form the main storage 'reservoir' which may itself be either permeable or impermeable. In reality, however, the rock mass probably contains many fractures of different scales. TMG rocks are therefore generally considered to form dual porosity, fractured-rock aquifer systems, where it is difficult to simultaneously quantify the groundwater flow within the fractures and the rock matrix, as well as the hydraulic interaction between these two subsystems.

The determination of the sustainability of the TMG aquifer system is linked to the determination of reliable hydraulic properties that can further be used for quantitative analysis as in numerical flow modeling. Wooford (2002) indicated that hydraulic properties of the aquifer are often incorrectly determined using conventional analytical methods for analyzing flow in porous aquifers, and this information is rarely ‘tested’ or used for further quantitative analysis (i.e. numerical flow modeling) as the reliability of the information is generally doubted. Very little research has been directed towards improving the testing or interpretative techniques aimed at quantifying the hydraulic characteristics of this fractured-rock aquifer – due mainly to lack of a plausible conceptual model that adequately describes its geometry and groundwater flow system. Van Tonder and Xu (1998) developed the flow characteristic (FC) method to provide a first-order estimate of the long-term sustainable yield of a borehole, as well as the hydraulic parameters for both primary and secondary aquifers. Hartnady and Hay (2002) and Kotze (2000, cited in Woodford, 2002) provide some hydraulic properties from tests conducted in the Boschkloof Wellfield, Citrusdal, and Little Karoo area respectively using various methods. Mulder (1995, cited in Woodford, 2002) and Jolly (1998, cited in Woodford, 2002) also did some tests on a production borehole in the Vermaaks River Wellfield in 1991 and 1997 respectively.

The majority of aquifer-tests conducted in the TMG aquifers are aimed at obtaining a first-order estimate of the sustainable yield of a production borehole, as well as the design of the pump equipment and abstraction schedule. Various evaluation methods are used by geohydrologists with varied degrees of success. The case study of the Little Karoo Rural Water Supply Scheme - borehole safe-yield versus the sustainable yield of the aquifer as reported by Woodford (2002) provides a test case for the sustainable development of the TMG aquifer. Details of the case study will be discussed later in another section. The gross overestimation of the long-term supply potential of the Vermaaks River wellfield when relying solely upon conventional methods of aquifer-test analysis serves to highlight a problem that is currently being experienced by many groundwater practitioners working in the TMG fractured-rock aquifers and has led some to question the value of such tests (Woodford, 2002). In concluding his report on the interpretation and applicability of pumping-tests in TMG aquifers, Woodford (2002) suggested further research in order to improve the aquifer-testing and analysis techniques and thereby the understanding of the flow dynamics of the TMG.

Jolly (2002) reported that the unscientific testing and evaluation of boreholes drilled in TMG aquifers has often created a false impression of the aquifer's long term sustainable potential. Often 'blow yields' measured at the end of drilling have been mistakenly taken as borehole yields. He affirmed that even the normal scientific assessment of the borehole's potential via step and 72 hr constant rate tests can grossly over-estimate sustainable yield, if assessments do not take into account issues like existing boundaries and matrix transmissivity and storativity. He believes that many schemes have failed because the abstraction has exceeded recharge, resulting in water levels declining to the depth of the pump. He however, advised that aquifer storage must be utilized before the next recharge event topped up the aquifer because not only is recharge low but it is also sporadic. According to Jolly (2002), the ultimate cause of borehole or wellfield failure in the TMG aquifers is the poor management of the resource and suggests that the decline in water levels must be carefully managed to make certain that water levels do not drop below the top water strikes in the hole. He believes the storativity in the TMG is lower than traditionally expected.

In discussing the necessary conditions for the TMG aquifer and its sustainability, Weaver (2002) indicated that the prime controller of an aquifer's sustainability is recharge but that recharge in the TMG was one of the least studied in the country. However, there has been previous work done by various researchers at different times in different areas of the TMG on recharge based on percentage of MAP. These researchers attempted to estimate recharge using a variety of methods (Maclear, 1996; Rosewarne and Kotze, 1996; Weaver *et al*., 1999; Hartnady and Hay, 2000; Kotze, 2000; Kotze *et al*., 2000; Xu *et al*., 2007; Jia, 2008). The methods include:

- the cumulative rainfall departure (CRD) method;
- the saturated volume fluctuation (SVF) method;
- the chloride mass balance (CMB) method;
- the C-14 method;

- the baseflow method (which provides an estimate of minimum recharge);
- catchment mass balance models;
- groundwater flow models;
- the rainfall infiltration breakthrough (RIB); and
- water balance models using GIS.

Each method has advantages and disadvantages. However, lack of suitable data is often a prime reason why recharge was not quantified (Parsons, 2002). Parsons (2002) proposed that, as a general rule, those methods based on direct measurement of groundwater levels, spring flow and river flow should be preferred. Those methods where groundwater is calculated as a residual should be avoided as the quantification of evapotranspiration remains problematic. He agrees with other geohydrologists that small errors in the quantification of evapotranspiration and run-off in water balance models, for example, can have significant impact on the resultant quantification of recharge. Also direct measurement of levels and flows will allow for a degree of verification and validation.

Xu *et al*. (2007) recently did a study of TMG aquifer recharge and sought to improve the understanding of the recharge processes, in-depth analyses of factors influencing recharge, such as climate, geomorphology and hydrogeological settings which are of paramount importance in determining recharge for the sustainable development of the TMG aquifer systems. They developed conceptual recharge models to improve the understanding of recharge mechanisms and processes at various geomorphologic settings and under changing climatic conditions. Results from that study and critical issues raised in considering those results are presented later in a separate chapter of this thesis.

The current study also focuses on the understanding of the historical trends in climate variables notably rainfall and temperature and their impact on recharge to groundwater. Some previous researches in the TMG have dealt with different aspects of the system, i.e. estimation of recharge rates (Xu *et al.*, 2007), flow characteristics and storativity (Lin, 2008), groundwater-surface water interactions (Roets, 2008), groundwater dependent eco-systems (Roets, 2008; Colvin *et al*, 2007, Sigonyela, 2006; Le Maitre *et al*, 2002), interpretation and applicability of pumping tests, (Woodford, 2002), the use of geochemistry and isotopes (Cavé *et al*, 2002) and several others. In discussing the sustainable use of TMG aquifers and problems related to scheme failures, Jolly (2002) attributed the causes of over-abstraction to wrong estimates of borehole yields, wrong estimates of storativity and recharge rates. Failure of a scheme may also be caused by iron clogging (chemically induced biofouling) of the borehole. Traditional pumping test analysis may not be enough to set sustainable pumping rates if boundary conditions and matrix storativity are not taken into consideration. This study provides more in-depth analysis of the rainfall variability and climate change impacts on TMG aquifers and their sustainable yields.

2.4 Methodology

2.4.1 Methodology in determining sustainability

The author believes that any methodology to be adopted in a groundwater scheme to achieve sustainability must be based on the principles suggested by Kalf and Woolley (2005). These are:

- Definition or methodology to be based on sound hydrological and groundwater flow principles (i.e. law of conservation of mass) so as to remove ambiguity of meaning and allow determination of quantitative output.
- Sustainable yield must enable the groundwater system to reach a new state of equilibrium in time.
- Allow numerical models (and modelers) to provide the quantitative output such as basin mass balance (water budget), aquifer parameters in assessing sustainability and also, if required, production facility "performance" or wellfield optimal yield and drawdown.
- Allow a particular sustainable yield (or non-sustainable yield) derived from such models to be selected based on or constrained by other criteria (i.e. water authority ground and surface water usage limits, community needs, legal factors, economic issues, ecological requirements, water quality, effects of subsidence).

Again, a call to differentiate and separate the sustainability of a basin aquifer system and the "performance" of the production facility abstracting groundwater is made by Kalf and Woolley (2005). The sustainable yield can be derived from conservation of mass principles in a groundwater basin or sub-basin as follows: Inflow – Outflow = Change in storage or

$$I - O = \Delta S / t \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.1)$$

Where I and O are defined as the total inflow and outflow rates ($L^3 T^{-1}$) from various sources or sinks and ΔS is the storage accretion of groundwater or depletion volume (L^3) and t is time (T). If the outflow is greater than inflow then some storage is depleted and groundwater level falls, whilst if the inflow is greater than outflow then there is storage accretion and groundwater level rises. If inflow equals outflow then the water levels remain static because there is no gain or loss in storage. Inflows would normally include, for example, rainfall recharge, runoff and stream/lake leakage, whilst outflows would include springs, evapotranspiration, base flow, drains and pumping abstraction. Artificial recharge is also a possible inflow component.

Numerical modeling has become an indispensable decision tool in groundwater management. Such models can generate the transition curve from storage depletion to induced recharge from surface water bodies for the system under consideration, so that management plans and planning horizons can be thoroughly assessed (Sophocleous, 2000). The reliability of such models however, often suffers from the uncertainty of their input parameters. The estimation of key primary parameters such as recharge will continue to be a major challenge because of its strong spatial and temporal variability. Recent technological improvements with the development of graphical user interfaces and decision support systems however, enhances modeling, taking advantage of the continuing development of Geographical Information Systems (GIS) and visualization technologies as mentioned by Sophocleous (2000).

2.4.2 Data Requirements

In order to assess the sustainability of the aquifers of the TMG it was evident that an assessment of the pattern of natural recharge by precipitation had to be done. A long term natural response of groundwater levels to rainfall provided some insights to this study. A selection of monitoring boreholes drilled in and around the TMG from which reasonably long available records were obtained from the Department of Water Affairs and Forestry (DWAF). In order to ascertain the influence of external factors on these boreholes or otherwise it required a GIS survey of all physical features that could have potential influence on these boreholes. This was made possible from information provided by digital topographic sheets obtained from Surveys and Mapping, Department of Land Affairs which was integrated with borehole locations and locations of rainfall stations from which data was collected. During a number of field work undertaken during the period of study physical inspections of some of the boreholes were also done to verify information obtained from the GIS mapping. It was important to know whether the water levels recorded at the selected boreholes had been influenced by external factors such as large scale abstraction for irrigation purposes, domestic supply to communities or their proximity to recharge sources (dams, rivers or wetlands).

A cursory view of published reports revealed that a number of different water level fluctuation patterns are recognizable in the records kept by DWAF. These are broadly classified as follows:

- Short term (~ 1 year) cyclical fluctuations in the water level data;
- Sharp increases in water level usually associated with extreme climatic events;
- Relatively steep and short term declining trend presumably associated with external factors such as abstraction;
- Medium term (~ 5-10 years) declining trends in the water level data; and
- Longer term usually declining trend which may be of a cyclic nature, but due to the short time series, it is not clear whether it does reflect a specific cycle.

Meyer (2005) reports that it would appear that each aquifer (or even borehole) has a unique water level response curve and that it would not be possible to make any general statements about aquifer response to rainfall patterns or events. Bredenkamp *et al* (1995) have reported reasonable correlations between the water level and “Cumulative Rainfall Departure” datasets although they also added that there are many cases where no correlations could be established. It would also be worth investigating the correlations between water level and “Rainfall Infiltration Breakthrough, (RIB)” datasets. Meyer (2005) has successfully also shown a remarkable good visual correlation between the Standard Precipitation Index (SPI) of rainfall time series and some groundwater level records. It appears there is still more research work in this area that needs to be done and a lot of work was put into this work to address some of the issues.

2.4.2.1 Precipitation data

Precipitation data was obtained from the records of rainfall stations within the study area compiled for the WR90 and its later update, WR2005 project. Records were from 1920 to 1989 for WR90 and 1989 to 2004 for WR2005. Recent records (up to 2007) were also obtained from SAWS for stations considered significant to the study. Monthly records were obtained and values of Mean Annual Precipitation (MAP) computed for each station.

2.4.2.2 Water levels and borehole information data

Groundwater levels data were obtained from the Department of Water Affairs' (DWA) databases, NGDB and Hystra, which also include groundwater chemistry for certain boreholes. The data comprises production and monitoring boreholes, their geographic locations, topographic height and borehole information such as depth, lithology, water strike and purpose among others. In some cases, pumping test data was also available for some boreholes.

2.4.2.3 Temperature data

Data on daily maximum and minimum temperatures for station within the study area were sourced from SAWS (Cape Town Intl. Airport office). Records available from 1950 to 2009 were obtained for trend analysis.

2.4.2.4 Other data and information

Other relevant data used in the study included runoff, soils, vegetation, evaporation and recharge which were obtained from the WR90 and WR2005 projects. Additional information on recharge, climate variability and climate change were obtained from literature on previous and current projects. Lithological information and aquifer properties were obtained from literature and field observations. Field measurements included borehole drilling and logging, groundwater sampling, stream and spring sampling, pumping test and groundwater levels. Runoff data was used to estimate baseflow as the groundwater contribution to stream flow. Soil information is vital in water balance computations such as infiltration capacity and soil moisture content. Vegetation type and density was used to compute evapotranspiration amounts together with energy from the sun. Reports on alien vegetation and their influence on groundwater storage was also relevant in the discussion of groundwater dependent ecosystems.

2.5 Summary

The definition and approach to groundwater sustainable yield as operate in different parts of the world are similar in content. The America, Australian and South African approach to implementation of a sustainable groundwater scheme all recognize the fact that a sustainable scheme must be beneficial to the current and future population of society with limited or no adverse hydrological, ecological, environmental, economic or social impacts. The management of sustainability must be considered a dynamic process which changes over time and space especially with increase in knowledge and experience. The dynamics of every groundwater scheme must be known especially its demands and boundaries. The demands of society must be prioritized with the basic needs of all dependable life forms the first priority. The management must adopt an adaptive management approach by seeking the concerns of all stakeholders in managing trade-offs between abstractions for development and risk of groundwater storage depletion that may adversely impact on other sectors of the economy. The Table Mountain Group aquifers are used as a case study to discuss the concept and its implementation. The methodology in determining sustainable yield of an aquifer for example must be based on sound groundwater flow principles. The quantitative outputs from models must be constrained by any legal framework, community needs, ecological and environmental requirements and based on sound economic and social principles.

CHAPTER 3 HYDROGEOLOGICAL SETTING OF THE TMG

3.1 History and Lithostratigraphy

The stratigraphy, lithology and structure of the TMG have been described extensively in a number of literatures and will only be briefly discussed in this volume. The Cape Supergroup consists of sediments deposited from early Ordovician to early Carboniferous times, approximately between 500 and 340 million years ago. The predominantly siliclastic sequence is exposed along the entire length of the Cape Fold Belt (CFB), the 280 to 220 million year old orogenic belt straddling the west and south coasts of South Africa. The Table Mountain, Bokkeveld and Witteberg Groups are the subdivisions of the Cape Supergroup (Rust, 1967; Theron, 1972; Broquet, 1992; de Beer, 2002). These sediments were deposited in shallow marine environments under tidal, wave and storm influences, as well as in non-marine, braided-fluvial environments. The medium to coarse grain size and relative purity of some of the quartz arenites, together with their well indurated nature and fracturing due to folding and faulting in the fold belt, enhance both the quality of the groundwater and its exploitation potential (de Beer, 2002).

The TMG is the lowest member of the Cape Supergroup and comprises of an approximately 4000 m thick sequence of quartz arenite and minor shale layers deposited in a shallow, but extensive, predominantly east-west striking basin, changing to a northwest orientation at the west coast. The maximum thickness in the east section (Port Elizabeth) is approximately 3010 m (Rust, 1973). The TMG comprises of the Piekenierskloof Formation, Graafwater Formation, Peninsula Formation, Parkhuis Formation, Cederberg Formation and Nardouw Subgroup (Table 2.1; Figure 3.1). The lowermost unit of the TMG, the Piekenierskloof Formation, consists of conglomerate, quartz arenite and minor mudrock that are confined to the West Coast. The reported maximum thicknesses for the Piekenierskloof Formation vary between 900 m northwest of Citrusdal (Rust, 1967) and 390 m at Piketberg (Thamm, 1993). It unconformably overlies phyllites and quartzites of the Neoproterozoic Malmesbury Group and sediments of the early Palaeozoic Klipheuwel Formation.

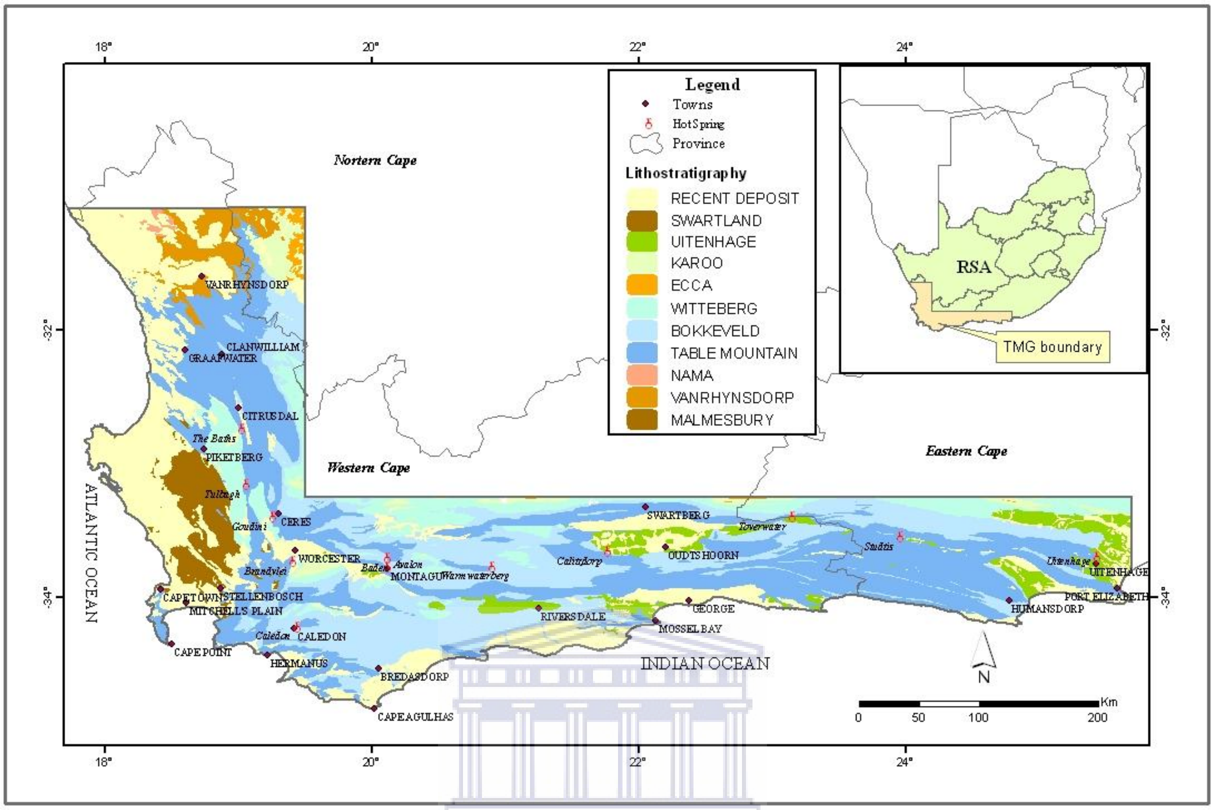

Figure 3.1: Distribution of Table Mountain Group

The Graafwater Formation is characterized by purple, thin-bedded, ripple-marked and mud-cracked sandstone, siltstone and shale beds. These features, together with the presence of trace fossils, prevent confusion with any other unit within the TMG (Rust, 1967). Rust (1967) calculated a maximum thickness of 424 m in the type area west of Clanwilliam (Figure 3.1).

The name of the Peninsula Formation is derived from the Cape Peninsula where the full succession (550 m) is exposed against Table Mountain. It comprises a succession of coarse-grained, white quartz arenite with scattered small pebbles and discrete thin beds of a matrix-supported conglomerate (Rust, 1967). The formation reaches a thickness of about 1800 m at Clanwilliam in the west (Rust, 1967), but is reportedly much thicker in the Eastern Cape (Rust, 1973; Johnston, 1991). The Pakhuis Formation occurs above the Peninsula Formation and comprises about 40 m of glacially derived sediments, but is restricted to the southwestern Cape (Rust, 1967; Broquet, 1992).

The Cederberg Formation is a thin (maximum 120 m) but remarkably continuous unit, consisting of black silty shale at the bottom, grading into brownish siltstone and fine sandstone at the top. It is best exposed within the southwestern Cape but continue along the whole length of the southern Cape Fold Belt. It is a prominent marker band between the Peninsula Formation and the Nardouw Subgroup. Its confining character makes the Cedarberg Formation very important in a hydrogeological sense (de Beer, 2002). The Nardouw Subgroup, with its three subdivisions, the Goudini, Skurweberg and Rietvlei (Baviaanskloof in the Eastern Cape) Formations, is another thick (maximum 1200 m) unit of sandstone that varies between quartz arenite, silty and feldspathic arenites, accompanied by some very minor inter-bedded conglomerate and shale. This lithological diversity, together with textural, grain size and bedding thickness differences, lead to pronounced differences in weathering, structural and hydrogeological characteristics. The basal unit, the Goudini Formation, is characterised by reddish weathering, thin sandstone beds with common shale intercalations, which are less resistant to weathering than the thick-bedded, arenitic Skurweberg Formation. The topmost unit, the Rietvlei Formation, consists of finer grain and high feldspar content with resultant dense vegetation cover. The contact with the overlying dark shale of the Bokkeveld Group is usually abrupt (de Beer, 2002). Table 3.1 is the stratigraphical succession of the Table Mountain Group.

Table 3.1: Stratigraphical succession of the Table Mountain Group

Group	Subgroup	Formation	Bed Thickness (m)	Maximum Thickness (m)	Lithology
Bokkeveld			4000		Siltstones, shales, sandstones
Table Mountain	Nardouw	Rietvlei/Baviaanskloof	0.5 - 1	280	Feldspathic quartz arenite
		Skurweberg	1 – 2	390	Quartz arenite
		Goudini	0.3 – 0.5	230	Silty sandstone, siltstone
		Cedarberg	0.1 – 0.3	120	Shale, siltstone
		Pakhuis	variable	40	Diamictite, shale
		Penninsula	1 – 3	1800	Quartz arenite
		Graafwater	0.1 – 0.5	420	Impure sandstone, shale
		Piekenierskloof	0.3 – 1.5	900	Quartz arenite, conglomerate, shale
Basement		Underlying the TMG are the Malmesbury shales, the Gamtoos and the Kaaimans argillites, comprising moderately to lightly metamorphic sedimentary rocks; and cape granite suite.			

3.2 Structure

The presently exposed structure and thickness of the TMG rocks are the result of initial deposition within an east-trending basin or trough (Rust, 1973) along the southern and southwestern Cape regions, as modified by two major tectonic events, namely the Permo-Triassic Cape Orogeny and the fragmentation of southwestern Gondwana during the Mesozoic. The Cape Fold Belt (CFB) is traditionally divided into two branches, namely the western and southern branches, and in between is the structural syntaxis (Figure 3.2), of which the structural backbone extending from the northwest to the south near Cape Peninsula and incurve to the east near Port Elizabeth. The exposed width of the western branch is about 150 km, and the southern branch is about 200 km. Both branches are arcuate in plan view and concave towards the Karoo Basin, converging with northeast-trending folds in the syntaxis of the southwestern Cape (de Beer, 2002). The western branch differs in two major aspects from the southern branch (De Villiers, 1944, Söhnge, 1983). The first one is its much lower shortening intensity and the second, its northwesterly fold trend. The large-scale structure of the resistant TMG and resultant topography was determined by the physical properties of the competent units. Faults of the western branch trend north-westerly, the major ones being De Hoek Fault, Redelinghuys Fault and Clanwilliam Fault. Numerous subsidiary splays and sets of transverse northeast-trending minor faults are also present (Figure 3.2).

The southern branch displays northerly-verging, often overturned first-order folds, sliced by a few thrusts and normal faults, with strong fracture cleavage in the quartz arenites and slaty cleavage in the Cedarberg Formation (Booth & Shone, 1992). The two most important regional fold structures are the Swartberg and the Outeniqua anticlines. The major faults trend easterly but are accompanied by a transverse set of minor, approximately northeast trending transfer faults. The major ones are the Worcester Fault and the Kango-Baviaanskloof Fault Zone, both of which remain seismically active to this day. All of these faults display zones of brecciation a few tens of metres wide (de Beer, 2002).

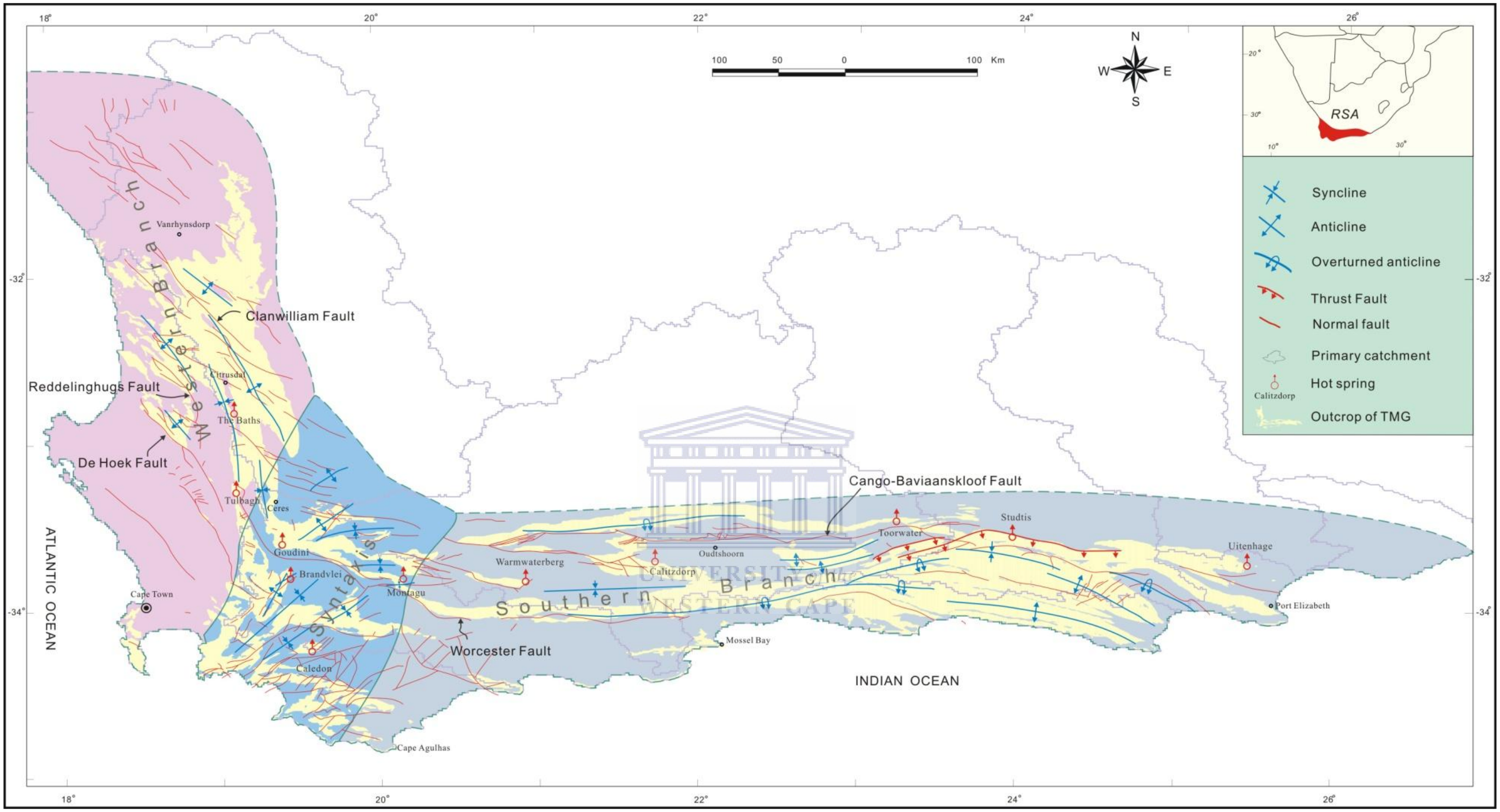

Figure 3.2: Structural sections of the TMG

(Modified after Wu, 2005; faults adapted from Council of Geoscience, 1977)

Fold axial traces of the western and southern branches form open arcs in the Western Cape Province where they merge with the broad zone of northeast-trending structures of the syntaxis. Based on differing fold trends and shortening intensity, the syntaxis may be divided into two separate domains lying north and south of the Hex River anticline. The northern domain is characterized by north, northwest, northeast and minor east trending folds, while the southern domain contain only east and northeast trending folds. The syntaxis is the most fractured part of the CFB, with components of the western and southern branch faulting both being present. The Worcester Fault changes trend from easterly to northwesterly and the area south of it is dominated by numerous large northeasterly trending faults. The latter set of fractures must have formed contemporaneously with the Worcester Fault or slightly later, because they end against this major fracture, with attains its maximum displacement of more than 5 km in the syntaxis (de Beer, 2002).

3.3 Geomorphology and Drainage

On a regional scale the TMG covers mountains, wave-cut plains and intermontane drainage basins, which form the main geomorphologic setting in the area. The modern landform patterns of the TMG result from quaternary processes including crust heaves, physical and chemical erosions, which lead to the rolling landscapes with a relative relief of 200~1700 m. The mountain peak can reach 1900~2250 m in Hex River Mountain and 1500~2000m along Langeberg and 1700~2000 m on Swartberg Mountains. Comparing with overlying argillaceous rock formations and underlying metamorphic rocks, geomorphologic patterns of the TMG are also characterized by the highly stick-out mountains and steep slopes with quite thin and in most places no soil cover over the outcrops. The mountains form the backbone of the TMG geomorphologies that are firmly controlled by the structure and lithologies. Among them, from west to east, is Bokkeveldberg - Cedarberg - Skurweberg and Hex River Mountain, turning eastward to Langeberg - Outeniqua Mountains. To the north there are Witteberg-Swartberg-Baviaanskloof Mountains. In between are intermontane basins and flood plains, most of which are covered by weathered mantles from argillaceous rocks and fluvial deposits.

The drainage system of the TMG is highly influenced and controlled by the numerous structures and features that have been developed over time as a result of past tectonic activities. Eleven primary and 551 quaternary catchments drain the region controlled by the Berg, Olifant-Doring, Breede, Gouritz, Bree, Salt, Sounrits, Gamtoos and Sundays rivers. The rivers cut through various formations of the TMG and structural units of the area producing diverse water courses and slope systems which lead to both the TMG’s rough and rugged surface and different relief mountains and hill systems. The ability of the TMG rocks to contain water is determined by the amount and properties of fractures that they contain as well as their secondary porosity. Most of these rocks are remarkably densely packed and such porosity can only be created through deformation and faulting during various tectonic movements in the geological history.

3.4 Hydrogeological Domains

The physiographic setting of the TMG regional aquifer is extremely varied. The northern outcrops border on desert areas with less than 150 mm/a of precipitation, while around Worcester and Ceres, precipitation of over 2000 mm/a occur. In the latter mountainous areas, elevations reach over 2000 m, while at the Cape Peninsula and along the Southern and Eastern Cape coast, wave-cut platforms occur at sea level. Rosewarne (2002) broadly divided the outcrop and sub-outcrop area into two hydrogeological domains; intermontane and coastal domains. These two domains are interconnected except where there may be natural barriers to flow, such as the Cedarberg formation or faults. They are however, inhomogenous in that the major formations within the TMG have different hydrogeological properties and potential. The former is characterised by direct recharge from rain and snow melt, deep groundwater circulation (often with hot spring) and low conductivity groundwater. The coastal domain is characterized by shallow groundwater occurrence usually with moderate to poor quality, indirect recharge from mainly rainfall and where springs occur they are usually cold (Rosewarne, 2002).

In earlier studies the TMG has been subdivided into a number units based on their different geological and hydrogeological characteristics. Vegter (2001) divided South Africa into 64 groundwater regions based on Lithostratigraphy, physiography and climate. The TMG area is covered by 23 of those regions with 16 regions covering the outcrop area. He does not however differentiate between the significance of the TMG arenites from the Bokkeveld and Witteberg groups which overly parts of the TMG. Xu *et al* (2007) divided the TMG into 19 hydrogeological units while Lin (2007) provides 15 hydrogeological units within the TMG.

These subdivisions are generally based on different boundary conditions which are controlled by lithology, geomorphology and structural discontinuities such as the various local and regional fault systems. Therefore the basis for subdividing the TMG into hydrogeological units will largely depend on the scale of study. In a complex fractured rock system like the TMG the hydrogeological units become the unit of study on the local scale and may constitute a primary hydrogeological catchment of which further subdivisions may become necessary if considerations are made on the basis of potential flow regimes, recharge and discharge zones.

3.5 Aquifer types and characteristics

The characteristics of the TMG aquifers derive from their complex history of tectonics, lithology and climate. The description and characterization of these aquifers can be both difficult and subjective; hence the majority of TMG aquifers have been characterized on the basis of their formation with the aid of geological cross sections, boundary conditions and flow dynamics. Xu *et al* (2007) summarized the TMG aquifers into four main categories on the basis of their geologic structure.

- Horizontal terrain aquifer system
- Fold strata aquifer systems (syncline or anticline)
- Fracture zone aquifer system
- Composite aquifer system

An example of the horizontal terrain aquifer occur in the Cape peninsula where the gently-dipping TMG terrain controls both the extension of the aquifer and the topographical features that in turn influence the aquifer’s recharge (Fig.3.3). This type of aquifer may be unconfined or perched.

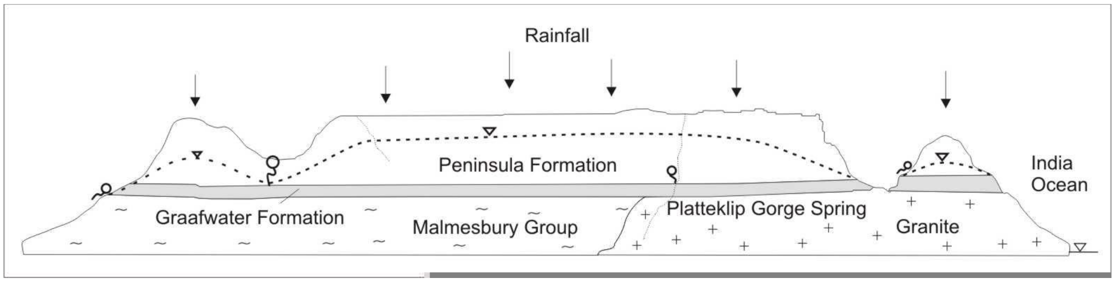

Figure 3.3:A horizontal terrain aquifer in the Table Mountain, Cape Town (Xu et al, 2007)

In this present study the aquifers within the TMG are generally grouped into three types on the basis of their response to the climate and environmental changes.

- Shallow aquifers
- Deep aquifers
- Coastal aquifers

The Coastal aquifer which could also be categorized as a shallow or deep aquifer is considered a specialized aquifer due to their proximity to the sea where several activities emanate to affect the environment in Climate Change science.

The shallow phreatic aquifers of the TMG are generally the Nardouw subgroup aquifers which are in direct hydraulic contact with surface water bodies due to their proximity to the land surface (up to a few tens of meters below the ground). The numerous outcrops of the Peninsula formation within the TMG may also constitute shallow aquifers if they are sufficiently fractured and or weathered to store substantial amounts of water. These aquifers supply baseflow to rivers and because of their direct contact with surface water bodies and hence the atmosphere any impact of climate change and climate variability on surface water bodies is likely to affect them substantially. Shallow aquifers are also affected substantially by land use and land cover changes due to alterations in surface run-off and soil moisture characteristics.

Deep aquifers in the TMG are generally derived from the sandstones of the Peninsula formation which is a potential source for bulk water supply in the Western and Eastern Cape provinces due to their excellent water quality and sometimes their artesian conditions. Several boreholes drilled to depths of between 200 m and 800 m have yielded excellent quantity and quality water for bulk water supply in recent years. In Rietfontein, 10 km from Graafwater in the northwest coast, a borehole was drilled to a depth of 800 m in 2001 through the TMG formation. The borehole, G40145, had an initial artesian flow of 0.3 *l*/s but dropped to 0.01 *l*/s in two years. During the DAGEOS project in the Oudtshoorn area of the TMG a wellfield of shallow and deep wells was established for exploratory and water supply purposes. Six boreholes ranging in depth from 152 m to 715 m were drilled during the project from 2002 to 2007. The deep wells of 715 m and 608 m had artesian conditions.

There are a number of coastal aquifers in the study area. These are found near the western and southern Cape coast. Figure 3.4 is a map showing the types of aquifers occurring within the study area. The coastal aquifers are generally made up of shallow unconsolidated sands and gravels and sometimes mixed with clays and silts. They are generally very vulnerable to pollution and salinisation and often require special protection and management. Excessive withdrawals from coastal aquifers are always a threat to saline intrusion.

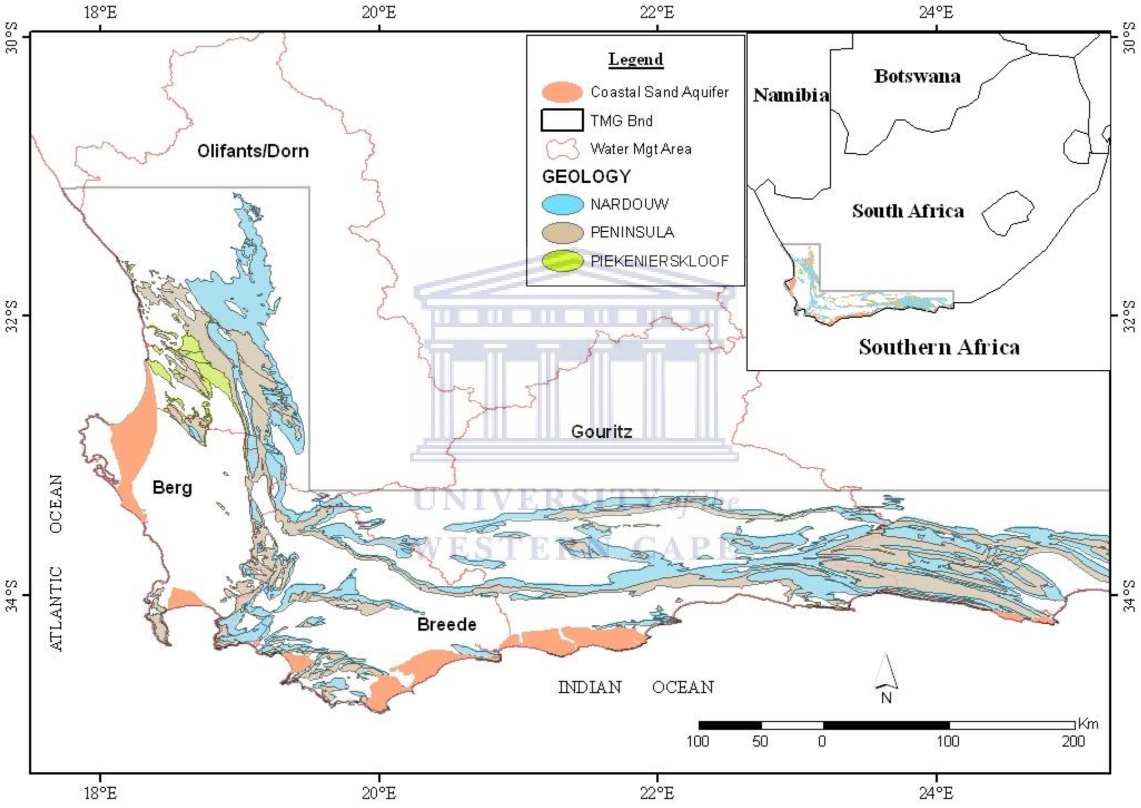

Figure 3.4:Types of aquifers occurring in the TMG

3.6 Occurrence of Springs

The presence of numerous geologic features such as folds, faults, fractures, fissures and intricate joint systems within the TMG give rise to the abundance of springs which is one of the distinct characteristics of the formation. Meyer (2002) differentiated the TMG springs into three categories according to the mode of occurrence, namely, shallow circulating springs, lithology controlled springs and fault controlled springs. The shallow circulating springs seep from a network of joints, small, irregular fractures and from bedding planes draining small reservoirs during and after rainy spells. They are generally low yielding and seasonal drying up with the onset of dry weather conditions. The lithology controlled springs issue due to the presence of impervious layers. The Cedarberg formation is a well-known interbedded shale layer in the TMG as described above. It serves as a hydrogeologically impervious layer separating the Nardouw aquifer from the Peninsula aquifer and accounts for most of the perennial springs within the TMG. The quality of these springs is generally excellent with ECs ranging between 10 and 35 mS/m (Meyer, 2002). The Marnewicks spring in the Kamanassie Mountains and the Humansdorp spring are examples of the Cedarberg formation related springs.

There are eleven fault controlled springs in the TMG from the Baths (Citrusdal) in the west to Uitenhage in the east (Figure 3.1). These springs are hyperthermal, thermal and hypothermal in nature with temperatures ranging from 23^{o}C to 64^{o}C indicating deep circulation flow from deep seated faults. Five of these thermal springs are located in the relatively limited syntaxis domain of the TMG (Figure 3.2) which is indicative of a greater frequency of deep fracturing within that domain compared to the rest of the TMG area. The fault controlled springs are generally high yielding and have excellent water quality. One of the important features of the TMG is invaluably the springs which support agriculture and some local communities. In particular, the thermal springs are known and highly patronized for their recreational value (Spa) and domestic water supply (Figure 3.5). Due to the economic value of these hot springs any extensive groundwater development around the recharge areas could pose serious threat to their sustained flows. The protection of all springs within the TMG is a vital element in the overall sustainable development of groundwater resources as they provide us with valuable information on quantity and quality of water in the aquifer without the cost of drilling. Table 3.2 provides important information on the TMG hot springs.

Table 3.2: Important information on TMG hotsprings (After Meyer, 2002)

Name of Spring	Temp (oC)	Yield (l/s)	Cond (mS/m)	Probable depth of circulation (m)	Classification of thermal water	Major Utilization
The Baths	43	29	8	2000	Hyperthermal	Recreation
Goudini	40	11	7	1700	Thermal	Recreation
Brandvlei	64	127	8	3600	Hyperthermal	Domestic

Caledon	37	9	20	1600	Thermal	Recreation
Avalon (Montagu)	43	38	11	2000	Hyperthermal	Recreation
Baden	38	37	10	1500	Thermal	Recreation
Warmwaterberg	45	9	26	2100	Hyperthermal	Recreation
Calitzdorp	50	8	31	2500	Hyperthermal	Recreation
Toverwater	44	11	15	2000	Hyperthermal	Irrigation
Studis	24	31	18	480	Hypothermal	Irrigation
Uitenhage	23	45	34	400	Hypothermal	Domestic

Sampling at the Brandvlei hotspring

View from The Baths hotspring source

Brandvlei hotspring used for domestic supply

Avalon hotspring, a major source of recreation

Figure 3.5: TMG hot springs are a major source of domestic water supply and recreation

3.7 Porosity, Storativity and Transmissivity

3.7.1 Porosity

The porosity of a rock or formation is defined as the percentage of total void spaces to the total volume of the rock or formation. If V_t is the total volume of the rock, V_v is the volume of voids, the *porosity n* is defined as *n* = V_v/V_t. It is worth distinguishing between *primary porosity*, which is due to the rock matrix, and *secondary porosity*, which may be due to such phenomena as secondary solution or structurally controlled fracturing. The TMG rocks are generally considered to form a dual porosity, fractured-rock aquifer system. This indicates that the rock mass consists of two major components, the fractures and the rock matrix. Ideally, the fractures will serve as the more permeable conduits for the rapid movement of groundwater, whilst the matrix block forms the main storage compartment which in itself may generally be composed of micro fractures that make it permeable howbeit low. In discussing the storativity of the TMG rocks it will be appropriate to discuss the rock porosity that inadvertently controls the storage capacity. Porosity of the TMG rocks may also be considered on two fronts, the fracture porosity and the matrix porosity which together will constitute the total porosity of the rock formation. It is also well documented (Woodford, 2002; Lin, 2008) that it is extremely difficult to simultaneously determine the fracture and matrix porosities as there is yet no distinguishing criteria to separate one from the other. One may however, determine the porosity of a rock mass from a laboratory analysis of a rock sample or geophysical logging of a borehole (e.g. density, sonic and neutron logs) whereas fracture aperture is usually used to represent the fracture porosity of a rock in particular. Lin (2008) calculated a wide range of porosity values of TMG rocks from borehole geophysical logging, rock core samples and aquifer tests (Table 3.3).

Table 3.3: Porosity derived from core samples, aquifer tests, field measurements and density logging.

Type of measure	**Sample Depth [m]**	**Porosity [%]**		**Reference**
		Range	**Average**	
Core samples	42.5 – 135.5 (5 samples)	1.2 – 3.6	2.5	Core samples of Gevonden BH1, TMG
	Unknown (1 sample)	1	1	Core samples of Gevonden BH2, TMG
Aquifer tests	Koo Valley	0.01 – 0.35	0.06	Pumping tests, Jacob
	Kammanassie	0.11 – 0.22	0.15	Kotze (2002)
	Boschkloof	0.1 – 0.01	0.05	Umvoto (2000)
	Gevoden	0.21 – 1.2	0.57	Pumping tests, Jacob
Field measurement	Kirstenbosh,	0.04	0.26	Sandstone block measurement
	Rawsonville,	0.52		Rock surface measurement
	Montague	0.22		Rock surface measurement
Remote Sensing	Rawsonville		1.24×10^{-6}	
Density Logging	Clean Sandstone	1.7 - 12.6	5.7	Rietfontein Deep Borehole
	Fractured Sandstone	13.1 - 37.1	16.4	Rietfontein Deep Borehole
	Siltstone	4.3 – 16.7	12.1	Rietfontein Deep Borehole
	Shale	4.5 – 20.4	14.0	Rietfontein Deep Borehole

The table shows a wide range of porosity values which is dependent on the methodology and the particular sample that is being analysed. It is also evident that porosity values depend on the scale of analysis. The values are higher on individual core samples. On an aquifer scale, porosity values are much lower as given by the aquifer test results (Table 3.3). The values are even much lower when they are determined on a regional scale as shown by the remote sensing results.

3.7.2 Storativity

The *storativity S,* of a saturated confined aquifer can be defined as the volume of water that the aquifer releases from storage per unit surface area of aquifer per unit decline in head normal to that surface. It is dimensionless. For an unconfined aquifer we define the *specific yield* S_y, as the volume of water that the unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table. The specific yields of unconfined aquifers are much higher than the storativities of confined aquifers. The usual range of S_y is 0.01-0.30 while S is of the order of 10^{-3} to 10^{-6}.

The determination of storativity for the TMG rocks has been done mainly from interpretation of aquifer tests results. As may be expected the values are wide ranging from 10^{-2} to 10^{-5} from the different wellfields within the TMG as determined by several researchers in recent times. The variability of the storage coefficient for a fractured rock system like the TMG is highly dependent on the interconnectivity of the different fracture systems hence recommendation for a range of values is preferred rather to the use of single values. For the purposes of regional groundwater resource evaluation Vegter (1995) proposed a storativity value of less than 10^{-3} for the TMG while Jia (2007) proposed separate range of values of storativity for the Peninsula and Nardouw multi aquifers (Table 3.4). During this study a number of aquifer tests conducted on a couple of boreholes drilled in the Peninsula formation at the Gevonden study site yielded storativity values ranging between 6.9×10^{-4} and 2.8×10^{-5}. As with the case of porosity, the scale dependency of storativity for a regional aquifer system like the TMG cannot be over-emphasized.

Table 3.4: Recommended storativity values for TMG aquifers (Jia, 2007)

Aquifer type	Range	Storativity	
		Specific yield (unconfined)	**Storage coefficient (confined)**
Nardouw aquifer	Low	7.0×10^{-5}	7.0×10^{-6}
	Medium	3.5×10^{-4}	7.0×10^{-5}
	High	3.5×10^{-3}	7.0×10^{-4}
Peninsula aquifer	Low	1.0×10^{-4}	1.0×10^{-5}
	Medium	5.0×10^{-4}	1.0×10^{-4}
	High	5.0×10^{-3}	1.0×10^{-3}

3.7.3 Transmissivity

The transmissivity (T) of a confined aquifer is defined at the product of the hydraulic conductivity (K) and the saturated thickness of the aquifer (D). Thus K = TD. The hydraulic conductivity is a measure of the formation to transmit water. It depends both on the properties of the medium (rock material) as well as of the fluid. In sedimentary formations, grain-size characteristics are most important as coarse-grained and well-sorted material will have high hydraulic conductivity as compared with fine-grained sediments like silt and clay. Increase in degree of compaction and cementation reduces hydraulic conductivity. In fractured rocks, K depends on density, size and interconnection of fractures. A more rational concept than the hydraulic conductivity is the permeability (k) as it is independent of fluid properties and depends only on the properties of the medium. The relation between the hydraulic conductivity, K and permeability is expressed as:

$$K = \frac{k\gamma}{\mu} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{(3.1)}$$

Where μ is the fluid viscosity, expressing the shear resistance, and γ, the specific weight, expressing the driving force of the fluid. The transmissivity, T, of an aquifer in general is determined by a well pumping test using the traditional solutions developed by Thiem for steady-state flow or Theis for unsteady-state flow. The methodology and formulae for the determination of transmissivity of an aquifer can be found in any standard hydrogeology text book. In the TMG fractured aquifer, transmissivity calculated for different wellfields in the past by several authors have produced wide range of values from 9 m^2/day to 400 m^2/day. Transmissivity values calculated by a team of students including this author at the wellfield in Gevonden during this study resulted in values ranging from 9 to 30 m^2/day. The variation of the transmissivity values is largely due to the anisotropic nature of the TMG aquifer from borehole to borehole and from site to site showing variation of hydraulic properties in the different areas of study. Sometimes the estimation of the aquifer thickness poses a real challenge to the estimation of transmissivity of an aquifer especially if the borehole is not fully penetrating the entire aquifer. This is because the cost of a borehole is generally calculated by length of hole drilled and this can be excessive if the borehole is deep. The methodology used for the analysis would also give variations in the hydraulic parameters of S, K and T.

3.8 Groundwater Quality in the TMG

The quality of groundwater from the TMG is generally high for almost all purposes with usually low salinity. This has been attributed to the inert nature of the quartzites which make up the host rock. The water is also characterized by low calcium and magnesium in most of the area. Smart and Tredoux (2002) reckon that the low salt composition of the TMG is partly due to the fact that the resistant rock formation which usually form topographic highs with elevated rainfall undergo flushing of salts via recharge.

3.8.1 Hydrochemical characteristics

The electrical conductivity (EC) values of water samples from the TMG reported in most of the areas are under 100 mS/m. The median value reported by Smart and Tredoux (2002) range between 20 and 50 mS/m. The EC values in the Peninsula are usually slightly lower than that from the Nardouw which has more shally lithology. In the Piekenierskloof and Graafwater Formations elevated ECs may be obtained due to their shale-rich composition. In the coastal areas salts from marine origin may increase EC from groundwater (Weaver et al., 1999). Field water samples collected from boreholes and a stream sourced from TMG rocks at the UWC Groundwater Research site at Gevonden, Rawsonville indicate EC values in the range of 30 to 60 mS/m. Table 3.5 shows results from water quality analysis conducted on water samples from boreholes and a perennial stream at the foot of the TMG rocks at Rawsonville. Borehole 1 (BH1) is an inclined core drilled hole into the Nardouw formation with an artesian flow of 0.15 *l*/s (figure 3.6). Borehole 2 (BH2) is a vertical core drilled hole of depth 201 m into the Peninsula formation (figure 3.7) and borehole 3 (BH3) is a percussion hole of depth 200 m drilled in the Peninsula. Borehole 4 (BH4) is a very shallow drilled hole tapping the overburden formation and borehole 5 (BH5) is a percussion hole of 175 m depth used in the Peninsula. All the boreholes are for monitoring purposes except BH5 which is used as production hole for irrigation during peak dry season.

Figure 3.6: BH1 at Gevonden (High Fe conc)

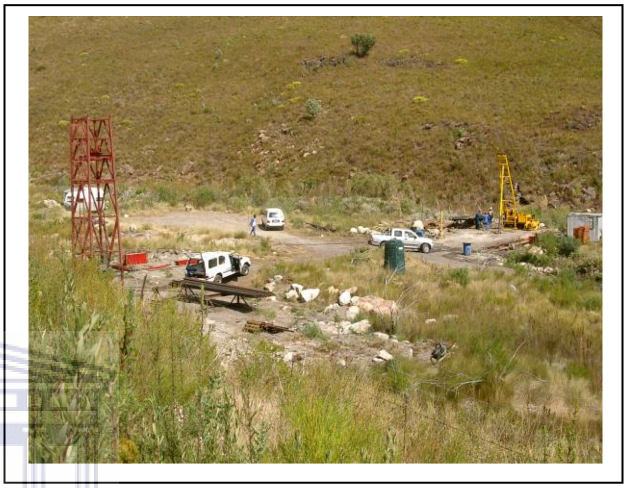

Figure 3.7: Drilling of BH1 (right) and BH2 (left)

Table 3.5: Results of water quality analysis from boreholes in Gevonden, (2006-2007).

	Temp (^oC)	pH	EC (mS/m)	Na (mg/*l*)	K (mg/*l*)	Mg (mg/*l*)	Ca (mg/*l*)	Fe (mg/*l*)	Cl (mg/*l*)	HCO_3 (mg/*l*)	SO_4 (mg/*l*)
BH 1	21.5	6.5	82.0	6.9	1.0	3.5	7.1	2.6	8.8	68.0	1.8
BH 2	21.2	5.8	37.5	2.6	0.6	0.7	2.8	0.7	6.6	31.4	0.6
BH 3	21.8	6.0	81.6	4.8	0.4	0.9	1.8	1.2	11.9	19.9	3.4
BH 4	22.0	6.1	90.0	5.5	0.4	0.5	12.5	4.0	9.7	62.0	0.7
BH 5	20.1	5.5	59.0	5.3	0.4	1.3	1.5	0.4	16.2	5.6	2.9
Stream	17.2	4.8	10.9	1.9	0.0	0.3	0.2	0.1	6.6	6.8	0.4

The major ions found in the TMG water samples are sodium (cation) and chloride (anion) together with other minor constituents characterizing the water type as Na-Cl dominant. The groundwater tends to be slightly acidic, soft to very soft and could be corrosive. The Fe content is higher than potable standards (figure 3.6). The Fe content in the Nardouw sub formation is generally higher than that found in the Peninsula. The presence of Fe has been noted to cause borehole clogging and related problems (Smart and Tredoux, 2002). The Cl concentration from the boreholes at the Gevonden study site appears to be lower than the average concentration from other areas in the TMG which is about 35 mg/*l*. In general, TMG groundwater does not contain significant trace elements and therefore any occurrence of these elements would be assumed to indicate contamination. The hydrochemistry of hot springs from the TMG, according to Kotze (2000), differs from that of boreholes drilled into the formation. He reports that thermal springs are more mineralized and consider them to be a mixture of TMG water from depth and groundwater from the overlying Bokkeveld shale during the upward flow to the surface. Chemical analysis of hot springs and borehole samples however, appear to be similar in constitution with some hot springs plotting only slightly to the left on the Piper diagram as shown in Figure 3.8 (after Wu, 2005).

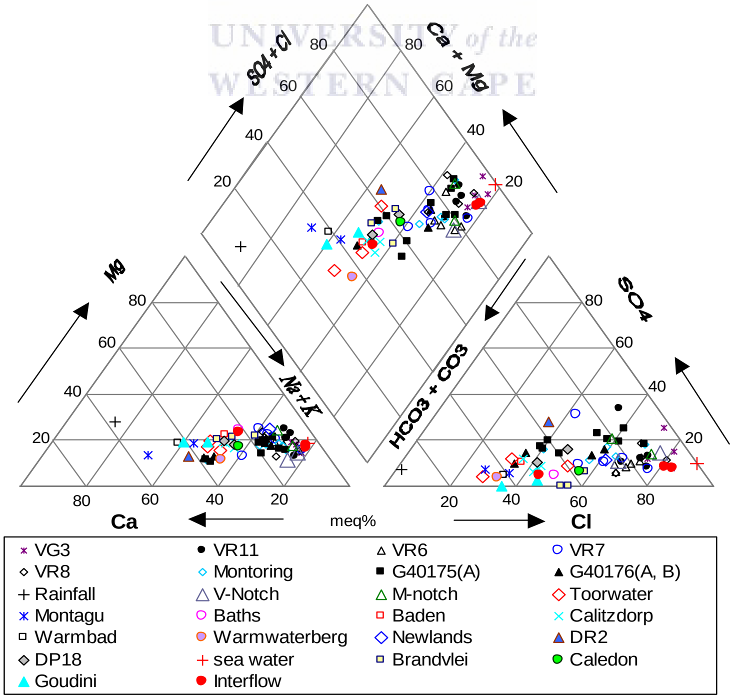

Figure 3.8: Piper diagram of TMG boreholes and hot springs (2005)

3.8.2 Isotope analysis of deep borehole and hot springs

The occurrence of thermal springs in the TMG has been discussed and data on them presented earlier in section 3.6. During this study water samples were taken from 7 of these thermal springs for chemical and isotopic analyses. Two borehole samples, one from the deep well in Oudtshoorn (DAGEOS project) and the other from a relatively shallow well near the Brandvlei spring source were also analysed for isotopes. Table 3.6 is the results of the isotope analysis.

Table 3.6: Results of isotope analysis of TMG hot springs and boreholes

Location	Date	Geology	z (m)	d^{18}O (‰SMOW)	d^{2}H (‰SMOW)	TU ± 0.2	^{14}C (pMC)	±	^{13}C (PDB)
Caledon	18/6/2008	Peninsula	360	-6.00	-29.5	0.2	44.6	2.0	-17.16
Avalon (Montagu)	18/6/2008	Nardouw	280	-7.15	-37.4	0.5	50.9	2.1	-12.48
Warmwaterberg	20/6/2008	Nardouw	500	-7.49	-43.1	0.0	9.3	1.6	-11.87
Brandvlei	18/6/2008	Nardouw	220	-6.17	-35.3	0.5	64.4	2.2	-14.67
Brandvlei BH	18/6/2008	Nardouw	225	-6.23	-35.3	0.5			
The Baths (Citrusdal)	18/6/2008	Peninsula	250	-5.33	-25.7	0.0	72.0	2.3	-15.84
Baden	18/6/2008	Nardouw	280	-7.12	-38.8	0.0	62.9	2.2	-15.86
Goudini	18/6/2008	Peninsula	290	-4.96	-24.7	0.7	79.0	2.4	-14.67
Oudtshoorn BH	5/11/2008	Peninsula		-7.25	-38.6		3.0	1.6	-13.23

The hydrochemical analyses of the hot springs are plotted on a piper diagram shown in figure 3.9. The borehole at Brandvlei is believed to be tapping the same hydrothermal source having similar temperature and chemistry. The hydrochemical analysis is presented in Appendix 1. The waters are of the type Na-Ca-Cl-HCO_3 but could be generally referred to as Na-Cl type waters. The low tritium content indicates that the water in all the springs (except perhaps Goudini) contains little or no recent (post 1952) water. The Oudtshoorn borehole water can be inferred to be older than the hot springs having ^{14}C value of 3.0 pMC compared to the higher values obtained for the hot springs. The ^{14}C contents of 62-79 pmC for Baden, Brandvlei, The Baths and Goudini springs are interpreted to represent shorter turnover times. Caledon and Montagu have lower ^{14}C content (44.6 and 50.9 pmC respectively) which represents much longer turnover times. The ^{14}C content of 9.3 pmC for the Warmwaterberg spring represents a very long turnover time of tens of thousands of years.

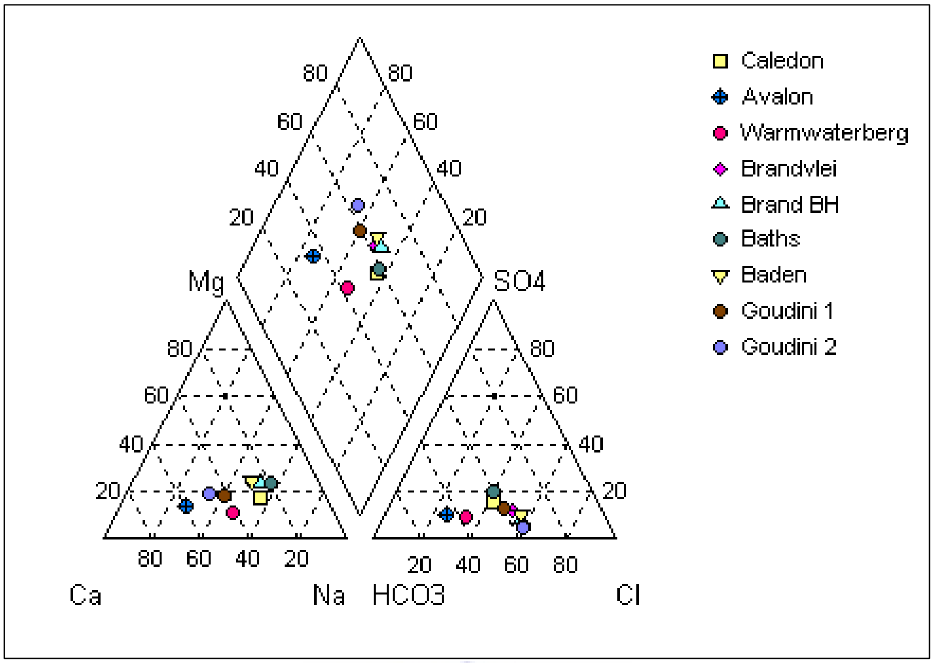

Figure 3.9: Piper diagram of TMG Hot Springs (2008).

3.8.3 Problems associated with TMG groundwater

The major problem that has been reported in the past with TMG groundwater comes from its acidic nature. The low pH, softness and also its poor buffering capacity results in the water being aggressive which tends to attack pump parts. Care must be taken in selecting materials for borehole construction (screens and casings), piping and reservoirs. Corrosion of pump parts, pipes and reservoirs can have substantial financial implications as well as affect water quality in the long run. Stainless steel pumps and PVC casings and screens, pipes and reservoirs are recommended for use with TMG groundwater. The problem of high Fe concentration affects the taste of the water and stains containers and laundry. It could also cause the rapid rust of pump parts if the right materials are not used. The major problem however, with high Fe concentration in groundwater is the formation of iron bacteria which together with other bacteria can combine to clog pump inlets and well screens. The coastal aquifers of the TMG are particularly susceptible to seawater intrusion and sea spray. This has been reported in Struisbaai by Weaver *et al* (1999).

CHAPTER 4 GROUNDWATER FLOW DYNAMICS IN THE TMG

The flow of groundwater in the TMG is a complex process involving flow through weathered rock formation, a network of fractures, faults and bedding planes. The flow circulation involves local shallow circulation and regional deep circulation from the recharge areas to the discharge points. Recharge to the TMG aquifer system is generally via the 37,000 km^2 of outcrop. Groundwater flow is through varying depths of the approximately 4,000 m (deepest section) thick sequence of highly indurated quartz arenite and minor shale layers. TMG discharge occurs in the intermontane valleys through stream channels, mid and lower slopes of hills by spring discharges and at the coastline to the oceans as well as borehole abstractions of point discharges.

4.1 Aquifer Recharge to the TMG

Assessment of groundwater recharge is a big challenge yet it is widely accepted as a key to determining the sustainable yield of aquifers. It is even more challenging in arid and semi-arid environments where the need for reliable estimates of groundwater recharge is greatest. In these environments recharge rates are generally low compared to annual precipitation or evapotranspiration. Recharge to groundwater may occur naturally from precipitation, rivers, canals and lakes and as a man-induced phenomenon via such activities as irrigation and urbanization with irrigation losses frequently providing a contribution which exceeds that from rainfall (Lerner *et al*, 1990). The principal types of recharge are the direct or local (diffused) and indirect or localized recharge. Direct recharge occurs when water is added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone. Indirect recharge results from percolation to the water table following runoff and localization in joints and fractures, as ponding in low-lying areas and lakes or through the beds of surface watercourses (Lerner *et al*, 1990). Recharge is arguably the most difficult hydrologic parameter to quantify with confidence (NRC, 2004).

4.1.1 The Conceptual recharge model

The key elements controlling recharge to any aquifer system such as the TMG can be illustrated by the model shown in Figure 4.1. It shows the various components and mechanisms involved in the recharge processes from the primary source of precipitation to the saturated zone where it becomes recharge to the aquifer. The figure was modified after Lloyd (1986).

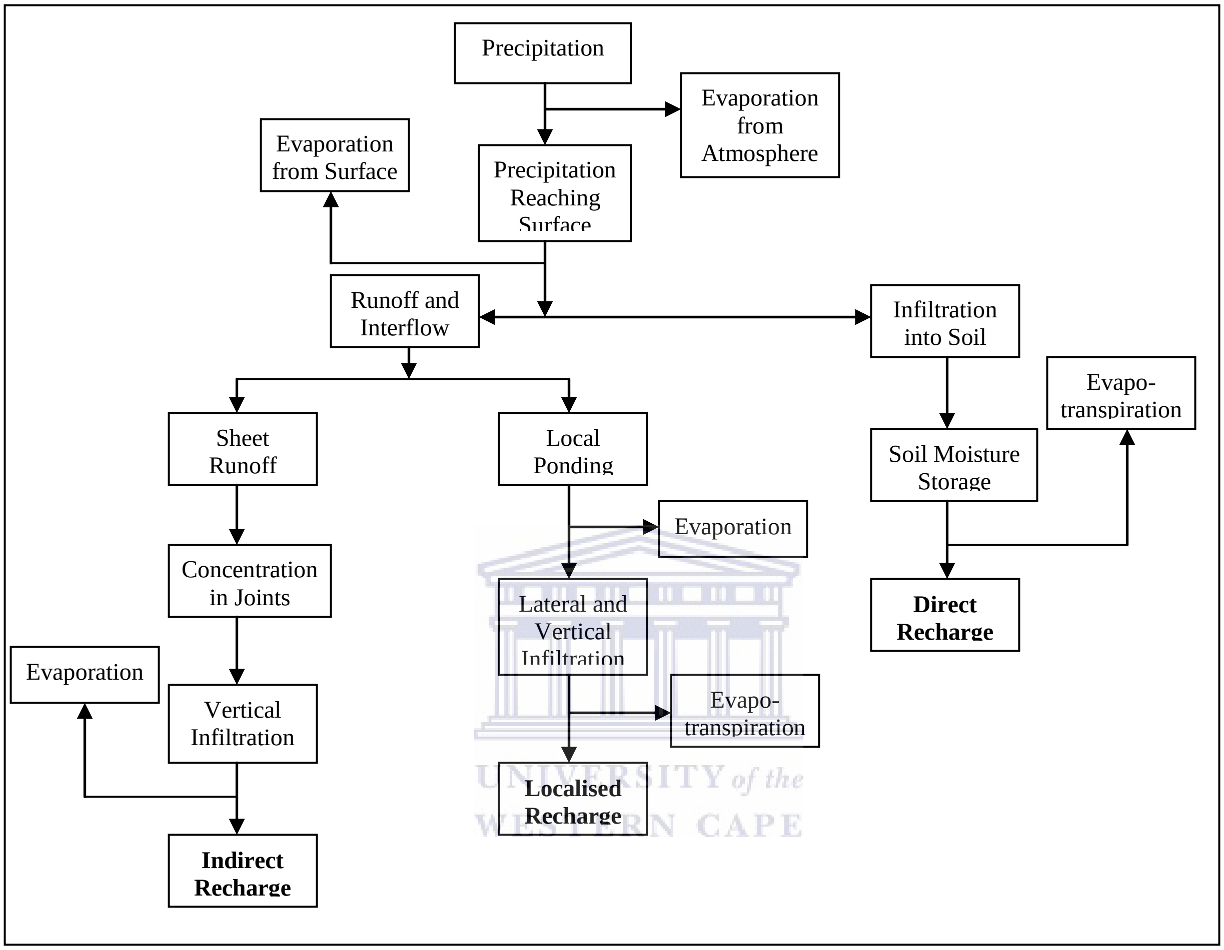

Figure 4.1: The various processes involved in recharge

4.1.2 Recharge Mechanisms

Recharge may be classified in different forms according to Beekman *et al* (1990) by:

- Origin of water (direct or indirect percolation of precipitation to the water table).
- Flow mechanism through the unsaturated zone (piston or preferential flow).
- Area of influence (point, line or areal source)
- Time scale during which it occurs (for both episodic and perennial recharge).

Although these mechanisms are reasonably well known, deficiencies are evident in quantifying the various elements. Problems affecting the estimation of direct recharge include inhomogenous properties of the unsaturated zone as well as the complex manner in which volumetric water content and flow mechanisms vary in the zone of aeration. The irregular occurrence of preferred pathways in even relatively homogenous material is an added complication for recharge estimation as well as problems arising from process space and time variability which is quite common to arid and semi-arid areas such as the Southern African region. The differences in sources and processes of groundwater recharge will mean that the applicability of available estimation techniques will also vary. It is therefore evident that quantification of groundwater recharge is fraught with problems of varying magnitude and hence substantial uncertainties. It is therefore prudent to apply and compare results from a number of independent methods in order to reduce some of these uncertainties.

4.1.3 Spatial and temporal variability of recharge

The major causes of variations in groundwater recharge with respect to time and in space are the temporal variations in precipitation, spatial variability in soil characteristics, vegetation, landuse and topography. The choice of methods in estimating recharge will therefore depend on their applicability in terms of space and time scales. Some methods are applicable over an area for long time periods, while others are intended for short time periods only. The factors that influence the choice of time scales are generally the study objectives, i.e. size and level of study. Other factors may include degree of aridity, resource exploitation and quantity of data available (Lerner *et al*, 1990). The time scales include instantaneous, event, seasonal and annual scales as well as historical averages. Spatial scales will include local, catchment or basin, zonal and regional scales. In particular, arid and semi-arid zone precipitation is characterized by high interannual variability resulting in very variable processes over a long time scale. This in turn can lead to considerable recharge estimation problems if long-term values are required with only short-period data available. Thus understanding the impact of environmental change, including natural vegetation change, human landuse changes, and climate variability on recharge will be essential to understanding how recharge rates may change with time (Hogan *et al*, 2004).

In the TMG area, like all arid and semi-arid regions, coupled with the fractured rock system recharge is driven by single or multiple events and not annual averages. Most of TMG outcrop areas occur on topographic highs with steep slopes, little or no soil cover and sparse vegetation.

In such areas recharge generally occurs by direct infiltration through joints and fractures (preferred pathways) and subsequent percolation to the water table during rainfall events. A lot of infiltrating water on topographic highs eventually seeps out as interflow (Fig. 4.2 and 4.3) through the bedding planes and joints before they can reach the water table. This explains the flowing of water from high rocky hills several days after rain events, a feature very common in the TMG area, feeding the many rivers and streams along the valleys. The complex nature of the fracture system coupled with the nature of fractures in terms of density, extent, orientation and connectivity makes even more difficult the determination of recharge.

Figure 4.2: Interflow in fractured rocks

Figure 4.3: Interflow in bedding planes

4.1.4 Selection of Recharge methods

There are several methods available for quantifying recharge and selection of an appropriate method or methods will depend largely on the dominant mechanism(s) prevailing in the region. In addition to the controlling recharge mechanisms other factors that will inform the selection of an appropriate method include availability of data, expertise and the overall cost involved in the process. The goal of the study determines the space and time scales of the recharge estimates (Scanlon *et al*, 2002), either for a water resource evaluation in which case information on recharge over large spatial scale and on decadal time scale is essential or for the evaluation of aquifer vulnerability to contamination, which requires detailed information on spatial variability and preferential flow. Methods based on unsaturated zone data and models provide estimates of potential recharge, whereas those based on groundwater data generally provide estimates of actual recharge (Scanlon *et al*, 2002, Xu & Beekman, 2003).

4.1.4.1 Hydrostratigraphic regions of the TMG

On the basis of the understanding that regions with similar sequences of rocks which have undergone similar geological history and are located in similar climatic zones will have more or less the same hydrogeological character, Wu (2005) identified 19 hydrogeological units within the TMG coverage area of 248 000 km^2. In a more detailed study of the historical development of the Cape Fold Belt and analysis of flow characteristics and storage within the TMG, Lin (2008) divided the TMG into 15 hydrogeological units according to the elements of the hydrodynamic system and boundary conditions of groundwater storage and flow within the TMG aquifer system. In this study the TMG area was subdivided into 14 hydrostratigraphic units based on hydrology, geology, soils distribution, vegetation and landuse patterns as shown in figure 4.4.

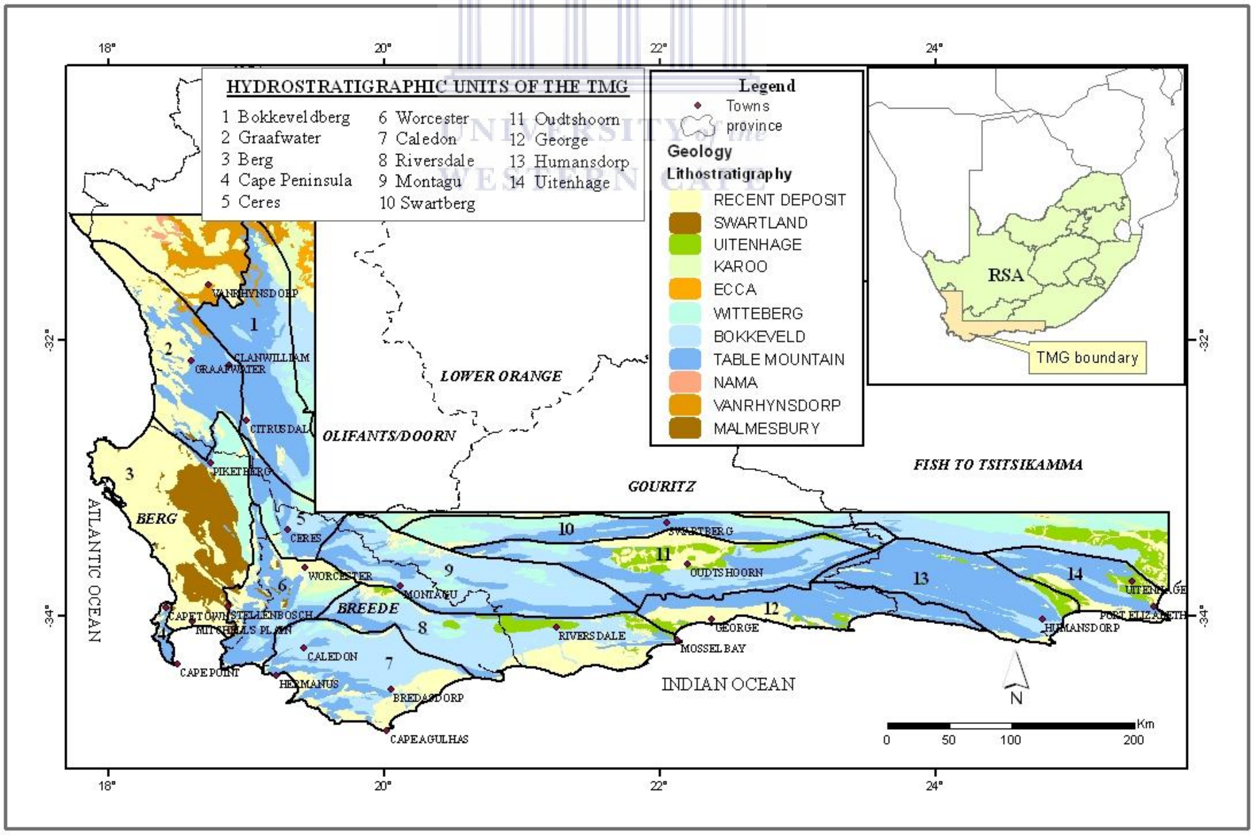

Figure 4.4: Hydrostratigraphic units of the TMG area

The reclassification is similar to Lin’s (2008) classification but with a few modifications defined by vegetation and soil distributions. The importance of the vegetation is due to their dependence or otherwise on the aquifers in the area. The understanding of these hydrostratigraphic units form the basis of a right conceptual hydrogeological model before any preliminary evaluation of recharge amounts could be determined. This is because it has been known that regions with similar climatic, geological and soil conditions as well as vegetation distribution also have similar ratios of recharge (Lerner *et al*, 1990).

4.1.4.2 Commonly used recharge methods in Southern Africa

A study of the available literature details a number of recharge methods in use in Southern Africa which are also applicable to arid and semi-arid regions elsewhere. They may be classified into zones of occurrence (hydrogeological and hydrologic zones) or process of occurrence (physical and tracer approaches). Extensive literature is available on the details of these and other methods by notable authors such as Lerner *et al*, 1990; Bredenkamp *et al*, 1995; Beekman *et al*, 1999; Scanlon *et al*, 2002; Kinzelbach *et al*, 2002; Xu and Beekman (eds), 2003 *etc*. A summary of these methods are given in Table 4.1 (adopted from Xu and Beekman, 2003).

A brief description of the principles, limitations and references is given for each method. Methods applied to surface water and the unsaturated zone estimate the potential recharge, whereas methods applied to the saturated zone estimate the actual recharge. Scanlon *et al*. (2002) and Xu and Beekman (2003) presented a comprehensive review on choosing the appropriate technique for quantifying groundwater recharge, including the applicable space and time scales, the range of recharge rates that have been estimated with each method, the reliability of the estimates, and important factors that promote or limit the use of the various methods.

Methods that have great potential to forecast recharge are those which have established relationships between rainfall, abstraction and water level fluctuations, such as the CRD, EARTH, Auto Regression Moving Averages and empirical methods. Critical in reliable forecasting of recharge is the accuracy of forecasting rainfall in terms of frequency of events, quantity and intensity. Note that the accuracy of forecasting recharge is further complicated by the non-linearity of groundwater resources in their response to rainfall (Xu and Beekman, 2003).

Table 4.1: Recharge estimation methods commonly used in (semi-) arid Southern Africa (modified from Xu and Beekman, 2003)

Zone	Approach	Method	Principle	Limitation	Refs
Surface Water	Physical	**HS**	Stream hydrograph separation: outflow, evapotranspiration and abstraction balances recharge	Ephemeral rivers	10
		CWB	Recharge derived from difference in flow upstream and downstream accounting for evapotranspiration, inflow and outflow and channel storage change	Inaccurate flow measurements	5
		WM	Numerical rainfall-runoff modeling; recharge estimated as a residual term	Ephemeral rivers	6
Unsaturated[1]	Physical	**Lysimeter**	Drainage proportional to moisture flux / recharge	Many estimations needed; not applicable in hard rock	2
		UFM	Unsaturated flow simulation e.g. by using numerical solutions to Richards equation	Poorly known relationship between hydraulic conductivity -moisture content	2, 5
		ZFP	Soil moisture storage changes below ZFP (zero vertical hydraulic gradient) proportional to moisture flux / recharge	Subsurface heterogeneity; periods of high infiltration	2, 3, 7
	Tracer	**CMB**	CMB – Profiling: drainage inversely proportional to Cl in pore water	Long-term atmospheric deposition unknown	1, 2, 3, 7
		Historical	Vertical distribution of tracer as a result of activities in the past (^{3}H, ^{36}Cl)	Poorly known porosity; Present ^{3}H levels almost undetectable,	1, 2, 3, 7
Saturated - Unsaturated	Physical	**CRD**	Water level response from recharge proportional to cumulative rainfall departure	Deep (multi-layer) aquifer; sensitive to specific yield (S_y)	2, 9
		EARTH	Lumped distributed model simulating water level fluctuations by coupling climatic, soil moisture and groundwater level data	11 parameters required. Poorly known S_y	3, 4
		WTF	Water level response proportional to recharge/discharge	In/outflow and S_y usually unknown	2
	Tracer	**CMB**	Amount of Cl into the system balanced by amount of Cl out of the system for negligible surface runoff/runon.	Long-term atmospheric deposition unknown. Cl recycling in biosphere unknown	1, 2, 3, 7
Saturated	Physical	**GM**	Recharge inversely derived from numerical modeling groundwater flow and calibrating on hydraulic heads / groundwater ages	Time consuming; poorly known transmissivity; sensitive to boundary conditions	2, 3
		SVF	Water balance over time based on averaged groundwater levels from monitoring boreholes	Flow-through region; multi-layered aquifers	2
		EV-SF	Water balance at catchment scale	Confined aquifer	2
	Tracer	**GD**	Age gradient derived from tracers, inversely proportional to recharge; Recharge unconfined aquifer based on vertical age gradient (^{3}H, CFCs, ^{3}H/^{3}He). Recharge confined aquifer based on horizontal age gradient (^{14}C)	^{14}C, ^{3}H/^{3}He, CFC: poorly known porosity / correction for dead carbon contribution	1, 7, 8

HS:	Hydrograph Separation – Baseflow	**EARTH**:	Extended model for Aquifer Recharge and Moisture Transport
CWB:	Channel Water Budget		
WM:	Watershed Modelling	**WTF**:	Water Table Fluctuation
UFM:	Unsaturated Flow Modelling	**GM**:	Groundwater modelling
ZFP:	Zero Flux Plane	**SVF**:	Saturated Volume Fluctuation
CMB:	Chloride Mass Balance	**EV-SF**:	Equal Volume - Spring Flow
CRD:	Cumulative Rainfall Departure	**GD**:	Groundwater Dating

1 Beekman et al., 1996	4 Lee and Gehrels, 1997	7 Selaolo, 1998	10 Xu et al., 2002
2 Bredenkamp et al., 1995	5 Lerner et al., 1990	8 Weaver & Talma, 1999	
3 Gieske, 1992	6 Sami & Hughes, 1996	9 Xu & van Tonder, 2001	

4.1.4.3 Recharge forecasting

The onset of climate change brings with it the prospects of diminishing fresh water resources in arid and semi-arid regions by way of increasing temperatures and reduction in precipitation. This has made forecasting of groundwater recharge an important feature in groundwater management. The different scenarios that are employed in climate models are used to predict changes in long-term precipitation patterns across the different regions. Changes in long-term precipitation patterns affect the long-term average groundwater recharge, which is equivalent to the renewable groundwater resources and hence the sustainable use of groundwater. The methods that have great potential to forecast recharge are those that have established relationships between rainfall, abstraction and water level fluctuations, such as CRD, EARTH, Auto Regression Moving Averages and empirical methods (Beekman & Xu, 2002). There is still a great deal of uncertainty in forecasting rainfall as a result of indirect impacts by GHG emissions. This uncertainty particularly in terms of frequency and intensity of rainfall makes recharge forecasting even more uncertain. An added complication is the non-linearity of groundwater levels response to rainfall. Nevertheless, forecasting of recharge should still be regarded as an important step for the sustainable use of groundwater resources as long as the uncertainties are recognized.

4.1.5 Recharge Estimation in the TMG

Results from the several recharge studies conducted in the TMG area over the years by different individuals and groups of people using different methods indicated varying estimates in the range of 1% to 55% of MAP. Methods used included CMB, SVF, CRD, EARTH, Base Flow, Isotopes, Water Balance and GIS. Wide variations in estimates ranged between 165 and 2020 mm per annum from these methods however, it has been accepted that the scale of the recharge study often dictates the most appropriate methods to be used to determine aquifer recharge. Concerns were raised for review of recharge estimates in the Kammanassie area due to the continual decline of groundwater levels in the Vermaaks River Wellfield from 1994. The recharge estimate of 17% of MAP in the Wellfield was adjusted downwards several times to arrest the situation. Recently there were calls by managers to researchers for more realistic estimates of recharge in the Kammanassie area. This led to the study, “Groundwater recharge estimation of Table Mountain Group aquifer systems with case studies,” and the publication of the report on the project in 2007. A comprehensive review and analysis of four methods namely, CMB, CWD-CRD, spring flow and water balance, were evaluated and integrated resulting in a recommended recharge range of 1.63% - 4.75% of MAP for the Kammanassie area (Xu et al. 2007). The major factors limiting the accuracy of these recharge estimation methods were identified as the accurate measurements of the recharge area and aquifer storativity among other factors. These and other factors still present potential errors in recharge estimation especially for a fractured rock aquifer like the TMG. The results ranged from 0.2% to 12% of MAP. The upper range of values were derived from integrated approach such as water balance methods while the lower range of values were obtained from methods such as the CMB, CRD and RIB. For a given study area, the recharge rate is recharge-area dependent for the CMB mixing model and regression of Cumulative Flow (CF) methods, while the CWD-CRD method is dependent on the storativity of the aquifer. Errors would therefore depend on how accurate the recharge area and storativity values are obtained. Recharge rates are less than 5% of precipitation in contrast to the 15%-20% and over proposed by earlier researchers. The recharge rate ranges between 0.38%-2.04% and 0.01%-4.23% from the two-component and three-component models of the CMB respectively. The results indicate that the recharge rate varies from 0.24% to 7.56% of the MAP using a storativity of between 0.0001 and 0.001 with the CWD-CRD method, but the average recharge rate from RIB method is 2.28% of MAP against storativity of 0.001 from 1994 to 2003. The average recharge rate was 5.38% of MAP or 48.67 mm, which equals to 3.88% of total precipitation of 1256 mm under storativity of 0.001 in considering impact of preceding rainfall in the *G40171* monitoring borehole from 1998 to 2001. The spatial variation of recharge rates are in a non-linear positive relationship with the MAP. Most high recharge percentages are related to rainfall of 300 mm.a^{-1} to 1100 mm.a^{-1}. The recharge in terms of percentage of rainfall is lower if precipitation is greater than 1100 mm.a^{-1} or less than 300 mm.a^{-1}. The recharge rate is constrained by fracture characteristics but not by infiltration rate in bulk rainfall or snowmelt rate (Xu et al., 2007). Recharge estimation methods have their uncertainties and inaccuracies arising from spatial and temporal variability in processes and parameter estimations, measurement errors and validity of assumptions. However, Xu et al. (2007) concluded that the following methods have been used in the study area with much certainty based on their reliability in space and time scales in the sub-region spanning a period of three decades: the Chloride Mass Balance (CMB), Cumulative Rainfall Departure (CRD), Rainfall Infiltration Breakthrough (RIB), Water Balance (WB) and Regression of Spring Flux.

In this study a regional estimation of recharge was carried out using a water balance approach with GIS methodology due to the extent of the TMG aquifer system and more so to complement the extensive work done by Xu et al (2007) in the area.

4.1.6 Regional Water Balance in the TMG

The evaluation of a sustainable yield for the TMG regional aquifer is the broad objective of this study for which a regional estimate of recharge is vital to this goal considering the arguments raised earlier on in the first chapter of this study. The complex structure of the TMG fractured aquifer system makes an exercise such as a regional recharge evaluation a more complicated task. It is important to understand the processes that may influence groundwater recharge which may be observed by water level rise in wells. Groundwater recharge may occur where the aquifer is unconfined in an outcrop or if overlain by sediments. Water levels in unconfined aquifers rise when a wetting front generated by recharge from rainfall percolates downwards and reaches the water table or by lateral transmission of a pressure pulse generated from up-gradient recharge. Conversely the water level may fall if groundwater is removed from the system by artificial or natural discharge through abstraction, evapotranspiration or down-gradient flow. For a confined aquifer, a rise in piezometric level is attributed to the transmission of upstream flow in response to a potential gradient. A decrease in hydraulic head may be generated by groundwater extraction. In its general form, the groundwater balance equation for both unconfined and confined aquifers is:

$$\text{Inflow} - \text{Outflow} = \text{Change in Storage} \qquad (4.1)$$

Changes in groundwater storage are measured by fluctuations in the water table, or fluctuations in hydraulic head for a confined aquifer. Minor seasonal fluctuations about the long-term level may occur in response to climatic or man-induced influences. The time delay from rainfall infiltration to water table response is dependent on the magnitude and intensity of the rainfall event, vegetation cover, vertical permeability and porosity of the formation and the depth to water table. As the depth to water table increases and/or permeability of the formation decreases, the response to individual recharge events may not be distinguishable because of the considerable residence time in the vadose zone. A sustained rise or fall in the water table elevation may reflect climate change.

In the vadose zone the water balance equation may be expressed as:

Recharge = Rainfall – Runoff - Actual Evapotranspiration ± Change in Field Moisture Capacity of Soils or:

$$R_E(t) = P(t) - R(t) - E(t) \pm \Delta S(t) \qquad (4.2)$$

where $R_E(t)$ is groundwater recharge, $P(t)$ is precipitation, $E(t)$ is actual evapotranspiration, $R(t)$ is direct runoff and $\Delta S(t)$ is the change in volumetric moisture content in the soil. The (t) designates that the terms are dependent on time. Direct runoff will include surface runoff and interflow.

- Surface runoff is the precipitation that exceeds infiltration and moves across the land surface and enters a water body (stream, river or lake) or a wetland. Sometimes referred to as overland flow which occurs on an impervious surface or when the soils are fine textured or heavily compacted.
- Interflow occurs when precipitation enters the soil and moves laterally in the upper part of the vadose or unsaturated zone and directly enters a stream channel or other water body without having first emerged on the land surface in which case it is referred to as *throughflow*. It occurs when the deeper depth of the vadose zone is completely saturated with water or less permeable. It is usually above the region where baseflow takes place.

Monthly rainfall records were obtained from the South Africa Weather Service and Runoff and Evaporation records from the WR2005 project. If one assumes that change in storage is negligible between the subsequent years, recharge can be calculated from equation (4.2).

4.1.6.1 Components of the water balance model

The key to any successful recharge estimation study is the objective of the study (Simmers, 1987). In this study a regional estimation of recharge is envisaged, hence an assembly of reliable local and site specific data and information coupled with remote sensing and GIS techniques offer a good perspective of a reliable recharge estimates over an extended area. There are several factors that influence recharge particularly in a semi-arid area like South Africa. The various processes involved in the recharge estimation are outlined below.

4.1.6.1.1 Precipitation

Rainfall records within the study area were obtained from the WR2005 project (Middleton & Bailey, 2008). These records were obtained from the Water Resources Information Management System (WRIMS) from the DWAF. Rainfall stations with relevant data such as the mean annual precipitation (MAP), opening and closing years and number of years with data as well as the geographic positions of the stations can be assessed. In the WR2005 project, rainfall stations were screened and selected to represent the several rainfall zones. In the WR90 project, records from 1920 to 1989 were considered and in the WR2005 additional records up to 2004 were used including additional stations previously not considered in the WR90 project. In this study, a number of rainfall stations were selected based on their locations and records with respect to the TMG. Additional records were obtained from the South African Weather Service (SAWS) up to the end of 2007 for detailed analysis especially the trend analysis described in chapter 5. In the WR2005, rainfall records from quaternary catchments were grouped into rainfall zones from which representative MAPs were used to obtain rainfall grids. Contours were then developed from the grids and rasterized in GIS. Figure 4.5 is a raster map of the MAP in the study area.

4.1.6.1.2 Streamflow

Data on streamflow records were obtained from the WR2005 database which was also obtained from DWAF. There are streamflow records for gauge stations and the generation of natural monthly flows for all catchments for the period of study, 1920-2004. Calibrated model parameters were extended to ungauged catchments based on similarities in geology, topography, soil type, natural vegetation and climate in order to generate natural flows for all catchments in the country. Records have been preprocessed for reliable analysis. The distribution of mean annual runoff (MAR) for the study area has been extracted from the national MAR map (figure 4.6). The records from the gauge stations are based on the concept that streamflow is a combination of surface runoff and baseflow. A digital recursive filter method is employed to separate the baseflow from the surface runoff which will also include interflow.

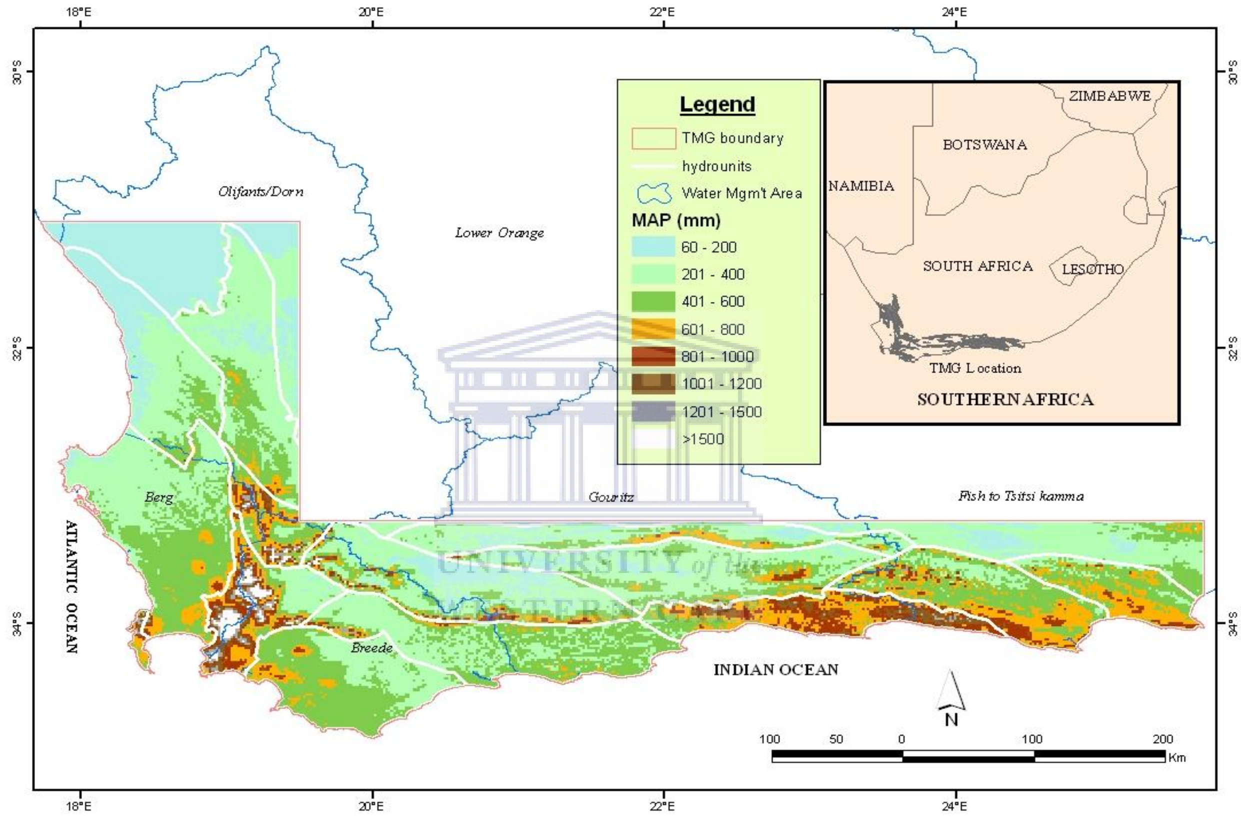

Figure 4.5: Distribution of precipitation in the TMG area

4.1.6.1.3 *Evapotranspiration*

Evapotranspiration (ET) is the sum of evaporation and plant transpiration from the earth’s land surface to the atmosphere. Evaporation accounts for the movement of water to the atmosphere from sources such as soil, canopy interception and water bodies. Transpiration accounts for the movement of water within the plant and the subsequent loss of water as vapor through its leaves. Evapotranspiration is an important part of the water balance equation.

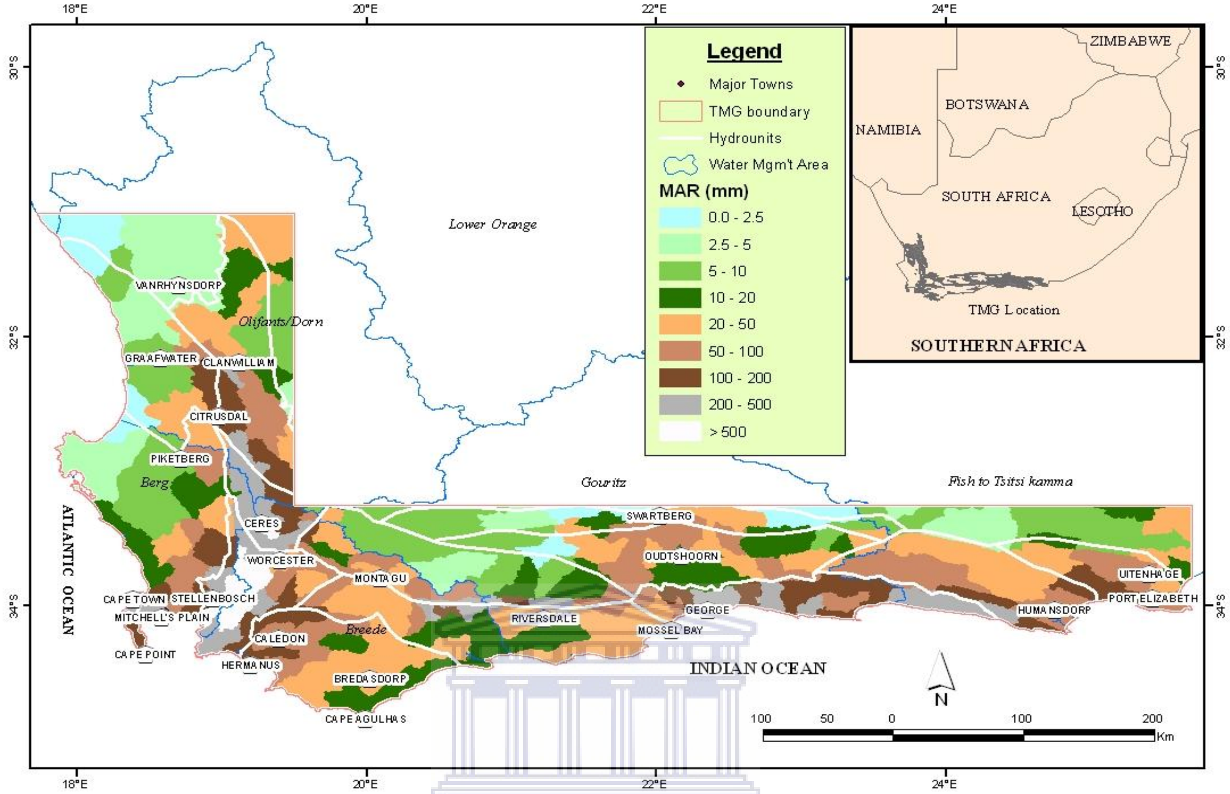

Figure 4.6: Distribution of mean annual runoff (MAR) within the TMG area.

Potential Evapotranspiration (PET) is the total amount of water that could be evaporated from the soil surface and transpired by the plant roots if there was sufficient water available. PET is usually measured indirectly from other climatic factors and expressed in terms of depth of water just like precipitation. Factors that affect evapotranspiration include the vegetation type, plant's growth stage, land use, solar radiation, humidity, temperature and wind. PET can be estimated using the following equation:

$$PET = ET * Pan\ factor * Crop\ factor \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4.3)$$

where *Pan factor* is the ratio of open water evaporation or catchment transpiration to Pan Evaporation. It varies with location and season. *Crop factor* is coefficient expressing the proportion of open water evaporation transpired by a crop under the same energy gradient, varying with stage of growth, plant type, plant density, sunlight, wind and soil conditions.

Pan Evaporation data from WR90 has been interpolated for each location based on data from major regional centers. Monthly pan evaporation data derived as a percentage of mean annual evaporation (MAE) is available for each evaporation zone in the database. The Pan factors for open water evaporation and catchment evapotranspiration and Crop factors for vegetation types in the TMG area are presented in Tables 4.2 and 4.3 respectively. The distribution of MAE and the vegetation types in the study area are shown in figures 4.7 and 4.8 respectively.

Table 4.2: Pan factors for open water evaporation and catchment evapotranspiration in TMG area.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Lake evaporation	0.81	0.82	0.83	0.84	0.88	0.88	0.88	0.87	0.85	0.83	0.81	0.81
Catchment Evapotranspiration	0.80	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.88	0.88	0.88

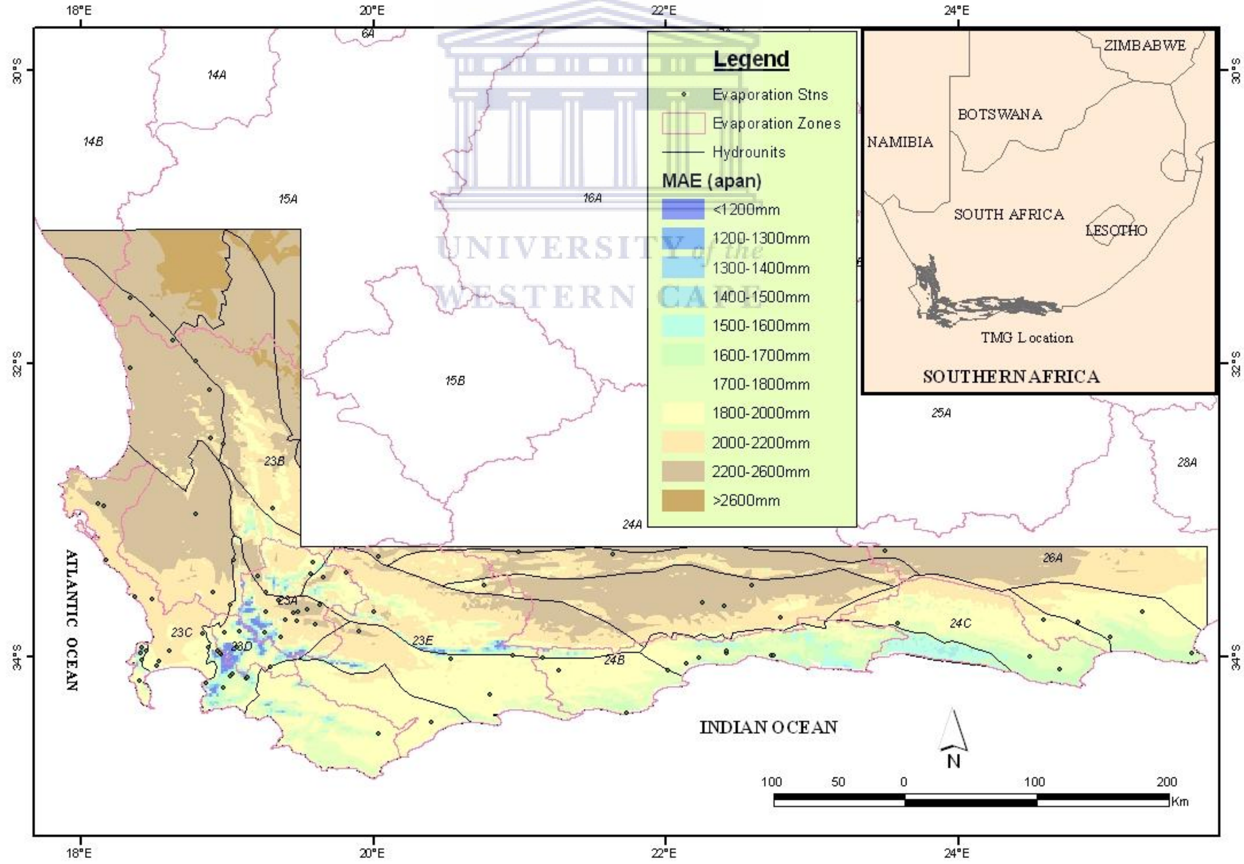

Figure 4.7: Mean annual evaporation (A-pan) in the study area.

Table 4.3: Crop factors for vegetation types found in the TMG area (Acocks classification).

Vegetation type	Crop factors											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Coastal Tropical Forest	0.67	0.69	0.75	0.75	0.75	0.74	0.69	0.61	0.56	0.40	0.51	0.60
Karoo and Karroid	0.41	0.46	0.50	0.50	0.50	0.48	0.46	0.37	0.25	0.20	0.22	0.33
False Karoo	0.36	0.45	0.50	0.50	0.50	0.46	0.36	0.26	0.21	0.20	0.20	0.27
Temperate and Transitional Forest and Scrub	0.58	0.61	0.61	0.61	0.60	0.60	0.57	0.46	0.36	0.29	0.36	0.48
Fynbos (Sclerpophylous Bush)	0.60	0.60	0.60	0.60	0.55	0.55	0.55	0.45	0.40	0.20	0.35	0.50
False Fynbos	0.55	0.55	0.55	0.55	0.55	0.50	0.50	0.40	0.35	0.20	0.35	0.50

NB: Applicable for A-pan data only.

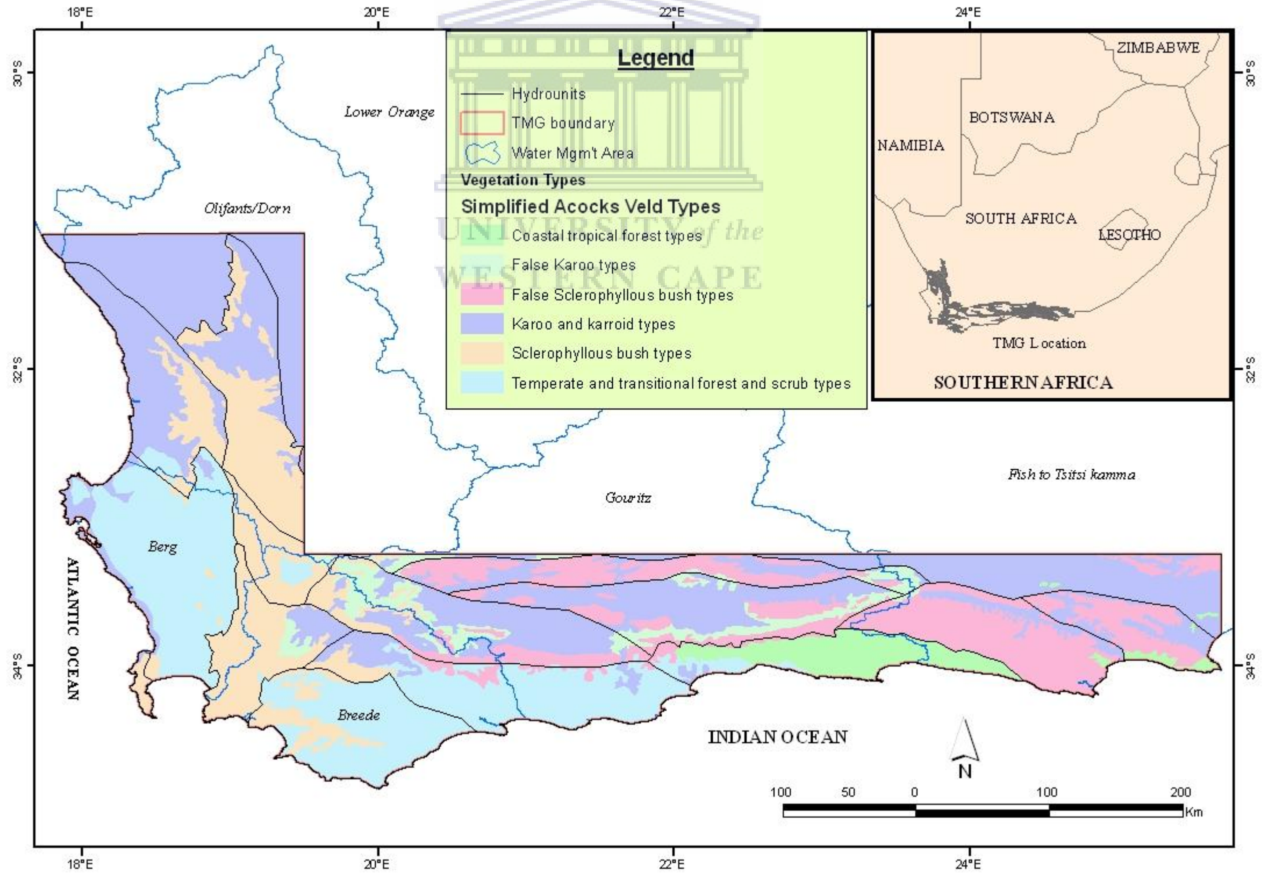

Figure 4.8: Vegetation types in the study area

Actual Evapotranspiration (AET) is the rate of evapotranspiration from a given area in time since water is not always readily available for the process. There are periods especially during summer times when plants and soil are not capable of moving water to the surface for evapotranspiration as fast as the atmosphere is able to do the evaporation leaving bare soils dry and plants wilting. AET in most instances be less than PET. There are ways in which the AET is calculated from the PET using the soil moisture extraction function or coefficient of evapotranspiration, *f*, which is based on some function of the current soil moisture content and the water holding capacity.

$$AET = f * PET \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4.4)$$

$$f = wc / wc^* \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.5)$$

where *f* is the function in which the ratio of evapotranspiration to potential evapotranspiration is proportional to the current moisture level (Dingman, 1994). *wc* is the current soil moisture and *wc** is the water holding capacity.

4.1.6.1.4 Recharge

The recharge distribution in the project area using the water balance approach is shown in figure 4.9 based on data derived from WR90 and WR2005 projects which were validated with recharge estimates from CMB and rainfall-recharge relationship. The scale used is 1 km x 1 km GIS grid. The high recharge areas are associated with high rainfall regions of the TMG outcrop areas. The recharge values range between 0 and 800 mm/a. The upper limit is about 35% MAP. The high values of recharge derived from the water balance model could be attributed to the fact that of the several factors that are considered to control recharge not all of them can be accurately mapped, determined or quantified. Increased levels of uncertainties are introduced into the model with the increasing number of parameters considered in the estimation process.

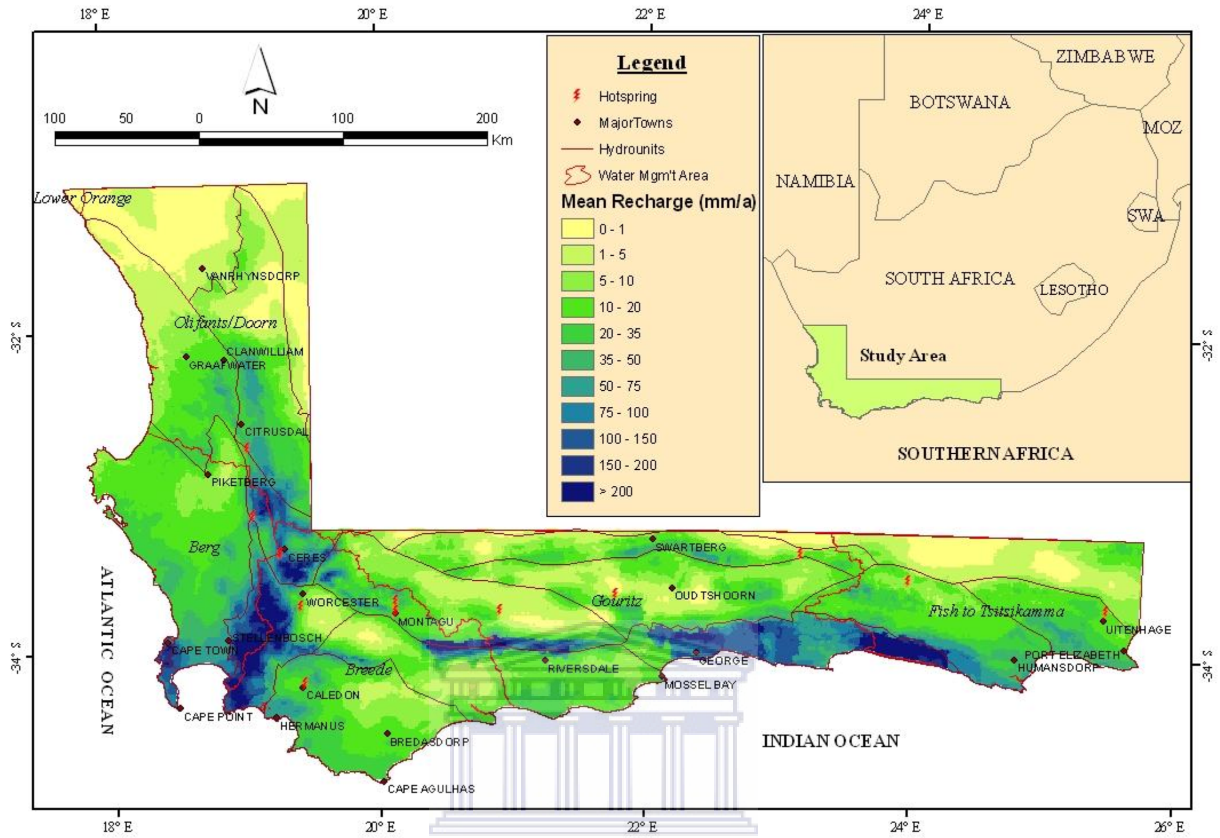

Figure 4.9: Mean annual recharge in the study area

4.2 Aquifer Discharges from the TMG

The determination of the sustainability of an aquifer system is an all inclusive process. In the twenty first century paradigm this will involve the design and management of aquifer inflows and outflows (both natural and artificial) that meet the development needs of current and future societies and also maintain ecological and environmental integrity. The historical development of the concept from aquifer yield to safe yield then sustainable pumping rates (incorporating the capture principle) and its expansion to sustainability to include dependable ecosystems and the environment has been discussed earlier in the literature review. Maimone (2004) pointed out that if sustainable development must be all-inclusive, the idea that there exists a single, number representing sustainable yield must be abandoned and it may not even be possible to completely address the full complexity of the concept of sustainability in many situations. Much can be gained, however, by an organized approach coupled with an adaptive management approach. Other important aspects include the spatial and temporal considerations, a conceptual water budget (groundwater and surface water), influence of boundaries (especially systems near water bodies), water supply and demand and stakeholder involvement. Discharges from the TMG regional aquifer include natural discharges and artificial discharges, the latter mainly due to abstractions through boreholes. The natural discharges occur through baseflow to streams and rivers, spring flows, evapotranspiration, leakage to adjacent aquifers and discharge to the ocean. The various components of the aquifer discharge are discussed in this section.

4.2.1 Natural discharges from the TMG aquifer

The major discharges from the TMG that occur naturally are discussed in this study. Some estimates made in the past are provided. Some other discharges that occur include flow into the sea and leakage to adjacent aquifers but without much information these are mentioned briefly. Major discharges with sufficient information include baseflow to streams and spring flows.

4.2.1.1 Baseflow in the TMG

Baseflow (Figure 4.10) is widely regarded as the upper limit of groundwater discharge to streamflow considering the contribution from interflow. A quantitative determination can be achieved from the study of the groundwater’s interaction with surface water bodies. The interaction is controlled by the position of the surface water body in relation to the groundwater level as well as the characteristics of the underlying beds. Baseflow is calculated as a function of the head difference between groundwater and surface water. When groundwater head exceeds surface water head, as can occur during low flow months, groundwater baseflow is generated, simulating effluent conditions (gaining stream). When surface water head exceeds groundwater head, as can occur during very wet months, influent conditions (losing stream) arise and transmission losses to bank storage or to the aquifer are simulated. In the TMG outcrop area, most of the streams flow along the incised valleys of the mountainous terrain. The interactions of groundwater with lakes, wetlands and estuaries are also recognised as important processes however, in the TMG, only the baseflow to streams in the outcrop area was considered in the analysis as the non-outcrop areas of TMG aquifers are considered deeply buried to have any interaction with streamflow. Using the digital recursive filtering method of baseflow separation,

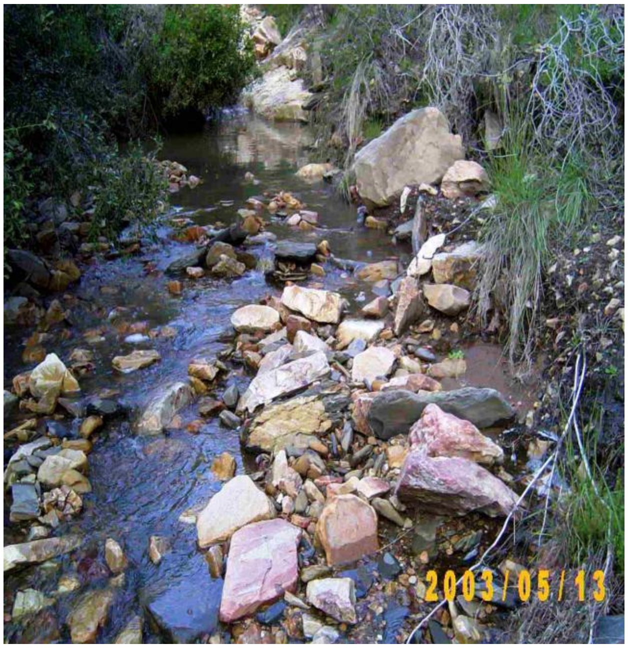
2003/05/13

Figure 4.10: Baseflow in the TMG

Jia (2007) estimated the total annual baseflow volume in the TMG outcrop area to be 1.08 x 10^9 $m^3.a^{-1}$. The National Water Act of South Africa makes flow requirement for preservation of aquatic ecosystem a priority. This is referred to as the Ecological Reserve or the In-stream flow requirement (IFR) for streams that are fed by artificial reservoirs such as dams. The IFR is released before water allocations are carried out for commercial water users. The IFR is determined by baseflow calculations from the stream hydrograph.

4.2.1.2 *Spring flow in the TMG*

Spring sources are a regular occurrence in and around the TMG area. The National Groundwater Database (NGDB) of the Department of Water Affairs records about 501 springs in the TMG area of which 103 are recognised as TMG-related springs according to their geographical position within the formation. Without sufficient information however, these 103 spring sources have not been classified into their occurrence types. Jia (2007) recorded the total combined yield of the 103 springs as 141 *l*/s or 4.45×10^6 $m^3.a^{-1}$. The much publicised 11 fault controlled hot springs of the TMG have been described in Table 3.2. They constitute a major natural discharge from the formation with a combined yield of approximately 355 *l*/s or 1.12×10^7 $m^3.a^{-1}$.

4.2.1.3 *Discharge to other water bodies*

There are discharges from the TMG to other water bodies that may not be accurately estimated due to their complexity. Leakages to adjacent aquifers are highly probable but difficult to measure due to the highly fractured nature of the TMG aquifers. With over 200 km of coastline in contact with the TMG formation there have been attempts to estimate discharge into the ocean from the TMG but there has been no documented study to quantify these estimates. Jia (2007) provided a figure of 3.17×10^6 m^3/yr as being the annual discharge from the TMG to the ocean.

Other important discharges from the TMG are those that support wetlands, swamps and riparian regions which are discussed later under *Groundwater Dependent Ecosystems* (GDEs).

4.2.2 Artificial discharges from TMG

The major discharge from the TMG attributed to human intervention is through borehole abstractions. There are numerous boreholes drilled within the formation over the years for different purposes such as monitoring water levels, core studies and water supply. Our concern here will be to try to assess abstractions for bulk water supply.

4.2.2.1 Borehole abstractions from TMG

The TMG formation was not seen as a potential for bulk water supply until early 2000 (Weaver *et al*., 2002). Earlier attempts to solicit funding to conduct studies in the region were not successful. However, a couple of earlier successful projects such as the Klein Karoo Rural Water Supply Scheme (KKRWSS) around 1989 and the Citrusdal Artesian Groundwater Exploration (CAGE) project in 1998 brought increased interest in TMG research. During the KKRWSS several boreholes were drilled of which about 18 were used as production boreholes. The scheme was designed to supply up to 4.7×10^6 $m^3.a^{-1}$ of groundwater to two purification plants at Dysselsdorp and Calitzdorp (figure 4.11), the Eastern and Western Sectors of the scheme respectively. The Eastern Sector of the Kammanassie Mountains near Dysselsdorp is fed by 13 boreholes of which the Vermaaks River Wellfield comprising 5 boreholes is the major supplier. The Western Sector is supplied by 5 boreholes at Calitzdorp. Water is supplied to end users from these two plants. Total abstraction from the scheme varies seasonally due to summer (high) and winter (low) demands. The total average abstraction from the scheme is approximately 1×10^6 $m^3.a^{-1}$ generated from a combined abstraction of 50 *l*/s during summer and 25 *l*/s during winter. Water levels however, dropped by an average of 30 m over 7 years indicating over abstraction (Jolly and Kotze, 2002). This will be further discussed under sustainable utilization of TMG aquifers as a case study in a later section.

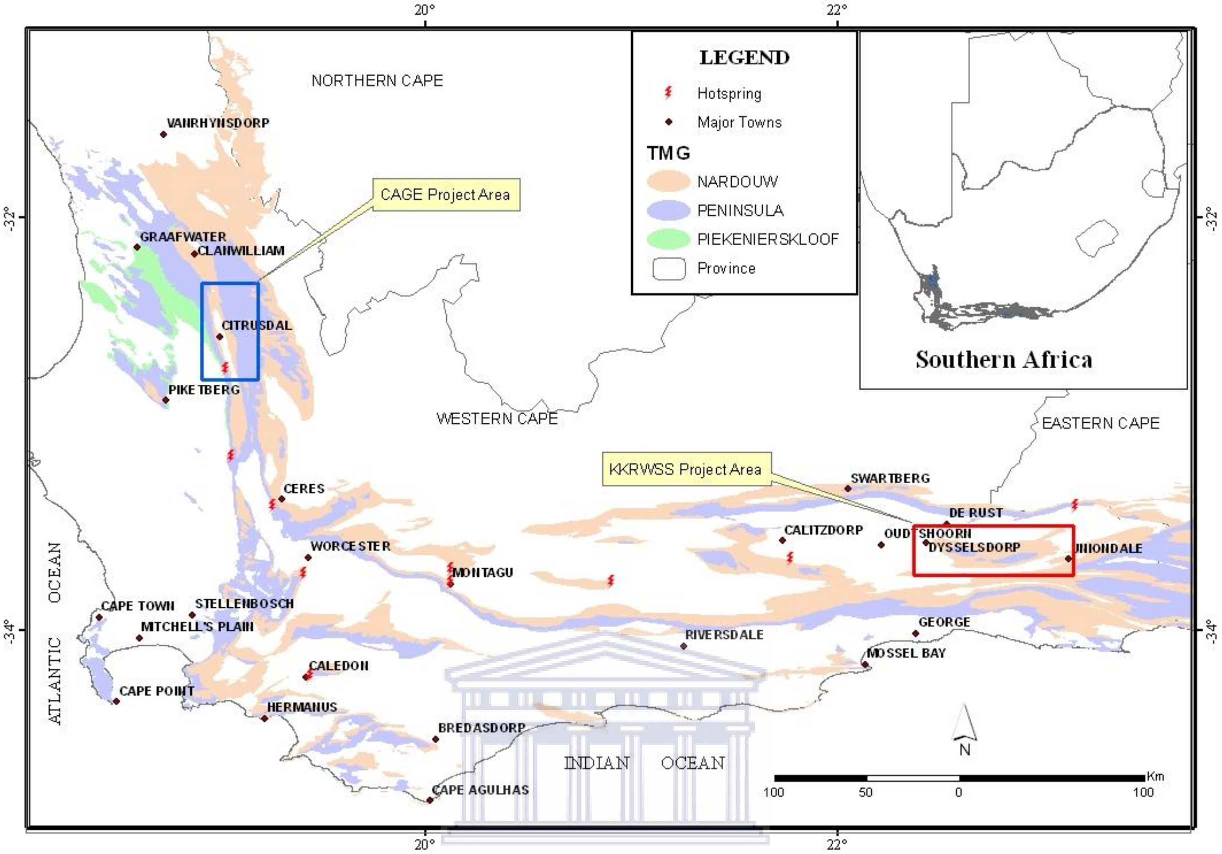

Figure 4.11: Location of KKRWSS and CAGE Project areas in the TMG

The CAGE project by Umvoto Africa in the Citrusdal area produced a number of deep boreholes (174-350 m) tapping the Peninsula formation of the TMG with high yields (up to 120 *l*/s) of good quality groundwater in 1998 (Hartnady^1 and Hay, 2002). Other high-yielding deep wells have been drilled in the Ceres area in the late 90's (Hartnady^2 and Hay, 2002). Several other borehole projects have since emerged within the TMG area including recently the Deep Artesian Groundwater Exploration for Oudtshoorn Supply (DAGEOS) project in 2008 by Umvoto Africa and the DWAE. A wellfield of shallow and deep wells was established for exploratory and water supply purposes. Six boreholes ranging in depth from 152 m to 715 m were drilled during the project from 2002 to 2007. The deep wells of 715 m (core drilling) and 608 m (percussion drilling) had artesian conditions. The recommended flow rate of the production well was 40 *l*/s (Hartnady, 2008). Figure 4.12 shows an artesian flow from a deep well during the DAGEOS project in Oudtshoorn.

Figure 4.12: Artesian flow from deep well (DAGEOS Project) at Oudtshoorn

(Courtesy, UMVOTO)

The Department of Water Affairs' NGDB holds data and information on the numerous boreholes scattered throughout the country even though these are mostly public boreholes. Private borehole records are difficult to obtain but those are generally shallow wells with minimal yields that may not seriously affect the groundwater balance. It will be difficult to know the combined abstraction rate of all these numerous boreholes but Jia (2007) estimated a combined yield of 189.71×10^6 $m^3.a^{-1}$ from the TMG in her resource evaluation research. It is obvious that in 2010 the figure will be well below current estimates. The ecological and environmental impacts of these abstractions are yet to be evaluated. The sustainable utilization of the TMG aquifer system must be given a serious look in the light of these and other major abstractions occurring within the formation.

4.2.3 Groundwater Dependent Ecosystems

Water is required by plants to grow by keeping their leaves turgid and to provide a medium for all the biochemical reactions that take place in the plant cells. During photosynthesis, a process where plants manufacture its own food, a large amount of water is lost through transpiration from the leaves when the stomata are opened to allow carbon dioxide in. The most common source of water for plants is rainfall but there is a class of vegetation that routinely uses groundwater to support growth and photosynthesis. This type of vegetation is referred to as groundwater dependent because the absence of groundwater will have a negative impact on its health and growth. The prolonged absence of groundwater from sites that previously had groundwater leads to plant death and ecosystem structure and function. Eamus (2009) defined groundwater dependent ecosystems (GDEs) as ecosystems whose current composition, structure and function are reliant on a supply of groundwater. This reliance might be expressed every day of the year, or only for a few months every few years, but the reliance becomes apparent when the supply of groundwater is removed for a sufficient length of time that changes in plant function (typically rates of water use decline first) are observable. All the GDEs may be classified into two types according to Eamus (2009):

- aquatic ecosystems which rely on the surface expression of groundwater, such as a river ecosystem where some portion of the dry-season baseflow may be derived from an adjacent groundwater body; temporary or permanent springs, seeps and surface wetlands wholly fed by groundwater. When groundwater availability declines, river flow is reduced and swamps, wetlands and springs may become dry, temporary or permanently.
- Terrestrial ecosystems which rely on the availability of groundwater below the surface but within the rooting depth of the vegetation.

Groundwater as defined above may include soil water and interflow from the unsaturated zone, which in the hydrogeological sense are not classified as groundwater. In South Africa, the term, *Aquifer Dependent Ecosystem* (ADE) was proposed to distinguish between water from the saturated zone and elsewhere. Colvin et al. (2007) defined ADEs as ecosystems which depend on groundwater in, or discharging from, an aquifer; where an aquifer is a saturated zone formation capable of releasing extractable amounts of water into a well penetrating the formation. They are often ecosystems which contrast with their surrounding environment as a result to their access to groundwater, often occurring at the transition of different ecosystems and representing an important ecologic and hydrologic interface. In arid and semi-arid areas of South Africa, they may form oasis, riparian corridors or wetland habitats that support a much more extensive surrounding environment and function as keystone ecosystems. They provide important ecological services and goods to communities. GDE and ADE are used interchangeably in this study.

4.2.3.1 Level of Dependency and Threats to GDEs

The level of dependency of GDEs according to Sigonyela (2006) may range from facultative to entire dependency. Facultative dependency derives from ecosystems that are either opportunistic, proportional or being highly dependent on groundwater. Highly dependent ecosystems are those that need large amounts of groundwater for both nutrients and water needs, but are also subject to some proportion of water from overland flow. Most wetlands (fens, marshes and swamps) belong to this category. Ecosystems that are proportionally dependent are those that use any moderate amounts of available water, either from groundwater or soil moisture. Changes in groundwater availability will have moderate to high impact on such GDEs. An example will be the *Hyporheic zone.* Opportunistic dependency is described as when ecosystems only use groundwater as a mere surrogate, and may not alter at all when groundwater availability is reduced. On the other hand, the entirely dependent ecosystems are those that depend fully on groundwater to exist such as the *in-aquifer* ecosystems (found in underground caves). These ecosystems will perish when groundwater becomes unavailable or polluted.

There are generally two main threats to ADEs; the first arises from land-use changes which are not directly linked to groundwater development. The development of land for commercial purposes and urbanization often result in removal of riparian forests while the drainage of wetlands and swamps for grazing or construction use represents a significant threat to these ADEs. While this threat results from active decision to remove these types of vegetation from a site the second threat is as a result of an unintended consequence of groundwater extraction. When groundwater is extracted at a rate exceeding recharge the water table drops. This eventually reduces the flow of groundwater into rivers, streams, wetlands, swamps and some spring flows, thereby causing these systems to become water stressed. The water table may also drop to depths exceeding the maximum rooting depths of some ADEs resulting in these vegetations becoming water stressed. This second threat is poorly understood and mostly ignored. The response of vegetation to reduced water availability, in this case groundwater, is incremental (Eamus, 2009). Initially, plants will show short-term adaptive responses, the most important of which is a reduced opening of the stomata on leaves. This occurs to reduce the amount of water required by the plant canopy, but it also reduces the rate of carbon fixation and hence growth is also reduced. If the decline in groundwater availability persists, the leave area index (LAI) of the site declines as trees lose their leaves in an effort to further reduce their water use and consequently growth is further reduced. This may further lead to the development of new species of seedlings adaptive to more arid environments. Methods to identify and measure GDEs are outlined in literature such as Eamus (2009) and Colvin *et al*. (2007) but are outside the scope of this study.

4.2.3.2 The Presence of GDEs in the TMG

Studies undertaken to address the presence of GDEs or ADEs in South Africa was done by Colvin et al. (2007) while specific studies were designed to address the issue within the TMG first by Fortuin (2004), then Sigonyela (2006) and further by Roets (2008). Colvin *et al*. (2007) identified springs and seeps from the TMG as the main source for sustaining ADEs existing in the area and called for strict adherence of regulations within the National Water Act (NWA) and the National Environmental Management Act (NEMA) to sustain ADEs under the principle of Integrated Water Resources Management (IWRM). Furtuin (2004) delineated areas of ecological importance within the TMG and Sigonyela (2006) identified the TMG discharge zones as the target areas for the vast GDEs made up of wetlands, baseflow to rivers, springs and estuaries. He recommended an ecosystem approach as an effective management strategy for the GDEs. Roets (2008) further delineated the areas of sensitive aquatic ecosystems within the quaternary catchments of the TMG aquifer area. He showed both the areas of high groundwater development potential and areas of high conservation value and sensitivity to groundwater use. Due to the nature of occurrence and depths of TMG aquifers GDEs are widely believed to be dependent on discharges from TMG other than groundwater from storage. This will include discharge to springs, wetlands, swamps, riparian zones, baseflow in rivers either directly or indirectly and extensive abstractions from groundwater could potentially reduce the availability of water to these ecosystems. Hence all the previous studies have called for management strategies that will critically assess each application for groundwater use with respect to their location and potential threat to sensitive ecosystems. Fortunately the NWA of South Africa makes provision for the *Reserve*, made up of basic human needs and ecological reserve before any consideration for water use licenses and this will ensure sustainability of groundwater resources without endangering ecological and environmental integrity.

4.3 Summary

Groundwater recharge is the inflow component to the groundwater balance and may take different forms from direct percolation of precipitation through the unsaturated zone or indirectly through preferential pathways of fractures and faults. Recharge may also be induced from adjacent water bodies such as a river channel, lake or dam and from adjacent aquifers. Groundwater recharge varies in time and space particularly in semi-arid and arid regions where rainfall is irregular and sporadic added to the inhomogeneous properties of the unsaturated zone. There are several recharge estimation methods and the selection of the applicable methods must be based on factors such as type of aquifer, data availability, expertise and the objective of study. For these and other reasons the quantification of groundwater recharge is fraught with problems of varying magnitude and substantial uncertainties. To reduce uncertainties and increase the reliability of recharge estimates results from a number of independent methods are applied and compared. In the TMG, fractured outcrops on topographic highs receive substantial recharge through preferred pathways of fracture networks in the rock mass.

The TMG area is subdivided into 14 hydrostratigraphic units based on hydrology, geology, soils distribution, vegetation and landuse pattern. The hydrostratigraphic units form the basis of the recharge distribution pattern in the study area. In the past, different methods of recharge estimates in the TMG have yielded results ranging from 1% to 55% of MAP however, Xu *et al*. (2007), have shown that the average recharge rate is between 1% and 5% of MAP. They also reported that in the TMG the following recharge estimation methods are more reliable; the Chloride Mass Balance (CMB), Cumulative Rainfall Departure (CRD) and Rainfall Infiltration Breakthrough (RIB), Water Balance (WB) and Regression of Spring Flux. The CMB method is dependent on the recharge area while the CRD and RIB methods depend on aquifer storativity. A regional water balance using GIS established that recharge to the TMG aquifers vary spatially from less than 1 mm.a^{-1} to over 200 mm.a^{-1} on the high elevation outcrops where rainfall values are usually high. The mean annual recharge range is 5% to 10% of MAP.

The outflow components from the TMG include natural and artificial discharges. Natural discharges comprise the numerous springs including the thermal springs, baseflow to streams and rivers, flow to the ocean and other reservoirs such as wetlands, marshes and estuaries. Most of these discharges are difficult to quantify and only crude estimates may be available. There are about 11 thermal springs identified within the TMG which are being utilized for water supply, irrigation and mostly recreation. The artificial discharges are easy to quantify especially for big schemes that are well managed however several private boreholes and dug wells may not be captured even though such point sources are not known to generate high amounts of abstractions. The TMG is known for its good quality freshwater and several groundwater schemes have emerged in the past to provide potable water to urban communities from the deep bowels of TMG sandstones. Baseflow from groundwater in the TMG to rivers and streams constitutes one major source of discharge from TMG aquifers in the region of 1.1×10^9 $m^3.a^{-1}$. The total discharges from spring flows (including thermal springs), baseflow and groundwater abstractions are estimated to be in the region of 1.3×10^9 $m^3.a^{-1}$ (Jia, 2008). These estimates are reckoned to be the upper limits of TMG discharge. The borehole abstractions if not well managed can create negative impacts on streamflow, dependent ecosystems and the environment. Even though there are few terrestrial ecosystems that depend solely on groundwater many aquatic ecosystems are known to survive directly and indirectly from groundwater flow to streams, wetlands, marshes and riparian zones.

CHAPTER 5 CLIMATE VARIABILITY AND ITS IMPACT ON GROUNDWATER

5.1 Introduction

Natural external causes of climate variability include variations in the amount of energy emitted by the Sun, changes in the distance between the Earth and the Sun, and the presence of volcanic pollution in the upper atmosphere. Internal variations of the climate system also produce fluctuations, through the feedback processes that connect various components of the climate system. These variations arise when the more rapidly varying atmospheric conditions ‘force’ the slow components of the system like internal variations in the ocean, cryosphere, or biosphere. They are intensified by coupling of the components of the system that would not have such an effect on an individual basis (Appleton, 2003).

Semi-arid and arid areas are particularly exposed to the impacts of climate change on freshwater (high confidence). Many of these areas (e.g. southern Africa) will suffer a decrease in water resources due to climate change (very high confidence). Efforts to offset declining surface water availability due to increasing precipitation variability will be hampered by the fact that groundwater recharge will decrease considerably in some already water-stressed regions (high confidence), where vulnerability is often exacerbated by the rapid increase in population and water demand (very high confidence) (Kundzewicz *et al*, 2007). It is well known that climate variability, particularly seasonal variability, affects water levels in aquifers. From a regional or national perspective, our understanding of the impact of climate variability and change on groundwater resources, in terms of availability, vulnerability and sustainability of fresh water, remains limited. It is expected that changes in temperature and precipitation will alter recharge to groundwater aquifers, causing shifts in water table levels in unconfined aquifers in the short term and confined aquifers in the long term. The concern of water managers is the potential decrease in groundwater supplies for municipal and agricultural use. Decreases in quantity oftentimes results in decrease in quality which could have detrimental environment effects on other dependant sectors including changing baseflow dynamics in streams.

Groundwater level fluctuations occur due to natural variations in climate, and changes in climate caused by human activities could have dramatic and unpredictable effects. Climate variability has a pronounced impact on the capacity of groundwater systems to maintain water supplies, in-stream conditions, and aquatic habitat; impacts such as these may increase as a result of climate change. A look at the historical trend of climatic variables notably rainfall and temperature over the last few decades should form a good foundation for the current climate variability.

5.2 Historical Climate Trends in Southern Africa

Southern Africa experiences a high inter-annual and intra-annual variability of precipitation under present climatic conditions (Schulze *et al.*, 2001). Schulze (2005) reports that extensive research has shown that large parts of South Africa experience the most variable rainfalls worldwide with MAP ranging from 50 to 3000 mm. This renders the detection of changes in rainfall patterns, which are hypothesized to result from global warming, very difficult. Any changes in precipitation patterns, however, have important implications for the hydrological cycle and for water resources, as precipitation is the main driver of variability, over both time and space in the water balance. Thus global warming induced changes in regional rainfall must be assessed on two time- scales: the daily one through modification of probability distribution of extreme rainfall events and the monthly-to-seasonal one through changes in the probabilities of extended deficits or excess. Southern Africa's geographic location, steep orography, contrasted oceanic surroundings and atmospheric dynamics are conducive to extreme weather events and great interannual variability of the hydrological cycle (Fauchereau *et al*, 2003).

The recent (20th century) historical rainfall records in the Western Cape and the Eastern Cape Provinces show strong trends in the regional climate patterns, most notably in terms of the intensity and frequency of rainfall (New *et al*., 2006; Hewitson *et al*, 2005). Coupled with this are strong temperature trends towards higher long-term averages. Warburton and Schulze (2005) did a split-sample analysis of Quaternary Catchments' rainfall between the years 1980-1999 and 1950–1969. They concluded that for the winter rainfall region of the Western Cape Catchments, the lowest annual rainfall in 10 years as well as the median annual rainfall increased in the latter years. However, the number of rainfall events in excess of 25 mm in winter decreased in the latter years. These changes evident in rainfall patterns vary from relatively unsubstantial amounts to significant increases or decreases (Warburton & Schulze, 2005). Changes in rainfall are amplified by the hydrological cycle, with a unit change in rainfall frequently resulting in changes in runoff by 2-4 times the change in rainfall over most areas of South Africa, and with 4-5 fold sensitivity along the west coast (Schulze, 2005).

5.2.1 Climate patterns in the South Western Cape

The Southwestern Cape (SWC) region of South Africa is characterised by winter rainfall brought mainly via cold fronts and by substantial interannual variability. About 60% - 70% of the annual rainfall over the SWC occurs during May – September. Previous work has found evidence that the interannual variability in SWC winter rainfall may be related to sea surface temperature (SST) in the South Atlantic Ocean and to large-scale ocean-atmosphere interaction in this region. Observations indicate that a warm-cold-warm sea surface temperature (SST) pattern across the subtropical mid-latitude South Atlantic is a robust feature associated with many wet SWC winters (Reason and Jagadheesha, 2005). The Cape Peninsula has a Mediterranean climate with well-defined seasons. In winter, which lasts from May to August, large cold fronts come across from the Atlantic Ocean with heavy precipitation and strong north-westerly winds. The winter months are cool, with an average minimum temperature of 7 °C. Table 5.1 presents the average temperature and precipitation values for the Cape Peninsula based on monthly averages for the 30-year period 1961-1990 (South Africa Weather Service, 2008).

Table 5.1: Average Temperature and Precipitation values for Cape Town (1961 -1990)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Highest recorded temp (°C)	39	38	42	39	34	30	29	32	33	37	40	35	42
Average daily maximum temp (°C)	26	27	25	23	20	18	18	18	19	21	24	25	22
Average daily minimum temp (°C)	16	16	14	12	9	8	7	8	9	11	13	15	11
Lowest recorded temp (°C)	7	6	5	2	1	-1	-1	0	0	1	4	6	-1
Average monthly precipitation (mm)	15	17	20	41	69	93	82	77	40	30	14	17	515
Average no. of rain days (>= 1 mm)	6	5	5	8	11	13	12	14	10	9	5	6	103
Highest 24-hour rainfall (mm)	41	27	42	39	65	58	61	56	29	53	30	21	65

Source**:** South African Weather Service

Most of the region's annual rainfall occurs in winter time, but due to the mountainous topography, rainfall amounts for specific areas can vary dramatically. In the Hex River mountain complex (within the syntaxis region), the highest mean annual precipitation (MAP) in the country is obtained between 1000 and over 1500 mm. MAP falls off rapidly in the valleys and with decreasing trend towards the interior and northwest where values of 200 mm and below are recorded. The average MAP along the southern coast is about 500 mm. Figure 5.1 is the mean annual precipitation map of the TMG and surrounding areas.

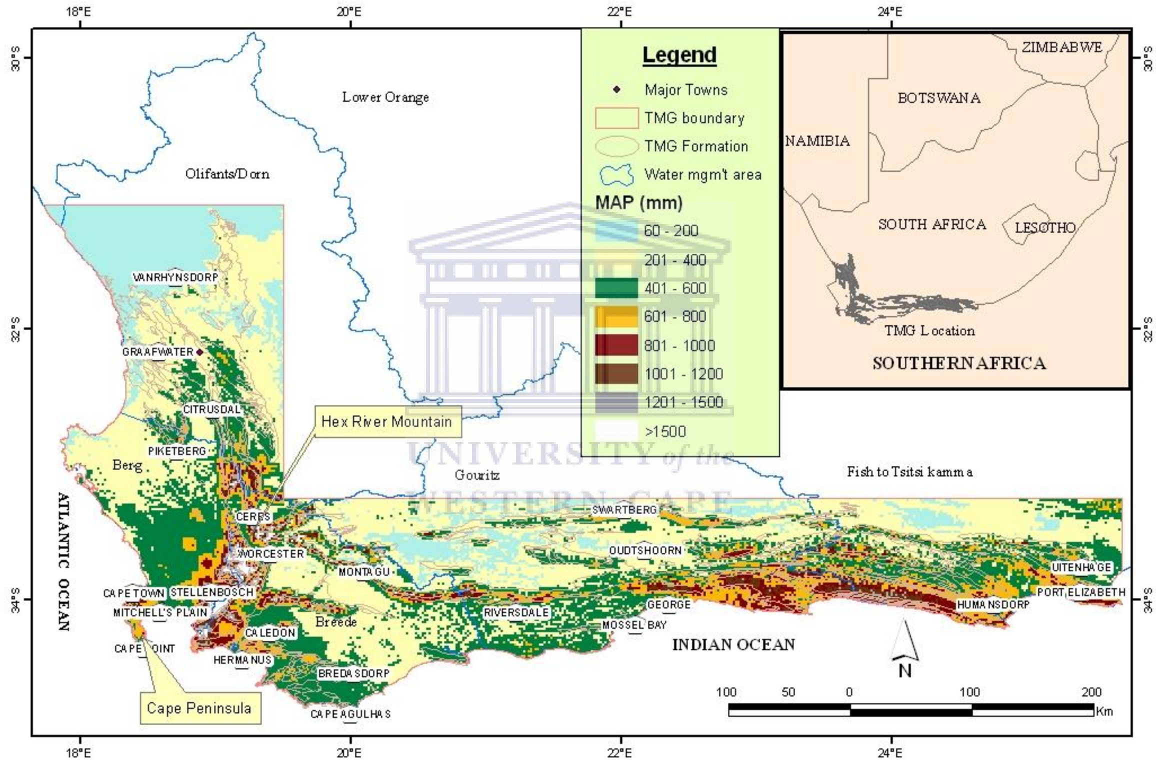

Figure 5.1: Mean annual precipitation within study area (Data: WRC WR2005)

5.2.2 Global temperature changes

Temperature influences evaporation processes from the surfaces of water and soil as well as transpiration from plants. Thus increases in temperature affect potential and actual evapotranspiration and soil moisture. Soil moisture deficiencies on the other hand affect runoff processes such as interflow and baseflow and subsequently recharge to groundwater. In the on-going debate on climate change all schools of thought seem to agree on the fact that world temperature has increased in recent years at a rate not experienced in the past due to anthropogenic increases in greenhouse gases. It is hypothesized that there will be further increases in world temperature in coming years if no efforts are made to curtail the emissions of greenhouse gases notably Carbon dioxide (CO_2), Methane (CH_4) and Nitrous oxide (NO).

The IPCC (2007) reported that the concentration of Carbon dioxide in the atmosphere in 2005 (379 ppm) exceeded the natural range of the last 650,000 years (180 to 300 ppm) (IPCC 2007). The current (2009) concentration of Carbon dioxide in the atmosphere is 386.28 ppm, (Tans 2010). The concentration of Methane in the atmosphere in 2005 (1774 ppb) also exceeded the natural range of the last 650,000 years (320 to 790 ppb). In 2009, Methane concentration rose to 1865 ppb (Blasing 2009). Nitrous oxide concentrations rose from a pre-industrial value of 270 ppb to a 2005 value of 319 ppb (IPCC 2007) and 322 ppb in 2009 (Blasing 2009). More than a third of this is due to human activity, primarily agriculture. The primary source of the increase in Carbon dioxide is fossil fuel use, but land use changes also make a contribution. The primary source of the increase in methane is very likely to be a combination of human agricultural activities and fossil fuel use. Eleven of the twelve years in the period 1995-2006 rank among the top 12 warmest years in the instrumental record (IPCC 2007).

In a recent article by the United Press International, Washington (UPI)' it was reported that Record-setting temperatures in March, April and June made 2010 the warmest year worldwide since the start of record keeping in 1880, climate experts said. National Oceanic and Atmospheric Administration (NOAA) data showed the average temperature in June to be 1.22 degrees higher than the historical average, "It's part of an overall trend," Jay Lawrimore, climate analysis chief at NOAA's National Climatic Data Center, said. "Global temperatures have been rising for the last 100-plus years. Much of the increase is due to increases in greenhouse gases." If the trend continues, Lawrimore said, flooding rains will become more common. "The atmosphere is able to hold more water as it warms, and greater water content leads to greater downpours," he said. “Heavy snows, droughts and Arctic ice melts will also increase and become more severe,” he said (culled from the internet on 16th July, 2010).

It is likely that greenhouse gases would have caused more warming if not for the cooling effects of volcanic and human-caused aerosols. Along with the projected future warming there will be changes in atmospheric and oceanic circulation, and in the hydrologic cycle, leading to altered patterns of precipitation and run-off. The most likely will be an increase in global average precipitation and evaporation as a direct consequence of warmer temperatures. Evaporation will increase with warming because a warmer atmosphere can hold more moisture and higher temperatures increase the evaporation rate. On average, current climate models suggest an increase of about 1%–2% per degree Celsius from warming forced by CO_2 (Allen and Ingram, 2002).

5.3 Trend Analysis

In the current research trend analysis was done on historical records of temperature and rainfall to find out if there have been any positive or negative shifts in their patterns. Depending on the characteristics of the data being studied, either parametric or nonparametric method may be employed for trend detection. Nonparametric tests are more robust compared to their parametric counterparts (Xu *et al*, 2003). The nonparametric Mann-Kendall (M-K) (Mann, 1945; Kendall, 1975) test has been widely used to detect trends in hydrologic and climatic time series by several researchers (Hamed, 2008; Warburton & Schulze, 2005; Xu *et al*, 2003; Burn & Elnur, 2002; Hirsch *et al*, 1991).

5.3.1 The Mann-Kendall (M-K) trend test

In a trend test, the null hypothesis H_0 is that there is no trend in the population from which the data set X is drawn. Hypothesis H_1 is that there is a trend in the record. The M-K trend test is based on the correlation between the ranks of a time series and their time order. For a time series $X = \{x_1, x_2, \ldots, x_n\}$, the test statistic is given by

$$S = \sum_{i=1}^{n-1} \sum_{j=i-1}^{n} Sgn(X_j - X_i) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.3)$$

$$Sgn(X_j - X_i) = Sgn(R_j - R_i) = \begin{cases} 1 & X_i < X_j \\ 0 & X_i = X_j \\ -1 & X_i > X_j \end{cases} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.4)$$

and R_i and R_j are the ranks of observations X_i and X_j of the time series, respectively. As can be seen from Eq. (5.4), the test statistic depends only on the ranks of the observations, rather than their actual values, resulting in a distribution-free test statistic. The M-K test has two parameters that are of importance to trend detection. These parameters are the significance level that indicates the trend's strength, and the slope magnitude, β that indicates the direction as well as the magnitude of the trend and is given by

$$\beta = Median\left(\frac{X_j - X_i}{j - i}\right), for\ all\ i < j \qquad \text{………………………………………(5.5)}$$

A positive value of β indicates an 'upward trend', i.e. increasing values with time, and a negative value of β indicates a 'downward trend', i.e. decreasing values with time. If the data series are at least 10, the normal approximation test is used and the test statistic, Z is calculated instead of S. If there are several tied values in the time series, it may reduce the validity of the normal approximation when the number of data values is close to 10. First the variance of S is computed by the following equation which takes into account that ties may be present.

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right] \qquad \text{………………………(5.6)}$$

q is the number of tied groups and t_p is the number of data values in the p^{th} group. The values of S and $VAR(S)$ are used to compute the test statistic Z as follows.

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} & if\ S < 0 \end{cases} \qquad \text{…………………………………………...(5.7)}$$

The presence of a statistically significant trend is evaluated using the Z value. A positive value of Z indicates an upward trend and vice versa. The statistic Z has a normal distribution. To test for either an upward or downward monotonic trend (a two-tailed test) at α level of significance, H_0 is rejected if the absolute value of Z is greater than $Z_{1-\alpha/2}$, $Z_{1-\alpha/2}$ is obtained from the standard normal cumulative distribution tables. In this study the tested significance levels, α, are 0.001, 0.01, 0.05 and 0.1. To estimate the true slope in Eq (5.5) of an existing trend (as change per year) the Sen's nonparametric method is used. The Sen's method (Gilbert, 1987) uses a linear model to estimate the slope of the trend and the variance of the residuals should be constant in time. The linear model is of the form

$$f(t) = Qt + B \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5.8)$$

where *f(t)* is the continuous monotonic increasing or decreasing function of time, *Q* is the slope and *B* is a constant. A 100(1-α)% two-sided confidence interval about the slope estimate is obtained by the nonparametric technique based on the normal distribution. The method is valid for *n* as small as 10 unless there are many ties.

An Excel template MAKESENS (Mann-Kendall test for trend and Sen's slope estimates) developed for detecting and estimating trends in the time series of the annual values of atmospheric and precipitation concentrations was used in the analysis (Salmi *et al,* 2002). MAKESENS performs two types of statistical analyses. First the presence of a monotonic increasing or decreasing trend is tested with the nonparametric M-K test and secondly the slope of a linear trend is estimated with the nonparametric Sen's method. The two methods offer many advantages that have made them useful in analyzing atmospheric data. Missing values are allowed and the data need not conform to any particular distribution. Besides, they are not affected by outliers. The procedure in MAKESENS computes the confidence interval at two different confidence levels; $\alpha = 0.01$ and $\alpha = 0.05$, resulting in two different confidence intervals (Salmi *et al*, 2002).

5.3.2 Temperature trends in South Africa

Warburton *et al* (2005) analysed the annual means of both minimum and maximum daily temperatures of South Africa temperature records for trends and found that two clusters of warming emerged over a 50 year period (1950-1999). These were a cluster of stations in the Western Cape and a cluster of stations in the Midlands of KwaZulu-Natal. The Western Cape cluster of stations occurred within the Cape Peninsula and the TMG syntaxis. The trends had a 95% confidence interval using the Mann-Kendal trend analysis.

5.3.3 Current temperature trends in the Western Cape

Temperature records of the Western Cape in recent times were analysed for trends using the Mann-Kendall nonparametric trend test. A trend analysis will determine if there have been any significant changing trends in the records of variables as well as the direction of the trends (positive or negative) if any. The daily maximum and minimum temperatures for available stations within the study area were compiled from which monthly and annual averages were computed. The annual mean values were tested with the Mann-Kendal trend test and the Sen's slope analysis. Maximum and minimum temperature records ranging between 11 and 60 years i.e. 1950 and 2009 were analysed. The full trend results of maximum and minimum temperatures are presented in Appendix IIA and IIB respectively. There were six stations with data in excess of 25 years out of the 12 stations for which data was obtained. The summary of results of the temperature trend analyses are shown in Table 5.2. Q is the Sen's slope estimate. Four of the six long-term data stations showed high positive trends (increasing temperatures) for both maximum and minimum temperatures at $\alpha = 0.001$ level. The other two stations also had positive trends, one at $\alpha = 0.01$ level and the other at $\alpha = 0.05$ level. Only one station, Worcester, showed negative trends for both maximum and minimum temperatures at $\alpha = 0.01$ level. At Oudtshoorn and Hermanus there were positive trends at $\alpha = 0.01$ level for the maximum and minimum temperatures respectively whiles at Clan William station the maximum temperature had a positive trend at $\alpha = 0.05$ level. At the Cape Town station it was the minimum temperature which had a positive trend at $\alpha = 0.1$ level. Three stations did not show any significant trends in both maximum and minimum temperatures.

Table 5.2: Results of M-K trend tests for max and min temperatures in study area

Temp Station	Alt	Temp	n	Test Z	Signif	Q	Qmn99	Qmx99	Qmn95	Qmx95
Paarl *1993-2009*	109	Max	17	0		0	-0.1	0.092	-0.053	0.067
		Min	17	-0.123		-0.006	-0.08	0.069	-0.057	0.056
Porterville *1990-2009*	122	Max	20	0.16		0	-0.063	0.1	-0.05	0.073
		Min	20	0		0	-0.053	0.059	-0.035	0.037
Excelsior Ceres *1990-2009*	958	Max	20	-0.26		-0.01	-0.096	0.064	-0.067	0.033
		Min	20	-0.097		-0.003	-0.058	0.05	-0.041	0.035
Cape Town WO	42	Max	17	1.5		0.021	-0.02	0.087	-0.011	0.06

1993-2009		Min	17	1.936	+	0.037	-0.015	0.105	0	0.076
Worcester-AWS	204	Max	11	-2.77	**	-0.143	-0.2	0	-0.183	-0.071
1999-2009		Min	11	-3.113	**	-0.126	-0.277	-0.056	-0.18	-0.086
Cape Point	228	Max	59	6.69	***	0.025	0.018	0.032	0.02	0.03
1950-2009		Min	59	4.662	***	0.016	0.008	0.026	0.01	0.023
Hermanus	16	Max	13	1.17		0.031	-0.049	0.083	-0.02	0.066
1997-2009		Min	13	2.745	**	0.047	0.007	0.095	0.013	0.077
Cape Agulhas	11	Max	60	5.07	***	0.018	0.009	0.025	0.012	0.024
1950-2009		Min	60	6.008	***	0.017	0.012	0.023	0.013	0.022
Tygerhoek	157	Max	45	4.49	***	0.031	0.016	0.05	0.019	0.047
1965-2009		Min	45	4.549	***	0.024	0.012	0.037	0.015	0.033
Clanwilliam Dam	152	Max	26	2.46	*	0.045	0	0.091	0.009	0.076
1982-2009		Min	26	0.132		0.003	-0.044	0.056	-0.025	0.038
Vredendal	35	Max	51	5.66	***	0.014	0.026	0.055	0.031	0.051
1959-2009		Min	51	3.72	***	0.018	0.006	0.028	0.009	0.025
Oudtshoorn	314	Max	32	2.84	**	0.04	0.008	0.069	0.017	0.059
1977-2009		Min	32	1.621		0.015	-0.012	0.045	-0.004	0.037

Level of significance: **+** if trend at α=0.1; ***** if trend at α=0.05, ****** if trend at α=0.01; ******* if trend at α=0.001
If no symbol, the significance level is greater than 0.1

5.3.4 Precipitation trends

Precipitation is the source of recharge and any changes in precipitation directly or indirectly impacts on recharge. A much detailed analysis was therefore conducted on the precipitation data to assess any trends and or variability that would likely impact on recharge to groundwater. In determining trends in natural series one needs to recognize the inherent variability of hydrologic and meteorological time series. There is a difficulty associated with differentiating between natural variability and trends (Askew, 1987). This requires a rigorous procedure for detecting trends and their significance. Rainfall time series from several rainfall stations located in and around the TMG formation were compiled and analysed with statistical analysis to determine the basic parameters of long-term mean and variations from the mean. The time series were derived from rainfall stations within the four main water management areas (WMA) of the Western Cape namely; Olifants-Dooring, Berg, Breede and Gouritz within which most of the TMG formation is located. The series ranged from 12 to 89 years of usable data of monthly averages. The data was initially screened and most of the incomplete series were rejected leaving those with complete and or those with minor gaps capable of being handled by the statistical tests.

5.3.4.1 Basic statistics

The basic statistics for the selected stations data are presented in Table 5.3. Some of the stations were closed down and others got started only a few years ago. Analysis was based on consistent data within the same period of recording in order to justify trends or otherwise. There are several missing gaps in the dataset. The values of the standard deviation show that there is wide variation in the dataset with the mean annual precipitation ranging from 147 mm at Lambertsbaai to 2168 mm at Virgin Peaks in the Peninsula.

Table 5.3: Basic Statistics of Rainfall Data

Rainfall Station	WMA	Valid data	Missing data	Mean	Std Dev	CV	Min	Max
Algeria_Bos	O/Doorn	88	0	700.3	199.4	0.28	366.0	1412.4
Puts		75	13	357.8	105.9	0.30	183.1	693.0
Elandsfontein		82	6	497.9	128.4	0.26	313.5	883.2
Graafwater		74	14	233.0	43.5	0.19	46.6	455.0
Redelinghuys_Pol		71	17	272.9	76.9	0.28	126.0	508.0
Elandsbaai		29	59	210.4	69.4	0.33	101.8	396.1
Lambertsbaai		41	47	147.3	50.5	0.34	55.3	300.0
Franschhoek_RB	Berg	19	69	926.4	168.0	0.18	603.1	1185.0
Franschhoek_LM		84	4	827.2	219.4	0.27	352.3	1878.4
Bainskloof		12	76	1507.1	381.4	0.25	796.7	2040.8
Virgin_Peaks		50	38	2168.7	439.0	0.20	1465.3	3770.2
Waaivlei		35	53	1544.3	441.4	0.29	852.0	2776.4
Woodhead_Dam		55	33	1563.1	316.2	0.20	947.6	2536.8
Simonstown		45	43	663.2	150.0	0.23	251.0	933.0
Klaasjagersberg		24	64	615.1	93.2	0.15	431.0	778.0
Silvermine NR		27	61	1110.7	226.1	0.20	686.3	1437.7
Hermanus	Breede	72	16	628.5	122.1	0.19	279.1	1006.3
Rawsonville-Pol		76	12	593.6	213.7	0.36	128.1	1306.5
Walker Bay		56	32	666.2	107.0	0.16	436.0	937.0
Boskloof		73	15	450.4	112.0	0.25	234.0	727.0
Montagu		69	19	297.4	84.1	0.28	126.8	537.6
Ceres		53	35	1037.2	301.5	0.29	313.0	1822.0
De Doorns		60	28	265.5	128.6	0.48	53.5	545.6
Stettynskloof		54	34	907.3	353.3	0.39	494.7	2342.6
Zoetendale		87	1	459.3	145.9	0.32	124.5	980.7
De Rust Pol	Gouritz	88	0	316.0	94.0	0.30	103.4	637.8
Le Roux Sar		65	23	235.8	73.1	0.31	49.7	390.3
Rooirivier		82	6	252.6	80.3	0.32	127.5	491.7
Buffelsklip		79	9	213.2	84.9	0.40	67.3	450.8
Albertina Pol		79	9	441.0	117.2	0.27	190.4	707.6
Rooiklip		22	66	295.8	78.7	0.27	180.6	463.7

The coefficient of variation (CV) is a normalized measure of dispersion of a probability distribution. It is defined as the ratio of the standard deviation σ to the mean μ.

$$CV = \sigma/\mu \quad \text{..}(5.9)$$

This is only defined for non-zero mean, and is most useful for variables that are always positive. It is a useful statistic for comparing the degree of variation from one data series to another, even if the means are drastically different from each other. It lets you compare the scatter of variables. The location of rainfall stations in the Western Cape and the selected stations for the trend test are shown in figure 5.2.

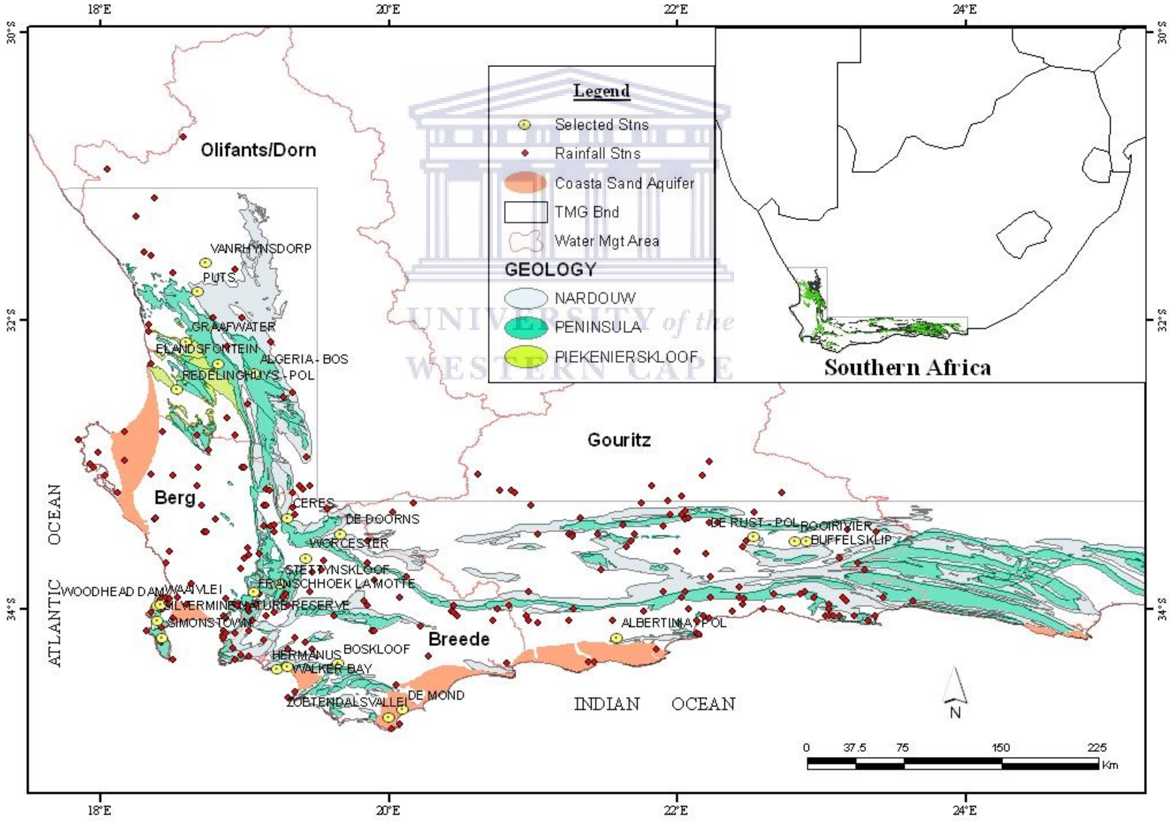

Figure 5.2: Locations of selected rainfall stations in the study area.

5.3.4.2 Autocorrelation function

In investigating trends especially for rainfall time series, it is recommended that the autocorrelation function (ACF) be first calculated in order to find out any significant correlations between the observations and their lagged values. The lagged values are the values observed one or more time points earlier to the observed values, i.e., lag 1 value being the value of the Annual Series one year prior, lag 2 value is the value two years prior, etc. If there is some pattern in how the values of the time series change from observation to observation, this can be detected by the autocorrelation function. The general formula for calculating the autocorrelation for lag k (denoted by r_k) is:

$$r_k = \frac{(y_{k+1}-\bar{y})(y_1-\bar{y})+(y_{k+2}-\bar{y})(y_2-\bar{y})+\cdots+(y_n-\bar{y})(y_{n-k}-\bar{y})}{(y_1-\bar{y})^2+(y_2-\bar{y})^2+\cdots+(y_n-\bar{y})^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5.2)$$

where;

$\bar{y}$ is the mean value for the series. The ACF calculated for the time series show a random pattern meaning limited or no correlations exist between the observed values and their lagged values for all the variables. Some of the ACF plots are shown in figure 5.3. Almost all the coefficients are within the upper and lower confidence limits indicating no significance for the 95% confidence width boundaries. This suggests that there is not much correlation between past and future rainfall observations, *i.e*. past observations cannot be used to predict future observations.

5.3.5 Current precipitation trends in the Western Cape

Three trend tests were conducted on the rainfall time series. The first test looked for trends in the time series from the years 1950 to 1979. The second split test looked for trends in the time series between 1980 and 2007. The final test looked for consistent trends in the time series spanning the whole time frame i.e. 1950–2007. Table 5.4 shows the summary of results of the trend tests on the precipitation time series. The complete trend results are presented as Appendices IIIA, IIIB and IIIC respectively. Fourteen variables were tested with two of them having less than 20 data points. In the first split test two stations recorded significant trends at $\alpha = 0.01$ level, Hermanus station with a negative trend and De Doorns station with a positive trend. Two other stations had significant trends at $\alpha = 0.05$ level, Worcester station with a negative trend and

Simonstown station with a positive trend. All the other stations showed no significant trends within the tested levels of significance.

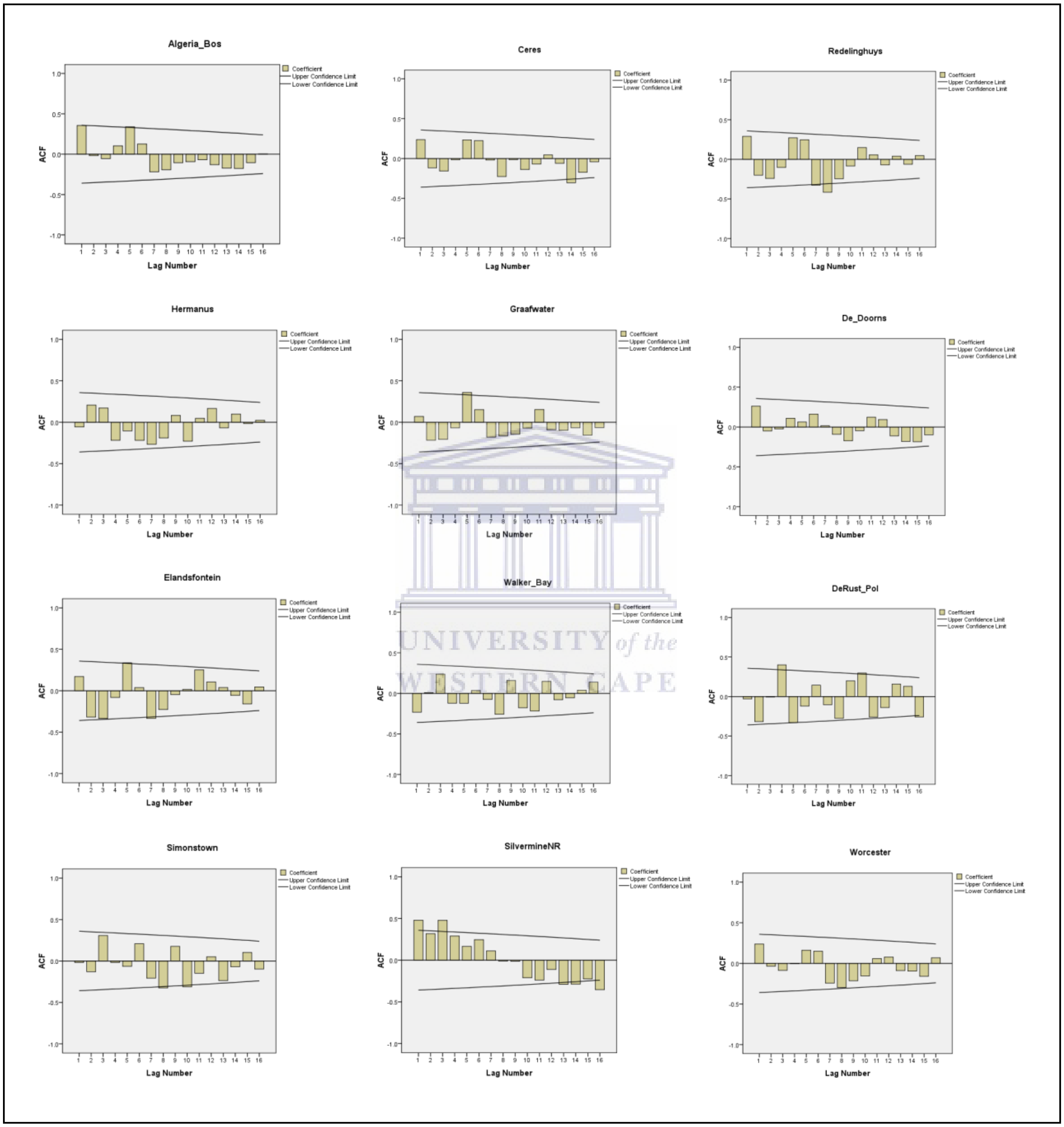

Figure 5.3: Autocorrelation plots for rainfall time series within the study area.

Table 5.4: Summary of results of trend tests on precipitation time series

Rainfall Station	Alt(m)	Period	n	Test Z	Sig	Q	$Q_{min}99$	$Q_{max}99$	$Q_{min}95$	$Q_{max}95$
Algeria-Bos	517	1950-1979	30	0.5		2.58	-8.93	18.16	-5.59	13.80
		1980-2007	28	-1.52		-7.24	-19.32	5.62	-15.31	2.87
		1950-2007	58	0.42		0.83	-3.08	5.30	-2.08	4.27
Vanrhynsdorp	122	1950-2006	53	0.07		0.06	-1.20	1.25	-0.91	0.98
Redelinghuys-Pol	61	1950-1979	30	-1.32		-2.68	-6.49	2.95	-5.55	1.36
		1980-2007	28	0.36		0.97	-2.91	7.11	-1.85	5.29
		1950-2007	58	0.48		0.32	-1.14	2.24	-0.78	1.81
Graafwater	198	1950-1979	26	-1.28		-1.93	-6.34	3.07	-4.72	1.56
		1980-2007	28	-0.02		-0.12	-4.37	4.68	-3.31	3.12
		1950-2007	49	1.92	+	1.19	-0.47	2.94	-0.05	2.45
Elandsfontein	457	1950-1979	30	-0.45		-1.85	-10.99	8.63	-7.51	6.03
		1980-2007	28	0.06		0.26	-5.88	7.32	-4.73	4.91
		1950-2007	58	-0.45		-0.51	-3.38	2.14	-2.65	1.49
Puts	595	1950-2007	58	-1.19		-0.93	-3.18	1.25	2.60	0.62
Ceres	456	1955-1979	25	0.07		0.44	-28.66	28.23	-21.22	19.04
		1980-2007	28	-1.13		-6.12	-23.61	9.22	-19.78	4.59
		1955-2007	53	1.13		3.07	-4.63	10.04	-2.61	8.63
De Mond	2	1952-2006	55	0.61		0.63	-2.23	3.46	1.51	2.62
De Doorns	470	1964-1979	16	2.70	**	12.38	0.76	31.06	3.68	27.72
		1980-2007	28	-1.96	+	-4.33	-9.39	2.55	-8.17	-0.00
		1965-2007	43	1.53		2.13	-1.66	5.76	-0.43	4.70
Hermanus	61	1950-1979	30	-2.89	**	-8.59	-16.90	-0.83	-14.58	-3.08
		1980-2007	28	0.77		1.98	-5.16	8.69	-3.07	6.69
		1950-2007	58	-0.76		-0.75	-3.64	1.73	-2.99	1.19
Walker Bay	30	1952-1979	28	-1.01		-2.49	-9.97	5.31	-8.17	3.60
		1980-2007	28	-0.14		-0.34	-6.59	8.26	-4.81	5.73
		1952-2007	56	0.71		0.69	-1.58	3.32	-1.04	2.79
Worcester	220	19501979	30	-2.00	*	-3.14	-7.76	1.80	-6.39	-0.07
		1980-2007	28	-1.52		-3.36	-8.68	3.15	-6.99	1.54
		1950-2007	58	0.78		0.62	-1.25	2.73	-0.90	2.23
Boskloof	122	1950-2007	58	0.30		0.27	-2.34	2.66	-1.63	2.07
Stettynskloof	430	1953-2006	54	1.42		2.75	-2.53	9.64	-1.03	8.12
Zoetendal	21	1950-2006	57	-0.31		-0.46	-3.86	3.00	-2.92	2.06
Albertina Pol	183	1950-2006	52	0.21		0.21	-2.95	3.26	-2.16	2.56
Zachariasfontein	815	1950-2006	49	0.66		0.33	-1.02	1.84	-0.59	1.46
De Rust-Pol	533	1950-1979	30	-0.89		-2.04	-7.85	4.04	-6.26	2.40
		1980-2007	28	1.24		3.01	-2.98	7.65	-1.51	6.30
		1950-2007	58	0.60		0.53	-1.46	2.49	-1.03	1.92
Rooirivier	564	1950-1979	29	0.75		1.55	-2.97	7.59	-1.94	5.73
		1980-2006	27	-0.58		-1.55	-5.77	5.24	-4.49	4.65
		1950-2006	56	1.14		0.83	-0.91	2.76	-0.49	2.19
Buffelsklip	610	1950-1979	28	-0.65		-1.08	-4.86	4.17	-3.92	2.78
		1980-2006	27	1.08		2.24	-4.39	7.87	-2.10	6.40
		1950-2006	55	0.94		0.62	-0.95	2.25	-0.62	1.77
Franschhoek LM	206	1950-2003	54	0.28		0.63	-4.43	5.58	-3.11	4.46
Simonstown	30	1963-1979	17	2.35	*	16.28	-5.29	42.94	2.67	32.70
		1980-2007	28	-0.34		-1.17	-9.90	7.50	-7.50	5.09
		1963-2007	45	2.16	*	3.73	-0.88	8.73	0.54	7.45
Woodhead Dam	747	1955-1979	25	-0.30		-3.10	-28.57	20.87	-20.39	12.53
		1980-2007	28	0.02		0.51	-17.86	22.75	-11.80	15.08
		1955-2006	52	1.30		2.99	-3.51	9.73	-1.87	7.76
Waaivlei	705	1980-2002	23	0.85		15.67	-30.68	59.35	-22.10	53.07
Silvermine NR	442	1980-2007	28	-3.10	**	17.96	-31.10	-3.18	-27.48	-6.60

Level of significance**: **+** if trend at α=0.1; ** if trend at α=0.05, ****** if trend at α=0.01; otherwise the significance level is greater than 0.1*

In the second split test, i.e. 1980-2007, results showed that only one station, Silvermine Nature Reserve, had a negative or decreasing trend at the $\alpha = 0.01$ level whiles De Doorns station had a negative trend at $\alpha = 0.1$ level. At De Doorns station, whiles the first split test showed a positive trend, the second test showed a negative trend. This means rainfall has been decreasing in the latter years at the station. In the final trend test (1950-2007), the only stations with significant trends are the positive trends recorded at the Simonstown and Graafwater stations. The former at a significant level of $\alpha = 0.05$ and the latter at $\alpha = 0.1$ level. The remaining 21 stations showed no significant trends within the tested levels. In all, nineteen variables showed no significant trends whiles six variables showed some trends in the data sets. The results meant that in general rainfall patterns in the study area have not changed significantly. They showed minor increases at the least. In terms of aquifers in the area there should be no significant negative impacts from rainfall on recharge.

5.3.6 Rainfall Variability

Rainfall time series from several rainfall stations located in and around the TMG formation within the four main water management areas namely; Olifants/Doorn, Berg, Breede and Gouritz were analysed for their variability over the years of available records. The records were dated from 1920 to 2007 but some of the stations were established much later. The variability analysis was done using annual rainfall values from several rainfall stations with available records. The series records ranged from 12 to 88 years of usable data of annual means. There are different ways of measuring variability which shows how rainfall varies from year to year. In this study the percentile analysis method was employed in determining the index of variability of an area. The method has been employed by the Bureau of Meteorology of the Government of Australia (Commonwealth of Australia 2010). The index of variability (IV) is defined as:

$$IV = \frac{90p - 10p}{50p} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.1)$$

Where *90p, 50p* and*10p* are the 12 month 90th, 50th (median) and 10th rainfall percentiles respectively. The index varies from low to extreme.

Index of Variability

0 – 0.5	Low
0.5 – 0.75	Low to moderate
0.75 – 1.0	Moderate
1.0 – 1.25	Moderate to high
1.25 – 1.5	High
1.5 – 2.0	Very High
> 2.0	Extreme

If a place has lower rainfall variability, it means rainfall will tend to be more consistent from one year to the next. On the other hand, higher rainfall variability means rainfall is likely to be irregular from one year to the next; heavy rainfall in some years and little rainfall in others. Arid areas tend to have this kind of rainfall pattern. Most of the areas in the study area show moderate variability, a more likely pattern for semi-arid regions. There were a few areas of high variability in the study area as shown in figure 5.4.

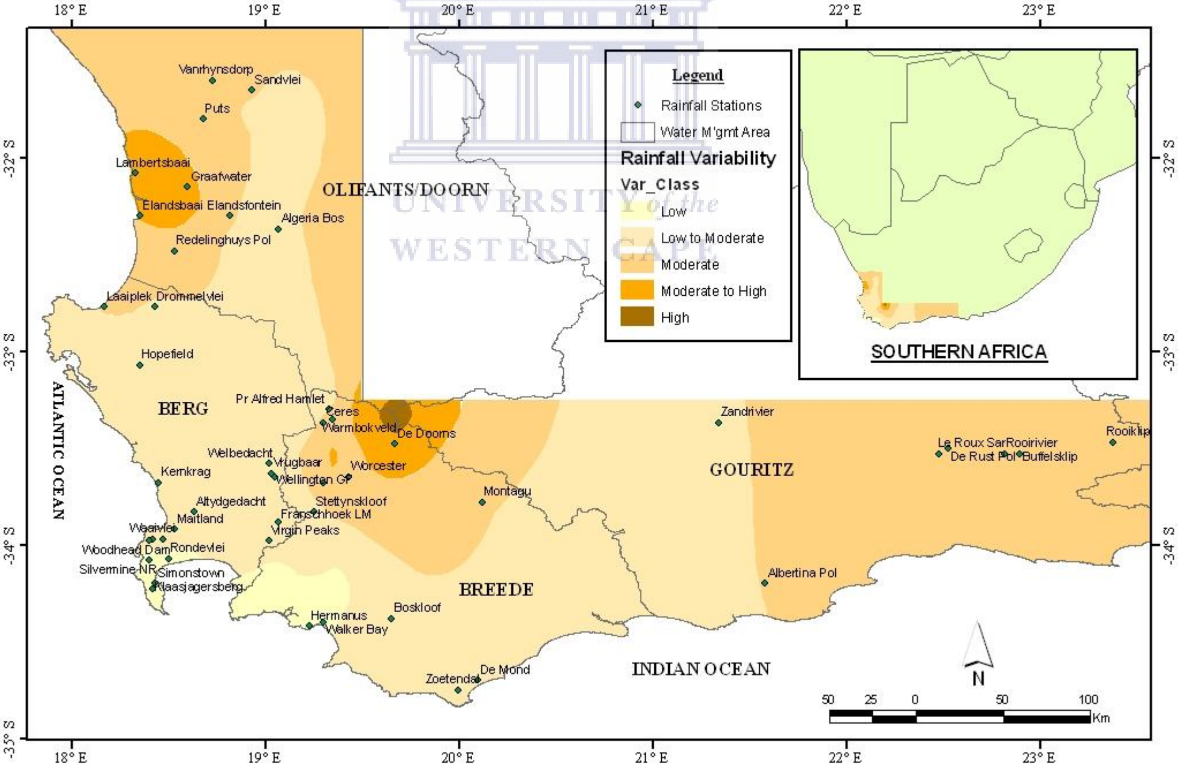

Figure 5.4: Rainfall variability (Annual) map of the study area

Table 5.5 shows variability index for the selected rainfall stations in the study area using the percentile analysis method described above. The results of the analysis shown in Table 5.5 were based on data from 1920 to 2007. The Cape Peninsula and the coastal region of the Overstrand Municipality were the areas with low rainfall variability. These areas show consistent annual rainfall values from year to year. The areas of high variability in the region were the upper Breede catchment and the Sandveld in the Olifants/Dorn catchment area. Figure 5.4 is the rainfall variability map of the study area.

Table 5.5: Index of variability of some rainfall stations in the study area.

Rainfall Station	WMA	N		Percentiles			Index of Variability	Description
		Valid	Missing	10th	50th	90th		
Algeria Bos	O/Doorn	88	0	466.31	672.85	969.34	0.75	Low to Moderate
Vanrhynsdorp	O/Doorn	79	9	96.7	155.3	218.8	0.79	Moderate
Sandvlei	O/Doorn	31	57	134.34	186.5	271.7	0.74	Low to Moderate
Puts	O/Doorn	75	13	229.02	339.5	484.04	0.75	Low to Moderate
Elandsfontein	O/Doorn	82	6	354.37	477.8	689.27	0.7	Low to Moderate
Graafwater	O/Doorn	74	14	143.25	228.5	330.05	0.82	Moderate
Redelinghuys Pol	O/Doorn	71	17	172.14	271.8	382.06	0.77	Moderate
Elandsbaai	O/Doorn	29	59	114.7	201	345.5	1.15	Moderate to High
Lambertsbaai	O/Doorn	41	47	86.96	137.4	228.82	1.03	Moderate to High
Franschhoek LM	Berg	84	4	571.9	813.5	1080.4	0.63	Low to Moderate
Virgin Peaks	Berg	50	38	1649.8	2174.4	2739.6	0.5	Low
Waaivlei	Berg	35	53	1095.9	1443	2184.8	0.75	Low to Moderate
Woodhead Dam	Berg	55	33	1237	1468.9	2087.8	0.6	Low to Moderate
Simonstown	Berg	45	43	467.6	654.4	859.96	0.6	Low to Moderate
Klaasjagersberg	Berg	24	64	474.45	605.75	748.8	0.45	Low
Silvermine NR	Berg	27	61	750.14	1118.2	1389.7	0.57	Low to Moderate
Drommelvlei	Berg	48	40	210.72	318.3	454.81	0.77	Moderate
Laaiplek	Berg	29	59	108.5	219.7	275.6	0.76	Moderate
Hopefield	Berg	88	0	225.45	308.95	434.16	0.68	Low to Moderate
Wellington GF	Berg	70	18	354.29	590.25	793.8	0.74	Low to Moderate
Vrugbaar	Berg	87	1	581.36	730.7	947.72	0.5	Low
Welbedacht	Berg	76	12	474.96	598.7	791.49	0.53	Low to Moderate
Altydgedacht	Berg	82	6	423.15	557.05	746.61	0.58	Low to Moderate
Maitland	Berg	88	0	326.38	466	656.7	0.71	Low to Moderate
Groote Schuur	Berg	39	49	869.9	1153	1455.7	0.51	Low to Moderate
Kernkrag	Berg	19	69	274.4	347.3	467.8	0.56	Low to Moderate
Rondevlei	Berg	55	33	465.52	629	882.5	0.66	Low to Moderate

Hermanus	Breede	72	16	487.91	620.75	802.85	0.51	Low to Moderate
Worcester	Breede	88	0	153.69	244.85	376.21	0.91	Moderate
Rawsonville Pol	Breede	76	12	337.07	551.25	912.93	1.04	Moderate to High
Walker Bay	Breede	56	32	523.38	672.2	789.2	0.4	Low
Boskloof	Breede	73	15	282.12	444	591.2	0.7	Low to Moderate
Montagu	Breede	69	19	206.3	278.7	429.4	0.8	Moderate
Ceres	Breede	53	35	700.28	1032.4	1447.1	0.72	Low to Moderate
De Mond	Breede	55	33	293.04	412.6	585.14	0.71	Low to Moderate
De Doorns	Breede	60	28	87.95	262.65	453.49	1.39	High
Zoetendal	Breede	87	1	297.16	443.1	618.92	0.73	Low to Moderate
Stettynskloof	Breede	54	34	542.4	815.25	1328.8	0.96	Moderate
Warmbokveld	Breede	37	51	363.86	560.5	862.32	0.89	Moderate
Pr Alfred Hamlet	Breede	37	51	332	524.6	738.04	0.77	Moderate
De Rust Pol	Gouritz	88	0	191.89	302.3	452.38	0.86	Moderate
Le Roux Sar	Gouritz	65	23	136.88	230.9	335.56	0.86	Moderate
Rooirivier	Gouritz	82	6	149.74	244.8	365.01	0.88	Moderate
Buffelsklip	Gouritz	79	9	108.1	210	304	0.93	Moderate
Albertina Pol	Gouritz	79	9	299.3	434	607.4	0.71	Low to Moderate
Zachariasfontein	Gouritz	54	34	108.8	184.75	261.9	0.83	Moderate
Rooiklip	Gouritz	22	66	196.29	282.65	432.99	0.84	Moderate
Zandrivier	Gouritz	17	71	298.8	441	556.92	0.59	Low to Moderate

5.4 The Standard Precipitation Index

The Standard Precipitation Index (SPI) is derived from the analysis of rainfall and measures how much precipitation for a given period of time has deviated from historically established norms. The SPI was originally developed for the purpose of defining and monitoring drought. The understanding that a deficit of precipitation has different impacts on groundwater, reservoir storage, soil moisture, snow pack, and streamflow led McKee, Doesken, and Kleist to develop the SPI in 1993. The first step in calculation of the SPI is to determine the probability density function that describes the long-term series of observations. Once this distribution is determined, the cumulative probability of an observed precipitation amount is computed. The inverse normal (Gaussian) function is then applied to the probability and these results in the SPI. The gamma distribution is defined by its frequency or probability density function:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \qquad \text{for } x>0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.2)$$

where:

$\alpha > 0$	α is a shape factor …………………………(5.3)
$\beta > 0$	β is a scale parameter ………………………(5.4)
$x > 0$	x is the precipitation amount ……………….(5.5)

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1} e^{-y} dy \qquad \Gamma(\alpha) \text{ is the gamma function } \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.6)$$

Computation of the SPI involves fitting a gamma probability density function to a given frequency distribution of precipitation totals for a station. The alpha and beta parameters of the gamma probability density function are estimated for each station, for each time scale of interest (3 months, 6 months, 12 months, etc.), and for each month of the year. From Thom (1966) , the maximum likelihood solutions are used to optimally estimate α and β:

$$\hat{\alpha} = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.7)$$

$$\hat{\beta} = \frac{\bar{x}}{\hat{\alpha}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.8)$$

where:

$$A = \ln \bar{x} - \frac{\sum \ln x}{n} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (5.9)$$

n = the number of precipitation observations.

The resulting parameters are then used to find the cumulative probability of an observed precipitation event for the given month and time scale for the station in question. The cumulative probability is given by:

$$G\,(x) = \int_0^x g(x)dx = \frac{1}{\hat{\beta}^{\hat{\alpha}}\Gamma(\hat{\alpha})} \int_0^x x^{\hat{\alpha}-1} e^{-x/\hat{\beta}}\, dx \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.10)$$

Letting $t = x / \hat{\beta}$, this equation becomes the incomplete gamma function:

$$G\,(x)=\frac{1}{\Gamma(\hat{\alpha})}\int_0^x t^{\hat{\alpha}-1}e^{-t}\,dt \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5.11)$$

Since the gamma function is undefined for x=0 and a precipitation distribution may contain zeros, the cumulative probability becomes:

$$H\,(x) = q + (1 - q)G(x) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5.12)$$

where *q* is the probability of a zero. If m is the number of zeros in a precipitation time series, Thom (1966) states that *q* can be estimated by *m/n*. Thom (1966) uses tables of the incomplete gamma function to determine the cumulative probability *G(x)*. McKee *et al*. (1993) use an analytic method along with suggested software code to determine the cumulative probability. The cumulative probability, *H(x)*, is then transformed to the standard normal random variable Z with mean zero and variance of one, which is the value of the SPI.

The SPI values are positive (or negative) for greater (or less) than median precipitation. The SPI was designed to quantify the precipitation deficit or increase for multiple time scales. These time scales reflect the impact of drought or otherwise on the availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, streamflow, and reservoir storage reflect the longer-term precipitation anomalies. For these reasons, McKee *et al*. (1993) originally calculated the SPI for 3, 6, 12, 24, and 48–month time scales based on the long-term precipitation record for a desired period (Hayes, 2002). Table 5.6 describes the SPI indices. The SPI is the number of standard deviations that the observed value would deviate from the long-term mean for a normally distributed random variable. The SPI allows the determination of the probability of occurrence of dry or wet events at the different time scales and can be calculated for all stations having a continuous rainfall time series. Additionally, no matter the location or time scale, the SPI represents a cumulative probability in relation to the base period for which the gamma parameters were estimated. The probability of occurrence of a climatic event is indicated by the percentage occurrence indicated in Table 5.6. For example, a SPI of –2 and less indicating a severe drought will occur approximately twice per century; a SPI of –1.5 to –1.99 about 4 times per century, and so on.

Table 5.6: The SPI indices and description.

(*According to Hayes et al. (1999) and Rouault & Richard (2003)*).

SPI Index value	Description	Occurrence (%)
>2.0	Extremely wet	2.3
1.5 to 1.99	Very wet	4.4
1.0 to 1.49	Moderately wet	9.2
–0.99 to 0.99	Near normal	68.2
–1.0 to –1.49	Moderately dry	9.2
–1.5 to –1.99	Severely dry	4.4
< –2.0	Extremely dry	2.3

With a time series of monthly precipitation data for a location, the SPI can be calculated for any month in the record for the previous i months where i = 1, 2, 3, …, 12, …, 24, …, 48, … depending upon the time scale of interest. Therefore, the SPI for a month/year in the period of record is dependent upon the time scale. For example, the 6 month SPI calculated for January, 1979 would have utilized the precipitation total of August, 1978 through to January, 1979 in order to calculate the index. Likewise, the 24 month SPI for January, 1979 would have utilized the precipitation total for February, 1977 through January, 1979.

A 3-month SPI may be used for a short-term or seasonal index, a 12-month SPI for an intermediate-term index and a 48-month SPI for a long-term index. In this study the 3-month, 6-month, 12-month, 24-month and 48-month time scales were computed and analysed. The 12-month SPI was found to be significant to groundwater recharge some of which are presented in figure 5.5. Rainfall variations over the years could be mapped on the SPI plots. Lambertsbaai station moved from a dry period between 1968 and 1973 to a wet period from 1990 to 1997. The period between 2001 and 2003 were extremely wet years. There have been more wet years in recent times (post 1980) than there have been dry years. Graafwater station data shows a shift from a dry period in the late twenties to the early forties. From the mid-eighties there have been more wet periods. The Redelinghuy station plot shows a more variable trend throughout the period from 1938 to 2007 with more extreme conditions of dry and wet periods. It also shows more wet weather in recent years. The Elandsbaai station plot shows a more uniform pattern of dry and wet periods throughout the range. The dry and wet periods appear to be balanced in recent years. The SPI plot from Hermanus station on the other hand shows a wet period from the fifties to the early sixties after which there have been more dry periods until the early twenty hundreds when more rains have been recorded. At De Doorns station a persistent dry spell was recorded between 1964 and 1974. There have been more wet periods since the 1980s. In general there have been high variations in rainfall patterns in all stations and more wet weather in recent years for more stations than not in the Olifants and Breede catchments of the project area.

.

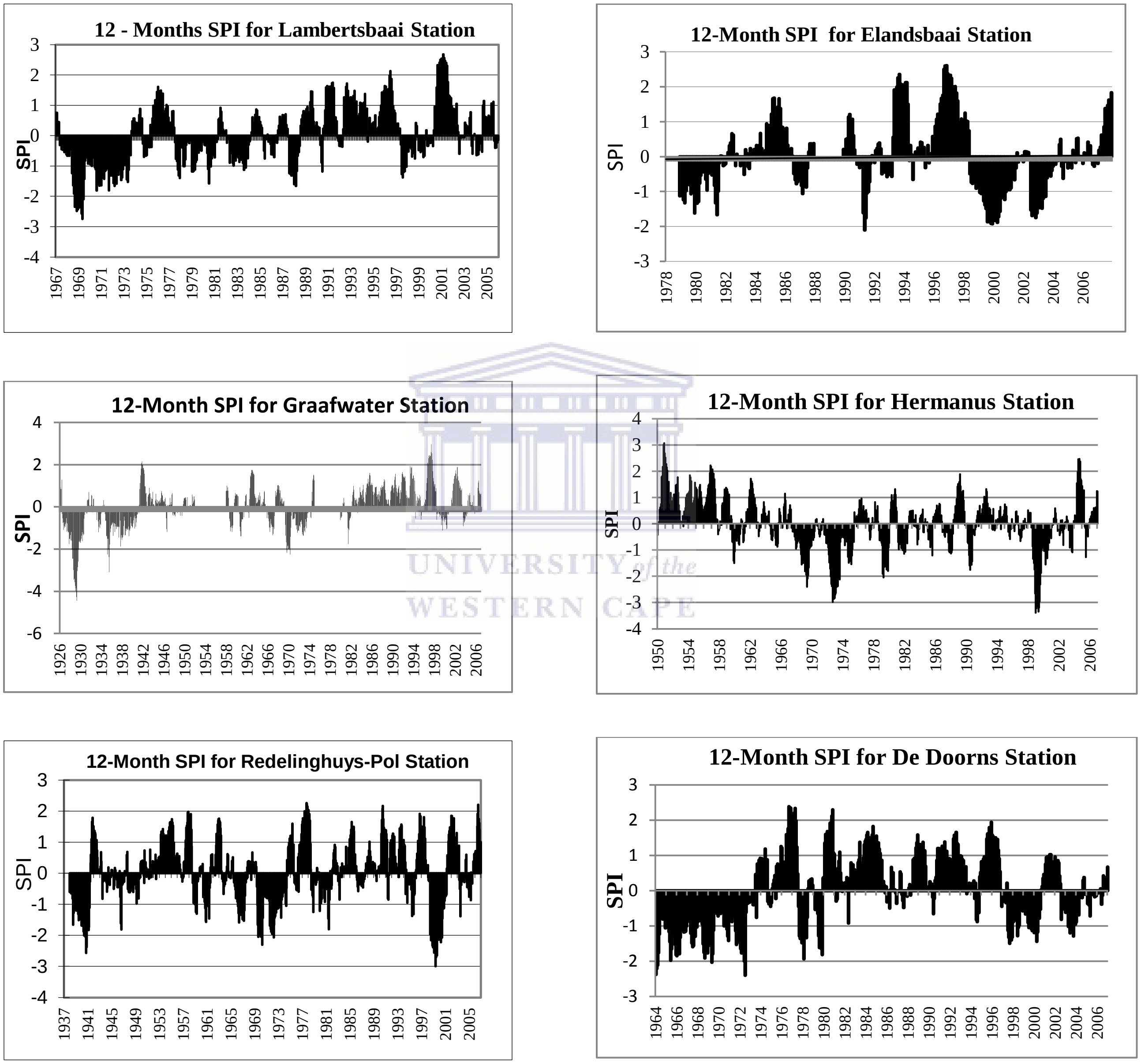

Figure 5.5: 12-Month SPI plots for some rainfall stations in the Olifants and Breede Catchments

In the Little Karoo area of the Gouritz catchment the SPI analysis were done on records from rainfall stations in the Little Karoo Rural Water Supply Scheme (KKRWSS) (Figure 5.6).

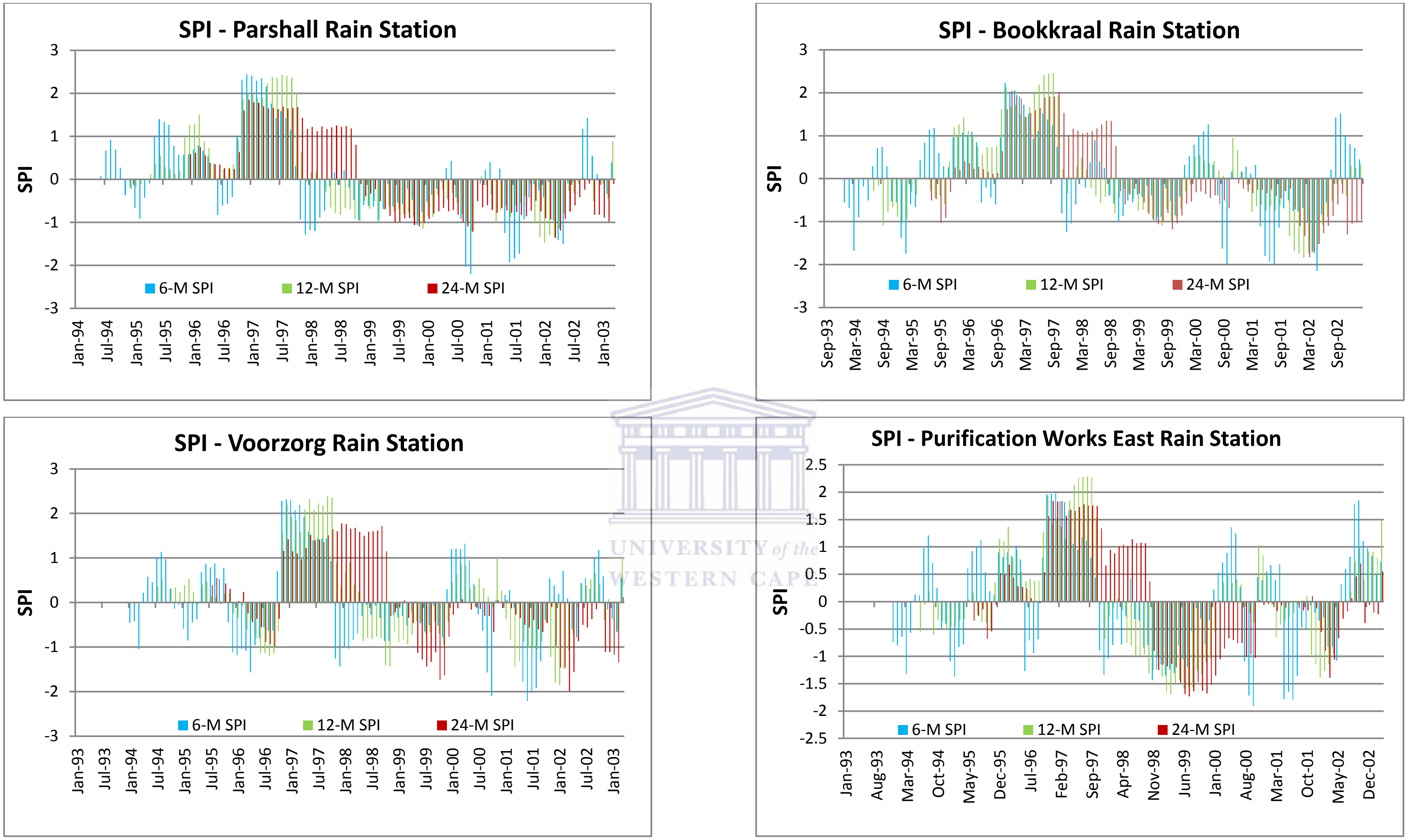

Figure 5.6: Comparative variations of 6-, 12- and 24-month SPIs for rainfall stations in the KKRWSS project area.

The results of the 6-month, 12-month and 24-month SPIs are compared on the plots to assess the impacts of the different time scales on the analysis. The shorter time scale which represents the seasonal variations has higher SPI values and reflects all the short-term variations in the weather. The longer time scales reflects the long-term effects of the weather and tend to have lower SPI values. The SPI values of a longer time scale could be higher if the rainfall totals are also high. This would reflect the effect of long duration rainfalls which also come with high intensity. This would have more impact on recharge to groundwater than the shorter time scale which impacts on surface runoff and soil moisture.

The duration of a drought or otherwise depends on the time scale selected, only severe (long duration and high intensity) conditions are reflected in all time scales such as the wet spell between January, 1997 and January, 1998 which was reflected in all the time scales and all the stations. The period between January, 1999 and January, 2000 also show a severe dry condition in all the time scales and in all the stations. The period of low rainfall from January, 1999 in the Little Karoo area together with groundwater abstraction greatly contributed to the decline in water levels in the well fields. Some of the production wells have continued their decline in water levels in spite of reduction in abstraction rates over recent times. The results of the SPI analysis in this study have shown that there are wide variations in rainfall records in most of the stations which could be attributed to climate variability. It is still not very clear if the variations are increasing with time. With the results of the autocorrelation analysis the present trend cannot be used to predict the future trend of rainfall in the region. Increases in wet conditions in recent years in the Olifant and Breede catchments would have a positive impact on groundwater recharge. Higher temperatures would however, increase evapotranspiration which would in turn reduce direct recharge. In the Gouritz catchment there have been more drought effects in recent years resulting in reduced recharge which together with groundwater abstraction have resulted in massive groundwater level declines the area.

5.4.1 SPI and groundwater fluctuations

In this study the different time scales of SPI values from rainfall datasets were correlated with groundwater level data from boreholes. The Department of Water Affairs (DWA) maintains the National Groundwater Database (NGDB) and Hystra Database of groundwater levels for several boreholes in South Africa but most of the data contain missing gaps. Several groundwater level data were obtained from DWA database (NGDB and Hydstra). After compilation of the data into time series several of them could not be used due to their short span and and/or many gaps. In all about 65 groundwater level data were compiled and less than half were of good quality. Two each of water level data from the Olifants and Breede catchments could be used while several good quality water level data from the Gouritz catchment were used to correlate rainfall data. The SPI plots from the rainfall time series were correlated with the suitable water level time series of considerable time span. The 6-month, 12-month and 24-month SPI plots were used in the correlations. There were no apparent correlations between the water levels and SPI plots from the two datasets in the Olifants catchment (Graafwater and Elandsbaai). The plots between the SPI and water level time series for the two stations from the Breede catchment are presented in figures 5.7 and 5.9. Figure 5.7 is the water level plotted along with the 6-month, 12-month and 24-month SPI from the De Doorns station. A considerably good correlation can be observed between the water level and the SPI curves. The only available water level data was between 1982 and 1993 as shown in figure 5.7.

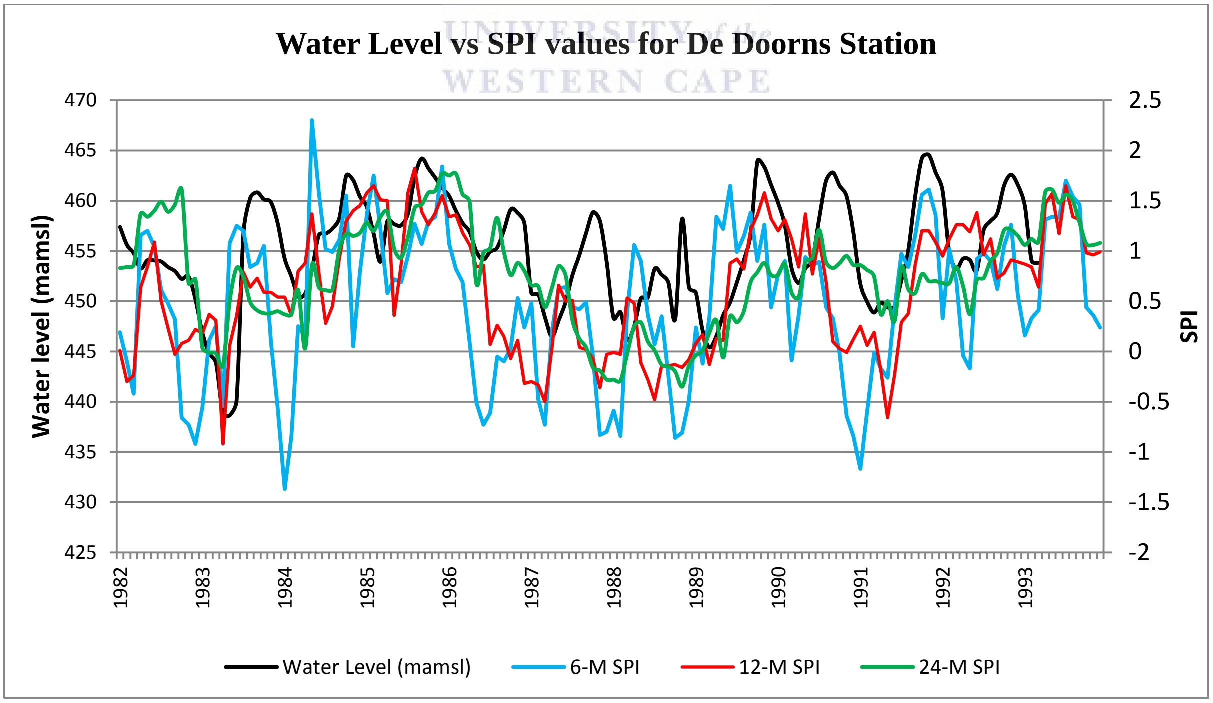

Figure 5.7: Water level vs 6, 12 and 24-Month SPI for De Doorns Rain Station

To examine the relationship between the water level and SPI curves, a linear regression analysis and correlation was done. A linear regression estimates a linear equation that describes the relationship, whereas correlation measures the strength of that linear relationship. Figure 5.8 shows the scatter plots for the water level and the 6-month, 12-month and 24-month SPIs.

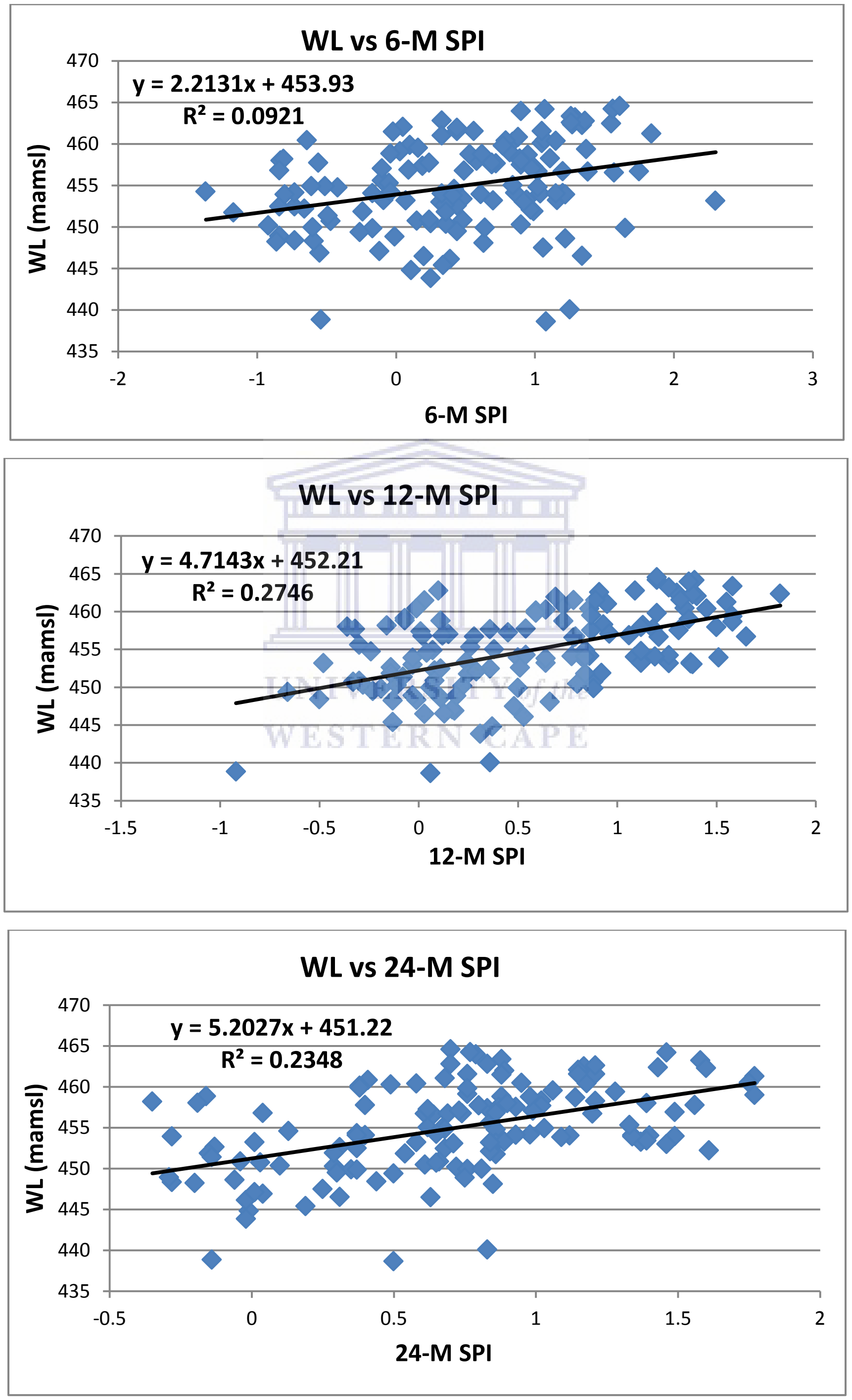

Figure 5.8: Linear regression between Water Level and SPIs from De Doorns station

The coefficient of determination, R^2, measures the percentage of variation in the values of the dependent variable (in this case, water levels) that can be explained by the change in the independent variable (SPI). From figure 5.8, the value of the coefficient is highest for the 12-month SPI ($R^2 = 0.275$). This means about 27% of the variation in Water levels can be explained by the change in the 12-month SPI. The 12-month SPI shows the strongest correlation with the water levels. Correlation indicates the relationship between two variables without assuming that a change in one causes a change in the other. The results of the correlation analysis between the water levels and the SPIs are presented in Table 5.7.

Table 5.7: Results of Correlations between Water Level and SPIs for De Doorns

		6-MTH SPI	12-MTH SPI	24-MTH SPI
WATER LEVEL	Pearson Correlation	.304**	.524**	.485**
	Sig. (2-tailed)	.000	.000	.000
	N	135	135	135
WATER LEVEL	Spearman Corr Coeff	.333**	.508**	.509**
	Sig. (2-tailed)	.000	.000	.000
		135	135	135

**. Correlation is significant at the 0.01 level (2-tailed).

Results showed the strongest correlation is (+0.524) with the 12-month SPI. The correlation is average but significant at the 0.01 level. The Pearson correlation is very similar to the slope of the regression line, except that the correlation is designed to measure the strength of the linear relationship. The slope can be any real number, but the correlation must always be between -1 and +1. A correlation of +1 means that all the data points fall perfectly on a line of positive slope and a correlation of -1 means the data points all fall on a line of negative slope. If correlation, *r*, is +1 or -1, then the equation for the line can be used to predict *y* perfectly from *x*. Highly correlated data will fall close to a straight line, and then we should be able to predict y from x with accuracy. However, if the correlation is 0, then the slope of the line is 0, which means the line is horizontal. Then no prediction can be made as all values of *x* will give be the same value for *y*. A correlation near 0 means a weak linear relationship, and a correlation near +1 or -1 means a strong linear relationship. Having a significant correlation also mean that the null hypothesis of 0 correlation is rejected.

In figure 5.9 the water levels from the Hermanus station are plotted with the 6-month, 12-month and 24-month SPIs. The correlations are low as shown by the linear regression equations of the scatter plots in figure 5.10.

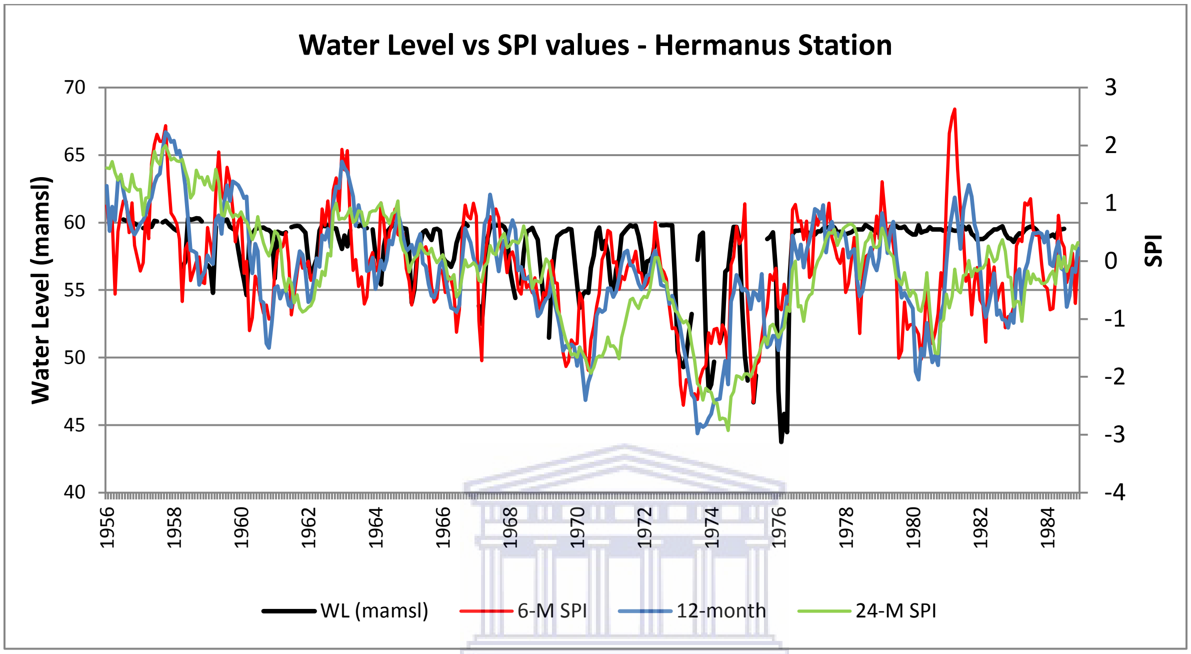

Figure 5.9: Water level vs 6-M, 12-M and 24-M SPIs for the Hermanus station

The SPI values show a wet period of decreasing trend from 1956 to 1961. Between 1968 and 1978 was a period of drought in the region even though there was rain in some intervening years. Rainfall amounts returned to normal after 1978. The groundwater levels show fluctuations of about 5m throughout the period from 1958 to 1972 until the height of the drought period when the level went down about 15m (1976). With increasing rainfall after this period water levels remained fairly constant with little or no stress. The water level data was from an observation borehole. The regression analysis between the water level and SPI results are shown in figure 5.10. The 24-month SPI had the highest coefficient of determination, R^2 = 0.18 and therefore the strongest correlation with the water level data even though all the results generally show low correlations between water levels and SPI values. The results indicated that less than 20% of the variations in the Water levels can be explained by the change in the SPI values of all the time scales.

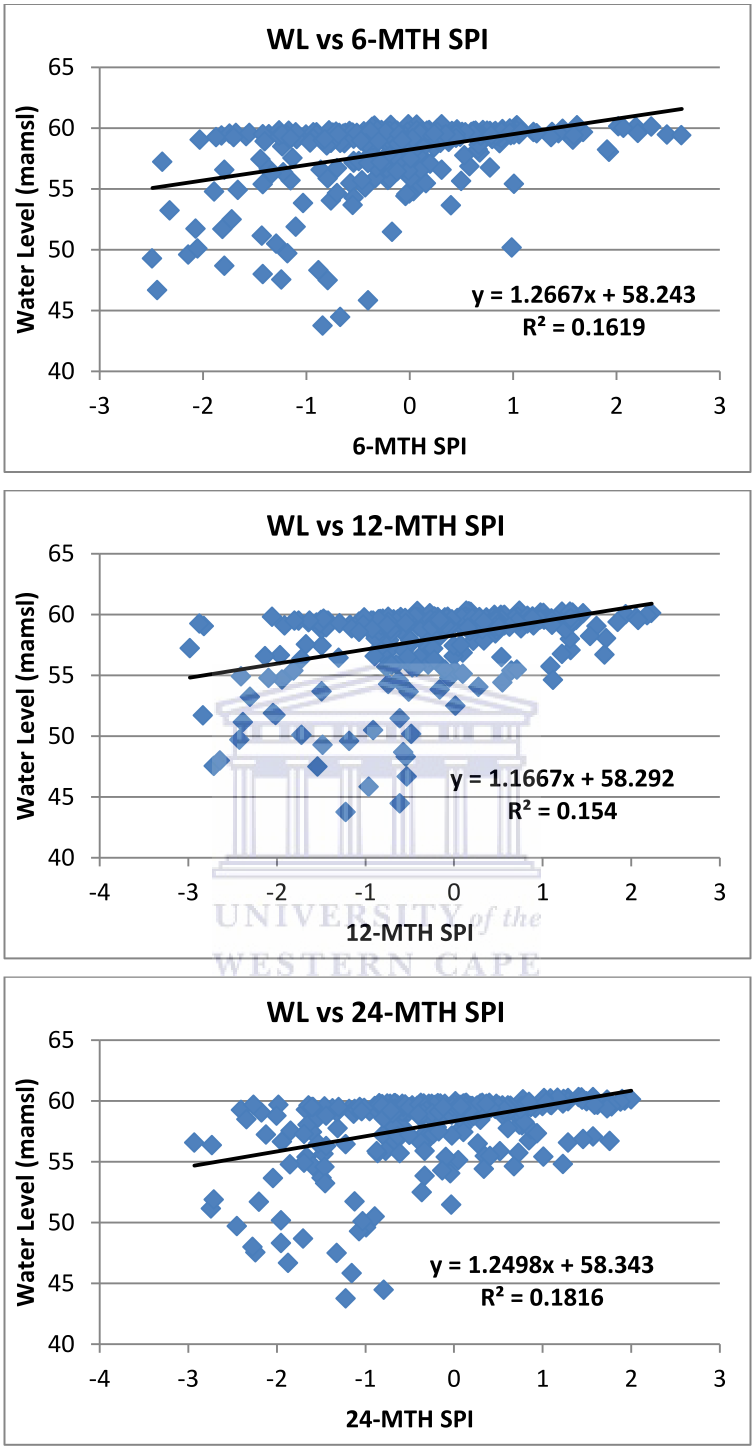

Figure 5.10: Linear regression between Water Level and SPIs from Hermanus station

The results of the correlation analysis are shown in Table 5.8. The strongest correlation of the water levels is with the 24-month SPI data. From Table 5.8, it appears the Spearman's correlation coefficient gave better results than the Pearson correlation.

Table 5.8: Results of Correlations between Water Level and SPIs for Hermanus

		6-MTH SPI	12-MTH SPI	24-MTH SPI
WATER LEVEL	Pearson Correlation	.402**	.392**	.426**
	Sig. (2-tailed)	.000	.000	.000
	N	315	315	315
WATER LEVEL	Spearson's Corr Coeff	.417**	.405**	.427**
	Sig. (2-tailed)	.000	.000	.000
	N	315	315	315

**. Correlation is significant at the 0.01 level (2-tailed).

The Spearman's statistic is the non parametric equivalent test for correlation. In this case, the observed values are replaced with their ranks and the statistic test (Pearson correlation *r*) is calculated on the ranks. Spearman's rank correlation, like other non parametric tests, is less susceptible to the influence of outliers and is better than Pearson's correlation for nonlinear relationships. On the other hand, it is not as powerful as the Pearson correlation in detecting significant correlations in situations where the assumptions for linear regression are satisfied. The correlations were not strong but were significant at the 0.01 level. Other correlations of water levels with SPI from the Gouritz catchment are presented in the Appendix. In general the correlations of the water level data and SPIs are not strong enough to predict water levels from SPI data without errors. Predictions can only be made in situations where good correlations between the SPI and water levels exist.

The weak correlations of water levels with SPI plots showed that groundwater levels from the study area could not be solely explained from the change in variation of rainfall. This appears to be the situation with several aquifers in hardrock terrain especially when unconfined conditions are envisaged. The largely consolidated and fractured aquifers often have indirect hydraulic connections with the surface processes. This means recharge from rainfall in the catchment could take considerable time to reach the aquifer though complex flow paths and large quantities may be removed by interflow or by evapotranspiration before they can reach the aquifer. The aquifers are largely influenced by a complex fracture system that control water movement within the system. Some of the aquifers are also under confined conditions by overlying Cedarberg formation and their sources of recharge may be distant from the catchment.

5.4.2 Time Lag between Rainfall and Recharge

The study was aimed at identifying aquifers which had good correlation between the water level and rainfall using the SPI plots and if possible to identify the time lag between rainfall and recharge through the different time scales of the SPI. Meyer (2005) analysed South African groundwater level data using the SPI with the 24-month time scale. In his examples where groundwater level data were correlated with the SPI a remarkably good correlation was obtained for two datasets over the entire record period in both cases. A good correlation between groundwater level and both macro and micro changes in SPI were shown to exist even though he did not make a regression analysis nor calculate the correlation coefficient between the datasets. Meyer (2005) concluded that for both cases in his example the time lag between rainfall and recharge to groundwater was about 24 months. He also indicated that for many of his analysis, there were no clear correlation or only very weak correlations existed. In the examples shown above the correlation coefficient obtained between water levels and SPI for De Doorns and Hermanus datasets were 0.52 and 0.43 respectively. The correlations were not very strong even though they were very significant at the $\alpha = 0.01$ level. In both cases an analysis of time lag was done using the monthly rainfall values and the water levels taken on or about the same time of the month. Results showed that an 8 month and 9 month time lags gave the best correlations between rainfall and water levels for De Doorns and Hermanus respectively. Tables 5.9 and 5.10 present the summary of results of the correlation analysis for both De Doorns and Hermanus respectively. The time analysis showed weak but significant correlations between rainfall values and water levels. As already indicated earlier, weak but significant correlations indicate that only certain percentage of the variations in water levels could be explained by variations in rainfall as the independent variable in this situation. It appears at this stage that each analysis has their own unique characteristics and generalizations could not be made for other stations based on outcomes of certain stations. Results showed the complex nature of the terrain as discussed above. Wu (2005) attempted to find time lags between rainfall and water levels using Cumulative Rainfall Departure (CRD) and Cumulative Water level Departure (CWD) with data from the Vermaaks River Well field in the Kammanassie area and found that most of the patterns were not clear for predictions. He however found time lags of between 45 and 52 months for some boreholes water level and rainfall. These results were highly disputed to be on the high side. Based on this study the lag time appears to be between 6 and 24 months in most of the area.

Table 5.9: Summary output for 8 month time lag between Rainfall and Water Level for De Doorns

Regression Statistics								
Multiple R	0.3391793							
R Square	0.1150426							
Adjusted R Square	0.1076679							
Standard Error	5.2284949							
Observations	122							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	426.45264	426.45264	15.599743	0.000132525			
Residual	120	3280.459	27.337158					
Total	121	3706.9117						
	Coeffs	*Std Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	452.96999	0.6312515	717.57455	7.98E-220	451.7201538	454.21982	451.720154	454.2198217
29	0.0540364	0.0136813	3.949651	0.0001325	0.026948351	0.0811244	0.02694835	0.081124418

Table 5.10: Summary output for 9 month time lag between Rainfall and Water Level for Hermanus

Regression Statistics								
Multiple R	0.24952154							
R Square	0.062261							
Adjusted R Square	0.0591559							
Standard Error	2.833146							
Observations	304							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	160.945542	160.945542	20.05123101	1.07027E-05			
Residual	302	2424.06831	8.02671624					
Total	303	2585.01385						
	Coeffs	*Std Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95%*	*Upper 95%*
Intercept	57.0698866	0.27150064	210.201663	0	56.53561398	57.6041591	56.535614	57.60415914
X Variable 1	0.01946119	0.00434609	4.47786009	1.07027E-05	0.010908733	0.02801365	0.01090873	0.028013647

5.5 The Response of Groundwater Flow Dynamics to Climate Change and Variability

The TMG aquifer is a regional aquifer system comprising deep, shallow and coastal aquifers. The impacts of climate variability and climate change on the different aquifers are numerous and varied. Figure 5.11 shows a conceptual model of the TMG aquifer types.

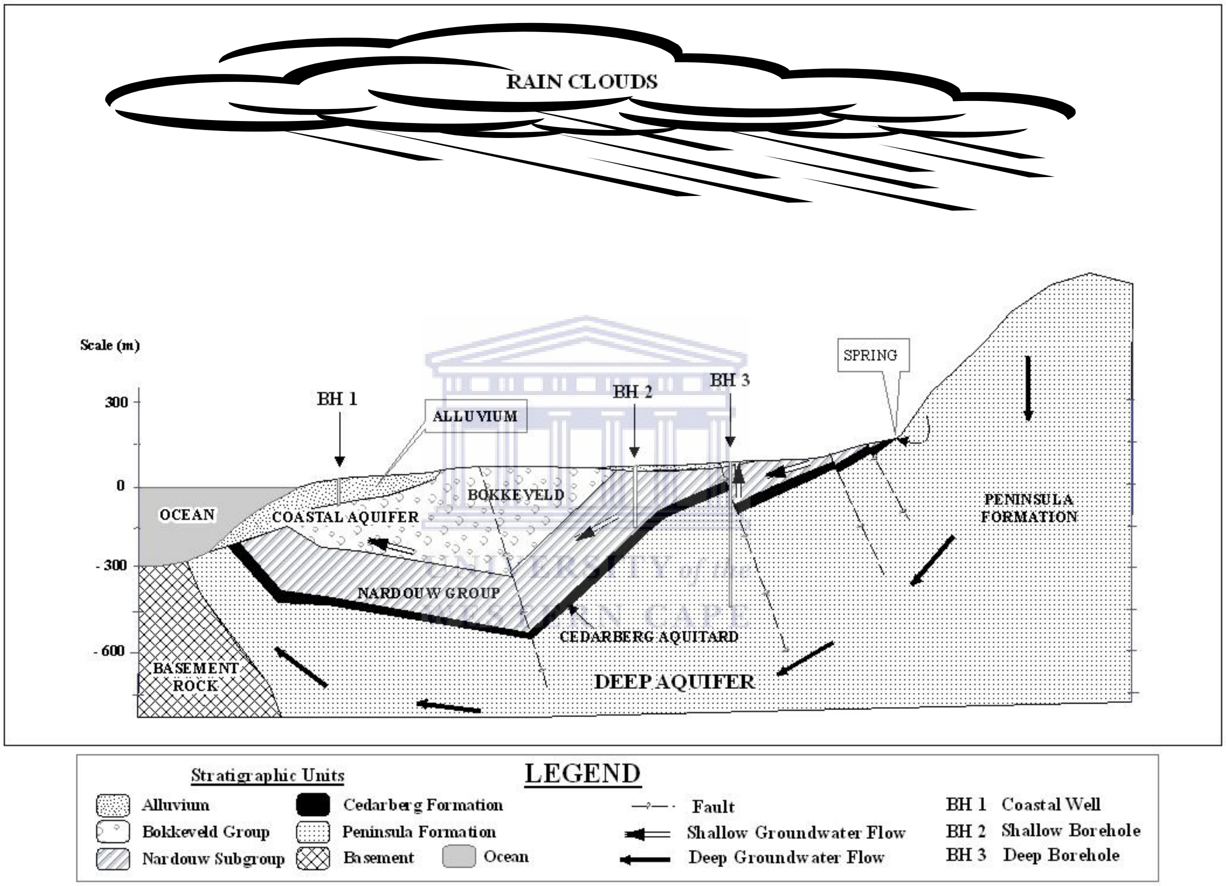

Figure 5.11:A conceptual model of the different aquifers in the TMG

Precipitation is the primary source of recharge hence any changes in precipitation distribution in terms of amount and variability will eventually be transferred to the recharge regime. How changes in precipitation and temperature affect aquifer recharge depend on the hydrogeological regime i.e. the type of aquifer and the flow dynamics involved. In semi-confined and confined aquifers, recharge not only occurs in a vertical but predominantly in a horizontal direction. The distance from the recharge area, aquifer transmissivity and storativity therefore are all major factors that contribute to the water-level rise at a given point in an aquifer. The farther away a point is from the recharge area, the more delayed and lesser is the response of the water level to recharge. Most aquifers in the TMG are fractured aquifers where storage of groundwater is mostly confined to fractures, faults and joints rather than the rock matrix. Permeability and storativity depend on the amount of fractures and joints which vary considerably with depth. Hence lower or deeper aquifers can take several months or years to respond to a recharge event. Abstractions impose additional stresses on water levels causing further decline. The further drop in water level will depend on the amount of abstraction and storativity of the aquifer.

The impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature, sea level rise and precipitation variability. The United Nations *Intergovernmental Panel on Climate Change* (IPCC) assesses scientific, technical and social-economic information concerning climate change, its potential effects and options for adaptation and mitigation. In the Fourth Assessment Report (AR4) of the IPCC, the working group II (Kundzewicz *et al*, 2007) on impacts, adaptation and vulnerability projected that:

- Sea-level rise will extend areas of salinisation of groundwater and estuaries, resulting in a decrease in freshwater availability for humans and ecosystems in coastal areas.
- Increased precipitation intensity and variability is projected to increase the risks of flooding and drought in many areas.
- Increased precipitation intensity, and longer periods of low flows will exacerbate many forms of water pollution, with impacts on ecosystems, human health, water system reliability and operating costs.

Semi-arid and arid regions are particularly exposed to the impacts of climate change on freshwater. Climate change may also lead to vegetation changes which affect groundwater recharge. Climate variability and climate change affect different types of aquifers in different ways either directly or indirectly. Generally there are two types of groundwater resources – renewable and non-renewable. Renewable groundwater is derived from shallow aquifers and non-renewable groundwater supplies are usually derived from deep aquifers. Shallow aquifers are directly tied to the near-surface hydrologic processes and thus intricately tied to the overall hydrologic cycle and could be directly affected by climate change. In many places, the overdraft of renewable groundwater aquifers occurs because the rate of withdrawal exceeds the rate of recharge. In fact, renewable groundwater supplies are often thought of being the same resource as surface water because they are so intertwined. Thus, climate changes could directly affect these recharge rates and the sustainability of renewable groundwater. Non-renewable groundwater supplies are usually derived from deep earth sediments deposited long ago and so have little climatic linkage.

5.5.1 Impacts on Shallow Aquifers

There is evidence that flooding is likely to become a larger problem in low land areas requiring adaptation (IPCC, 2007). Floods and droughts projected to result from climate change could present potential challenges to shallow aquifers in terms of the quality and quantity of the groundwater resources. Climate change is likely to alter the hydrologic cycle in ways that may cause substantial impacts on freshwater resource availability and changes in water quality. For example, the amount, intensity and temporal distribution of precipitation are likely to change. The most likely will be an increase in global average precipitation and evaporation as a direct consequence of warmer temperatures. Evaporation will increase with warming because a warmer atmosphere can hold more moisture and higher temperatures increase the evaporation rate. On average, current climate models suggest an increase of about 1%–2% per degree Celsius from warming forced by CO_2 (Allen and Ingram, 2002). An increase in global average precipitation does not mean that it will get wetter everywhere and in all seasons. In fact, all climate model simulations show complex patterns of precipitation change, with some regions receiving less and others receiving more precipitation than they do now; changes in circulation patterns will be critically important in determining changes in local and regional precipitation patterns. Many have argued that, in addition to changes in global average precipitation, there could be more pronounced changes in the characteristics of regional and local precipitation due to global warming. For example, Trenberth *et al*. (2003) hypothesized that, on average, precipitation will tend to be less frequent, but more intense when it does occur, implying greater incidence of extreme floods and droughts, with resulting consequences for water storage. Thus, the prospect may be for fewer but more intense rainfall events.

Equally important is the changes in run-off that could arise from the fact that the amount of water evaporated from the landscape and transpired by plants will change with changes in soil moisture availability and plant responses to elevated CO_2 concentrations. This will affect stream flows and groundwater elevations. Run-off changes will depend on changes in temperature and precipitation, among other variables. Arnell (2003) used several climate models to simulate future climate under differing emissions scenarios. The study linked these climate simulations to a large-scale hydrological model to examine changes in annual average surface run-off by 2050. Warburton and Schultz (2005) anticipated decreases in streamflow in the winter rainfall region of South Africa which includes most of the TMG area from simulations with the regional ACRU model. Most of these simulations which yield a global average increase in precipitation likewise exhibit substantial areas where there are large decreases in run-off. Thus, the global message of increased precipitation clearly does not readily translate into regional increases in surface and groundwater availability. Thus shallow aquifers which are in direct interaction with surface water processes are more likely to be affected by higher temperatures causing reductions in groundwater availability than the advantages any increases in precipitation could bring about.

5.5.2 Impacts on Coastal Aquifers

Coastal regions are generally water-scarce (less than 10% of the global renewable water supply) and are under rapid population growth (Small and Nicholls, 2003; MEA, 2005). In coastal aquifers saline intrusion due to excessive water withdrawals is expected to be exacerbated by the effect of sea-level rise, leading to even higher salinisation and reduction of freshwater availability (IPCC, 2007). Increased recharge from adjoining highlands (mountain front recharge) in areas such as the Cape Peninsula and the Overberg on the other hand could lead to lowland inundation and wetland displacement. Shallow aquifers in coastal areas are particularly prone to floods during high rainfall events leading to water quality problems as have occurred in recent times in the Cape coast region. Heavy precipitation events may result in increased leaching and sediment transport, causing greater sediment and non-point source pollutant loadings to watercourses. Floods, in particular, increase the risk of water source contamination from sewage overflows, agricultural land, and urban run-off. In regions where intense rainfall is expected to increase, pollutants (pesticides, organic matter, heavy metals, etc.) will be increasingly washed from soils to water bodies. Higher runoff is expected to mobilise fertilisers and pesticides to water bodies in regions where their application time and low vegetation growth coincide with an increase in runoff.

In arid and semi-arid regions, increased evapotranspiration from increasing temperatures will lead to further salinisation of shallow coastal aquifers. Where stream flows and lake levels decline, water quality deterioration is likely as nutrients and contaminants become more concentrated in reduced volumes. Warmer water temperatures may have further direct impacts on water quality, such as reducing dissolved oxygen concentrations. Prolonged droughts also tend to allow accumulation of contaminants on land surfaces, which then pose greater risks when precipitation returns.

5.5.3 Impacts on Deep Aquifers

Climate change may not affect deep aquifers directly due to the fact that they are generally removed from contact with the atmosphere however, indirect impacts are envisaged. There is the likelihood of increased abstraction from deep aquifers due to increased demand for groundwater from increased water use as a result of increased population. Another reason may be the need to offset declining surface water availability due to increasing precipitation variability in general and reduced summer low flows. In areas where shallow aquifers get contaminated due to flooding, or with reduced water availability in shallow aquifers due to reduced recharge rates, more attention will be directed to deep aquifers to offset the deficit.

5.5.4 Timing of Recharge and Aquifer Properties

Although climate change is set to affect groundwater recharge rates and groundwater levels, knowledge of current recharge in relation to groundwater availability, vulnerability and sustainability is still limited. Two important factors serve to complicate and limit our understanding and ability to measure these potential impacts directly; the timing of recharge and aquifer properties (Environment Canada, 2004). While surface waters typically see rapid response to climate variability, the response of groundwater systems is often difficult to detect because the magnitude of the response is lower and delayed. Longer-term variations in climate are often well preserved in aquifers. Thus, the magnitude and timing of the impact of climate variability and change on aquifers, as reflected in water levels, are difficult to recognize and quantify. This is because of the difference in time frame that exists between climate variations and the aquifer's response to them. In the TMG study area the shallow aquifers are mostly found in the overlying Nardouw formation whiles the deeper aquifers usually occur in the deep seated Peninsula formation as described earlier in chapter 3. Different types of aquifers in terms of composition and properties respond differently to surface stresses. Shallow aquifers usually weathered and unconsolidated sediments often have a quicker response to changes in the climate. Water levels in such aquifers take a few days to a few weeks to respond and often depicted by sharp variations in water levels. The deeper aquifers tend to be more isolated from surface conditions by overlying aquitards. The response of deep consolidated and fractured aquifers to changes in climate variables can take several months to decades to show.

Shallow aquifers are affected by local climate variability through land use changes and surface processes, whereas water levels in deeper aquifers are likely to be affected by regional climate changes. Therefore, climate variability, being of relatively short term compared to climate change, will have greater impact on the unconsolidated aquifer systems. In contrast, consolidated aquifers have an increased capacity to buffer the effects of climate variability, and are therefore able to preserve the longer-term trends associated with climate change.

5.6 Summary

There is much concern in the world about global climate change and its impacts on almost all sectors of life. There are natural and anthropogenic causes of climate change. The natural external causes include variations in the amount of energy emitted by the Sun, changes in the distance between the Earth and the Sun, and the presence of volcanic pollution in the upper atmosphere. Internal variations of the climate system also produce fluctuations, through the feedback processes that connect various components of the climate system (Appleton 2003).

Alternating dry and wet years associated with the 21-year periodicity of the double sunspot cycle have been well documented (Alexander *et al.* 2007) with floods and droughts occurring at the beginning and end of the period, respectively. Other authors such as Bailey (2006) and Bredenkamp (2008) have suggested that rainfall and river flows in South Africa are much higher during the first half-period of the double sunspot cycle than they are during the second half-period. Much of recent rapid changes in climate have however been attributed to human interventions by the upsurge in global atmospheric concentrations of green house gases notably, carbon dioxide, methane and nitrous oxide. The expected impacts of climate change on water resources including groundwater have been widely discussed. Temperature increases are worldwide however; precipitation decreases or increases are highly variable in time and space. Trend tests in the Western Cape region have shown gradual increases in temperature over recent years while generally no significant trends have been observed with precipitation amounts. Variations in precipitation patterns however have been observed such as the intensity, duration and shifts in seasons. Frequent floods and droughts are likely to affect the region. The high temperatures in the atmosphere can cause droughts during the summer whiles in the winter the atmosphere can absorb more moisture and cause floods. The implications of these changes on freshwater resources either directly or indirectly are of much concern to all. Responses to climate variations by surface water resources are fast and intense however groundwater response is much delayed even though it is likely to be affected indirectly by the absence of fresh surface water resources. Semi-arid and arid regions of developing countries are particularly vulnerable to impacts of climate variations and there is an urgent call for mitigation and adaptation measures to sustainably utilize our freshwater resources particularly the groundwater.

Climate change is likely to alter the hydrologic cycle in ways that may cause substantial impacts on freshwater resource availability and changes in water quality. For example, the amount, intensity and temporal distribution of precipitation are likely to change. The most likely will be an increase in global average precipitation and evaporation as a direct consequence of warmer temperatures. Shallow aquifers are likely to suffer reduction in groundwater availability due to global increases in temperatures than any likely increase in precipitation. In coastal aquifers saline intrusion due to excessive water withdrawals is expected to be exacerbated by the effect of sea-level rise, leading to even higher salinisation and reduction of freshwater availability. Droughts and floods are likely to bring about deterioration in groundwater quality in shallow and coastal aquifers due to increased leaching and sediment transport, causing greater sediment and non-point source pollutant loadings to watercourses. Floods, in particular, increase the risk of water source contamination from sewage overflows, agricultural land, and urban run-off.

CHAPTER 6 SUSTAINABLE UTILISATION OF GROUNDWATER RESOURCES – A CASE STUDY OF THE KLEIN KAROO RURAL WATER SUPPLY SCHEME (KKRWSS).

6.1 Introduction

The potential for the TMG aquifers to supply bulk water for domestic and irrigation needs as well as sustain ecological and environmental water requirements has been adequately demonstrated in the previous sections and in other reports. The challenge however is to ensure a more pragmatic utilization of the water resources to cater for the present populations of life forms that depend on it as well as protecting enough of it for future users. “Every drop counts,” is a common adage for water use and as human populations continue to grow and climatic changes become uncertain there must be better ways of managing the dwindling fresh water resources available for use by all. As groundwater moves from the recharge area toward the discharge area (e.g. a river), it constantly flows through the storage volume which may take a few hours to several decades. If the groundwater is abstracted by a well before it reaches the discharge area then less water will flow toward the river. This phenomenon causes perennial rivers to become seasonal and sometimes wetlands diminish or completely dry up. One important fact is that most groundwater systems are in dynamic interaction with surface water resulting in some kind of a dynamic equilibrium. Once the groundwater is removed it may take several years for a new equilibrium to be established and certain species that depended on it may not have survived the process. The concept of sustainability and approaches toward its implementation taken by some groups and governments were reviewed earlier in chapter two. In this chapter we look at a practical approach to dealing with a water supply scheme that has attracted attention in many ways than its fare share of problems. The KKRWSS was selected as a case study because of the extensive research that has been done in the area in the past years since the project began. The many research studies done on the scheme include aquifer tests, water balance and estimation of recharge and response of the aquifer to long-term continuous pumping using numerical modeling among others. All of these studies have provided a lot of knowledge and understanding into the aquifers potential to provide bulk water supply as well as its vulnerability to continuous unsustainable abstraction. The water levels in the most productive boreholes continue to fall in spite of all the knowledge and experience gained in the past. This short coming of the scheme is the basis for selecting it as a case study on sustainable utilization of a TMG aquifer.

6.2 Background of the KKRWSS Study Area

6.2.1 Topography and Drainage

The study area is located in the Little Karoo area of the TMG in the Western Cape Province (Figure 6.1). The project area between the towns of Calitzdorp and De Rust comprises a broad valley, with an elevation of approximately 500 m (amsl) and surrounded by mountain ranges, the Kammanassie Mountain range with elevation of up to 1950 m (amsl) on the east and the great Swartberg Mountain range in the north of up to 2150 m (amsl). The Rooiberg Mountains occur in the western part of the scheme and down south is the Outeniqua Mountains. The area is drained by two perennial rivers, the Olifants River to the north of the Kammanassie Mountain range and the Kammanassie River to the south (Figure 6.2). One minor but important river, the Vermaaks River drains the Vermaaks River wellfield which is the most important wellfield of the KKRWSS. The Marnewicks River drains the eastern part of the Vermaaks River wellfield. The two minor rivers are ephemeral in the steep upper reaches, with more sustained flow in the lower reaches, and drain northward into the Olifants River. Runoff from the mountains is captured in a number of dams and used for irrigation and water supply to Oudtshoorn. The area falls within seven quaternary catchments that controls the surface water drainage however, the groundwater flow regime is controlled by the boundaries of the geological formations. For example, the Cedarberg formation which is an aquitard and the contact between the Nardouw Subgroup and the Bokkeveld Group act as groundwater flow barriers. There is however an active interaction between the surface water and the groundwater regimes. Jia (2007) calculated the mean annual baseflow as approximately 22% of the mean annual river flow for this area. With the groundwater level decline over the years interaction will be restricted between rivers and the water in the shallow weathered zone.

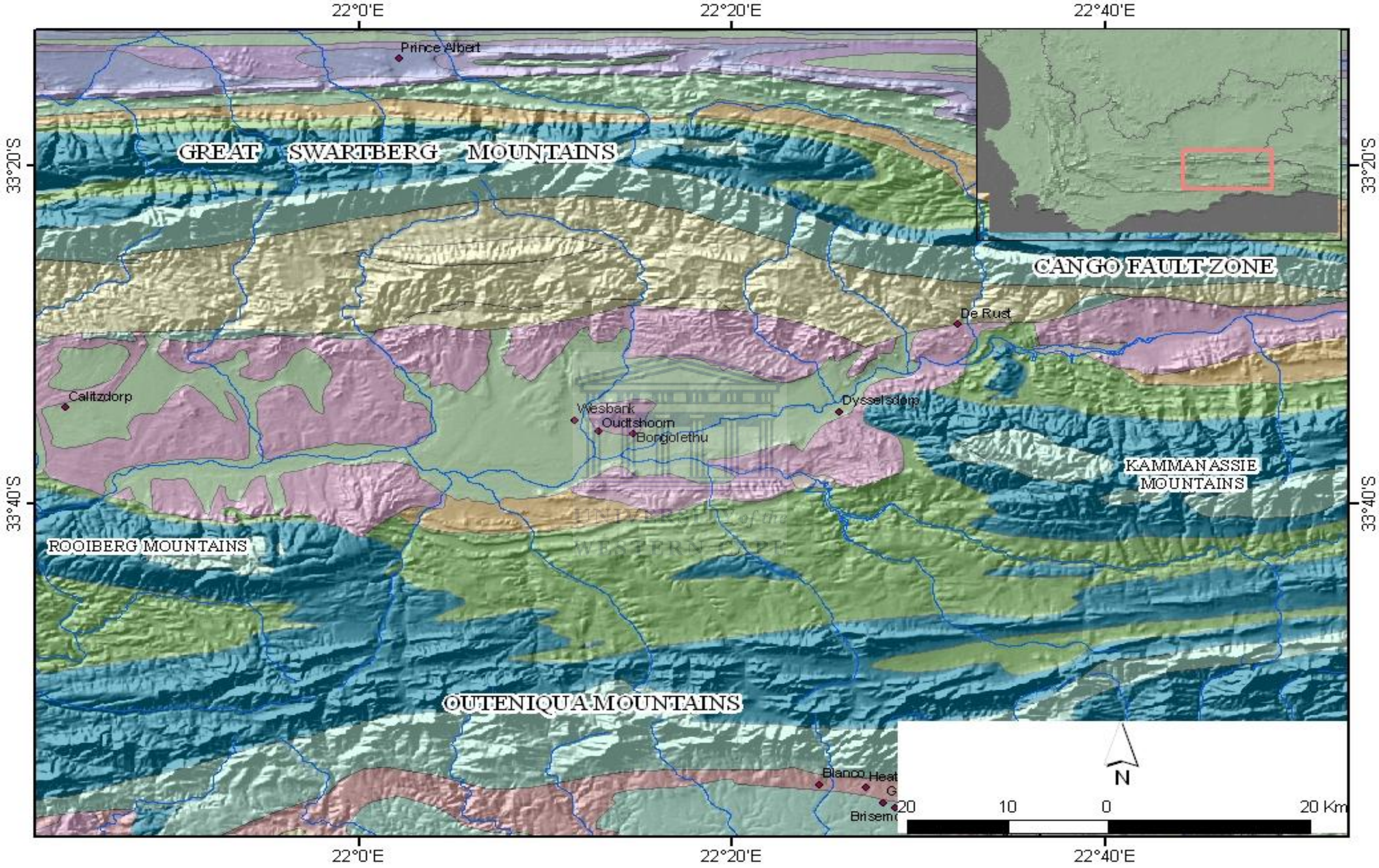

Figure 6.1: Location of KKRWSS area and Kammanassie Mountains

6.2.1.1 Spring flows

Many cold springs that used to flow along the lower western slopes of the Kammanassie range have dried up since the early 1970’s even though some still flow after rainfall events. Three minor hot springs used to flow separately from the valley bottom below the Bokkraal wellfield until the early 1970’s. Two springs emerge along the flow path of the Vermaaks River, one at the mid-slope and the other at the lower-slope. The mid-slope spring ceased flowing due to abstractions from nearby boreholes and subsequent decline of groundwater levels. The lower-slope spring which is perennial is being monitored by a V-notch weir built at the lower reaches of the Vermaaks River. Records of the spring flow from 1994 to 2001 show a moderate (0.576) positive correlation with rainfall and no correlation with groundwater abstraction from the Vermaaks River wellfield. Three major hot springs have been noted in the KKRWSS area, the Calitzdorp hot spring, the Dysselsdorp hot spring and the Toorwater hot spring. The Calitzdorp hot spring occurs at a NE-striking fault between the Nardouw Subgroup sandstones and the Bokkeveld Group shale (Meyer, 2002). The Dysselsdorp hot spring occurred between the intersection of faults from the TMG and the Bokkeveld but has long dried up since the abstraction of groundwater in the TMG nearby. The Toorwater hot spring on the other hand developed along the E-striking Cango fault, where the Peninsula sandstone faulted against the Enon conglomerate of the Uitenhage Group (Jia, 2007).

6.2.2 Climate

The region is characterized by a very large diurnal and seasonal fluctuation in temperature. The daily average minimum and maximum temperatures vary between 15 and 42 ^{o}C for summer and between -3 and 18 ^{o}C for winter. Rainfall in the valley varies between 200 mm at Calitzdorp and 330 mm at De Rust. In the Kammanassie Mountain area the mean annual rainfall ranges from 400 mm at the lower reaches to 800 mm at the upper reaches. Xu et al. (2007) did a comprehensive analysis of five rainfall stations in the area and found almost all of them exhibiting similar temporal patterns. They are the Parshall, Wildebeesvlakte, V-notch, Purification Works East and the Kammanassie Dam rainfall stations. Average annual evaporation ranges from 1760 mm a^{-1} to 2050 mm a^{-1} with 50% less evaporation in the winter (April to September) than in the summer (October to March).

6.2.3 Geology and hydrogeological setting of the Kammanassie Mountain area

The Kammanassie Mountain area of the eastern section of the KKRWSS is about 630 km^2. The TMG formation in the area comprises three blocks of Peninsula outcrops surrounded by the Nardouw Subgroup and the Cedarberg shale formation, the latter forming an effective confining layer between the two sandstone aquifers.(Figure 6.2) The contact between the Nardouw and the adjoining Bokkeveld Group acts as a flow boundary. As described in an earlier section, the Peninsula outcrops usually form the mountainous terrain and receive more recharge. It has less shale content, much higher transmissivity and better water quality than the Nardouw counterpart. The Kammanassie Mountain is a mega-anticline which was reworked while the Nardouw sub-group forms overturned folds together with the Bokkeveld group in the area. The Vermaaks fault cut the mega-anticline along the NW-SE strike. The contact between the Peninsula quartzites and the Cedarberg shale constitute a discharge zone where several springs originate.

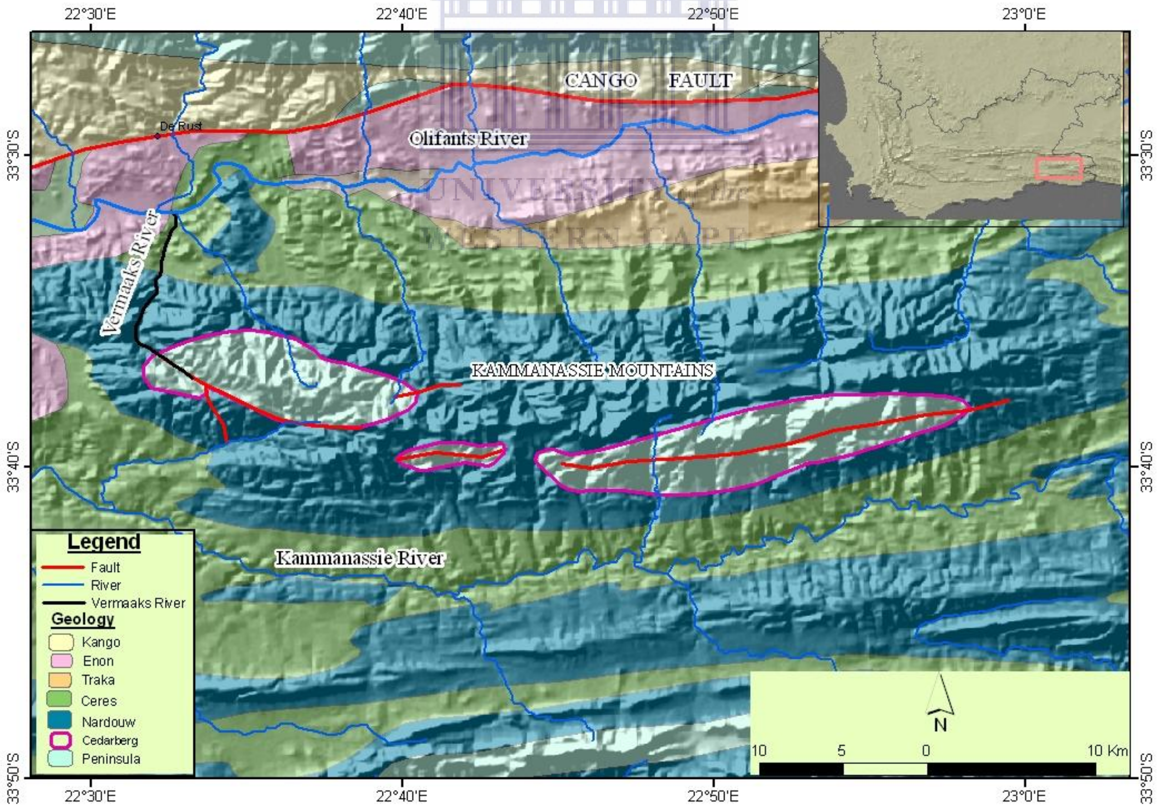

Figure 6.2: Geology map of the Kammanassie Mountain area.

A study carried out by the Council for Geoscience has indicated that two major fracture systems prevail in the Little Karoo area, an E-W striking fault system which consists of long and continuous faults and a N-S striking fault system in which shorter and more discontinuous fractures predominate. Two main fracture orientations are NNW and NNE trending which also form a conjugate set providing extensive opportunities for groundwater storage and flow in the area (Chevallier, 1999). The Vermaaks River valley lies along the 200 m wide and 9 km long Vermaaks River fault fracture zone. The "Vermaaks Keystone Block" was defined in this area due to the high permeability associated with the extensive faulting and a high density of structures concentrate in the block. In the Nardouw Subgroup, NW and NE trending open joints are dominant whiles in the Peninsula Formation E-W trending joints are filled with quartz and N to NE and NW trending joints are mostly open.

6.2.4 Wellfields

The KKRWSS has two sections, the Western Section at Calitzdorp and the Eastern Section at the Kammanassie Mountain area near Dysselsdorp. The Eastern Section is the most productive section of the scheme and also where the highest declines in water levels have been recorded. The KKRWSS was designed to supply up to 4.7×10^6 m^3a^{-1} of groundwater from two sections, the western and eastern sections. The eastern section initially had 13 boreholes of which 5 constituted the Vermaaks River wellfield. There are now 4 production boreholes in the Vermaaks River wellfield. The western section at Calitzdorp had 5 boreholes. Some 400 km of pipeline delivered the groundwater to two purification plants at Dysselsdorp and Calitzdorp before it is delivered to end-users (Jolly and Kotze, 2002). The eastern section is the most important abstraction area of which much attention is given. The unsuccessful boreholes were used for monitoring purposes of which about 27 are in use. The monitoring boreholes are used for different monitoring purposes. For example G40171, G40172 and G40173 are shallow boreholes drilled on the farm Voorzorg 124, upstream of the Cedarberg shale layer, to monitor the inter-relationships between alluvial and TMG groundwater. G40174 was drilled on the farm Rietfontein 142 to monitor the water level responses to abstraction from private production well RN1. Similarly, other monitoring boreholes are in place to monitor responses to abstractions in the different geologic formations. There are other boreholes about which data and information could not be traced. Figure 6.3 shows the location of the various boreholes in the eastern section of the KKRWSS (after Xu *et al*., 2007).

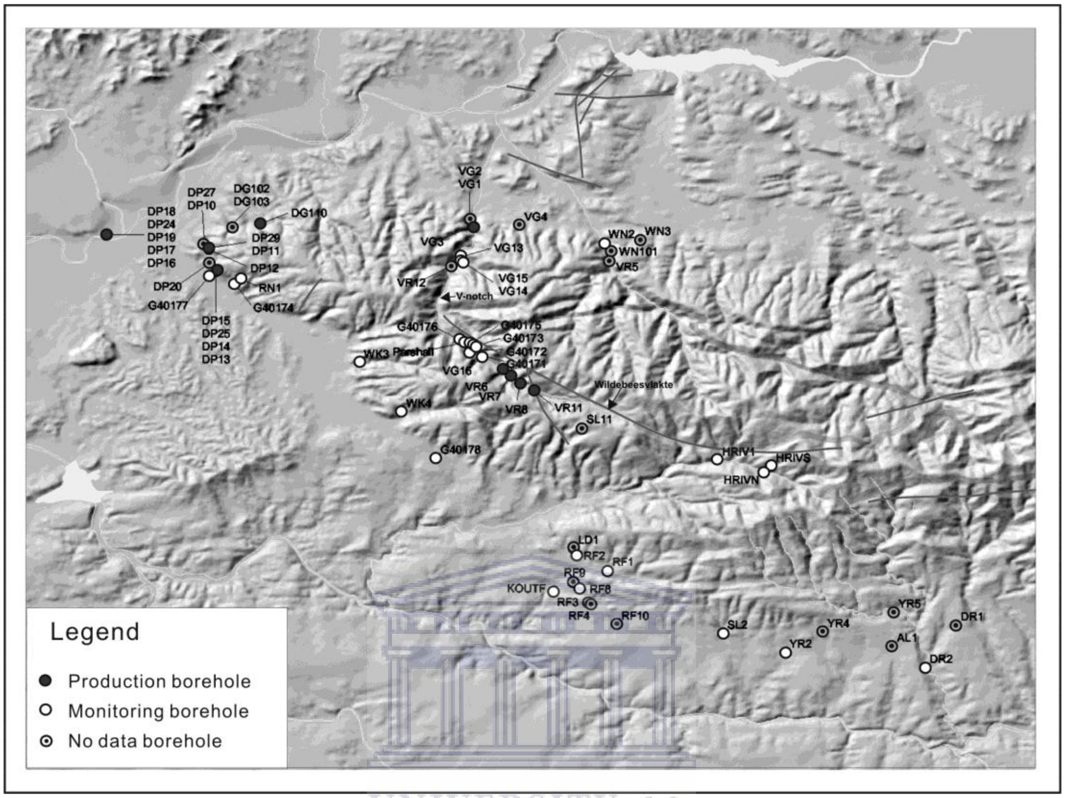

Figure 6.3: The locations of different purpose boreholes in the Kammanassie area.

The Vermaaks River Groundwater Unit (VRGU) forms part of Klein Karoo Rural Water Supply Scheme (KKRWSS) and some 36% of the annual 1.1 x 10^6 m^3 of groundwater abstracted is obtained from the Vermaaks River wellfield. A number of aquifer-tests have been conducted on the production boreholes in this wellfield over the years and evaluated in terms of their 'safe-yield' by various geohydrologists. Since being commissioned in 1993, the performance of the Vermaaks River wellfield has been monitored and therefore it provides a test case to assess the results of the aquifer-test evaluation techniques used to determine the long-term sustainable yield of the wellfield. The VRGU covers an area of approximately 10.85 km^2 and receives a mean annual precipitation (MAP) of 494 mm. The Vermaaks River wellfield consists of four production boreholes, namely; VR6, VR7, VR8 and VR11, which tap a fractured quartzite aquifer in the Peninsula Formation of the TMG. Other production boreholes are located in different wellfields as seen in figure 6.3. Boreholes DP10, DP12 and DP29 were drilled in the

Nardouw at the Varkieskloof wellfield; DP15, DP25 and DP28 drilled at the Bokkraal wellfield and VG3 at Voorzorg are also located in the Nardouw. Even though water levels of the production boreholes at the Vermaaks River wellfield have been declining the responses were not reflected in the monitoring boreholes except for borehole VG16. Table 6.1 is a summary of data on the production boreholes in the eastern section of the KKRWSS. Information on monitoring boreholes is provided in Appendix IV.

Table 6.1: Sumamary of data on production boreholes in the Eastern Section of KKRWSS

Borehole	Wellfield	Depth (m)	Water Level (m)		Water Strike (m)*	Depth of pump (m)	Screen Depth (m)
			First	Now			
VG3	Voorzorg	206.7	6.02	10	110-111(6.0), 190(3.0), 174 (3.0)	148	96.5-206.7
VR6	Vermaaks	250	34.64	60	228-244(15)	165	108.7-230
VR7	Vermaaks	177	63.3	90	78-81(8), 129-140(15)	159	53-177
VR8	Vermaaks	251.3	100.5	125.4	113-117(5) 156-170(4) 234-240(4)	163	89.6-251.3
VR11	Vermaaks	224.5	125.5	151	139(2) 183-194(8) 200-210(10)	180	18-224.5
DP10	Varkieskloof	210	114.07	90.2	183(7)	180	73-210
DP12	Varkieskloof	192	126.07	102.8	?(20)	180	66-192
DP29	Varkieskloof	240	120.6	97.09	160-170(2) 185-?(2)		
DP28	Bokkraal	246	117.8	94.57	122-124(1.5) 151-160(10) 195-210(11)	170	121-207
DP15	Bokkraal	224.5	103.8	86.04	110(3) 169(7) 187(11)	180	50-207
DP25	Bokkraal	203	104.9	83.5	109, 166,201	170	9-203
DG110	Dyselsberg	212	110.6	107.57	114-117(1.5) 137 200-203(6)	200	92-212
DP18	Dysselsdorp	17	3.6	3.2	4.2-9(15)	14	2-9.4

**The first water strike (fracture zone) depth (m), followed by yield, e.g. 110 – 111(6.0), after Kotze, 2002*

6.2.5 Properties of the TMG aquifer in the KKRWSS

The Peninsula aquifer is composed of quartz arenite with very low primary porosity due to cementation and recrystallisation. Rock induration has led to high potential for brittle fracturing during deformation. The high fracture frequency has given rise to secondary porosity. The

Nardouw Subgroup on the other hand contains silty and shally interbeds and is associated with high feldspar content. The shale layers have had great impact on the fracturing and folding style of the Nardouw aquifers given rise to large variations in their storativity. The ranges of transmissivity (T) and storativity (S) in the Vermaaks River wellfield as proposed by Kotze (2002) are provided in the Table 6.2.

Table 6.2: Ranges of transmissivity (T) and storativity (S) in the Vermaaks River wellfield.

Conditions	$\mathbf{T}_{min}(m^2{\cdot}d^{-1})$	$\mathbf{T}_{max}(m^2{\cdot}d^{-1})$	$\mathbf{T}_{aver\cdot}$ $(m^2{\cdot}d^{-1})$	$\mathbf{S}_{min}$	$\mathbf{S}_{max}$	$\mathbf{S}_{aver\cdot}$
Extreme	7	424	103.9	1.0E-3	2.2E-3	1.35E-3
Condition A	5	144	61.25	1.0E-3	2.2E-3	1.08E-3
Condition B	29	424	191.72	1.0E-3	2.2E-3	1.08E-3
Condition C	17	276	178.92	1.0E-3	2.2E-3	1.08E-3
Condition D	7	161	90.86	1.0E-3	2.2E-3	1.08E-3
Condition E	7	161	90.86	1.0E-3	2.2E-3	1.96E-3

6.2.6 Recharge Estimates of the Vermaaks River wellfield

The hydrogeological setting of the Vermaaks River wellfield suggests that recharge is likely to take place within the outcrops of the Peninsula Formation window (Xu et al., 2007). The high density of fracture interconnections appears to facilitate recharge to the deeper parts of the aquifer. Earlier studies by Woodford (2001) estimated recharge rates between 2.5 – 4.8% of MAP. Kotze (2002) also estimated the recharge in the area to be 14% and 5% of MAP for the Peninsula and Nardouw aquifers respectively. Xu et al. (2007) however, estimated lower recharge values in the range of 1.65 – 3.3% for the aquifers using a variety of different methods.

6.3 Problems Associated with the KKRWSS Project

The eastern section of the KKRWSS had a design capacity of 3.3×10^6 m^3 a^{-1} based on peak demand with the Vermaaks wellfield being the most important abstraction area (Jolly and Kotze, 2002). There are about 26 private boreholes with a total annual abstraction of 1.85×10^6 m^3 in the Kammanassie area (Wu, 2005) even though the scheme itself supplies about 1.1×10^6 m^3 a^{-1}. The major challenges of the scheme include the continuous decline of water levels in the production boreholes, the iron clogging of some boreholes and other water quality issues as well as environmental concerns.

6.3.1 Decline of water levels

The major concern in the area has been the decline of water levels. It is reported that groundwater levels of the production boreholes have been falling since 1984 in the Vermaaks catchment. Even though the Vermaaks River wellfield had a fairly good recharge, by 1999 the water level decline was approximately 20 m. By 2002 the decline had reached about 30 m and again approximately 40 m by 2006. At the Hydstra database at the Dept. of Water Affairs, the only available current record is for borehole VR7 and it shows that the decline as at 2008 was over 90 m and recently in June 2010 the decline has reached 108 m for a borehole of depth 177 m. Abstraction rates in the production boreholes have been reset a number of times since the scheme began its operations as the scheme managers battled the high demand for water and low recharge. In February 1993, after evaluating the step-drawdown and 72 hr constant discharge tests conducted upon the production boreholes in 1990-91, Mulder estimated the 24 hr production potential of the wellfield at 72 *l*/s – with a peak supply potential of 110 *l*/s. Costly, high-yielding pumps were installed in the production boreholes to meet this expected yield. In November 1993, after only eight months of production, Mulder re-evaluated the pump-test data in conjunction with the abstraction and water level monitoring data and down-scaled the long-term production potential of the wellfield to 40 *l*/s (peak 80 *l*/s). This indicates Mulder overestimated the production potential of the wellfield by at least 36% when using only aquifer-test information. In 1995, Kotze again re-adjusted the supply potential of the wellfield downwards to 20 *l*/s due to continual declines in water levels in the wellfield, representing a 72% downscaling of Mulder's original yield estimates. Jolly in 1998 conducted further step-drawdown tests on boreholes VR6, VR7, VR8 and VR11, as well as 72 hr constant-discharge tests on boreholes VR6 and VR7 and recommended that only boreholes VR7 and VR11 should be continuously pumped at a rate of 11 and 6 *l*/s, respectively, as boreholes VR6, VR7 and VR8 are interconnected with one another. Jolly added that this combined yield of 17 *l*/s is a conservative estimate upon the current water demand only. He also stated that boreholes VR7 and VR11 were capable of yielding up to 25 and 10 *l*/s respectively, on a continual basis, which could add an additional 18 *l*/s to the supply but added that accurate estimates of the volumes of rainfall recharge and a water-balance calculation were required in order to obtain the long-term sustainable yield of the Vermaaks River aquifer. Kotze in 2000 conducted such recharge and water-balance studies using 74 months of hydrological monitoring data, as well as a re-evaluation of the 1990 and 1997 aquifer-test data. Kotze estimated that the long-term supply potential of the wellfield is in the order of 8.5 *l*/s.

Figure 6.4 is a plot of water levels in the Vermaaks wellfield. VG16 is the only observation borehole which reflects the decline of the production boreholes. With the continued reduction in abstraction rates the decline of the production boreholes slowed down considerably from about 2001 except for occasional increased abstraction at high demand periods as can be seen from figure 6.4.

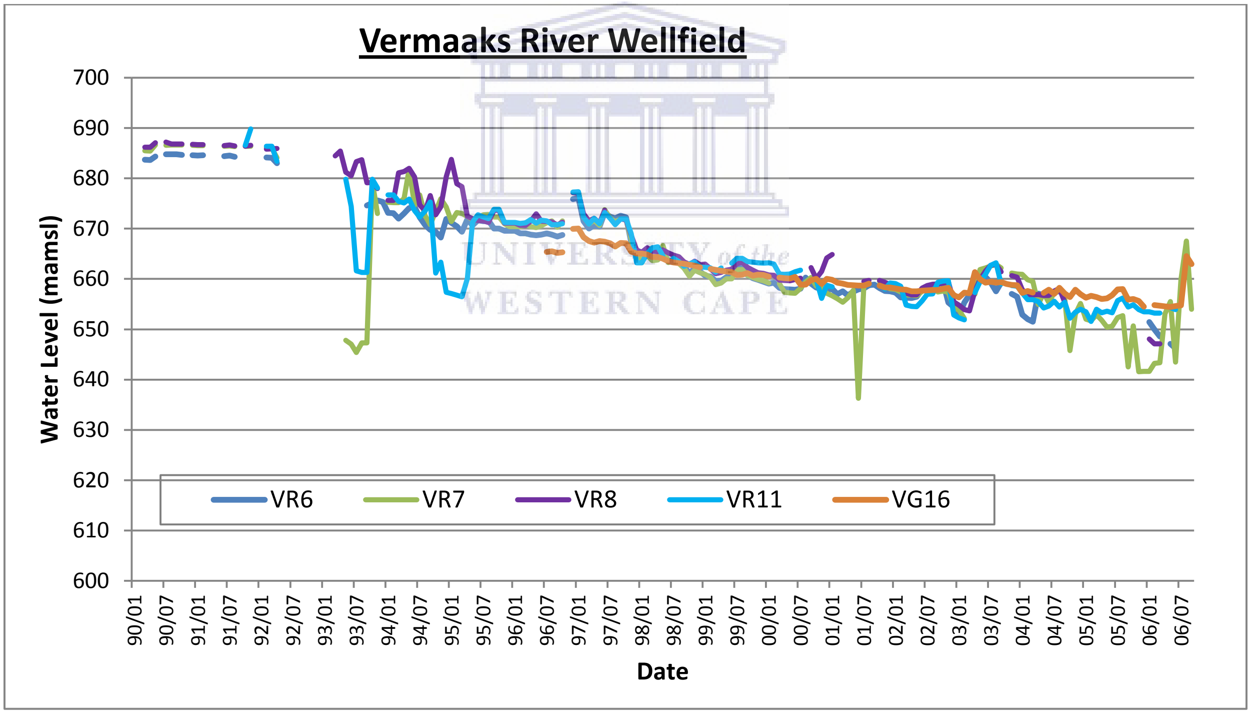

Figure 6.4: Decline of water levels in the production boreholes in the Vermaaks Wellfield

In the western wellfield, the total abstraction at 2000 from 5 boreholes was 0.137 × 10^6 m^3 (Jolly and Kotze, 2002). Water levels had slowly declined at an average of 30 m in five years (figure 6.5). Water level decline was also exacerbated by poor rainfall causing less recharge. After 1998 the decline of water levels slowed down and some even began to recover (figure 6.5) after the abstraction rates were adjusted downwards.

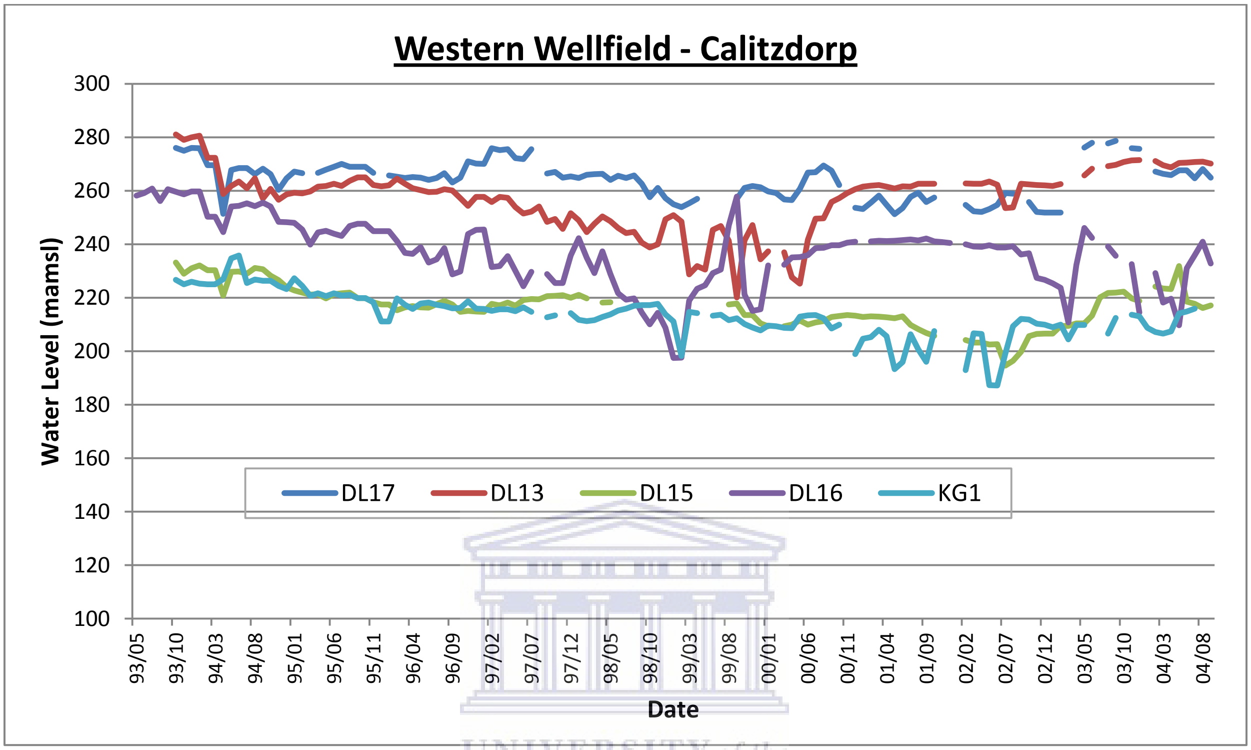

Figure 6.5: Water levels in production boreholes in the Western Wellfield

Some of the reasons given for the changes in borehole abstraction rates included the following (Jolly and Kotze, 2002):

- The Peninsula and Nardouw aquifers needed different management scenarios
- Interconnectivity between boreholes and wellfields (tapping same aquifer)
- Negative impact of Peninsula aquifer abstraction on springflow
- Potential environmental impact on vegetation by deep borehole abstraction
- Poor borehole construction must have caused poor supply delivery of several boreholes
- Considerable abstractions from other boreholes outside the scheme influenced borehole drawdowns (need to define boundaries of scheme).

In the Varkieskloof and Bokkraal Wellfields at the Eastern section of the Scheme, the production wells were holding well as can be observed in figures 6.6 and 6.7.

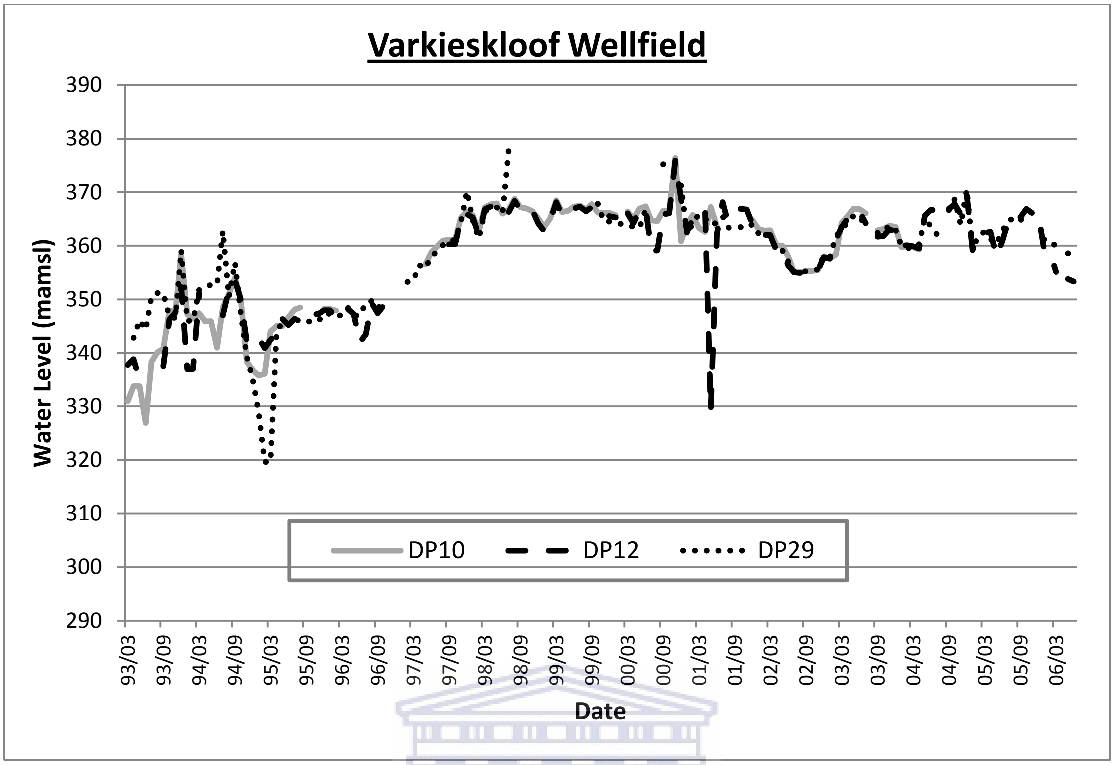

Figure 6.6: Water levels of Varkieskloof Wellfield in the Eastern Section

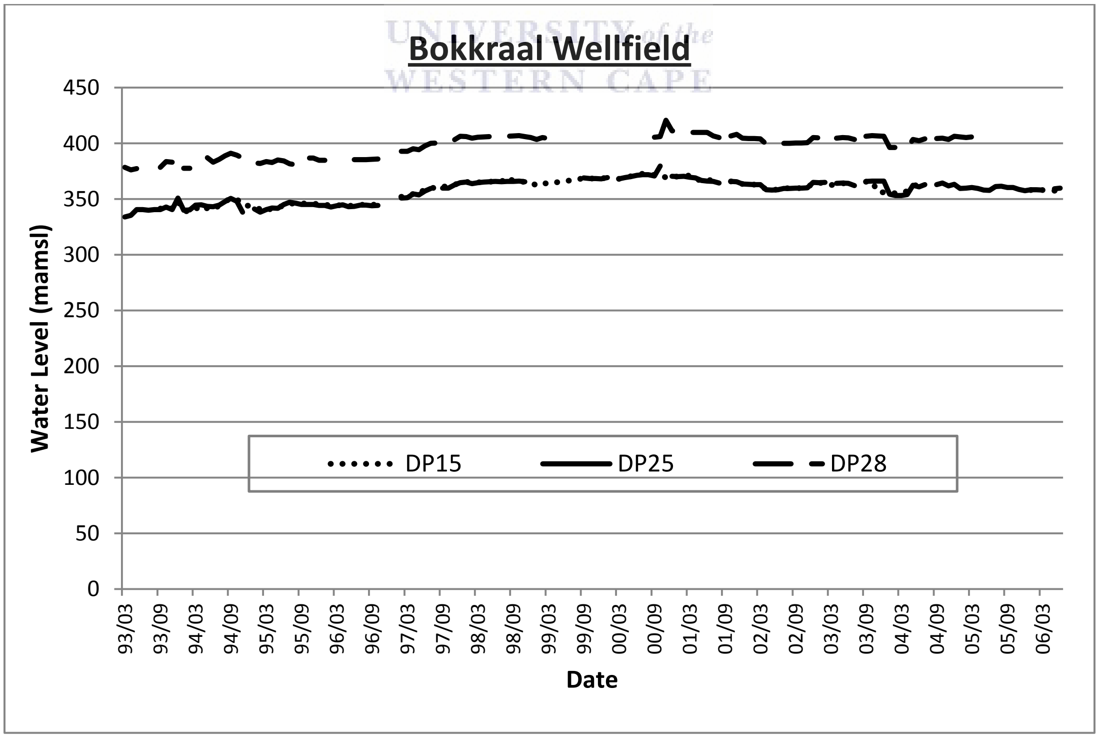

Figure 6.7: Water levels of Bokkraal Wellfield in the Eastern Section

Table 6.3 presents the readjustment of abstraction rates to some of the production boreholes in the KKRWSS as a result of declining water levels in the boreholes (Jolly, 2002).

Table 6.3: Readjustment of recommended abstraction rates for some KKRWSS boreholes

Borehole	Blow yield (*l*/s)	Recommended abstraction rate (*l*/s)		
		1992	1993	1998
DP10	7	14.3	4.5	-
VR7	15	19.7	-	11
VR8	13	9.8	-	8
DL17	15	15	3.5	3
KG1	15	15	-	3
DP25	20	9.8	-	7

The decline of water levels in the KKRWSS catchment has been attributed to over-abstraction due to recommended unsustainable abstraction rates and sometimes by clogging of the boreholes by iron bacteria. Recommended abstraction rates are derived from aquifer testing but in the event of wrong assumptions leading to bad judgment, aquifer parameters could be wrongly evaluated. This usually leads to over estimation of the aquifer's sustainable potential. It is reported that in many cases, "blow yields" measured at the end of drilling have been taken to represent borehole yields (Jolly, 2002). The routine assessment of aquifer parameters using the usual text book methods may sometimes yield wrong results because the assumptions underlying such methods are often overlooked. The resetting of abstraction rates in the KKRWSS over the years attest to the fact that the sustainable yields of the boreholes were over-estimated. The invaluable experience gained by management of the scheme over the years would be helpful in the successful future management of the scheme. This will be effective if adequate monitoring measures are put in place and records are effectively kept. The lowering of water levels may have other serious ecological and environmental impacts that should be evaluated and addressed to maintain sustainability.

6.3.1.1 *Abstraction management of the Vermaaks wellfield*

Data available on the abstraction rates from the Vermaaks wellfield where the bulk of water is produced has been used to match the water levels in the four production boreholes in the wellfield. Figures 6.8 – 6.11 show the plots for boreholes VR11, VR6, VR7 and VR8 respectively. Abstractions have been controlled by the seasonal demands and not on sustainable basis as would be expected from the response of the production boreholes. Adjustments have been made only in times of excessive water level decline. There is no doubt the boreholes could be very productive if they are managed sustainably. This can be achieved by having a regime of lower but continuous abstraction rates for each borehole depending on their production potential.

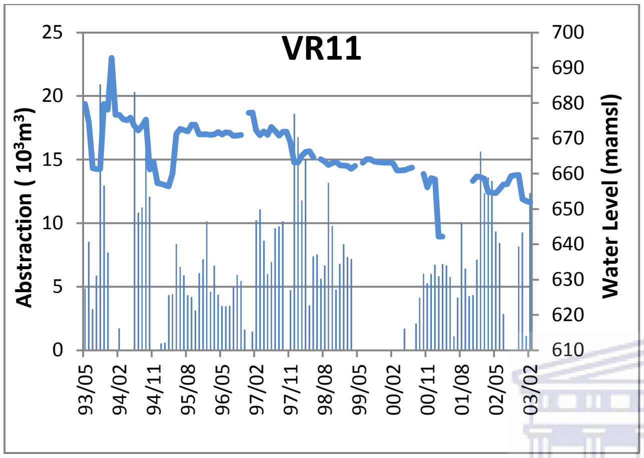

Figure 6.8:Abstraction vs Water level (VR11)

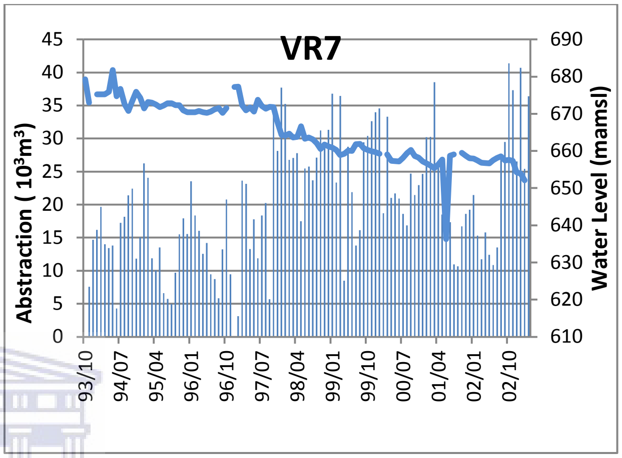

Figure 6.10:Abstraction vs Water level (VR7)

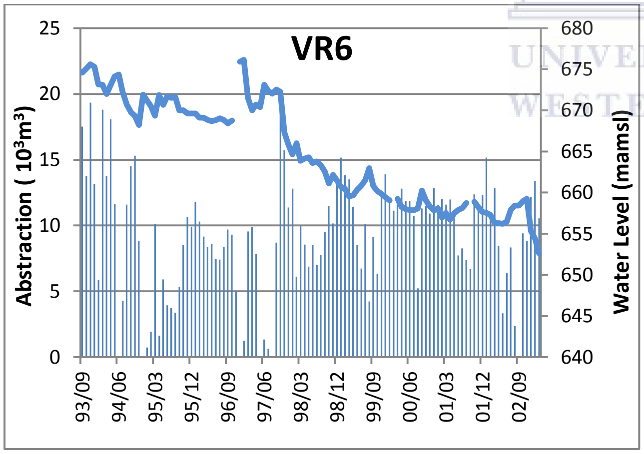

Figure 6.9:Abstraction vs Water level (VR6)

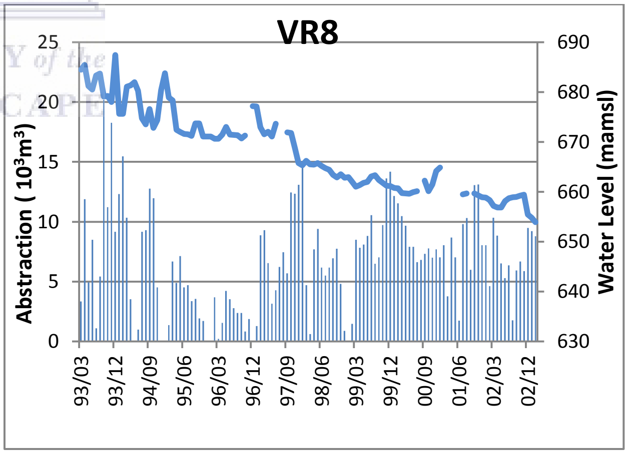

Figure 6.11:Abstraction vs Water level (VR8)

6.3.2 Iron clogging and changes in water quality

Another problem experienced by the KKRWSS and similar schemes was the clogging of borehole screens and pump parts by iron bacteria. The process is also referred to as chemically induced biofouling. The process occurs in boreholes with elevated iron content, a situation that seems to occur in many boreholes drilled in the TMG especially in the Nardouw Subgroup aquifers. In anaerobic conditions TMG groundwater contains ferrous iron (Fe^{2+}) of up to several milligrams per litre. For potable purposes the threshold is 0.3 m/*l* but concentrations above 0.2 m/*l* causes other aesthetic problems such as staining of laundry. The ferrous ion (Fe^{2+}) oxides to the ferric ion (Fe^{3+}) in the presence of oxygen and precipitates as $Fe(OH)_3$, an undesirable reddish brown substance commonly called rust. A major problem with ferruginous groundwater is the tendency for iron bacteria to establish themselves together with slime forming bacteria, which then create a slimy reddish brown substance clogging pump inlets, well screens, and the reticulation systems (Smart and Tredoux, 2002). The clogging causes reduced flow of groundwater to the borehole resulting in decreased borehole efficiency, a decrease in specific capacity, lowering of borehole yield and eventually, failure of the pump or borehole. The presence of biofouling can be detected by continual monitoring of borehole yield and water quality. Biofouling initially causes the change of colour of the abstracted water to an orange brown, often accompanied by a hydrogen sulphide odour. As the problem persists, there is an increase in pumping drawdown and if not checked the borehole yield eventually drops. It is reported by Jolly and Engelbrecht (2002) that the pumping drawdown in borehole DL17 at Calitzdorp (Western section) increased from 13 to 62 m over 6 months, while the static water level remained constant. The iron concentration levels in the borehole also increases in such situations. In the case of DL17, the iron concentration increased from 2 to 8 mg/*l*. Iron concentration in another borehole, DP28 (Bokkraal wellfield), increased from 0.3 to 8 mg/*l* between 1997 and 1998 due to biofouling. In boreholes with high iron content, the risk of clogging can be increased by overpumping which lowers the water level below the top fracture allowing water to cascade down the borehole. The cascading oxygenates the water, allowing chemical precipitation to take place and provides nutrients for rapid biofouling to take place inside the borehole (Jolly, 2002). Periodic monitoring of the iron concentration of high risk boreholes should be ensured and the water level should not be allowed to drop below fracture levels during abstraction.

Changes in water quality may occur sometimes as a result of biofouling even though it is not predictable. Increased iron concentration sometimes is accompanied with increase in electrical conductivity (EC) and a drop in pH. The pH of borehole DP28 dropped to 2 while EC increased from 30 to 90 mS/m. Low pH groundwater is aggressive and results in the corrosion of pump parts. Over-pumping could also induce poor quality water to flow into the borehole from adjacent formations.

6.3.3 Drying up of springs and impact on vegetation and ecosystems.

There are several springs in the KKRWSS catchment. Even though some of these springs are ephemeral their existences however have been affected by borehole abstractions in the catchment. In a report to the Department of Water Affairs, Xu *et al*. (2002) recorded a number of springs that have dried up as a result of borehole construction in the vicinity of those springs. A spring G46083, 2 km downstream of borehole VG16 and located near the Cedarberg shale outcrop in the Vermaaks valley dried up after the construction of borehole G40175A in the vicinity in September 1999. Further downstream the spring G46084 was affected when a borehole G46077 was drilled through the Cedarberg shale into the Peninsula formation nearby in November 2001. The initial high pressure in the borehole was lost eventually. It has also been reported by Xu *et al*., (2007) that a hot spring which used to flow at a regional discharge area in Dysselsdorp has dried up. The hot spring was located at the intersection of two faults between the TMG and the Bokkeveld group. The drying up of the hot spring has been attributed to earthquakes (Tulbagh in 1969, magnitude 6.5 and Oudtshoorn in 2001, magnitude 3.6) and the large abstractions from the wellfield near the site. There were reported losses of many springs in 2001 and a few before, in 1999 and 2000 as a result of low rainfall and borehole constructions. Investigations by Xu *et al*. (2002) also established that flow in the Vermaaks River had abruptly dipped since the onset of the Water Supply Scheme in the catchment even though rainfall is the major contributory factor to the continual flow of the river. The most comprehensive study on the impact of abstractions on spring flow in the Kammanassie area was done by Cleaver *et al*. (2003). The study grouped 53 springs in the area into 3 categories, 9 were considered most vulnerable to abstractions from the wellfield; 10 were considered as intermediate to vulnerability while the remaining 34 were considered least vulnerable. The study also confirmed that groundwater abstraction by the KKRWSS has impacted on the low-flow discharge in the Vermaaks River. On the impact of abstraction on vegetation, the study concluded that groundwater abstraction has a significant negative impact on plant water stress at the experimental sites in the Vermaaks River valley and recommended that changes in the water abstraction management could improve the situation. Spring losses caused localized impact on spring vegetation and ecosystems. Spring losses were also linked directly and indirectly to the death of four Cape Mountain Zebra on the Kammanassie Mountain between November 2000 and August 2001 as a result of inaccessibility to natural flowing water sources. Two artificial watering points were installed to protect the endangered species from extinction (Cleaver *et al*., 2003).

6.4 Sustainable management approach to Scheme problems

The major and minor problems affecting the smooth running of the KKRWSS as outlined above are those that are expected to confront any major scheme such as this one. There are a lot of positive impacts that such schemes bring to the beneficiaries and the general economy of the municipality and the nation as a whole. It is a laudable project that has brought a lot of improvements in the life of several communities, the right to access safe drinking water. Another positive indication from the project is the fact that the TMG has proven to be a good source of bulk water supply for many purposes. However, the challenges faced by the scheme need to be addressed not only to curb the negative impacts on the environment but also to ensure the long term survival of the scheme itself. In order to deal with the challenges facing the scheme there is a need to categorise them into what can be referred to as reversible and irreversible problems. The reversible problems are those that can be rectified or reversed because no permanent damage has been caused. On the other hand, an irreversible problem is that which causes permanent damage that cannot be reversed, life of species may be lost. Sometimes the full impact of a problem may not be immediately known until a thorough investigation has been done. There have been suggestions and remedies provided in the past to arrest the critical problems of the scheme and it is important that these and other issues are taken on board to maintain a sustainable project that will continue to improve the quality of life to human and other forms of life. The following recommendations are made some of which are already known and are re-emphasized.

6.4.1 Stabilization of water levels

The natural flow of water through aquifers is a slow process except for certain types of aquifers such as the dolomites which possess large cavities and caves through which large volumes of water can flow. In fractured aquifers such as the TMG significant flows could be achieved if hydraulic connectivity is established, however any artificial abstraction of water from the aquifer will force the re-adjustment of the natural equilibrium process towards a new dynamic equilibrium that will require time to achieve. The length of time needed to achieve this new equilibrium will depend on several factors including the abstraction rate as against the natural discharge rate of the aquifer, the type of aquifer (material composition) and its properties (transmissivity and storativity). The accurate determination of the aquifer properties is the most challenging of these factors. It is always advisable to use conventional methods to estimate these properties however, once abstraction begins, there should be adequate water level monitoring in place to ascertain the correctness of the estimates or if they need to be reviewed. TMG aquifers are known to have very low storativity even though their transmissivity may be high. Together with the physical and chemical quality of the water being abstracted, there should be a minimum allowable drawdown that will maintain the water quality and also not pose physical damage to the aquifer itself.

Even though water level decline is reversible, a high level and long-term decline could impose irreversible damage to the aquifer and particularly to the environment that depends on it. It is always a sound management practice to maintain a continuous gradual abstraction than the rapid high abstraction that can only last for a short while. It is known that abstraction rates have been increased during peak demand in the dry summer; ironically, this is the period of low recharge when the aquifer is vulnerable to stress and abstraction only causes storage depletion. During the rainy period in winter, less water is demanded and even though recharge to the groundwater is at its peak less water is abstracted and aquifer storage may be replenished. If the aquifer has undergone stressful periods earlier, it may have lost a percentage of its storage volume permanently due to subsidence and the storativity may have to be adjusted. If demand exceeds supply from groundwater sources during the dry period it may be advisable to store more water above the ground during the rainy period to supplement groundwater abstraction in the dry periods. This should only be necessary if it is established that the aquifer has limited storage since huge volumes of water are lost through evaporation from surface sources such as dams and storage reservoirs. Artificial recharge may be considered for high storage aquifers with good transmissivity.

6.4.2 Managing Iron clogging and water quality problems

The quality of groundwater from TMG aquifers are generally good and require little or no treatment before use but in some instances high iron concentrations and low pH has been of concern to groundwater managers who have had to deal with them. The cause of iron clogging has been discussed earlier and some suggestions already made from experts who have considerable knowledge with this particular issue. Boreholes with high iron concentration have the potential to clog if overpumped and must be adequately monitored to reduce the risk. Monitoring of the water level and quality is essential to limit the risk of clogging. Water must not be allowed to cascade down the borehole from top fractures to increase the presence of oxygen which facilitates clogging. The use of PVC pipes including borehole screens slow down clogging in boreholes. PVC screens have been found to plug on average 63% slower than stainless steel screens under same conditions (Jolly and Engelbrecht, 2002). Besides the precautionary measures that may be taken to slow down clogging, boreholes can be remediated when clogged but effective remediation requires knowledge on the causes of clogging. Clogging may either be chemical or biological even though biological clogging (commonly known as biofouling) is the most common form (80%) encountered in boreholes. The detailed information on the processes of remediation can be obtained from other literature e.g. the report by Jolly and Engelbrecht (2002).

Apart from high level of iron concentration in TMG groundwater the other concerns that has been expressed is the low pH. The low pH groundwater makes the water aggressive or corrosive to steel pumps and piping material. If encountered care must be taken to select corrosion resistant material such as PVC for borehole casing, piping and borehole screens as well as reservoirs. Good quality steel pumps may also be preferred as choice pumps for use in low pH boreholes. In general overpumping has been noted to induce other water quality problems in boreholes such as saline water intrusion from adjacent formations and from marine sources in coastal aquifers. Any other water quality problems such as high nitrate and phosphates are likely to be due to pollution sources that must be investigated and eliminated at the source.

6.4.3 Management of spring losses

The management of flow reduction and complete loss of springs in the vicinity of wellfields is both an environmental and an ecological issue that must be addressed. It has been discussed in an earlier section that a major scheme such as the KKRWSS is likely to have environmental and ecological consequences. Sustainability has been defined in various ways as having limited environmental, ecological, economic, hydrological and social consequences. What defines “limited” is the value placed on the affected sector. Some of these ephemeral springs are sourced from interflow during rainy periods and may still flow during rainfall. The ones with sources from underground may be lost as long as abstractions continue. Investigations conducted by environmental and ecological specialists have established the negative impacts of the loss of spring flow on flora and fauna and on the environment in general. Periodic studies would be necessary to assess any new dangers to vital species and possible remediation measures that may be necessary. Some of these concerns may be avoided if managers of such schemes conduct an environmental impact assessment involving various specialists before construction of boreholes are approved. The impact assessment report is usually discussed in a public forum where all stakeholders are invited to raise their concerns is vital for the long-term sustainability of such schemes. Such processes are lengthy and expensive but in the long run will prove to be cost effective. In many situations where some losses are envisaged, the value of the scheme may override that of the environmental concerns and trade-offs are discussed and amicably settled by all stakeholders.

In the situation where the scheme is in operation before environmental and ecological concerns are raised, the call for an adaptive management will be an appropriate course to take. It is also important to adopt such approach to deal with any challenges that could not be anticipated before the beginning of the scheme and there are always many such issues to battle with unique to every project. Adaptive management, as discussed earlier on treats management policies and actions as experiments, not fixed policies. Management continually improves by learning from experiences. Changing technology and increasing knowledge and understanding change our perception of risk and our priorities with regard to the acceptability of trade-offs, hence water resource management must be adaptive and flexible. Adaptive management links science, values, and the experience of stakeholders and managers to the art of making management decisions.

6.5 Summary

Sustainable utilization of groundwater resources of the TMG aquifers has been addressed using the KKRWSS as a case study. The TMG's potential as a bulk water supply to urban and rural communities has been demonstrated by the KKRWSS and other similar schemes in operation in other areas of the Western and Eastern Cape Provinces. The scheme serves a vital role of water service delivery to many communities and must be sustained by providing the needed assistance in terms of research and knowledge generation in order to improve its operations in a more efficient and sustainable manner. The major problems encountered by the KKRWSS have been a continual decline in water levels and sometimes water quality concerns that occasionally lead to operational challenges. Several investigations and research have revealed that abstraction rates have been too high especially in the Vermaaks River wellfield where water level declines have been persistent. The most productive borehole in the scheme, VR7 has seen a decline of over 100 m as at June 2010 this is not good for the scheme. The average monthly pattern of rainfall in the area according to Cleaver *et al*. (2003) shows that there are two peak periods in April and November whiles January and June are the two lowest periods of rainfall. These are the two periods of highest and lowest recharge to the aquifers respectively. Recent research by Xu *et al*. (2007) indicates lower recharge to the aquifers than earlier thought. In addition, aquifer properties especially, storativity has been shown to be much lower than earlier estimates. These observations of low recharge and low storativity result in storage depletion if transmissivity is high which is evident in the decline of water levels. The operation of the scheme has also unearthed other hydrological, ecological and environmental impacts. The reduction in low-flows in the Vermaaks River, the loss of spring flows and the resultant loss of certain vegetation types as well as threat to local ecosystems have led to temporal and permanent losses. It has also been established that low rainfall in recent years in the study area has contributed in no small way to the problems imposed on the scheme. A reduction in abstraction rates may be the needed option to halt the decline in water levels and limit the challenges facing the scheme.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

7.1.1 Groundwater resources potential of the TMG

The Table Mountain Group (TMG) aquifer system is a regional fractured sandstone aquifer with huge potential for domestic and irrigation water supplies. TMG aquifers are mainly composed of either the Peninsula Formation sandstones or the Nardouw Subgroup sandstones. The Peninsula Formation distributes along the mountain crests and is composed of uniform succession of medium to coarse grained, thickly bedded, grey sandstone characterized by cross bedding. They are more brittle to deformation creating numerous fractures and joints and major faults which serve as conduits for recharge. The Nardouw Subgroup distributes around the Peninsula, the two often separated by the Cedarberg Formation which acts as an aquitard between the two prominent aquifers. The rocks of the Nardouw Subgroup are in general more brownish on weathered surfaces and thin intercalations of shale are more prominent and contain more feldspar. Due to their high shale content they are less competent and deformation tends to be more ductile, giving rise to complex fold geometries. Many groundwater schemes are currently exploiting resources from the TMG to meet domestic and irrigation water needs in several locations mostly in the Western Cape and also in the Eastern Cape. Recharge to the TMG aquifers is generally low and sporadic although high recharge events could be obtained at mountainous terrains where the highly fractured TMG outcrops are exposed to heavy rainfall events. Many schemes have failed as a result of abstractions exceeding recharge resulting in aquifer storage decline between recharge events leading to water levels falling to the depths of the pumps. TMG aquifers generally have low storativity and Jolly (2002) recommends that water level decline must be carefully managed to make certain water levels do not drop below the top water strikes in the boreholes otherwise the risks of microbial induced biofouling which causes clogging of pumps and screens exist due to often high concentrations of iron in the groundwater. Except for sometimes high concentrations of iron and manganese especially in the Nardouw groundwater and low pH TMG aquifers have excellent water quality with very low electrical conductivity. They are generally Na-Cl type water.

Several reported abstraction schemes from the TMG in the Western Cape included the Arabella Country Estate, near Botrivier where 4 production wells supply about 30 *l*/s of groundwater to the estate (Parsons, 2002); Botrivier water supply project with 6 wells supplying about 20 *l*/s (Weaver, 2002); Ceres Municipality wellfields where 7 boreholes from the TMG supply 48 l/s and 3 boreholes from the Bokkeveld supply 50 *l*/s (Rosewarne, 2002); the Hex River valley project and the CAGE project at Citrusdal are also documented. In the Eastern Cape, the Plettenberg Bay Municipality utilizes a maximum of 300,000 $m^3.a^{-1}$ of groundwater from the TMG to meet domestic water supply needs (Jolly and Stemmet, 2002). In the Port Elizabeth Municipality, a total of approximately 390,000 $m^3.a^{-1}$ of groundwater was privately abstracted from the TMG for various purposes (Rosewarne[2], 2002). In St. Francis-on-sea, Steytlerville and Uitenhage among others in the Eastern Cape several wellfields have been established to abstract large volumes of groundwater from the TMG to meet water supply needs.

Some of these drilling projects have little or no management plans while others are well managed even though ecological and environmental concerns are hardly integrated in the management programmes. The impact of these groundwater projects on the surface water regimes i.e. the baseflow into rivers, wetlands and estuaries which also control the availability of water for plant use are hardly evaluated or monitored. Spring flows are often affected by groundwater abstractions within their vicinity and some even dry up. It is anticipated that a more comprehensive approach to groundwater development schemes in the TMG will be undertaken in the future to ensure sustainable utilization of TMG aquifers.

7.1.2 From Safe yield to Sustainable yield

Safe yield has been defined variously as an abstraction regime which does not deplete groundwater reserves to undermine its future use. It has been expanded over the century from Lee (1915) and Meinzer (1923) definitions to include degradation of water quality (Conkling, 1946), the contravention of existing water rights (Banks, 1953), and other factors. Alley and Leake (2004) further states that a common misperception has been that the development of a groundwater system is "safe" if the average annual rate of groundwater withdrawal does not exceed the average annual rate of natural recharge. Bredehoeft *et al* (1982) and Bredehoeft (2002) give examples of how safe development depends instead on how much of the pumpage can be captured from increased recharge and decreased discharge. Custodio (2005) referred sustainability to the use of natural resources without jeopardizing their use by future generations. A concept of human beings living in peace and harmony with the environment, both now and in the future. He strongly believes that in reality, scientific, technical, and social as well as space and time frameworks, under which sustainability is evaluated, are continuously changing and that what may be sustainable now may not be in the future, and what may appear unsustainable today may be sustainable in the future. Sophocleous (2005) however believes that sustainable use of groundwater must ensure not only that the future resource is not threatened by overuse and depletion, but also that the natural environment that depend on the resource are protected. The task of groundwater managers is to determine what limits of environmental impact are acceptable to the community and to manage extraction to maintain impacts within those limits. The shift from safe yield to sustainable yield has therefore been marked by ecological and environmental impact of groundwater abstractions. An all inclusive definition of sustainability was provided by the American Society of Civil Engineers (ASCE) Task Committee for Sustainability Criteria (1998) as: "*sustainable water resource systems are those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity*" (Loucks *et al*., 2000). This and similar definitions recognise the fact that sustainable yield is not a fixed figure but could vary over time as environmental conditions vary. This definition is similar to that of the National Groundwater Committee (NGC, 2004) of the Department of Environment and Heritage of Australia who defined sustainable groundwater yield as: "*the groundwater extraction regime, measured over a specified planning timeframe that allows acceptable levels of stress and protects dependent economic, social and environmental values*." In South Africa, the National Water Act (1998) does not define sustainable yield but incorporates its tenets in its implementation. The thrusts of the Act are sustainability, equity and efficiency. It is set to ensure that water resources are protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner, for the benefit of all. The Act emphasizes on the setting up of a Reserve as the only right to water. This is the provision of water of sufficient quantity and quality for basic human needs (Basic Human Needs Reserve) and water for ecosystems to maintain ecological integrity (Ecological Reserve).

7.1.3 TMG Recharge and Aquifer properties

TMG recharge is generally low in the region of 3% - 5% of MAP on the average but could be as low as <1% in the matrix block and as high as 40% in open fractures in mountainous terrains. Recharge studies in the TMG has shown that the more reliable estimation methods are the Chloride Mass Balance (CMB), Cumulative Rainfall Departure (CRD) and Rainfall Infiltration Breakthrough (RIB), Water Balance (WB) and Regression of Spring Flux. The CMB method is dependent on the recharge area while the CRD and RIB methods depend on aquifer storativity. Storativity is generally low averaging

1.0E-4 to 1.0E-3 while transmissivity could be high in the region of 100 m^2/day in the Peninsula Formation.

7.1.4 Climate Change impact on aquifers

The impact of climate change on the study area was investigated. Trend tests in the Western Cape region have shown gradual increases in temperature over recent years while generally no significant trends have been observed with precipitation amounts. Variations in precipitation patterns however have been observed such as the intensity, duration and shifts in seasons. Frequent floods and droughts are likely to affect the region. The high temperatures in the atmosphere can cause droughts during the summer whiles in the winter the atmosphere can absorb more moisture and cause floods. The implications of these changes on freshwater resources either directly or indirectly were of much concern. Responses to climate variations by surface water resources are fast and intense however groundwater response is much delayed even though it is likely to be affected indirectly by the absence of fresh surface water resources. The impacts of climate change and climate variation on aquifers are differentiated by the three aquifer types; shallow aquifers, deep aquifers and coastal aquifers. Warmer climate increases evaporation on the surface and near surface soil moisture resulting in lower percolation rates. There will generally be lower recharge rates to shallow aquifers however, during flood periods shallow aquifers will be substantially recharged. Deep aquifers are buffered by confining layers of sediment and are likely to be unaffected by direct climatic changes. Any impacts on deep aquifers may be as a result of deep abstraction due to limited shallow aquifers. Coastal aquifers are more vulnerable to climate change and variations especially to the quality of water. The likely rise in sea water levels will reduce freshwater resources in coastal areas. High temperatures will increase evaporation rates resulting in decreased freshwater in coastal areas. Floods are likely to increase contamination and pollution to coastal aquifers due to the high transmissivity of the sandy aquifers. Semi-arid and arid regions of developing countries are particularly vulnerable to impacts of climate changes and variations due to poverty and lack of infrastructure.

7.1.5 TMG Aquifer discharges

The outflows from the TMG include natural and artificial discharges. Natural discharges comprise the numerous springs including the thermal springs, baseflow to streams and rivers, flow to the ocean and other reservoirs such as wetlands, marshes and estuaries. Most of these discharges are difficult to quantify and only crude estimates may be available. There are about 11 thermal springs identified within the TMG which are being utilized for water supply, irrigation and mostly recreation. The artificial discharges are easy to quantify especially for big schemes that are well managed however several private boreholes and dug wells may not be captured even though such point sources are not known to generate high amounts of abstractions. It has been estimated that baseflow from groundwater in the TMG to rivers and streams constitutes one major source of discharge from TMG aquifers in the region of 1.1×10^9 $m^3.a^{-1}$. The total discharges from spring flows (including thermal springs), baseflow and groundwater abstractions are estimated to be in the region of 1.3×10^9 $m^3.a^{-1}$ (Jia, 2008). These estimates are reckoned to be the upper limits of TMG discharge.

7.1.6 TMG sustainability

TMG sustainability has been enhanced by the implementation of findings of many research studies that have been undertaken over the years. These include recharge studies, aquifer tests evaluations, groundwater quality determination, surface water and groundwater interaction studies, groundwater flow characteristics assessment, groundwater resource evaluation and groundwater dependent ecosystems assessment. The current study on sustainable utilization of the TMG aquifers has been undertaken on the basis of the findings of these previous studies in relation climate change impacts to formulate an approach that will guide the future utilization of the groundwater resources in a more sustainable manner that guarantees scientific, economic, hydrological, ecological, social and environmental integrity. Scientific integrity ensures that basic hydrogeological principles are not overlooked, darcy's law and conservation of mass is vital so that abstraction rates are based on a fair knowledge of reliable estimates of recharge, storativity and transmissivity. Economic considerations are based on fairly good yields and water quality preservation. In many cases if borehole yields are good a reasonable drawdown will not undermine the water quality of the delivery and pump and borehole maintenance will be reduced to the minimum. Abstraction should not seriously affect baseflow to streams and spring flows. Loss of spring flow and stream low flows deny ecological reserves and causes shifts and extinction of species. Hot springs which provide recreation and domestic supplies could also be affected if the cone of depression created by deep drawdown persists and intercept their flow path.

Sustainable utilization of groundwater resources of the TMG aquifers has been addressed using the KKRWSS as a case study. The TMG's potential as a bulk water supply to urban and rural communities has been demonstrated by the KKRWSS and other similar schemes in operation in other areas of the Western and Eastern Cape Provinces. The scheme serves a vital role of water service delivery to many communities and must be sustained by providing the needed assistance in terms of research and knowledge generation in order to improve its operations in a more efficient and sustainable manner. The major problems encountered by the KKRWSS have been a continual decline in water levels and sometimes water quality concerns that occasionally lead to operational challenges. Several investigations and research have revealed that abstraction rates have been too high especially in the Vermaaks River wellfield where water level declines have been persistent. The most productive borehole in the scheme, VR7 has seen a decline of over 100 m as at June 2010. The operation of the scheme has also unearthed other hydrological, ecological and environmental impacts. The reduction in low-flows in the Vermaaks River, the loss of spring flows and the resultant loss of certain vegetation types as well as threat to local ecosystems have led to temporal and permanent losses. It has also been established that low rainfall in recent years in the study area has contributed in no small way to the problems imposed on the scheme. A reduction in abstraction rates may be the needed option to halt the decline in water levels and limit the challenges facing the scheme.

7.2 Recommendations

The sustainable utilization of TMG aquifers depends largely on the reliable estimates of recharge at different scales in the TMG Formation. A number of estimates have already been done but values differ considerably however, recent studies and experiences suggest the lower estimates are more reliable. With low recharge and low storativity care must be taken not to rely on high transmissivity to recommend high abstraction rates for groundwater abstractions. It is important to recognise the fact that a sustainable yield is not necessarily a fixed figure but could vary over time as environmental conditions vary hence periodic monitoring and review measures must be put in place. Past experiences may provide the best options for review of abstraction rates. It is highly recommended that for groundwater abstraction schemes the following measures would be necessary before any major implementation programme is commenced.

- Evaluation of hydrological, ecological and environmental assessment of all potential sources of impacts; streamflow patterns and low flow regimes, spring flow patterns and sources, riparian and terrestrial vegetation and ecosystems, wetlands and marshes (in case they are groundwater dependent). These procedures will be repeated sometime after the scheme has commenced in order to ascertain whether any changes could be attributed to the operation of the scheme.

- Evaluation of long-term rainfall pattern for the area under study for trends.

Some other measures are important after the commencement of the scheme to ensure sustainability.

- It may be important to set limits to water level declines which may be different for each season in order to guide the review of abstraction rates and also allow declining water levels to recover.
- It will always be preferable to set low abstraction rates that can run continuously for a longer period as opposed to high rates for shorter periods. The latter puts more stress on the boreholes.
- Monitoring of water levels and water quality by periodic sampling and analysis.
- Setting up and monitoring of observation boreholes near potential sources of impact is essential.
- Implementation of adaptive management practices as experience is gained and challenges become evident. Management must be willing to accept realities of challenges and not be motivated only by demand targets.

With the reality of global climate change and its impacts on freshwater resources, mitigation and adaptation measures must form an integral part of sustainable utilization of freshwater resources particularly groundwater in this semi-arid region of the developing world.

CHAPTER 8 REFERENCES

Allen, M.R. & Ingram, W.J. (2002). Constraints on future changes in climate and the hydrologic cycle. *Nature* **419**, 224-232.

Alley, W.M., Reilly, T.E. and Franke, O.L. (1999). Sustainability of groundwater resources. *US Geological Survey Circular* **1186**, 79 pp.

Alley, W.M. and Leake, S.A. (2004). The journey from safe yield to sustainability. (Issue Paper), *Ground Water* **42** (1), 12-16.

Alley, W.M., LaBaugh, J.W. and Reilly, T.E. (2005). Groundwater as an element in the hydrological cycle. In: Anderson, M.G. (ed), Encyclopedia of hydrological Sciences.

Appleton, B. (Ed) (2003). "*Climate Changes the Water Rules*." International Dialogue on Climate and Water, Wageningen, Netherlands. pp 106.

Arnell, N.W. (2003). Effects of IPCC SRES emissions scenarios on river runoff: a global perspective. *Hydrol. Earth Syst. Sc.*, **7**, 619-641.

Askew, A.J., (1987). Climate change and water resources. In: Solomon, S.I., Beran, M., Hogg, W. (Eds). The influence of climate change and climate variability on the hydrologic regime and water resources **168**, 189-201. IAHS Publishers.

Australian Water Resources, (2005). Defining sustainable yield for groundwater. Published on line by the National Water Commission of Australia. http://www.water.gov.au/wateravailability/resourcesustainability/sustainableyield-definitions/index.aspx?menu=level1_3_6_1)

Banks, H.O. (1953). Utilization of underground storage reservoirs. Transactions, American Society of Civil Engineers **118**, 220-234.

Blasing, T.J. (2009). Recent Greenhouse Gas concentrations. DOI: 10.3334/CDIAC/atg.032. Culled from Carbon Dioxide Information Analysis Center, CDIAC website: http://cdiac.ornl.gov/pns/current_ghg.html in April, 2010.

Booth, P.W.K. and Shone, R.W. (1992). Folding and thrusting of the Table Mountain Group at Port Elizabeth, Eastern Cape, Rep. of South Africa. In: De Wit, M.J. & Ransome, I.G.D. (eds.) *Inversion tectonics of the Cape Fold Belt, Karoo and Cretaceous basins of South Africa*. Balkema, Rotterdam. 207-210.

Bredehoeft, J.D. (2002). The water balance myth revisited: Why Hydrogeologists model. (Issue paper), *Ground Water* **40** (4), 340-345.

Bredehoeft, J.D., Papadopulos, S.S. and Cooper Jr., H.H. (1982). The water-budget myth. In: Scientific Basis of Water Resources Management studies in Geophysics. Washington, D.C. National Academy Press, pp. 51-57.

Burn, D.H. and Elnur, M.A.H. (2002). Detection of hydrologic trends and variability. *J. Hydrol*. **255**, 107-122.

Broquet, C.A.M. (1992). The sedimentary record of the Cape Supergroup: A review. In: De Wit, M.J. & Ransome, I.G.D. (eds.) *Inversion tectonics of the Cape Fold Belt, Karoo and Cretaceous basins of southern Africa*. Balkema, Rotterdam. 159-183.

Cavé, L.C. Weaver, J.M.C. and Talma, A.S. (2002). The use of geochemistry and isotopes in resource evaluation: A case study from the Agter-Witzenberg valley in: Pietersen, K. and Parsons, R. (eds.) *A synthesis of the hydrogeology of the table mountain group – formation of a research strategy*. WRC report no. TT 158/01, 143-149.

Chevallier, L. (1999) Regional structural geological interpretation and remote sensing Little Karro, WRC Project: K8/324

Cleaver, G., Brown, L.R., Bredenkamp, G.J., Smart, M.C. and Rautenbach, C.J. de W. (2003). Assessment of environmental impacts of groundwater abstraction from Table Mountain Group (TMG) aquifers on ecosystems in the Kammanassie Nature Reserve and environs. WRC Report No. 1115/1/03. Pretoria, South Africa.

Colvin, C., Le Maitre, D., Saayman, I and Hughes, S. (2007). Aquifer dependent ecosystems in key hydrogeological typesettings in South Africa. WRC Report No. TT 301/07.

Commonwealth of Australia. (2010). Bureau of Meteorology (ABN 92 637 533 532) (Information from the website: http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall-variability/)

Conkling, H. (1946). Utilization of ground-water storage in stream system development. Transactions, American Society of Civil Engineers **3**, 275-305.

Custodio, E. (2005). Intensive use of ground water and sustainability. (Guest Editorial), *Ground Water* **43** (3), 291.

De Beer, C.H. (2002). The stratigraphy, lithology and structure of the Table Mountain Group. In: Pietersen, K. and Parsons, R. (Eds.) *A synthesis of the hydrogeology of the table mountain group – formation of a research strategy*. WRC report no. TT 158/01, 9-18.

Department of Water Affairs and Forestry. Guide to the National Water Act. Department of Water Affairs, Pretoria, South Africa.

De Villiers, J. (1944). A review of the Cape Orogeny. *Ann. Univ. Stellenbosch* 22 (Section A) 183-208.

Devlin, J.F. and Sophocleous, M. (2005). The persistence of the water budget myth and its relationship to sustainability. *Hydrogeology Journal* **13** (4), 549-554.

Environment Canada. (2004). Threats to water availability in Canada. National Water Research Institute, Burlington, Ontario. *NWRI Scientific Assessment Report Series No. 3* and ACSD Science Assessment Series No. 1. 128p.

Fauchereau, N., Trzaska, S., Rouault, M. and Richard, Y. (2003). Rainfall variability and changes in Southern Africa during the 20th century in the Global warming context. *Natural Hazards* **29,** 139-154. Kluwer Academic Publishers, The Netherlands.

Gilbert, R.O. (1987). Statistical methods for environmental pollution monitoring. Van Nostrand Reinhold, New York.

Hartnady, C.J.H. and Hay, E.R. (2002). Boschkloof groundwater discovery. In: Pietersen, K., Parsons, R. (Eds). *A synthesis of the hydrogeology of the table mountain group – formation of a research strategy*. WRC report no. TT 158/01, 168-177.

Hamed, K.H. (2008). Exact distribution of the Mann-Kendell trend test statistic for persistent data. J. Hydrol.

Hayes M. (2002). Drought indices, White paper, National Drought Mitigation Center, University of Nebraska, Lincoln, USA.

Hayes, M.J., Svoboda, M.D., Wilhite, D.A. and Vanyarkho, O.V. (1999). Monitoring the 1996 drought using the Standard Precipitation Index. *B. Am. Meteorol. Soc*. **80**, 429–438.

Hewitson, B., Engelbrecht, F., Tadross, M. and Jack, C. (2005). General conclusions on development of plausible climate change scenarios for southern Africa. In: Schulze, R.E. (Ed). Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation. WRC Report No. 1430/1/05. Chapter 5, 75-79.

Hogan, J.F., Phillips, F.M. and Scanlon, B.R. (Eds) (2004). Groundwater recharge in a desert environment: the southwestern United States. Water Science and Application 9, American Geophysical Union, Washington, DC.

Howard, C.D.D. (2002). Sustainable development – Risk and uncertainty. *Journal of Water Resources Planning and Management*, **128** (5), 309-311.

IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the*

Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 7-22.

Johnson, M.R. (1991). Sandstone petrography, provenance and plate tectonic setting in Gondwana context of the Cape-Karoo basin. *S. Afr. J. Geol*. **94**, 137-154.

Jolly, J.L. (2002). Sustainable use of Table Mountain Group aquifers and problems related to scheme failure. In: Pietersen, K., Parsons, R. (Eds). *A synthesis of the hydrogeology of the table mountain group – formation of a research strategy*. WRC Report No. TT 158/01, 108-111.

Jolly, J.L. and Stemmet, Q. (2002). Utilisation of the Table Mountain Group aquifer at Plettenberg Bay (Eastern Cape). In: Pietersen, K., Parsons, R. (Eds). *A synthesis of the hydrogeology of the table mountain group – formation of a research strategy*. WRC Report No. TT 158/01, 202-204.

Jolly, J.L. and Engelbrecht, P. (2002). Occurrence and management of iron related borehole clogging in Table Mountain Group aquifers. In: Pietersen, K., Parsons, R. (Eds). *A synthesis of the hydrogeology of the table mountain group – formation of a research strategy*. WRC Report No. TT 158/01, 131-140.

Jolly, J.L. and Kotze, J.C. (2002). The Klein Karoo rural water supply scheme. In: Pietersen, K., Parsons, R. (Eds). *A synthesis of the hydrogeology of the table mountain group – formation of a research strategy*. WRC Report No. TT 158/01, 198-201.

Kalf, F.R.P. & Woolley, D.R. (2005). Applicability and methodology of determining sustainable yield in groundwater systems. *Hydrogeology Journal*, **13** (1), 295-312.

Kendall, M.G. (1975). Rank correlation measures. Charles Griffin, London.

Kendy, E. (2003). The false promise of sustainable pumping rates. *Ground Water* **41** (1), 2-4.

Kresic, N. (2009). Groundwater resources: sustainability, management, and restoration. ISBN 978-0-07-149273-7. The McGraw-Hill Companies, Inc. USA.

Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen and I.A. Shiklomanov, (2007). Freshwater resources and their management. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 173-210.

Le Maitre, D.C., Colvin, C. and Scott, D.F. (2002). Groundwater dependent ecosystems in the fynbos biome, and their vulnerability to groundwater abstraction in: Pietersen, K., Parsons, R. (Eds). *A* *synthesis of the hydrogeology of the table mountain group – formation of a research strategy*. WRC report no. TT 158/01, 112-117.

Lerner, D.N., Issar, A.S. and Simmers, I. (Eds) (1990). Groundwater recharge: A guide to understanding and estimating natural recharge. Intl. Assoc. of Hydrogeologists, *Vol 8, 1990*.

Lloyd, J.W. (1986). A review of aridity and groundwater. *Hydrological Processes* **1**, 63-78.

Lohman, S.W. (1972). Ground-Water Hydraulics. *USGS Professional Paper* **708**. 70 pp.

Loucks, D.P., Stakhiv, E.Z. and Martin, L.R. (2000). Sustainable water resources management. *Journal of Water Resources Planning and Management*, **126** (2), 43-47.

Maimone, M. (2004). Defining and managing sustainable yield. *Ground Water Journal*, **42** (6), 809-814.

Mann, H.B. (1945). Non-parametric tests against trend. *Econometrica* **13**, 245-259.

McKee, T.B., Doesken, N.J.and Kleist, J. (1993). The relation of drought frequency and duration to time scales. Proceedings of the 8th Conference on Applied Climatology, 179-184, American Meteorological Society, Boston, USA.

Meinzer, O.E. (1923). Outline of ground-water hydrology with definitions. U.S. Geological Survey Water-Supply Paper 494.

Middleton, B.J. and Bailey, A.K. (2008). Water resources of South Africa, 2005 study (WR2005), Executive summary. WRC Report No. TT381/08.

Millennium Ecosystem Assessment (MEA), (2005). *Ecosystems and Human Well-being. Volume 2: Scenarios*. Island Press,Washington, District of Columbia, 515 pp.

National Groundwater Committee. (2004). Definition and approach to sustainable groundwater yield. Annex A, NGC. Department of the Environment and Heritage, Canberra, Australia. (http://www.environment.gov.au/water/publications/environmental/groundwater/pubs/annex-a).

National Research Council (NRC). (2004). Groundwater fluxes across interfaces, National Academic Press, Washington, DC, 85p.

New, M., Hewitson, B.C., Stephenson, D.B., Tsiga, A., Kruger, A., Manhique, A., Gomez, B., Coelho, C.A. S., Masisi, D.N., Kululanga, E., Mbambalala, E., Adesina, F., Saleh, H., Kanyanga, J., Adosi, J., Bulane, L., Fortunata, L., Mdoka, M. L. and Lajoie, R. (2006). Evidence of trends in daily climate extremes over southern and west Africa. *J. Geophys. Res.* **111**, D14102, 11pp.

Parsons, R. (2002). Recharge of Table Mountain Group Aquifer Systems. In: Pietersen, K., Parsons, R. (Editors), (2002). *A synthesis of the hydrogeology of the table mountain group – formation of a research strategy*. WRC report no. TT 158/01, 97-102.

Pietersen, K., Parsons, R. (2002). The need for appropriate research of the Table Mountain Group Aquifer Systems. In: Pietersen, K., Parsons, R. (eds.) *A synthesis of the hydrogeology of the table mountain group – formation of a research strategy*. WRC report no. TT 158/01, 4-6.

Reason, C.J.C. and Jagadheesha, D. (2005). Relationship between South Atlantic SST variability and atmospheric circulation over the South African region during austral winter. *Journal of Climate*, **18**, 3339-3355.

Roets, W. (2008). Groundwater dependence of aquatic ecosystems associated with the Table Mountain Group aquifer. PhD thesis submitted to the Dept. of Earth Sciences, University of the Western Cape, South Africa.

Rosewarne^{2}, P. (2002). Hydrogeological characteristics of the Table Mountain Group aquifers. In: Pietersen, K., Parsons, R. (eds.) *A synthesis of the hydrogeology of the table mountain group – formation of a research strategy*. WRC report no. TT 158/01, 33-44.

Rosewarne, P. (2002). Case study: Port Elizabeth Municipal area. In: Pietersen, K., Parsons, R. (eds.) *A synthesis of the hydrogeology of the table mountain group – formation of a research strategy*. WRC report no. TT 158/01, 205-208.

Rouault, M. and Richard, Y. (2003). Intensity and spatial extension of drought in South Africa at different time scales. *Water SA* **29**, 489–500.

Rust, I.C. (1967). On the Sedimentation of the Table Mountain Group in the Western Cape Province. Unpubl. D.Sc. Thesis. Stellenbosch University.

Rust, I.C. (1973). The evolution of the Palaeozoic Cape Basin, southern margin of Africa. In: Nairn, A.E.M. & Stehli, F.G. (eds.) *The Ocean Basins and Margins, Vol. 1: The South Atlantic.* Plenum Publishing Corporation, New York, 247-276.

Salmi, T., Määttä, A., Anttila, P., Tuija, R. and Amnell, T. (2002). Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen’s slope estimates – The Excel template application MAKESENS. Publications on air quality, No.31. Finnish Meteorological Institute, Helsinki.

Schulze, R. E., Meigh, J. and Horan, M. (2001). Present and potential future vulnerability of eastern and southern Africa's hydrology and water resources. *South African Journal of Science*, **97**, 150-160.

Schulze, R.E. (2005). Setting the Scene: The Current Hydroclimatic "Landscape" in Southern Africa. *In*: Schulze, R.E. (ed) Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation. Water Research Commission, Pretoria, RSA, WRC Report 1430/1/05. Chapter 6, 83-94.

Seward, P., Xu, Y. and Brendonck, L. (2006). Sustainable groundwater use, the capture principle and adaptive management. *Water SA*, **32** (4), pp

Sigonyela, V. (2006). Towards understanding the groundwater dependent ecosystems within the Table Mountain Group aquifer: A conceptual approach. MSc thesis submitted to the Dept. of Earth Sciences, University of the Western Cape, South Africa.

Simmers, I. (ed). (1987). Estimation of natural groundwater recharge. NATO ASI Series C, Vol. 222. D. Reidel Publ. Co., Dordrecht.

Small, C. and Nicholls, R.J. (2003). A global analysis of human settlement in coastal zones. *J. Coastal Res.*, **19**, 584-599.

Smart, M.C. and Tredoux, G. (2002). Groundwater quality and fitness for use. In: Pietersen, K., Parsons, R. (Eds). A synthesis of the hydrogeology of the table mountain group – formation of a research strategy. WRC Report No. TT 158/01, 118-123.

Söhne, A.P.G. (1983). The Cape Fold Belt – Perspective. *Spec. Publ. Geol. Soc. S. Afr*. **12,** 1-6.

Sophocleous, M. (2000). From safe yield to sustainable development of water resources: the Kansas experience. *Journal of Hydrology* **235**, 27-43.

Sophocleous, M. (2005). Groundwater recharge and sustainability in the high plains aquifer in Kansas, USA. *Hydrogeology Journal* **13** (2), 351-365.

Tans, P. (2010). National Oceanic & Atmospheric Administration/Earth System Research Lab, NOAA/ESRL (culled from the website: *http://www.esrl.noaa.gov/gmd/ccgg/trends*).

Thamm, A.G. (1993). Lithostratigraphy of the Piekenierskloof Formation (Table Mountain Group). *SACS Lithostratigraphic Series* 27.

Theis, C.V. (1940). The source of water derived from wells: Essential factors controlling the response of an aquifer to development. *Civil Engineer* **10**, 277-280.

Theron, J.N. (1972). The Stratigraphy and Sedimentation of the Bokkeveld Group. Unpubl. D.Sc. Thesis, Stellenbosch University.

Todd, D.K. (1959). Ground Water Hydrology, New York: John Wiley.

Trenberth, K.E., Dai, A.G Rasmussen, R.M. and Parsons, D.B. (2003). The changing character of precipitation. *B. Am. Meteorol. Soc.*, **84**, 1205-1217.

Warburton, M. and Schulze, R.E. (2005). Historical Precipitation Trends over Southern Africa: A Hydrology Perspective. In: Schulze, R.E. (ed) Climate change and water resources in southern Africa: Studies on scenarios, impacts, vulnerabilities and adaptation. WRC Report No. 1430/1/05. Chapter 19, 325-338.

Warburton, M., Schulze, R.E. and Maharaj, M. (2005). Is South Africa's temperature changing? An analysis of trends from daily records, 1950-2000. In: Schulze, R.E. (ed) Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation. WRC Report No. 1430/1/05. Chapter 16, 275-295.

Weaver, J.M.C., Talma, A.S. and Cavé, L. (1999). Geochemistry and isotopes for resource evaluation in the fractured rock aquifers of the Table Mountain Group. WRC Report No. 481/1/99.

Woodford, A.C. (2002). Interpretative and applicability of pumping-tests in table mountain group aquifers in: Pietersen, K., Parsons, R. (Eds). A synthesis of the hydrogeology of the table mountain group – formation of a research strategy. WRC Report No. TT 158/01, 71-84.

Wu, Y. (2005). Groundwater recharge estimation in Table Mountain Group aquifer systems with a case study of Kammanassie area. PhD Thesis, Dept. of Earth Sciences, University of the Western Cape, August 2005.

Xu, Y., Wu, Y. and Duah, A. (2007). Groundwater recharge estimation of Table Mountain Group aquifer systems with case studies. WRC Report No. 1329/1/07.

Xu, Y., Wu, Y. and Titus, R. (2002). Influence of the Vermaaks Wellfield abstraction on groundwater levels and streams in the vicinity. Technical report prepared for the Department of Water Affairs and Forestry, Bellville, Cape Town.

Xu, Z.X., Takeuchi, K. and Ishidaira, H. (2003). Monotonic trend and step changes in Japanese precipitation. *J. Hydrol*. **279**, 144-150.

Zhou, Y. (2009). A critical review of groundwater budget myth, safe yield and sustainability. *Journal of Hydrology* **370**, 207-213.

APPENDIX I: Results of hydrochemical analysis of hot springs in the TMG

Date received: 07/05/2008 Date tested: 08/05/2008

Origin	Lab. No.	pH	EC mS/m	Na	K	Ca	Mg	Fe	Cl	CO_3	HCO_3	SO_4	B	Mn	Cu	Zn	P	NH_4-N	NO_3-N
				mg/l															
1	1722	5.8	19	18.7	9.7	7.9	3.1	0.24	26.4		45.9	13	**0.04**	3.57	**0.00**	**0.00**	0.06	0.91	**0.00**
2	1723	6.4	17	9.7	4.4	18.8	2.7	**0.00**	14.1		62.8	8	**0.03**	0.04	**0.00**	**0.01**	0.16	0.27	**0.00**
3	1724	6.4	23	20.0	8.9	15.4	2.5	1.12	22.0		64.3	8	0.05	0.91	**0.00**	**0.00**	0.07	0.25	**0.00**
4	1725	5.3	9	7.5	2.3	3.6	1.9	**0.03**	12.3		15.3	4	**0.03**	**0.00**	**0.00**	**0.01**	0.25	0.23	1.73
5	1726	5.7	9	7.6	2.2	3.1	1.8	**0.01**	15.9		16.8	3	**0.03**	**0.00**	**0.00**	**0.01**	0.20	**0.12**	**0.08**
6	1727	5.4	9	8.5	2.1	2.6	1.9	**0.00**	8.8		15.3	6	**0.03**	**0.00**	**0.00**	**0.00**	0.22	1.49	1.22
7	1728	5.9	10	7.6	2.7	3.7	2.0	**0.03**	15.9		16.8	4	**0.03**	**0.00**	**0.00**	**0.01**	0.21	0.19	**0.00**
8	1729	5.6	8	5.7	0.9	5.1	1.4	**0.01**	10.6		15.3	4	**0.03**	**0.00**	**0.00**	**0.01**	0.13	1.03	0.58
9	1730	5.6	11	6.8	1.1	8.4	2.1	**0.00**	17.6		18.4	**2**	**0.04**	**0.02**	**0.00**	**0.01**	0.17	2.60	2.45
Methods$^{\#}$		W05	W04	W01	W01	W01	W01	W01	W07	W06	W06	W01	W01	W01	W01	W01		W02	W03

Values in **bold** is smaller than the lowest quantifiable concentration.

Legend

1. Caledon	4. Brandvlei	7. Baden
2. Montagu (Avalon)	5. Brandvlei B.H.	8. Goudini I
3. Warmwaterberg	6. The Baths	9. Goudini II

APPENDIX IIA: Results of Maximum Temperature Trends (1950-2009)

				Mann-Kendall trend			**Sen's slope estimate**									
Time series	First year	Last Year	n	Test S	Test Z	Signific.	Q	Qmin99	Qmax99	Qmin95	Qmax95	B	Bmin99	Bmax99	Bmin95	Bmax95
PAARL	1993	2009	17		0.00		0.00	-0.10	0.09	-0.05	0.07	24.90	29.90	20.37	27.65	21.67
P'TRVILLE	1990	2009	20		0.16		0.00	-0.06	0.10	-0.05	0.07	25.80	29.00	20.85	28.35	22.23
EXC CERES	1990	2009	20		-0.26		-0.01	-0.10	0.06	-0.07	0.03	22.44	26.92	18.81	25.42	20.30
CPT-WO	1993	2009	17		1.50		0.02	-0.02	0.09	-0.01	0.06	21.40	23.40	17.86	22.92	19.46
MOLTENO-RES	2001	2009	9	-7			-0.09					27.35				
WORCESTER-AWS	1999	2009	11		-2.77	**	-0.14	-0.20	0.00	-0.18	-0.07	33.39	36.40	26.00	35.53	29.58
CAPE PT	1950	2009	59		6.69	***	0.03	0.02	0.03	0.02	0.03	18.05	18.28	17.81	18.20	17.89
HERMANUS	1997	2009	13		1.17		0.03	-0.05	0.08	-0.02	0.07	19.15	23.31	16.42	21.81	17.25
CAPE AGULHAS	1950	2009	60		5.07	***	0.02	0.01	0.03	0.01	0.02	19.75	19.93	19.59	19.87	19.62
STRUISBAAI	1996	2009	14		1.27		0.08	-0.07	0.30	-0.03	0.23	16.13	24.08	4.91	21.80	8.00
TYGERHOEK	1965	2009	45		4.49	***	0.03	0.02	0.05	0.02	0.05	22.46	23.00	21.90	22.90	21.97
C'WILLIAM DAM	1982	2009	26		2.46	*	0.05	0.00	0.09	0.01	0.08	25.36	27.45	23.17	27.06	23.92
VREDENDAL	1959	2009	51		5.66	***	0.04	0.03	0.05	0.03	0.05	24.79	25.32	24.41	25.16	24.52
PRINS ALBERT	1990	1998	9	7			0.10					22.50				
OUDTSHOORN	1977	2009	32		2.84	**	0.04	0.01	0.07	0.02	0.06	24.11	25.62	22.87	25.17	23.29

Level of significance:

*******	**if trend at α = 0.001 level of significance**
******	**if trend at α = 0.01 level of significance**
*****	**if trend at α = 0.05 level of significance**
+	**if trend at α = 0.1 level of significance**

If cell is blank, the significance level is greater than 0.1

APPENDIX IIB: Results of Minimum Temperature Trends (1950-2009)

				Mann-Kendall trend			Sen's slope estimate									
Time series	First year	Last Year	n	Test S	Test Z	Signific.	Q	Qmin99	Qmax99	Qmin95	Qmax95	B	Bmin99	Bmax99	Bmin95	Bmax95
PAARL	1993	2009	17		-0.12		-0.01	-0.08	0.07	-0.06	0.06	12.91	16.66	9.14	15.57	9.73
P'TRVILLE	1990	2009	20		0.00		0.00	-0.05	0.06	-0.04	0.04	11.42	14.12	8.29	13.21	9.39
EXC CERES	1990	2009	20		-0.10		0.00	-0.06	0.05	-0.04	0.04	7.44	10.10	5.01	9.29	5.60
CPT-WO	1993	2009	17		1.94	+	0.04	-0.02	0.11	0.00	0.08	9.94	12.78	6.42	11.94	7.96
MOLTENO-RES	2001	2009	9	-6			-0.05					17.38				
WORCESTER-AWS	1999	2009	11		-3.11	**	-0.13	-0.28	-0.06	-0.18	-0.09	18.44	26.65	14.73	21.43	16.37
CAPE PT	1950	2009	59		4.66	***	0.02	0.01	0.03	0.01	0.02	12.47	12.68	12.22	12.62	12.28
HERMANUS	1997	2009	13		2.75	**	0.05	0.01	0.10	0.01	0.08	11.27	13.37	8.66	13.08	9.64
CAPE AGULHAS	1950	2009	60		6.01	***	0.02	0.01	0.02	0.01	0.02	13.80	13.95	13.61	13.91	13.66
STRUISBAAI	1996	2009	14		0.88		0.05	-0.10	0.31	-0.04	0.22	10.97	18.55	-2.49	15.63	2.04
TYGERHOEK	1965	2009	45		4.55	***	0.02	0.01	0.04	0.02	0.03	9.94	10.35	9.52	10.23	9.68
C'WILLIAM DAM	1982	2009	26		0.13		0.00	-0.04	0.06	-0.03	0.04	12.12	14.09	9.49	13.38	10.42
VREDENDAL	1959	2009	51		3.72	***	0.02	0.01	0.03	0.01	0.03	10.57	10.97	10.26	10.88	10.33
PRINS ALBERT	1990	1998	9	-10			-0.07					15.49				
OUDTSHOORN	1977	2009	32		1.62		0.02	-0.01	0.05	0.00	0.04	10.10	11.34	8.73	11.02	9.16

Level of significance:

***	**if trend at α = 0.001 level of significance**
**	**if trend at α = 0.01 level of significance**
*	**if trend at α = 0.05 level of significance**
+	**if trend at α = 0.1 level of significance**

If cell is blank, the significance level is greater than 0.1

Appendix IIIA: Results of annual rainfall trends (1950 - 1979)

(Based on MAKESENS algorithm developed by Salmi *et al*, 2002)

Time series	First year	Last Year	n	Mann-Kendall trend Test S	Test Z	Signific.	Sen's slope estimate Q	Qmin99	Qmax99	Qmin95	Qmax95	B	Bmin99	Bmax99	Bmin95	Bmax95
Algeria_Bos mm/yr	*1950*	*1979*	*30*		0.50		2.575	-8.931	18.159	-5.591	13.803	640.78	843.71	524.37	800.07	540.46
Redelinghuy mm/yr	*1950*	*1979*	*30*		-1.32		-2.675	-6.493	2.945	-5.551	1.360	295.71	342.12	230.46	331.88	249.48
Graafwater mm/yr	*1950*	*1979*	*26*		-1.28		-1.931	-6.339	3.068	-4.716	1.561	238.30	294.20	186.25	273.96	207.24
Elandsfontein mm/yr	*1950*	*1979*	*30*		-0.45		-1.850	-10.989	8.627	-7.506	6.028	515.00	657.22	437.32	613.85	468.51
Ceres mm/yr	*1955*	*1979*	*25*		0.07		0.438	-28.658	28.227	-21.215	19.042	855.40	1443.72	506.84	1311.41	621.74
Walker_Bay mm/yr	*1952*	*1979*	*28*		-1.01		-2.494	-9.965	5.314	-8.174	3.597	693.53	784.91	546.29	767.08	581.60
Hermanus mm/yr	*1950*	*1979*	*30*		-2.89	**	-8.590	-16.900	-0.831	-14.576	-3.084	754.70	890.76	629.13	845.97	662.07
De_Doorns mm/yr	*1964*	*1979*	*16*		2.70	**	12.380	0.760	31.063	3.683	27.720	-28.54	207.09	-376.00	157.12	-308.82
Worcester mm/yr	*1950*	*1979*	*30*		-2.00	*	-3.135	-7.756	1.796	-6.388	-0.067	279.11	345.20	202.93	324.75	238.39
Rooirivier mm/yr	*1950*	*1979*	*29*		0.75		1.549	-2.971	7.584	-1.940	5.726	220.46	286.02	127.495	267.92	160.94
Buffelsklip mm/yr	*1950*	*1979*	*28*		-0.65		-1.076	-4.863	4.167	-3.917	2.780	230.8	280.918	169.866	269.15	189.277
DeRust_Pol mm/yr	*1950*	*1979*	*30*		-0.89		-2.040	-7.848	4.039	-6.264	2.398	349.51	440.866	250.332	419.69	274.302
Simonstown mm/yr	*1963*	*1979*	*17*		2.35	*	16.281	-5.286	42.944	2.674	32.702	212.29	702.321	-313.005	543.13	-57.446
Woodhead_Dam mm/yr	*1955*	*1979*	*25*		-0.30		-3.100	-28.571	20.866	-20.391	12.529	1498	1941.29	1168.12	1802	1234.35

Level of significance:

- *** if trend at α = 0.001 level of significance
- ** if trend at α = 0.01 level of significance
- * if trend at α = 0.05 level of significance
- + if trend at α = 0.1 level of significance

If cell is blank, the significance level is greater than 0.1

Appendix IIIB: Results of annual rainfall trends (1980 - 2007)

(Based on MAKESENS algorithm developed by Salmi *et al*, 2002)

				Mann-Kendall trend			Sen's slope estimate									
Time series	**First year**	**Last Year**	**n**	**Test S**	**Test Z**	**Signific.**	**Q**	**Qmin99**	**Qmax99**	**Qmin95**	**Qmax95**	**B**	**Bmin99**	**Bmax99**	**Bmin95**	**Bmax95**
Algeria_Bos	*1980*	*2007*	*28*		-1.52		-7.236	-19.321	5.621	-15.306	2.874	835.18	984.44	713.13	952.78	737.78
Redelinghuy	*1980*	*2007*	*28*		0.36		0.968	-2.909	7.107	-1.851	5.293	270.22	308.53	214.64	291.83	232.53
Graafwater	*1980*	*2007*	*28*		-0.02		-0.124	-4.371	4.680	-3.306	3.124	264.56	318.79	214.39	302.66	240.97
Elandsfontein	*1980*	*2007*	*28*		0.06		0.257	-5.878	7.318	-4.726	4.914	491.21	544.18	404.67	530.73	430.79
Ceres	*1980*	*2007*	*28*		-1.13		-6.117	-23.606	9.215	-19.778	4.586	1177.67	1400.39	987.84	1362.86	1040.70
Walker_Bay	*1980*	*2007*	*28*		-0.14		-0.338	-6.592	8.255	-4.808	5.728	684.48	777.29	577.05	750.52	613.50
Hermanus	*1980*	*2007*	*28*		0.77		1.984	-5.159	8.693	-3.067	6.691	587.62	683.14	525.66	664.87	533.18
De_Doorns	*1980*	*2007*	*28*		-1.96	+	-4.332	-9.393	2.546	-8.166	-0.004	385.68	449.21	297.19	427.10	329.85
Worcester	*1980*	*2007*	*28*		-1.52		-3.359	-8.676	3.149	-6.993	1.542	354.22	434.70	266.63	399.35	288.15
Rooirivier	*1980*	*2006*	*27*		-0.58		-1.553	-5.768	5.235	-4.489	4.650	273.70	330.83	183.981	306.2	191
Buffelsklip	*1980*	*2006*	*27*		1.08		2.240	-4.386	7.869	-2.100	6.401	210.34	316.898	130.451	270.2	149.067
DeRust_Pol	*1980*	*2007*	*28*		1.24		3.013	-2.981	7.645	-1.514	6.302	276.13	357.51	202.981	333.74	227.614
Simonstown	*1980*	*2007*	*28*		-0.34		-1.165	-9.903	7.498	-7.495	5.091	734.79	848.487	607.124	822.21	635.586
SilvermineNR	*1980*	*2007*	*28*		-3.10	**	-17.961	-31.102	-3.178	-27.475	-6.604	1396.5	1552.91	1167.32	1527.5	1224.04
Woodhead_Dam	*1980*	*2007*	*28*		0.02		0.510	-17.862	22.748	-11.796	15.081	1469.4	1746.96	1259.57	1665.8	1328.71
Waaivlei	*1980*	*2002*	*23*		0.85		15.672	-30.680	59.348	-22.100	53.071	1469.8	2026.92	1000.78	1873.9	1094.73

Level of significance:

***	if trend at α = 0.001 level of significance
**	if trend at α = 0.01 level of significance
*	if trend at α = 0.05 level of significance
+	if trend at α = 0.1 level of significance

If cell is blank, the significance level is greater than 0.1

Appendix IIIC: Results of annual rainfall trends (1950 - 2007)

(Based on MAKESENS algorithm developed by Salmi *et al*, 2002)

				Mann-Kendall trend			Sen's slope estimate									
Time series	**First year**	**Last Year**	**n**	**Test S**	**Test Z**	**Signific.**	**Q**	**Qmin99**	**Qmax99**	**Qmin95**	**Qmax95**	**B**	**Bmin99**	**Bmax99**	**Bmin95**	**Bmax95**
Algeria_Bos mm/yr	*1950*	*2007*	*58*		0.42		0.827	-3.084	5.302	-2.082	4.269	709.49	808.46	569.33	785.90	611.62
Vanrhynsdorp mm/yr	*1950*	*2006*	*53*		0.07		0.060	-1.200	1.249	-0.913	0.978	165.02	188.70	135.86	182.53	145.80
Puts mm/yr	*1950*	*2007*	*58*		-1.19		-0.927	-3.175	1.254	-2.603	0.621	384.48	444.88	320.64	440.87	338.90
Elandsfontein mm/yr	*1950*	*2007*	*58*		-0.45		-0.509	-3.383	2.140	-2.646	1.489	508.08	586.64	425.45	573.33	444.01
Graafwater mm/yr	*1950*	*2007*	*49*		1.92	+	1.188	-0.470	2.936	-0.053	2.447	211.27	250.74	159.65	244.36	177.08
Redelinghuys_Pol mm/yr	*1950*	*2007*	*58*		0.48		0.319	-1.136	2.241	-0.780	1.806	264.22	304.59	205.77	296.53	216.97
Hermanus mm/yr	*1950*	*2007*	*58*		-0.76		-0.750	-3.644	1.731	-2.997	1.185	641.65	725.84	570.43	707.06	585.09
Worcester mm/yr	*1950*	*2007*	*58*		0.78		0.620	-1.251	2.731	-0.901	2.231	253.47	292.07	188.39	275.60	202.55
Walker_Bay mm/yr	*1952*	*2007*	*56*		0.71		0.694	-1.575	3.323	-1.040	2.792	650.73	727.91	561.14	710.97	580.39
Boskloof mm/yr	*1950*	*2007*	*58*		0.30		0.265	-2.343	2.661	-1.625	2.072	445.48	516.56	369.302	496.52	385.478
Ceres mm/yr	*1955*	*2007*	*53*		1.13		3.071	-4.626	10.043	-2.606	8.627	940.27	1214.73	685.894	1110.6	735.631
De_Mond mm/yr	*1952*	*2006*	*55*		0.61		0.629	-2.234	3.455	-1.510	2.624	386.5	472.362	301.58	449.92	321.756
De_Doorns mm/yr	*1965*	*2007*	*43*		1.53		2.126	-1.659	5.758	-0.427	4.704	221.87	373.587	109.56	310.47	133.533
Zoetendal mm/yr	*1950*	*2006*	*57*		-0.31		-0.461	-3.859	2.996	-2.915	2.058	454.14	573.951	350.689	543.73	371.518
Stettynskloof mm/yr	*1953*	*2006*	*54*		1.42		2.747	-2.526	9.637	-1.032	8.118	727.73	861.014	551.37	830.22	593.4
DeRust_Pol mm/yr	*1950*	*2007*	*58*		0.60		0.529	-1.461	2.485	-1.032	1.918	296.71	362.066	243.645	348.16	257.973
Rooirivier mm/yr	*1950*	*2006*	*56*		1.14		0.833	-0.909	2.762	-0.491	2.187	225.68	272.059	178.533	264.89	192.347
Buffelsklip mm/yr	*1950*	*2006*	*55*		0.94		0.620	-0.947	2.254	-0.616	1.774	218.18	259.836	167.276	248.92	181.666
Albertina_Pol mm/yr	*1950*	*2006*	*52*		0.21		0.211	-2.950	3.256	-2.158	2.558	446.82	555.988	361.284	531.65	375.619
Zachariasfontein mm/yr	*1950*	*2006*	*49*		0.66		0.332	-1.015	1.841	-0.592	1.459	178.98	210.043	142.392	195.25	153.062
Franschhoek_LM	*1950*	*2003*	*54*		0.28		0.627	-4.427	5.582	-3.106	4.461	837.91	963.753	679.113	934.77	722.084
Woodhead_Dam mm/yr	*1955*	*2006*	*52*		1.30		2.989	-3.507	9.729	-1.867	7.758	1377.9	1606.94	1190.65	1541.2	1250.9
Simonstown mm/yr	*1963*	*2007*	*45*		2.16	*	3.727	-0.875	8.725	0.535	7.454	529.46	689.777	348.175	643.96	393.517

Level of significance:

***	if trend at α = 0.001 level of significance
**	if trend at α = 0.01 level of significance
*	if trend at α = 0.05 level of significance
+	if trend at α = 0.1 level of significance

If cell is blank, the significance level is greater than 0.1

APPENDIX IV: Table of information on unsuccessful production boreholes in the KKRWSS

Borehole	Depth (m)	Yield (l·s^{-1})	Geology	Water level (m)	Altitude (m)
WN101	243.5	>2.0	Baviaanskloof Quartzite, shale at 28m 188, 203 m, fractures at 120 m.	1.25 (1997)	534.3
VR5	215	15.0	0-12 boulders; 12-215 Baviaanskloof, shale at 37, 46, 57, 111 m, fractures at 82, 102, 169 and 184-186 m. *(75-215).*	1.85 (1997)	549.5
VG12	173	4.7	0-4 boulders; 4-230 Tchando Formation, fractures at 19, 78, 98, 14 and 171-173 *(40-173)*	3.6 (2005)	563.8
VG4	113	<2.0	0-2 scree, 2-113 Baviaanskloof	17.92 (2005)	560
DG107	210	4.1	0-22 boulders, 20-210 Kouga Formation	41.28 (1996)	500
DG104	250	5.7	0-8 Enon, 8-250 Kouga Formation	99.68 (1997)	490
DP27	249	135-140 (2) 140-195 (10) 240(8)	0-22 Enon 22-249 Baviaanskloof Formation, Fractures at 150 to 155 m, open joints with showing weathering at 241, 242 and 248 m	96.4 (2002)	458.3
DP20	220	0.9	0-18 Enon, 18-220 Baviaanskloof Formation	83.29 (1998)	448.8
DP14	167	12	0-6 Enon, 2-30 weathered sandstone, 30 to 167 sandstone	98.74 (1997)	451.4
DP13	184.6	30	Baviaanskloof with shale	107.33 (1997)	458.9
Modified with updated information after Wu (2005)					

Appendix V: Rainfall records for rain stations in the KKRWSS area.

Purification Works East

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2000	55.7	52.5	52.55	10.1	1.7	5.9	6.7	6.1	20.9	2.8	155	19.5	389.45
2001	16	8.6	5.2	11.2	5.6	10	16.6	25.6	29.2	11.6	65.8	13	218.4
2002	6.3	22.5	0.6	11.7	34	53	23	44.6	75.8	44.6	12.5	67	395.6
2003	0	8.8	102.7			3.5	16	31.6	3.7	35.5	0	5	206.8
2004	18.7	35.3	9.2	51.4	1.2	37	25.1	30.9	18	35.5		35.5	297.8
2005	22.8	13.5	25.7	32.9	28.3	27	3	21.4	0	12.6	53.6	0	240.8
2006	9.3		90	25.6	48.5	20.3	84	110.9	0	10	13.5	18.4	430.5
2007	27.9		1.6	3.4	2.8	8.1	12.3	5.1	4.2	3.3	17.4	4.5	90.6
2008	17.4	13.6	2.6	4.8	4.2	9.8	12.7	54.4	16	33.5	17.9	0	186.9
2009	0	61.2	0	67.9	3.5	73.4	27.6	1.1	8.1		13.2	58.2	314.2
2010	5			10.4	12.4	42.6	14.5	17					
Mean	16.28	27.00	29.02	22.94	14.22	26.42	21.95	31.70	17.59	21.04	38.77	22.11	277.11

Purification Works West

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2000	71	28.5	76.5	2.5	0	8	9.1	5	6	8.4	53.5	4.2	272.7
2001	8.5	9.6	7.5	30.6	4.5	10.2	13.3	14	19.8	46.4	61.5	0	225.9
2002	4.9	5	1.5	5.3	20.8	19.1	13.2	32.6	18.2	32.6	1.4	73.5	228.1
2003	0	2	79.8			7.9	10	4.1	5.5	15.9	0	19	144.2
2004	35	16.4	12.5	67.8	0.7	22.6	4.2	63.9	0.5	39.9		39.9	303.4
2005	51.6	6.9	18	29.7	21.6	9.7	0	8.6	6.3	1.4	49	0.9	203.7
2006	2		10.5	32.3	74.6	3.4	56.9	68.4	14.9	34.1	5.6	1.4	304.1
2007	1.1		48.6	35.8	28.7	4	32.3	20.9	1.4	24.3	184.6	139.4	521.1
2008	184.6	65	7.4	15.4	2.6	5.9	3.2	13.4	4.4	4.7	40.9	1.9	349.4
2009	4.2	25.4	1.2	112.9	13.5	69.3	26.2	23.7	24		53.5	30.6	384.5
2010	43.8			15.1	23.5	20.2	34.6	8					
Mean	36.97	19.85	26.35	34.74	19.05	16.39	18.45	23.87	10.10	23.08	50.00	31.08	293.71

Bokkraal

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2000	55	30	65	17	2	6	6	5	25	3	125	15	354
2001	5	5	6	17	2	5	12	5	35	34	38	0	164
2002	5	0	0	6	8	50	25	40	66	40	10	68	318
2003	0	8					15	10	2		0	5	
2004	18	34	8	5	0	30	10	0	0	0		0	
2005	0	0	0	0	7.5	7.5	0.1	0	0	0	40	1	
2006	2.5		10	15	90	15	65	110	10	10	12	10	349.5
2007	20		25	5	10	10	0	10	5	0			

Droekloof

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2000	35	30	72	17	2	10	8	5	12	3	40	22	256
2001	15	25	15	14	5	5	17	10	5	20	32	0	163
2002	5	0	0	5	6	46	25	38	68	38	10	60	301
2003	0	6	45				15	10	2	32	0	5	
2004	16	6	26	4	0	10	10	10	0	0		0	
2005	0	0	0	52	13.5	29.5	1.5	15	2.5	4	1.5	1	
2006	1.5		2	15	22	26	40	100	15	15	0	0	236.5
2007													

Voorzorg

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2000	60	28	55	5	2	30	28	10	20	5	92	25	360
2001	19	7	6	0	0	10	40	10	45	60	52	0	249
2002	5	38	13	10	35	80	30	30	50	30	0	28	349
2003	0	2	140	5		10	17	40	4	50	0	0	268
2004	30	30	12	16	0	38	50	28	28	37		37	306
2005	0	0	75		10.5	31	0.3	15	2	7	40	1	181.8
2006	2.5		5	13	115	30	75	170	15	15	10	26	476.5
2007	0		45	10	105	20	15	35	25	25	65	120	465
2008	65	53	4	17	2	15	10	100	25	45	5	5	346
2009	0	60	0	80	3	40	45	5	5		10	45	293
2010	0			10	15	68	50	20					

V-Notch

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2000	37	38	54	8	2	30	5	24	2	8	140	24	372
2001	12	6	15	11	5	6	31	4	38	145	42	0	315
2002	6	29	6	8	26	78	30	46	134	46	0	70	479
2003	0	7	150	8		14	25	1.5	4	68	0	5	282.5
2004	17												
2005					13.5	32.5	3	19.5	3	3.5	1	1.5	
2006	2		7	15	100	20.5	80	100	19	19	4	9	375.5
2007	0		55	10	98	20	14	18	4	4	70	20	313
2008	70	3.5	2	8	2	10	4	28	10	6	4	4	151.5
2009	0	16	0	90	9	76	40	8	3		30	45	317
2010	0			14	14	62	30	12					

Parshall

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2000	40	40	69	17	5	34	5	8	28	15	150	35	446
2001	15	20	10	17	7	5	40	17	60	55	53	0	299
2002	7	42	6	6	30	77	32	47	90	47	0	48	432
2003	0	8	180	10		13	22	49	3	64	0	5	354
2004	20	36	14	14									
2005					20	33	3.5	22	3	1	1.5	0	
2006	0	5	5.5	12	100	42	80	100	20	20	0	3	387.5
2007	2		20	10	90	20	10	18	8	8	74		260
2008	74		2	4.5	3	18	4	41	8	9	4	4	171.5
2009	0	10	0	70	0	51	32	0	2		12	8	185
2010	0			0	0	70	0	10					

Wildbeesvlakte

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2000	42	56	77	12	10	33	4.2	6	32	36	150	2	460.2
2001	20	19	4	20	11	13	27	23	58	50	58	7	310
2002	13	40	8	6	32	82	38	55	76	55	9	78	492
2003	10	9		14		10	26	0	3		0	8	
2004	26												
2005					23.5	56.5	4.5	26	4	5	28	0	
2006	0		0	0	42	32	72	50	45	8	10	25	284
2007	14	25	5	14	46	36.5	13	14	9.5	0	109.5	99	385.5
2008	109.5	56.5	20.5	23.5	12.5	38.5	22	49	34.5	66	46.5	46.5	525.5
2009	1.5	41	41	60	2.5	100	52	12.5	12.5		12	10	345
2010	0			18	30	58.5	76.5						

Appendix VI: Total Abstractions from the KKRWSS from July 2009 to June 2010

DATE	Vermaaks River	Bokkraal	Varkieskloof	Calitzdorp	Olifants River	Dorps Meter	Total
Jul '09	73275	0	16070	6758	17410	0	113513
Aug '09	71936	0	13392	6964	11232	0	103524
Sep '09	158025	0	12960	2592	14602	0	188179
Oct '09	12041	6480	12960	4752	15140	0	51373
Nov '09	158630	6480	12960	4752	15163	0	197985
Dec '09	81958	0	13392	8726	17410	0	121486
Jan '10	82494	0	11785	9244	17410	0	120933
Feb '09	47428	15086	17166	7585	13322	32136	132723
Mar '10	39307	16299	17670	10534	12210	26337	122357
Apr '10	62774	21670	20389	15287	12461	5479	138060
May '10	35292	21054	16530	15355	11441	9311	108983
Jun '10	59501	21955	17908	8504	11441	0	119309
Total	882661	109024	183182	101053	169242	73263	1518425

Values in m^3