GROUNDWATER RECHARGE ASSESSMENT OF THE BASEMENT AQUIFERS OF CENTRAL NAMAQUALAND

Report to the Water Research Commission

by

Shafick Adams
Rian Titus
Yongxin Xu

Groundwater Group
University of the Western Cape
Private Bag X17
Bellville
7535

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Water Research Commission
Private Bag X03
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Executive summary

Introduction

Understanding groundwater recharge is a prerequisite for effective groundwater management. Recharge is defined as the portion of rainfall that reaches the saturated zone, either by direct contact in the riparian zone or by downward percolation through the unsaturated zone. To provide the necessary understanding, this study has investigated the recharge processes and rates of the Central Namaqualand area of the Northern Cape, South Africa. The area is characterised by a semi-arid to arid climate with groundwater occurring in the crystalline basement and alluvial aquifers. Recharge in arid to semi-arid crystalline basement aquifers are neither straightforward nor simple and needs both a qualitative and a quantitative approach. This was achieved by using a variety of methods, including the chloride mass balance (CMB) method, methods involving correlating storativity, rainfall and water level fluctuations (i.e. saturated volume fluctuations and cumulative rainfall departures), ^{18}O and ^{2}H stable isotope analyses, radiogenic isotope (^{14}C) interpretation, R- and Q mode factor analyses and a GIS approach.

The processes involved in recharge and the rate of recharge are influenced by several factors, which may include the geology, climate, geomorphology and soils. There exists no set procedure to estimate recharge in fractured rock dominated terrain. Assessing recharge depends on the application of a suite of methods.

Objective, scope and approach

The primary objective of the research is to quantify and characterise recharge to the crystalline basement and alluvial aquifers of Central Namaqualand for sustainable groundwater development and management.

The scope of the study includes:

(1) Identifying methods suitable for recharge studies in the Central Namaqualand region.

(2) Delineating recharge areas.

(3) Applying and comparing of a number of independent approaches for recharge characterisation/estimation as well as selecting the best method(s) for recharge estimation.

(4) Developing a conceptual model for the groundwater recharge.

The development of the conceptual model of the area is based on previous studies and hydrologic data (chemical and isotopic data, water-level measurements, borehole logs, geophysical measurements, climatological data, and hydraulic properties determined from aquifer tests, as well as information based on field observations). Areas for recharge studies will be identified based on the amount of data available (water levels, abstraction rates, climatic data, borehole distribution). A strong bias will be introduced towards areas where abstraction zones supply water to the rural communities. Methods, which are suitable for recharge estimation for the area, will be applied at selected sites.

Identifying methods suitable for recharge studies in the Central Namaqualand region

Five methods have been identified that can be applied in the study area, and they are:

- Chloride mass balance (CMB) method;
- Cumulative rainfall departures (CRD) method;
- Saturated volume fluctuation (SVF) method;
- Statistical approach; and
- GIS approach.

The methods were selected based on the availability of data and data that can be obtained easily and cost-effectively. A spreadsheet program was developed to assist in selecting different methods, based on data availability and requirements.

Delineating recharge areas

Recharge areas were delineated on regional and local scales. Regionally, recharge areas correspond with the higher lying areas that receive most of the annual rainfall. Recharge areas were identified using factor analysis, employing the interrelationship between groundwater chemistry, isotopes and altitude to define recharge and discharge areas as well as intermediate areas. The results of the factor analysis also indicated recharge of polluted water into the aquifer. The GIS approach correlated various thematic layers to recharge probability. The layers were then integrated to generate a recharge potential map. Applying the rainfall distribution map over the area effectively shows the areas most likely to receive recharge. Although the approach gives a map that is conceptually correct, it can be further refined.

Localised recharge areas are related to the type of aquifer. It was found that the alluvial aquifers are easily recharged due to their hydraulic characteristics and their position within the landscape. The structural control on the ephemeral drainage systems is evident in their alignment along fracture systems that are associated with the underlying bedrock. The alluvial systems are major pathways for groundwater recharge to the weathered and bedrock zone aquifers.

Application and comparison of a number of independent approaches for recharge characterisation/estimation and selection of the best method(s) for recharge estimation

Assessing recharge to any aquifer depends on the type of area under investigation, the availability of data, the distribution of available data and the ability to obtain meaningful data. Groundwater resources assessment is inherently complex in semi-arid to arid crystalline terrain. Groundwater recharge rates over large areas are difficult to estimate due to problems associated with upscaling and data distribution. Two approaches have been followed in this study whereby recharge was qualitatively and quantitatively assessed. The qualitative assessment involved using existing data from the area and applying statistical and spatial techniques to assess recharge processes and patterns. Applying the CMB method and water level to rainfall relationships gave quantitative estimates of recharge.

The qualitative assessments of recharge, using statistical analysis (R and Q mode factor analysis) and the GIS assessment techniques, identify areas that are receiving recharge as well as being favourable for potential recharge. The statistical analysis is useful in that it also indicates areas of localised artificial recharge through agricultural and domestic activities. The isotope approach also provided some useful information in terms of recharge processes and the time since recharge. It was found that most of the recharged water was evaporated at the surface, as evidenced in the stable isotope data. Recharge is thus mainly indirect except for the higher-lying mountainous areas where recharge is mainly direct. The isotope samples of the higher-lying areas plot in a distinct pattern on the

δ^2H- $\delta^{18}O$ plot. The radiogenic isotopes indicated the existence of very old water to recently recharged water.

The results of the quantitative analysis are shown in Table A. Recharge was calculated as the average annual recharge. However, it is well recognized that only certain rainfall events during the wet winter season will contribute to meaningful recharge. Higher rates of recharge are experienced in areas where groundwater is exploited from a combination of the alluvial and basement aquifers. Basement aquifers are used here to describe both the weathered zone and fractured rock aquifers. The CMB method underestimates recharge to alluvial aquifers associated with the ephemeral rivers (i.e. Buffels River Town and Rooifontein). This may be explained by additional chloride input from run-on during periods of recharge. The current calculation of the CMB method lacks chloride data from run-on. The recharge rates also tend to correlate with the ^{14}C ages from individual boreholes, except that the Leliefontein sample does not fit the expected age and may be due to a sampling or analytical error. The scatter of estimates is probably due to the fact that the CMB, CRD and SVF methods measures recharge at different temporal scales. The CMB method estimates recharge over an extensive period, as opposed to the CRD and SVF methods that estimate recharge over a shorter period. The CMB method also depends on the degree of groundwater mixing within the borehole. It has been shown that the groundwater quality generally deteriorates with depth and ^{14}C evidence suggests stratification of groundwater of different ages. The uncertainties in the degree of mixing and rainfall chloride can have a considerable effect on the error associated with an estimate.

Table A: Comparison of results between the CMB, SVF and CRD methods.

Site	Ave. Rainfall (mm/yr)	CMB (mm/yr)	SVF (mm/yr)	CRD (mm/yr)	MRT (yrs)	Aquifer
Buffels River Town	188	0.71	5.3	6.4	Modern	Alluvial/Basement
Bulletrap	172	1.14	0.3	0.1		Basement
Klipfontein	196	0.23	0.3	0.1	>30 000	Basement
Komaggas	229	1.04	4.4	0.7	Modern	Alluvial/Basement
Rooifontein	138	0.39	2.6	3.06		Alluvial/Basement
Spoeg River	200	0.22	0.2	0.1	>2000	Basement

Conclusions

This is the first systematic recharge study carried out in the central Namaqualand region. The results indicate that recharge is higher in the alluvial aquifers than in the hard rock basement aquifers. The results also indicate that recharge decreases from the escarpment zone to the coastal zone. Even under favourable rainfall conditions the areas around Klipfontein and Spoeg River receives minimal recharge. This phenomenon is probably related to the surface features in the areas. The chloride mass balance, saturated volume fluctuation (SVF) and the cumulative rainfall departures (CRD) methods were used to quantify recharge rates. Recharge was calculated as the average annual recharge. The CMB, SVF and CRD methods gave different recharge rates, mainly because of the fact that recharge are calculated over different temporal and spatial scales. The SVF and CRD methods generally gave results that are in close agreement. The stable isotopes, ^{18}O and ^{2}H, and the radiogenic isotope ^{14}C were used to assess groundwater recharge processes and mean residence times of the groundwater, respectively. The stable isotopes indicate that recharge is mainly indirect with direct recharge dominating in the mountainous areas. The mean residence times of the groundwater range from very old (>30 000 years) to recently recharged groundwater. A statistical and GIS approach were used to delineate recharge areas and discharge areas or where recharge is negligible. Recharge is higher in the mountainous areas than in the lower lying areas, with minimal recharge along the coastal lowland. It was also established that recharge mainly occurs through the alluvial aquifers associated with ephemeral rivers with significant soil cover. Some salient points are highlighted below:

- Groundwater recharge rates to the basement and alluvial aquifers are estimated to be within 0.1 and 10 mm/yr, with the higher values being mainly to the alluvial aquifers and high altitude sites, and the lower limits to the fractured rock aquifers.
- Groundwater level fluctuations and rainfall (CRD and SVF) was successfully used to estimate groundwater recharge. Water level data is usually available in most areas due to community water supply schemes. Uncertainties with regard to the determination of storage coefficients and contributing areas to recharge in fractured hard rock terrain are still of concern for most hydrogeologists. The estimates used in the calculations are ‘best estimates’.

- The CMB method is still a useful method for recharge estimations in most hydrogeological provinces as a first estimate of recharge. However, the method, if applied on its own, may not give an accurate account of recharge rates. The uncertainties and assumptions of the method need to be considered when interpreting the results. The recharge rates estimated for the alluvial aquifers are lower than expected. This is a result of the unaccounted chloride in the surface runoff flux.
- Isotope data indicate water ranging from very young to very old (<50 years - >30 000 years). Intermediate ages indicate active mixing of younger and old water.
- Recharge is related to the amount of rainfall and the position of the aquifers within the landscape, which is, in turn, related to altitude and topography. Recharge mainly occurs when rainfall is above normal. Above-normal rainfall produces more intense runoff that can travel further down the hydrological profile, recharging more of the alluvial aquifers.
- Recharge occurs as primary recharge in the mountainous areas where direct infiltration is more likely. Indirect recharge involves the infiltration of surface runoff and discharges from springs and adjacent aquifers, dominating in most of the areas.
- Flood events will produce significant recharge, mainly to the alluvial aquifers.
- Recharge estimates that may seem to be within acceptable limits of error when interpreted, may be significantly high when applied to determine aquifer sustainability. Rainfall in semi-arid regions is episodic in nature, where most of the annual rainfall can occur within a very short period of time with a concomitant increase in recharge if favourable conditions exist, as opposed to distributing the rainfall over an entire year. The use of mean annual recharge rates can be misleading, as the simulated period only includes years of above-average rainfall and not the long-term cyclicity of rainfall.
- Recharge in arid to semi-arid crystalline basement aquifers is neither straightforward nor simple and needs both a qualitative (e.g. field observations and local knowledge) and a quantitative approach.
- The approach can be adopted for similar hydrogeological regions or regions where there are limited data.

Recommendations for future research

Topics or issues that must be considered for future research include:

- Results and techniques provided by this baseline study should be used to acquire additional data to optimise the recharge rates estimated.
- The utilisation of complementary water sources needs to be highlighted, such as rainwater harvesting, fog water collection, and artificial recharge using runoff from the bornhardts. Some of these schemes are operated on a limited scale in the area and can be expanded to other areas.
- Measurement campaigns for chloride deposition.
- Application of the recharge estimates to management scenarios.
- Quantification of episodic recharge at various temporal scales.
- Scenario-based studies on the impact of climatic change on future groundwater resources**.**
- Expanding the GIS approach to distribute point estimates from a particular area to similar areas elsewhere. The spatial heterogeneity of recharge introduces difficulties in upscaling, and needs additional research aimed at improving the application of point data to larger areas.
- Hill slope processes and their impact on groundwater flow and recharge.

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Abbreviations and symbols

^{14}C	-	Carbon-14
^{18}O	-	Oxygen-18
^{2}H/D	-	Deuterium
CMB	-	Chloride mass balance
CRD	-	Cumulative rainfall departures
DWAF	-	Department of Water Affairs and Forestry
FC	-	Flow Characteristic
GMWL	-	Global meteoi water line
K	-	Hydraulic conductivity
LMWL	-	Local meteoric water line
MAE	-	Mean annual evapotranspiration
mamsl	-	Meters above mean sea level
MAP	-	Mean annual precipitation
MAR	-	Mean annual runoff
mbgl	-	Meters below ground level
NGDB	-	National Groundwater Database
pmC	-	Percent modern carbon
PMWIN	-	Processing Modflow for Windows
S-value	-	Storativity or specific yield
SVF	-	Saturated volume fluctuation
T	-	Transmissivity
WRC	-	Water Research Commission

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CHAPTER 1

Introduction

1.1 Introduction

The quantification of the rate of groundwater recharge is vital for efficient groundwater resource management or sustainable management of groundwater sources (Simmers, 1996, Bredenkamp et al., 1995). The prediction of sustainable yields of aquifers is dependent on the amount of water recharging the aquifers. Recharge is important in basement aquifers due to their small storage; it becomes even more important if the basement aquifers occur in arid regions. As a result, the need exists to assess recharge in these regions with suitable methods. The definition of recharge used in this report is: the portion of rainfall that reaches the saturated zone, either by direct contact in the riparian zone or by downward percolation through the unsaturated zone (Rushton and Ward, 1979).

Recharge estimation techniques are numerous and no two methods, if applied to the same area, will give similar recharge rates. These methods are often limited to particular environments (i.e. humid or arid), and the availability of data (especially long-term monitoring data). Techniques are not too often replicable from one environment to another. Recharge estimation is probably the most difficult hydrogeological variable to determine. Recharge is estimated by using known variables that are directly measurable, to some degree of accuracy. Recharge can be estimated by determining the fluxes in the unsaturated zone or by estimating the net contribution to the saturated zone. Methods that are applicable in the different zones can be classified as chemical and isotopic methods, physical methods, and combination methods that can be integrated into mathematical and GIS models. Crucial to the estimation of groundwater recharge is a proper understanding of the aquifer system being investigated.

Estimating recharge in the Namaqualand area is difficult, due to the paucity of data. This study provides a base for future groundwater resource assessments. The approach of this study is to use existing data and data that can be easily obtained, to systematically estimate and characterise recharge in the area.

1.2 Background

The South African climate is generally divided into a wet east coast and a drier west coast. The study area, Central Namaqualand, is situated on the west coast of the subcontinent and experiences an arid to semi-arid climatic regime, brought about mainly by the topography of the area, as well as the climatic systems operating on the subcontinent. No perennial river systems occur in the study area. The Orange River, to the north of the study area, is the only perennial river in the primary catchment area. Most rural communities rely on groundwater for their existence. The Orange River is a major source of piped water supply for the larger towns (Springbok, O'kiep and Steinkopf) and for the large-scale diamond and base-metal mining activities.

Groundwater development has been dominated by the rural community water supply subsidised by the government, the private water supply for domestic and agricultural activities and the exploitation of groundwater for mining activities. The development of the groundwater resource is a complex task, due to the complexity of the aquifer systems. Crystalline rocks are inherently poor aquifers due to their low storage capacity and water-quality problems. The basement aquifers are broadly divided into weathered zone aquifers and fractured rock aquifers.

Groundwater hydrology in South Africa mainly concerned itself with the supplying of water to areas where surface water was not sufficient or too expensive to meet demands. Vegter (2001) gives a detailed account of the various stages through which groundwater hydrology went in South Africa. The current trend is in the fields of integrated management of water resources; this is mainly as a result of the National Water Act promulgated in 1998.

The poor understanding of the aquifer systems and rates of aquifer recharge in Namaqualand led to poor management practices. The assessment of the groundwater systems and the socio-economic dynamics of the area have been the focus of research by the Department of Earth Sciences at the University of the Western Cape. One of the main constraints identified was that the processes and rates of aquifer replenishment/recharge were not fully understood. This study was initiated to specifically investigate the recharge characteristics of meteoric water to the aquifers of Central Namaqualand.

1.3 Previous work

The Department of Water Affairs and Forestry (DWAF) and Toens and Partners did most of the community water supply projects for the area, which led to numerous consultancy reports and monitoring data. The Atomic Energy Corporation (AEC) did hydro-geological work in and around the Vaalputs area (a radioactive waste repository) to the east of the study area. As of 1996, the Earth Sciences Department (University of the Western Cape) presented reports on the groundwater characteristics of the area. A detailed description of the groundwater resources and hydrogeology of the study area can be found in Titus et al. (2002). The recharge manual by Bredenkamp et al. (1995) gives an overview of recharge in South Africa, except for the crystalline basement aquifers. No detailed recharge studies, either published or unpublished, exist for the specific area. Toens and Partners (2001) estimated recharge in the Bitterfontein and Rietfontein areas to be between 0.9% (1.03 mm/yr) and 2.2% (3.62 mm/yr). Vegter (1995) cited recharge rates for the towns of Springbok and Garies of 7.3 mm/yr and 2.9 mm/yr respectively, based on Vegter's regional De Aar model. Recharge in the Komaggas area was estimated at 9.6 mm/yr (DWAF, 1990). Verhagen and Levin (1986), using environmental isotopes in the Vaalputs area, noted that recharge is "minimal", occurring only periodically during periods of above-normal rainfall.

1.4 Objective and scope

The primary objective of the research is to quantify and characterise recharge to the crystalline basement and alluvial aquifers of Central Namaqualand for sustainable groundwater development and management.

The scope of the study includes:

(1) Identifying methods suitable for recharge studies in the Central Namaqualand region.

(2) Delineating recharge areas.

(3) Applying and comparing of a number of independent approaches for recharge characterisation/estimation as well as selecting the best method(s) for recharge estimation.

(4) Developing a conceptual model for the groundwater recharge.

1.5 Approach

The development of the conceptual model of the area is based on previous studies and hydrologic data (chemical and isotopic data, water-level measurements, borehole logs, geophysical measurements, climatological data, and hydraulic properties determined from aquifer tests, as well as information based on field observations). Areas for recharge studies will be identified based on the amount of data available (water levels, abstraction rates, climatic data, borehole distribution). A strong bias will be introduced towards areas where abstraction zones supply water to the rural communities. Methods, which are suitable for recharge estimation for the area, will be applied at selected sites.

1.6 Outline

This report is divided into 7 chapters:

Chapter 1 outlines the objectives and scope of the thesis. The thesis outline and approach are also discussed in this chapter. An overview of previous hydrogeological investigations is outlined.

Chapter 2 gives an account of groundwater recharge to basement aquifers and the importance of these aquifers.

Chapter 3 deals with selecting appropriate methods for recharge estimation in arid basement areas. A theoretical overview of the methods used in the assessment of groundwater recharge to the arid basement aquifers is discussed here.

Chapter 4 describes the measurement and experimental techniques performed. The sampling and analysis of rainfall, and groundwater chemistry are discussed.

The collection of rainfall samples for chemical analysis is discussed. A new bulk rainfall sampler was developed for the sampling of rainwater for chemical analysis.

Chapter 5 gives an overview of the physiography of the study area in terms of the climate, topography, geomorphology, geology, hydrology and hydrogeology of the three catchments that constitutes the study area.

Chapter 6 focuses on the application of the different recharge estimation and characterisation methods suitable for assessment of recharge in the study area. The methods applied are the chemical and tracer approaches using the chloride mass balance (CMB) method and the stable and radiogenic isotopes ^{18}O, ^{2}H and ^{14}C. Methods involving the use of water levels and aquifer properties to estimate storativity and recharge (i.e. SVF and CRD) are used to estimate recharge. Complementary methods applied are statistical and GIS approaches, mainly to delineate recharge areas.

Chapter 7 summarises the main findings in terms of the research objectives and gives a regional perspective of the estimates of this study. Recommendations for further research are also made.

CHAPTER 2

Groundwater recharge to basement aquifers

2.1 Introduction

Literature on the characteristics of crystalline basement aquifers has increased considerably over the last few decades (e.g UNESCO, 1984; Wright and Burgess, 1992; Lloyd, 1999; Banks and Robins, 2002). These aquifer systems are mostly described for humid areas (e.g. Acworth, 1987; Chilton and Foster, 1995; Taylor and Howard, 1999). However, literature on systematic groundwater recharge studies in crystalline basement aquifers is still limited. Banks and Robins (2002) noted that "...we have a very poor understanding of exactly what proportion of rainfall ends up entering a crystalline rock aquifer". Groundwater recharge is probably the most difficult parameter of the hydrological budget to estimate (Stephens, 1993), even more so in crystalline basement aquifers.

Groundwater resources in crystalline basement aquifers in semi-arid areas are dependent on factors such as the presence of brittle structures and weathered zones. Infiltrating water and topography mainly drive the weathering of the bedrock at the surface and the subsurface. In humid regions the weathered zones are often thicker than in the arid zones. The term crystalline basement refers to igneous and/or metamorphic rocks, such as granites, gneisses, meta-quartzites, and basalts with negligible primary porosity. Crystalline basement aquifers are generally classified as two-layer systems comprised of fractured bedrock overlain by a weathered/regolith zone (Chilton and Foster, 1995). Regolith is defined as the solid product of intense *in situ* weathering (Howard and Karundu, 1992). Groundwater is primarily explored in the weathered and alluvial zones. Alluvial zones play a crucial role in the formation of basement aquifer systems. The alluvial aquifers are often the main source of water supply in arid and semi-arid areas underlain by basement aquifers.

2.2 Characteristics of arid and semi-arid zones

Classification of arid/semi-arid/humid zones is primarily based on mean annual precipitation (Figure 2.1). These zones comprise approximately 35% of the earth's surface, excluding the polar deserts (Potter, 1992, as cited in Stephens, 1993).

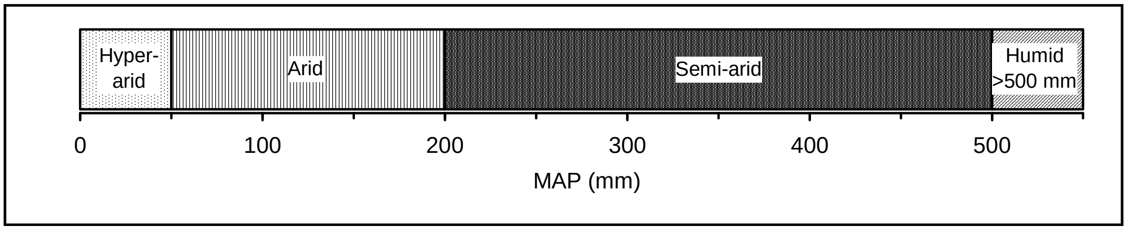


Figure 2.1: Classification of the different climatic zones.

There are four major factors that may cause aridity:

- Atmospheric high pressure;
- Topography;
- Cold ocean currents; and
- Continentality.

Rainfall in arid and semi-arid areas is subjected to high spatial and temporal variability. Evapotranspiration exceeds rainfall for most of the year in these areas. This is especially true for arid and semi-arid zones, where rainfall and recharge are highly unpredictable in time and space. Water fluxes in the unsaturated zone in arid regions can range from 100-1000 mm/yr to less than 0.01 mm/yr (Dong et al., 2003). The extent of bedrock outcrop versus soil cover, slope areas and differences between compaction of constituent material controls the spatial variability of runoff and infiltration (Berndtsson and Larson, 1987). It is believed that mean annual rainfall below 400 mm is unlikely to produce significant recharge (Gustafson and Krasny, 1994; Singhal, 2003). This assumption is often not valid due to the fact that arid regions receive occasional intense rain spells, which generate infiltration and recharge under favourable conditions (Gee and Hillel, 1988; Stephens, 1993). Groundwater recharge estimation in arid and semi-arid areas is error-prone due to the application of techniques that average values over time and space (Gee and Hillel, 1988). Recharge in arid and semi-arid areas is mainly indirect. In semi-arid regions recharge may be direct if favourable conditions exist (Figure 2.2). Direct recharge occurs when water enters the saturated zone of the aquifer directly from precipitation infiltrating through the unsaturated zone and indirect recharge occurs when recharging water enters the saturated zone indirectly through some form of runoff infiltration (Lloyd, 1999).

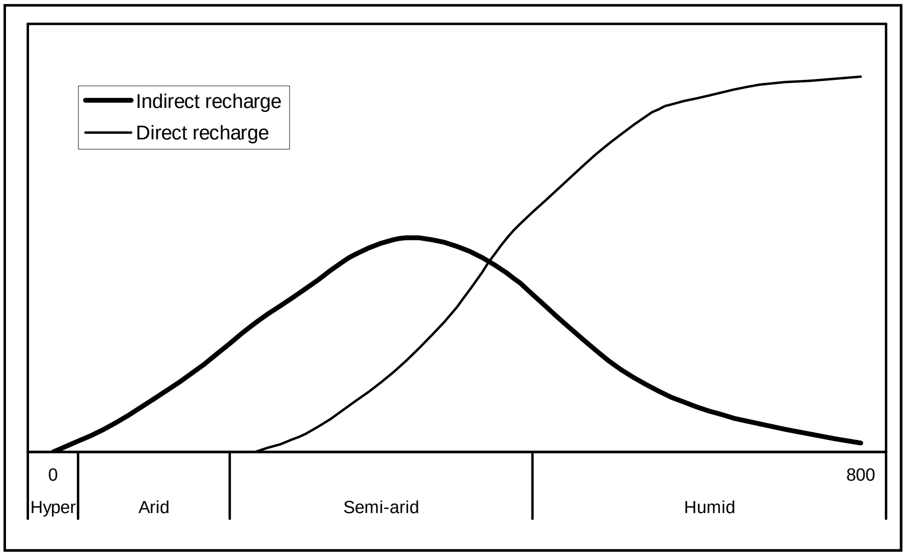


Figure 2.2: Recharge mechanisms in different climate zones (from KASAM, 2001).

2.3 Characteristics of basement aquifers

Areas underlain by basement aquifers are characterized by periods of weathering and/or stripping (Taylor and Howard, 1999). These processes are responsible for the landforms observed today. The most characteristic landforms that develop in these terrains are bornhardts or inselbergs (Figure 2.3). Bornhardts are a manifestation of crustal compression and minor forms are associated with the release of compressive stress (Vidal Romaní and Twidale, 1999). Inselbergs develop as a response to weathering of intensely weathered, jointed bedrock and the competence of the lithology (Figure 2.4). Preferential weathering along joints produces spheroidal weathering, resulting in the development of corestones within a regolith matrix (Phillips, 2001). Changes in climatic conditions determine the major characteristics of the current landforms (Garner, 1974).

The degree of weathering is dependent on the lithology and the fracture intensity. Crystalline aquifers usually consist of a two-component system (Van der Sommen and Geirnaert, 1990):

- A weathered mantle rich in clays. This zone has high porosities but low permeabilities; and
- Fractured bedrock zones with low porosities and much higher permeabilities. This zone is usually highly conductive.

Figure 2.3: Bornhardts of the Central Namaqualand area.

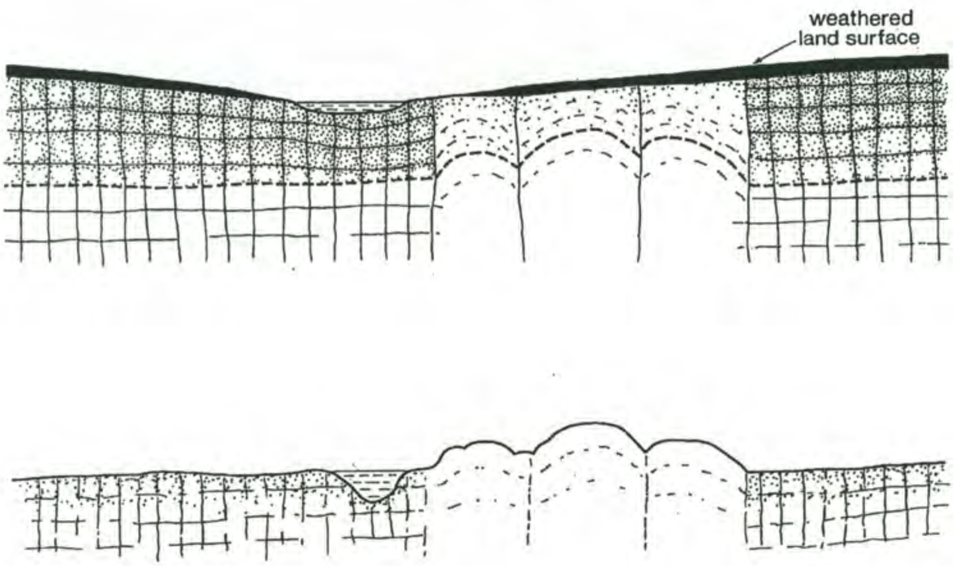


Figure: 2.4: Development of landforms in basement rock areas (Twidale and Bourne, 1998).

Several classification schemes based on vertical profiles have been developed for basement aquifers (e.g. Taylor and Howard, 1999; Chilton and Foster, 1995; Wright, 1992; Acworth, 1987; UNESCO, 1984), mainly for humid regions. Figure 2.5 depicts the different classification schemes for weathered basement aquifers. According to Butt et al. (2000) regolith has been forming continuously for over 100 Ma in parts of Africa, India, South America, SE Asia and Australia.

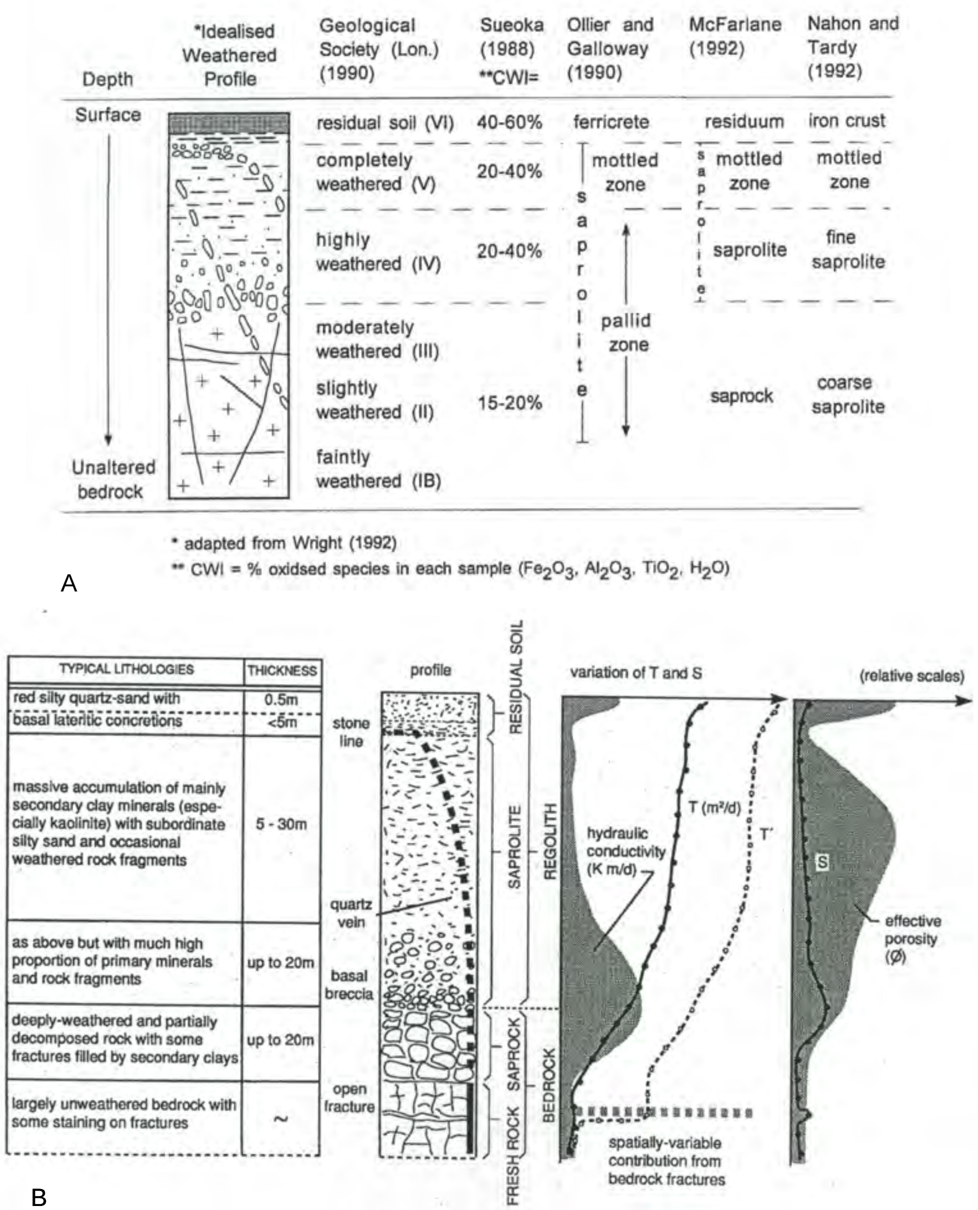


Figure 2.5: Weathered profiles for basement aquifers ((A) Taylor and Howard 1999, and (B) Chilton and Foster, 1995).

Weathered zone

The extent and depth of the weathered zone is determined by weathering susceptibility and moisture availability. The weathered zone in arid terrain is generally shallower than in more humid terrain. However, thick weathered zones occur in semi-arid areas and are a result of a more humid period during the Pleistocene Age (UNESCO, 1984). The higher the weathering susceptibility and moisture availability, the more the weathering rates dominate; greater permeability is created which leads to more moisture; and a faster weathering rate leads to more intense weathering (Phillips, 2001). The deeper the weathering, the higher the degree of fragmentation (Lan et al., 2003; Wright, 2002) :

intact rock → big block-like → fragment-like → gravel-like → sand-like → clay-like.

Regolith characteristics change in response to different conditions over time, as shown by Butt et al. (2000). The changes are shown in Table 2.1.

Table 2.1: Changes in regolith from the conditions of formation (Butt et al., 2000).

Uplift	Lowering of the water table. Irreversible dehydration and hardening of ferruginous and siliceous horizons. Increased leaching of upper horizons under more oxidising conditions. Increased erosion.
Down warping	Water logging of lower parts of the landscape and imposition of reducing conditions. Decrease in erosion; increased sedimentation in valleys.
More humid climate	Increased leaching and deeper soil development. Decreased erosion (due to denser vegetation).
Less humid climate	Decreased leaching. Increased erosion.
Semi-arid or arid climate	Decreased leaching. Retention and precipitation of silica, alkaline earths and alkalis in silcretes, clays, calcretes, and salts. Increased erosion.

In granitic rocks the weathered zone is usually uniform and less clayey than in schist and will show the intermediate zone of decomposed rock. Differential weathering occurs throughout the rock mass, as well as on fracture/joint planes. The transition zone is well-developed in fractured zones (Van der Sommen and Geirnaert, 1988). Percolation of water from the surface to the weathered zone and into the fractured rock is complex. Basement aquifers have low porosities, permeabilities and generally high transmissivities.

The mineral transformations in different weathering stages show the following sequences (Lan et al., 2003):

1. feldspar → sericite → hydromica → kaolinite;
2. pyroxene and hornblende → chlorite → montmorillonite → halloysite → kaolonite;
3. biotite → vermiculite → montmorillonite → kaolonite
4. quartz → silica → chalcedony → secondary quartz.

Fractured bedrock

Exposed fractured bedrock is mainly associated with higher-lying areas and the bornhardts/inselbergs that characterise the area. The porosity and permeability of hard rocks are mainly determined by the intensity, orientation, connectivity, aperture and infill of fracture systems (Skjernaa and Jørgensen, 1994). Black (1994) identifies three main fracture configurations in non-layered fractured rocks. These are: 1. random fracture locations (Poisson), 2. structured fracture locations (fractal) and 3. clustered fracture locations. Fracture zones may be infilled by secondary minerals due to the different modes of genesis, deformation and reactivation (Banks et al., 1994; Srinivas et al., 1999). Sheet structures are widely developed on bornhardts. Sheet fractures are arcuate fractures that trend parallel to the land surface (Vidal Romaní and Twidale, 1999). These fractures are convex-upward in many residual hills and concave-upward in the valley floors (Vidal Romaní and Twidale, 1999). The favoured explanation for these sheet fractures is that they are the result of expansion and tangential fracturing, consequent on erosional offloading (Vidal Romaní and Twidale, 1999). The frequency of the sheet fractures and the fracture openings decrease rapidly with depth. Fractures range from microns to hundreds of kilometers. The inherent complexity of obtaining accurate data on fractured formations, both structural and hydraulic, is a major obstacle in developing accurate fractured medium models (Berkowitz, 2002).

According to Gustafson and Krásný (1994), the hydraulic conductivity determined by field methods can vary by several orders of magnitude within the same rock unit, and usually over very short distances. Daniel (1996) states that, as a general rule, the abundance of fractures and size of fracture openings, decreases with depth as a result of lithostatic pressures. In central Spain Gonzales-Yelamos et al. (1993) showed, with permeability tests, that permeability generally declines with depth. Fracture apertures in granite, gneiss and metavolcanics, ranging from 75-100 µ in the upper 10 m of bedrock and decreasing to 50-100 µm at 15-60 m depth, have been reported by Snow (1968), using packer tests. Fracture zones usually occur along lineaments and often correspond to the surface drainage patterns. An aquifer in regolith is between one and two orders of magnitude more transmissive than the underlying bedrock aquifer (Tindimugaya, 1995).

2.4 Recharge, Storage and Groundwater flow

Recharge

Recharge to crystalline rocks is a function of the mode of chemical weathering of its surface, and the rate of fracturing (Lerner et al., 1990). Recharging or infiltrating water is responsible for the development of the weathered zone aquifers. Deep weathering in a stable tectonic environment is dominated by high infiltration rates, and land denudation is dominated by high runoff (Taylor and Howard, 1999). Recharge estimates for various basement aquifers are given in Table 2.2.

Table 2.2: Recharge estimates for basement aquifers around the world.

Country (area)	Geology	Evapotranspiration (mm)	Rainfall (mm)	Recharge (%)	Reference
INDIA					
Vedavati	Gr	437-474	616	13-21	Sukhija and Rao (1983)
Vedavati	Gr, Gn, Sc		565	1-7	Athavale and Rangarajan (1990)
Marvanka	Gr, Gn, Sc		550	8	Athavale and Rangarajan (1990)
Noyil	Gr, Gn, Sc		715	10	Athavale and Rangarajan (1990)
Vattamalaikarai	Gr, Gn, Sc		460	13	Athavale and Rangarajan (1990)
Ponnani	Gr, Gn, Sc		1320	5	Athavale and Rangarajan (1990)
Chitravati	Gr, Gn, Sc		615	5	Athavale and Rangarajan (1990)
Mahaboobnagar	Gr		573	6-3	Athavale and Rangarajan (1990)
Anantapur	Gr, Gn		390	6	Athavale and Rangarajan (1990)
AUSTRALIA					
Western Australia	Gr, volc., met	900-3000	300	0.05-5	Allen and Davidson (1982)
Western Australia	Gr, Gn (weath)	1630	1220	4-8	Johnston (1987)
AFRICA					
Ouagadougou (BF)	Gr, Gr (weath)	>2000	500-1100	2-16	Van der Sommen and Geirnaert (1988)
Ouagadougou (BF)	Gr, Gr (weath)		690	3-7	Thierry (1990)
Victoria (Zim)	Gr, Gn		736	2-5	Houston (1990, 1992)
Southern Sinai (Egypt)	Gr, volc., met		50	15	Issar and Gilad (1982)
Livulezi (Mal)			800-1000	10-23	Wright (1992)
Bua (Mal)			800-1000	8-20	Wright (1992)
Diamphe (Mal)			800-1000	12-18	Wright (1992)
D28 (Zim)				9-14	Wright (1992)
Kwara (Nig)	Gr, Gn		1689	15	Houston (1992)
Garies (SA)			142	2	Vegter (1995)
Springbok (SA)			211	4	Vegter (1995)
Nyabisheki (Uganda)	Gr, Gn, Sc	1400-1500	905	2	Howard and Karundu (1992)
Aroca (Uganda)		1451	1576	8	Taylor and Howard (1999)

Gr = granite; Gn = gneiss; Sc = schist; volc. = volcanic; met. = metamorphic.

Acworth (1987) correlated the relative probability of recharge to topographical settings within weathered basements (Table 2.3).

Table 2.3: Recharge probability to different basement aquifer settings (Acworth, 1984).

Topography	Recharge		
	Low	Medium	High
Mountains	Groundwater in fracture zones	Principal groundwater development in fracture zones and colluvium	Very active erosion with most groundwater in colluvial and alluvial deposits; very variable development of saprolite
Hills	Groundwater in fracture zones; little saprolite development	Disjointed saprolite aquifer developed along fracture zones	Extensive saprolite aquifer
Plains	Little available groundwater	Extensive saprolite aquifer, often with development of dambos	Thin saprolite aquifer with high throughput of groundwater, extensive springs

Storage

The storage coefficients within the crystalline aquifers generally increase within the weathered zones and in the highly fractured zones. The storativities for crystalline aquifers in different parts of the world are shown in Table 2.4.

Table 2.4: Storativities of crystalline aquifers in different parts of the world (based on pumping tests).

Country	S-values	Geology	Reference
Australia	4×10^{-4}	Weathered granite	Jacobson (1982)
Burkina Faso	4×10^{-4} 3×10^{-4} 2×10^{-2}	Hard rock Weathered zone	Van der Sommen and Geirnaert (1988)
India	1×10^{-2}		Srinivas et al (1999)
Korea	3×10^{-6} 6×10^{-6}	Fractured granite	Lee and Lee (2000)
Malawi	5×10^{-5} 4×10^{-5}	Weathered zone	Herbert et al (1992)
Sweden	4×10^{-6} 6×10^{-7} 9×10^{-6} 2×10^{-6} 6×10^{-7}	Fracture zone in gneiss	Andersson et al (1991)

Groundwater flow

Groundwater occurs in crystalline aquifers in the secondary porosity caused by weathering and fracturing. Groundwater flow and storage in these aquifers are inherently very complex. There is the heterogeneity associated with the mechanical discontinuity resulting from the presence of fractures. Water level rises, following water strikes during drilling, indicate the semi-confined to confined (artesian boreholes) nature of some of the aquifer systems. Weathering and fracturing decreases with depth in hard rock terrain, at which the cost of drilling deeper outweighs the chance of significantly increasing the yield of the borehole. This may be due to increasing lithostatic pressure, which tends to close fractures, which increases resistance to groundwater flow. It is not the rocks themselves that transmit the groundwater but the fractures and fissures that form the conductive openings through the impervious rock matrix (Gustafson and Krásný, 1993). Regional flow occurs within the major interconnected fracture systems. The main groundwater flow systems are relatively localised between recharge on watersheds to discharge by runoff or evaporation in valley bottomlands in crystalline terrains (Wright, 1992). Groundwater flow in topographic highs occurs along major fractures as a function of the naturally high hydraulic gradients in these regions.

Due to its larger porosity the weathered/regolith zone acts as a reservoir that slowly feeds water downward into fractures in the bedrock (Daniel, 1996). Fractures exposed at the surface act as preferential flow paths. Stephens (1993) defined preferential flow paths as open conduits or macropores that can short circuit the path to the water table. Infiltration at a point between soil and rock are dependent on the hydraulic conditions at that zone (Olofsson, 1994). If water enters a fracture above a point of saturation, the movement of the water will be predominantly in the direction of the dip of such fractures. Water will only enter a fracture after the fluid pressure exceeds the water-entering pressure of the fracture (Stephens, 1993). Below the saturated zone, movement can be both vertical and horizontal. The lateral motion along the strike of the fracture would predominate (Ellis, 1909). Any connected series of joints will have a complex circulation. Nevertheless, the main circulation will be towards and along the fractures having the largest openings and the nearest discharge points, and in these fractures the general movement will be in the direction of a land slope. Percolation of the groundwater from the surface to the weathered zone and into the fractured rock is complex. Flow paths in fractured rocks are very complex and heterogeneous, due to its complex geometry (Karasaki et al., 2000).

CHAPTER 3

Theoretical aspects of recharge estimation

3.1 Introduction

Aquifer recharge is dependent on factors such as: climate, geology (lithology and structures), geomorphology, vegetation, soil conditions and antecedent soil moisture. Recharge can either be diffuse and/or through preferential pathways. Lerner et al., (1990) defined three principle mechanisms for aquifer recharge:

- Direct recharge – the addition of water to the aquifer in excess of soil moisture deficits and evapotranspiration by vertical percolation through the unsaturated zone;
- Indirect recharge – the percolation of water through the beds of surface water bodies or ephemeral streambeds; and
- Localised recharge – this entails recharge from localised water ponding directly overlying the aquifer and percolating through the unsaturated zone.

Several methods have been developed over the last few decades to determine recharge originating from the above mechanisms. Publications that deals exclusively with recharge and the different methods include, among others, Lerner et al. (1990); Bredenkamp et al. (1995); Simmers et al. (1997); Kinzelbach et al. (2002); Scanlon and Cook (2002) and Xu and Beekman (2003). Estimation techniques are divided into physical techniques, tracer techniques and numerical models. Different techniques estimate recharge over different spatial and temporal scales (e.g. Scanlon et al., 2002; Beekman and Xu, 2003). Bredenkamp et al. (1995) and Beekman and Xu (2003) give an account of the recharge estimation methods applied in semi-arid southern Africa and identified the following methods as the most promising for application in semi-arid to arid conditions:

- Chloride mass balance (CMB);
- Cumulative rainfall departures (CRD);
- EARTH model;
- Water table fluctuations;

- Groundwater models (GM); and
- Saturated volume fluctuations (SVF).

3.2 Recharge estimation methods

The applicability of any recharge estimate depends on the availability of data and the potential to obtain data, the characteristics of the area and importantly the cost of obtaining data. Recharge estimation methods and case studies are well documented. It is beyond the scope of this document to describe all the techniques. A brief summary of the methods is listed in Table 3.1. Bredenkamp et al. (1995) and Beekman and Xu (2003) also give a comparison of methods used in estimating recharge. Only the methods identified in the next section will be described in this chapter. It should be noted that the accuracy and cost of a particular method are relative and depends on factors such as:

- The proximity of the study area to the research institution/headquarter;
- The availability of laboratories (in-house versus commercial);
- The availability of specialised sampling equipment (in-house versus commercial or acquisition);
- The availability of skilled human resources (in-house versus consultants); and
- Level of accuracy and quality assurance required.

3.3 Groundwater recharge estimation methods applicable for Central Namaqualand

In order to find methods that may be applicable for estimating recharge to the aquifers of Central Namaqualand an Excel spreadsheet was programmed to determine the suitability of different methods, based on the availability of data and the potential to gather data. An example of the elimination/validation process is shown in Figure 3.1. A suitability index was also created for specific areas to determine the data availability and type of data available, an example is also shown in Figure 3.1.

The suitability index is based on a simple approach whereby the amount of data available is listed and scored. The scores are calculated based on the availability of the data and whether the data is of a quantitative or qualitative nature. If the available information is quantitative it scores higher than more qualitative data. Qualitative data is also important for the development of conceptual models but it cannot be used to estimate recharge. The approach is subjective and requires that it be evaluated against the objectives of the study. If insufficient data is available the recharge study will become more complex and expensive, if the objective is to obtain reliable recharge estimates.

If sufficient quantitative and qualitative data are available, the user can proceed to the methods sheet. Different methods are listed and each method is preprogrammed with the minimum data requirements. The user can input the type of data available or data that can be obtained within a specific project. The minimum requirements of each method are assigned a value of 1, if the corresponding data is available or if it can be obtained. If all the data for a specific method is available the column will be totaled and if the total equals the preprogrammed value the applicable cell will return a yes. The sheet will essentially determine which methods are applicable for any specific area based on the available data.

Five methods have been identified that can be applied in the study area these methods are the CMB method, CRD method and the SVF method and a GIS approach using available data. The following sections will outline the selected methods. The CMB method cannot be applied in the unsaturated zone due to several conditions that cannot be met, as outlined in the next section. The use of the stable and radiogenic isotopes; ^{18}O, ^{2}H and ^{14}C, will be discussed as it is used to develop and constrain the conceptual understanding of groundwater recharge.

Table 3.1: Comparison of methods for estimation of recharge (adapted from API, 1997).

Estimation technique	Data Requirements	Optimal site characteristics	Relative accuracy	Relative cost	Comments
Soil water balance	1.Precipitation 2.Runoff 3.Evapotranspiration 4.Storage	Humid/temperate climate (P>ET); flat topography with negligible runoff; short uniform vegetation; small scale	Low	High to low	Commonly used technique, not appropriate for arid climates where ET>>P; uncertainty varies by a factor of 3 to 10 or more. High cost if micrometeorological equipment is used; low if ET is calculated from PET
Lysimetry	Water volume	Applied under any site conditions; construction results in devegetation	High	High	Direct, precise measurement of deep drainage; precision ±1 mm/yr; long term monitoring and maintenance required; when combined with soil-water balance is very reliable for arid site
Darcy flux	1.Hydraulic gradient 2.Unsaturated hydraulic conductivity	Applied under any site conditions	Low to moderate	Low to moderate	Results rely on measurement of unsaturated hydraulic conductivity; accurate with a factor of ±10 or more
Plane of zero flux	1.Soil water potential profile 2.Water content changes with time	Temperate, semi-arid or arid climates (ET>P); any soil type	Moderate	Moderate to high	Accuracy of ±15% or ~20 mm/yr; requires weekly monitoring; fails during periods when rainfall exceeds Ksat
Soil temperature gradient	Soil water potential profile from saturated zone	Deep aquifers with upward temperature gradient	Low	Low	Provides regionally averaged recharge estimate with accuracy similar to basin water balance
Electromagnetic resistivity	1.Electrical conductivity data 2.Independent recharge estimation for comparison	Fine grained soils; varied vegetation and soils	Non-quantitative	Low to moderate	Provides reconnaissance level, qualitative results that identify areas of recharge
Basin outflow	1.Aquifer transmissivity 2.Aquifer hydraulic gradient basin boundaries 3.Upstream catchment surface area 4.Specific yield 5.Transient hydraulic change	Any unconfined aquifer with a well characterised flow regime and well defined recharge areas	Low	Low to high	Provides regionally averaged recharge estimate with an accuracy similar to basin water balance; can often rely on existing data. Low cost provided data already exist; high cost if data collection is required
Water level fluctuations (incl. CRD, SVF)	1.Water table hydrograph 2.Specific yield 3.Rainfall 4.Area	Any unconfined aquifer with a well characterised flow regime and well defined recharge areas	Low-High	Low	Provides regionally averaged recharge estimate with accuracy similar to basin water balance; can often rely on existing data.
Stream gauging	Stream flow hydrograph	Humid/temperate climate; well developed unmanaged watershed with perennial streams;-stream connected shallow aquifer; minimal snowmelt	Moderate	Low	Avoids need to measure climatic parameters; provides regionally averaged recharge estimate for watershed with better accuracy than basin water balance
Tritium profile	1.Undisturbed soil profile below the root zone 2.^{3}H input function 3.^{3}H concentration in soil profile	Arid, semi-arid and temperate climates where R>10% MAP; sediment of any texture and pedogenic carbonates	High	Low	Very accurate water tracer; conceptual model assumes piston flow (ie. Ignores preferential flow); subject to vapour transport, which causes overestimate of R wher R<1 mm/yr
Chlorine-36 profile	1.Undisturbed soil profile below the root zone 2.^{36}Cl input function 3.^{3}H concentration in soil profile	Arid, semi-arid and temperate climates where R>10% MAP; sediment of any texture and pedogenic carbonates	High	Low to moderate	Fairly accurate water tracer, subject to anion exclusion and ultra filtration; conceptual model assumes piston flow (ignores preferential flow); high cost of analysis
Chloride mass balance	1.Undisturbed soil profile 2.Meteoric chloride concentration 3.Chloride concentration in soil moisture 4.Mean annual precipitation	Arid, semi-arid and temperate climates where R>10% MAP; sediment of any texture and pedogenic carbonates	High	Low	Conceptual model assumes (1) average rate of chloride deposition rate in P is constant and (2) piston flow. Inexpensive
Stable isotope profile	1.Undisturbed soil profile 2.Water content profile 3.D and ^{18}O concentration in soil moisture	Arid and semi-arid climates where soil water movement is in quasi-steady state; sediments of any texture	Unknown	Low to moderate	Conceptual model assumes one-dimensional, vertical, quasi-steady state soil water movement; non-routine soil water extraction process; requires further research to evaluate uncertainty
Groundwater age dating	1.Hydraulic gradient 2.Effective porosity 3.Distance to tracer peak 4.Apparent groundwater tracer age 5.Knowledge of other sources of C in aquifer	Shallow unconfined aquifer; vertical hydraulic gradients near the water table; applicable to any climate, soil texture and vegetation	High	High	Groundwater age best determined by ^{14}C, ^{3}H/^{3}He^{36}, Cl and/or CFC's; requires thorough understanding of aquifer flow system and careful application; very consistent results. High relative accuracy if source of ^{14}C and ^{3}H is known.
Soil water balance models	1.Precipitation 2.Runoff 3.Evapotranspiration 4.Soil water storage 5.Hydraulic properties	Applicable to any conditions and any scale where vertical flow occurs	Low to moderate	Moderate to high	Relies on estimates of AET and unsaturated hydraulic conductivity; uncertainty varies by an order of magnitude or more
Soil water models based on Richards equation	1.Climatic data 2.Soil hydraulic properties 3.Depth to water table 4.In situ pressure head or water contents	Homogeneous soil profiles above a shallow water table; moist soils	Low to moderate	Moderate to high	Uncertainty is due to climatic data and hydraulic properties. Extensive computational effort for deep water tables, dry heterogeneous soil
Groundwater models	1.Aquifer geometry 2.Transmissivity, storage 3.Aquifer boundary conditions 4.Initial head field	Applicable to any conditions and any scale	Moderate	Moderate to high	Cost can be considerable if data are not compiled. Requires thorough calibration

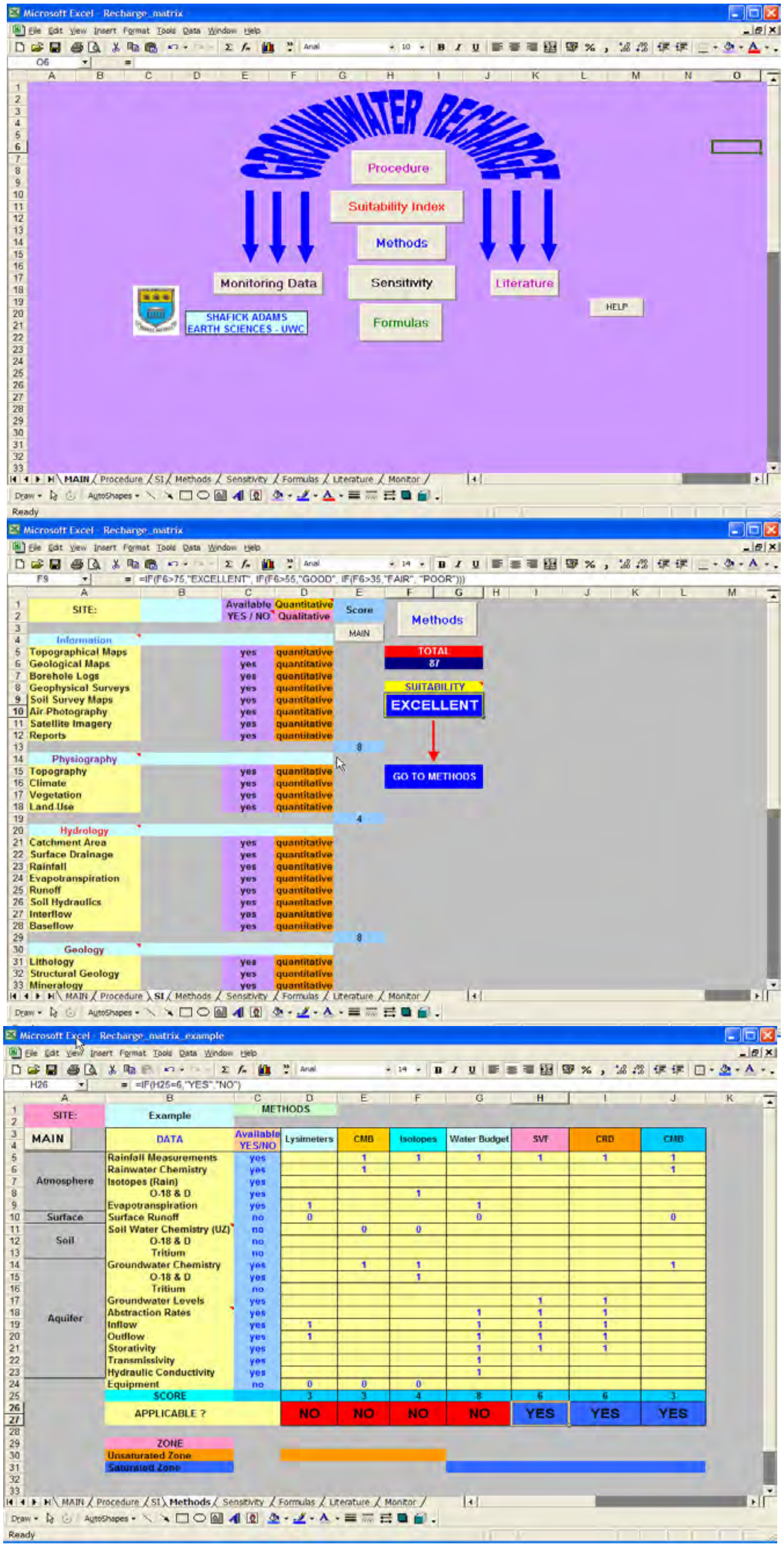


Figure 3.1: Example of the Excel programme for selecting suitable methods.

3.4 Physical and chemical recharge estimation methods

3.4.1 Chemical and isotope tracer methods

Chloride Mass Balance (CMB)

The method is often used as a first approximation of recharge due to its simplicity and relatively low cost. The method was first applied in the saturated zone by Eriksson and Khunakasem (1969) and has become one of the most widely used recharge estimation methods

The chloride ion is highly soluble, non-absorbing, chemically conservative and easily measurable. Chloride has the advantage over other tracers involving the water molecule (^{18}O, ^{2}H, ^{3}H) in that atmospheric inputs are conserved during the recharge process, allowing a mass balance approach to be used (Edmunds and Gaye, 1994). Preferably, results should be verified with other methods. There are three approaches to estimate recharge using the CMB method:

- The first approach involves the chloride concentration of rain and soil moisture (unsaturated zone) and gives an estimate of the moisture flux;
- The second approach involves the chloride concentrations of groundwater (saturated zone), whereby the total recharge is estimated; and
- The third approach involves the comparison of the first two approaches to define the recharge mechanism.

The use of the CMB method or methods that involve chemical tracers provide more accurate estimates of groundwater recharge in arid to semi-arid regions (Bazuhair and Wood, 1996). The method is applicable in areas of high evapotranspiration where the infiltrating water becomes concentrated (Johansson, 1987). The following is required when applying the method:

- Precipitation (mm);
- Precipitation chemistry (mg/l);
- Dry deposition (chloride) ($mg/m^2/yr$);
- Soil moisture chloride concentration (mg/l); and
- Groundwater chloride concentration (mg/l).

Unsaturated zone

The method is applied in the unsaturated zone between the deepest zero flux plane and the water table. The method yields a recharge flux for a specific locality and should ideally be integrated with area weights to estimate areal recharge. Most plant species do not take up significant quantities of chloride from soil water, thus chloride is mainly concentrated by evapotranspiration in the root zone (Allison et al., 1994). However, White and Broadley (2001) have shown that chloride can be taken up and accumulated by plants. Edmunds and Gaye (1994) correlated recharge with the chloride concentrations in soils. High chloride concentrations are generally associated with lower rates of recharge and visa versa. If a steady state is attained between the chloride flux at the surface and the chloride flux beneath the evapotranspiration and mixing zone, the following mass balance can be defined (Eriksson and Khunakasem, 1969):

$$R_{sm} = \frac{P * Cl_p + D}{Cl_{sm}} = \frac{TD}{Cl_{sm}} \qquad (3.1)$$

where:
R_{sm} = moisture flux (mm/yr)
P = precipitation (mm/yr)
Cl_p = chloride concentration in precipitation (mg/l)
Cl_{sm} = chloride concentration in soil moisture (mg/l)
D = dry chloride deposition ($mg/m^2/yr$)

The sum of $P*Cl_p$ and D is also referred to as the total atmospheric chloride deposition (TD) and originates from both precipitation and dry fall out.

A better estimate of the moisture flux is obtained from a mass balance, which integrates chloride and moisture contents cumulatively over a specific depth interval (Gieske, 1992):

$$R_{sm(c)} = \frac{TD * TM}{TC} \qquad (3.2)$$

where:
TM = total moisture content (mm/m^2)
TC = total chloride content (mg/m^2)

Three potential problems have been identified with the above calculation methods (Wood, 1999):

- It is difficult to quantitatively evaluate the mass flux of chloride that has run onto, or from, the topographic features present at the sampling sites;

- The system may not be at steady state with respect to the input mass flux; and
- This method cannot measure total recharge if any unmeasured recharge takes place through macropores in the system.

To incorporate the additional mass resulting from run-on Wood and Sanford (1995) suggests the following equation for a closed depression:

$$R_{sm} = \left(\frac{TD}{Cl_{sm}}\right) + r\left(\frac{A_b Cl_r}{A_f Cl_{sm}}\right) \tag{3.3}$$

where:
r = run-on flux from the catchment area (mm/yr)
A_b = total area of the basin (m^2)
Cl_r = chloride concentration of the runoff water to the basin floor (mg/l)
A_f = area of basin floor (m^2)

The transient chloride flux can be evaluated by plotting chloride concentration from the pore water as a function of depth. For steady state, a graphical plot of depth versus chloride will show chloride increasing gradually from the surface to a maximum value at shallow depth. The exact depth at which equilibrium is attained is a function of the climatic condition, grain-size distribution of the material and other factors.

Below this depth, the chloride concentration in the pore water should remain constant until it reaches the water table (where diffusion and water table fluctuation will distort the profile). In Figure 3.2, conceptual chloride profiles are shown. Any significant deviation from the equilibrium profile indicates a temporal variability in the chloride mass flux and thus steady state assumption would become questionable.

If recharge takes place through macropores the equation above is inappropriate. Total recharge is a combination of macropore and matrix recharge. If macropores exists in the area under investigation, the unsaturated zone core profiling method will not yield reliable results. The total recharge flux is thus the sum of the recharge attributed to diffuse flow through the matrix and recharge attributed to macropore or recharge through preferential flow paths.

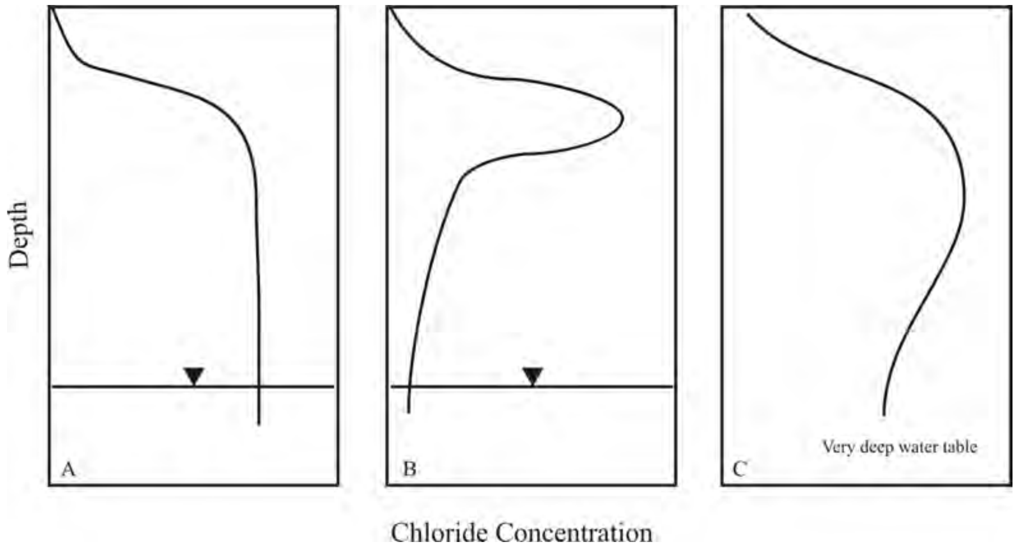


Figure 3.2: Conceptual depth profiles for the chloride tracer (after Allison, 1988).
A. Piston flow with abstraction of water by roots.
B. Abstraction of water by roots, but with either preferred flow of water to beneath the root zone, or diffuse loss of chloride to the water table.
C. Profile that may reflect the recharge history of a site.

Saturated zone

The ratio of average chloride content in precipitation (wet and dry deposition) to that of groundwater can be used to calculate recharge rates. The input flux is the product of the chloride concentration in precipitation multiplied by the amount of precipitation over the study area. The input flux is divided by the chloride concentration of groundwater. Total recharge is estimated using the equation:

$$R_T = \frac{TD}{Cl_{gw}} \tag{3.4}$$

where:
R_T = total recharge (mm/yr)
TD = total deposition ($mg/m^2/yr$)
Cl_{gw} = chloride concentration in groundwater (mg/l)

The Cl_{gw} originates from various flow components in the unsaturated zone. For an areal R_T, Cl_{gw} represents the harmonic mean of chloride concentrations in groundwater:

$$\overline{Cl}_{gw} = \frac{N}{\sum_{i=1}^{N} \frac{1}{Cl_{gw-1}}} \tag{3.5}$$

Edmunds and Gaye (1994) suggests that the combined use of unsaturated and saturated zone data for determining recharge reduces the uncertainties derived from using the water table data alone. In Botswana, Beekman et al. (1996) used the CMB and profiling method with other tracers to assess recharge in the Kalahari. Their results showed that preferential flow is a major mechanism for groundwater recharge in the Kalahari. The chemistry of groundwater at the water table may be further enriched in chloride due to uptake of evaporative salts or formation water in the saturated or unsaturated zone leading to underestimation of recharge. Similarly, lateral flow from different recharge areas in heterogenous porous media may give rise to salinities different from that found in the unsaturated zone (Edmunds and Gaye, 1994).

In a bimodal flow regime, it is assumed that R_T originates from only two flow components in the unsaturated zone which are fully mixed in the groundwater: a (slow) diffuse (R_{sm}) and a (quick) preferential (R_{pr}) flow component for $Cl_{pr} \ll Cl_{gw} < Cl_{sm}$, the relative contribution of either R_{sm} or R_{pr} to R_T expressed as a fraction is calculated as (Sharma and Hughes, 1985):

$$f(R_{pr}) = 1 - f(R_{sm}) \approx \left(\frac{Cl_{sm} - Cl_{gw}}{Cl_{sm}} \right) \tag{3.6}$$

A water mass flux crossing the plane of the water table can be calculated if (Gieske, 1992; Wood, 1999; Bazuhair and Wood, 1996):

- Chloride in groundwater originates only from precipitation (no unmeasured chloride mass from overlying, underlying or adjacent aquifers and no unmeasured run-on occurs);
- Chloride is conservative in the system;
- The chloride mass flux has not changed over time;
- There is no recycling or concentration of chloride within the aquifer;
- No evaporation of groundwater occurs upgradient from the groundwater sampling points; and
- The adsorption of chloride in soils and the vegetation uptake is considered negligible.

Thorburn et al. (1991) and Walker et al (1991) demonstrated non-steady state conditions in cases where changes in land use occurred. The main source of uncertainty in applying the CMB method is the rainfall chemistry for the preceding periods (Edmunds and Gaye, 1994). Cook (2003) states that when the CMB method is applied to fractured rock aquifers two factors need to be considered. Firstly, additional chloride produced by weathering must be considered and secondly, the time it takes for the chloride concentrations to reestablish equilibrium between the matrix and fracture after a change in environmental conditions. Long monitoring runs are also needed. Ideally, the method requires a minimum of three to four years of chloride input data and undisturbed soil samples up to the water table (Sukhija et al., 1988), if the unsaturated technique is applied. Other important sources that need to be considered are applied fertilisers (e.g. KCl) and biological activity of the soils. Cook et al (1989) used the CMB method with the electromagnetic geophysical technique to identify the spatial variability of groundwater recharge in a semi-arid area.

The CMB method gives site-specific estimates (up to $1m^2$) in the unsaturated zone (Scanlon et al., 2002; Figure 3.3). The method can be used to estimate recharge ranging from 0.05 mm/year to 300 mm/year over temporal scales ranging from a few decades to thousands of years (Scanlon et al., 2002; Figure 3.3).

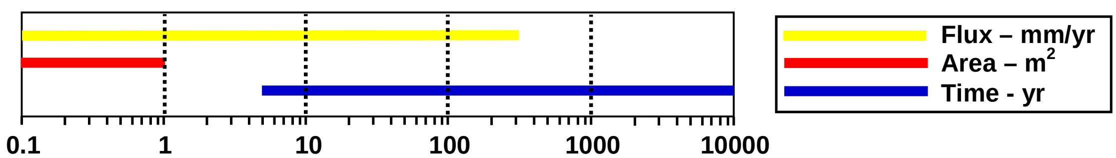


Figure 3.3: Range of fluxes that can be estimated in the unsaturated zone (Beekman and Xu, 2003).

Most reliable estimates of site-specific moisture fluxes may be obtained through a multiple tracer profiling approach (Simmers et al., 1997). This approach aims at deducing and quantifying, where possible, relevant transport processes occurring in the unsaturated zone. For example, the CMB method may reveal the thickness of the evapotranspiration zone and moisture fluxes. For the unsaturated zone preferential flow seems to be more the rule than the exception. Moisture fluxes may therefore be overestimated.

The spatial scale of recharge increases significantly when the saturated zone is used to estimate recharge and similar temporal scales and fluxes are observed as the unsaturated zone profiling techniques (Figure 3.4).

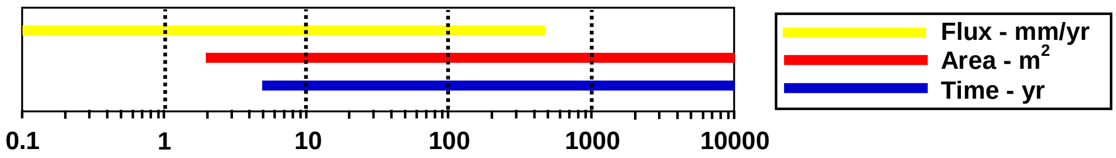


Figure 3.4: Range of fluxes that can be estimated in the saturated zone (Beekman and Xu, 2003).

The CMB method for the saturated zone may be especially useful in areas where groundwater levels do not fluctuate or data on groundwater levels are lacking.

Wood and Sanford (1995) observed that obtaining recharge rates using the CMB method is comparable to recharge rates obtained by physically based methods in semi-arid areas. The method is independent of whether recharge is focused or diffused (Bazuhair and Wood, 1996). Uncertainties in the rainfall chloride concentrations, as a result of measurement errors and other contributing sources, are the main factors that influence the accuracy of the method.

Stable and radiogenic isotopes

Oxygen-18 and deuterium

Sampling for the stable isotopes ^{18}O and $D/^{2}H$ has become routine, in most hydrogeological studies, over the last few decades. The stable isotopes ^{18}O and $D/^{2}H$ are useful in recharge studies as they can provide constraints on the possible location and altitude of recharge (Mazor, 1991). This approach is best suited when data from springs are used (e.g. Mazor, 1991; Diamond and Harris, 2000). The differences in the isotopic composition of groundwater may be due to several factors. Factors that may control the isotopic variation in precipitation are (Mook, 1994):

- Temperature;
- Latitude;
- Altitude; and
- Seasonality.

Oxygen-18 and deuterium are used to elucidate recharge by means of soil moisture profiling in the unsaturated zone. The isotopic composition of the groundwater is used to establish whether recharge was fast or delayed, if recharge took place immediately after a rainfall event the water would have undergone minimal evaporation prior to infiltration and visa versa. The isotopic composition of the groundwater is compared to the Global Meteoric Water Line (GMWL) of Craig (1961) or a Local Meteoric Water Line (LMWL) established for a specific area. The GMWL is represented by the equation:

$$\delta D = 8 * \delta^{18} O + 10 \tag{3.7}$$

In Australia, Allison et al. (1984) developed the δD displacement method for the unsaturated zone. This method uses stable isotope soil moisture measurements and plotting it on a δD – $\delta^{18}O$ diagram and the displacement from the GMWL or LMWL is used to calculate recharge using:

$$\Delta\delta = \frac{C}{\sqrt{Recharge}} \tag{3.8}$$

where:

$\Delta\delta$ = displacement of either D or ^{18}O from the MWL

C = slope of the line through the inverse of the square root of moisture fluxes obtained from δ displacements from the MWL for different sites. Allison et al. (1984) found that in Australia C equal 20.

__Carbon-14__

Groundwater ages or mean residence times can be used to elucidate recharge areas, recharge rates, groundwater flow as well as to identify non-renewable water resources (e.g. Mazor, 1991; Beekman and Selaolo, 1997; Plummer and Sprinkle, 2001; Verhagen, 2003). It is important that radiocarbon analysis and dating of groundwater be incorporated with other geochemical and isotopic data and interpretations to derive a meaningful interpretation. It is important that the combined inorganic and isotopic geochemistry first be used to develop a conceptual model of the groundwater system before interpreting the radiocarbon results (Edmunds and Wright, 1979).

Prior to 1952/3 most of the ^{14}C in the atmosphere was derived by the natural transmutation of nitrogen as a result of the bombardment of cosmic rays (Freeze and Cherry, 1979). Post 1952/3, additional ^{14}C was introduced by nuclear bomb testing. Carbon dioxide (CO_2) from the air is trapped in rain and snow and the water is tagged by atmospheric ^{14}C. As this water infiltrates into the subsurface it becomes isolated from the atmosphere. When water moves below the water table and becomes isolated from the earth's CO_2 reservoir radioactive decay causes the ^{14}C content in the dissolved inorganic carbon to gradually decline (Freeze and Cherry, 1979). Carbon-14 ages refer to the period of time that has elapsed since the water moved deep enough into the groundwater zone to be isolated from the earth's atmosphere (Freeze and Cherry, 1979).

Radioactive decay is expressed as:

$$A = A_0 2^{\frac{-t}{T}} \tag{3.9}$$

where:

A_0 = the specific activity (disintegrations per unit time per unit mass of sample) of ^{14}C
A = the activity per unit mass of sample
t = the decay age of the carbon isotope (years)
T = half life of ^{14}C (5730 years)

^{14}C is reported as percent modern carbon (pmC) determined as the ratio of the sample activity to that of the international standard expressed as a percentage. ^{14}C activities may exceed 100 pmC in areas where groundwater contains tritium (Izbicki and Martin, 1997). When equation 3.9 is rearranged and upon substitution of T = 5730 years the unadjusted age of groundwater can be determined by:

$$t = -8270 \ln\left(\frac{A}{A_0}\right) \tag{3.10}$$

Mook (1980), Reardon and Fritz (1978) and Wigley et al. (1978), as cited in Domenico and Schwartz (1990), list the following processes that can alter the ^{14}C activity of groundwater:

- The congruent dissolution of carbonate minerals, which add 'dead carbon' or carbon without ^{14}C activity to the groundwater. This process lowers the ^{14}C activity.
- The incongruent dissolution of carbonate or other Ca containing minerals accompanied by the precipitation of calcite. This process will remove ^{14}C as calcite precipitates and if dolomite is the mineral dissolving add dead carbon through the above process. This process could occur in the zone of saturation following the rapid solution of calcite to equilibrium with subsequent precipitation as dolomite slowly dissolves.

- The addition of dead carbon from other sources such as the oxidation of old organic matter, sulphate reduction and methanogenesis can reduce the ^{14}C activity.
- Isotopic exchange involving CO_3 and carbonate minerals could lower the ^{14}C activity. This process is generally considered to have a negligible effect at normal groundwater temperatures.

If the factors above are not considered radiocarbon dating can yield unrealistic old radiocarbon ages, these ages can be corrected using geochemical models (Plummer and Sprinkle, 2001). To better estimate the mean age of groundwater the following equation is used (Hendry, 1988):

$$t = -8270 \ln\left(\frac{A}{A_0}\right) + 8270 \ln Q \tag{3.11}$$

where:

Q = the fraction of dissolved inorganic carbon derived from mineral dissolution or the oxidation of organic carbon.

A value of 0.85 is used as an estimate for Q in most natural groundwater systems due to complexities in estimating Q (Hendry, 1988). The value of Q is not that important when solving groundwater flow problems for very old groundwater because of its logarithmic form (Hendry, 1988). At younger ages the value of Q becomes important. Vogel (1967) reported that numerous measurements have shown that the initial concentration of ^{14}C in dissolved bicarbonate is about 85 ± 5% that of modern biogenic carbon.

Mazor (1991) states that a practical way to determine the initial ^{14}C that groundwater attains due to rapid water-rock interactions is to measure the ^{14}C in recent local groundwater and apply it to the age calculation of older water of aquifers with similar rocks. Mazor (1991) further states that in the absence of recently recharged water, a drop of 60% of the initial ^{14}C may be attributed to water-rock interactions in carbonate aquifers and 90% in silicate rocks (plutonic and volcanic rocks, sandstone, shale and quartzite).

Vogel (1967) states that in a confined aquifer with uniform permeability no age stratification occurs in the aquifer and the groundwater age increases in the direction of flow and in unconfined aquifers age stratification occurs due to recharge from precipitation. Recharge rates can be calculated using ^{14}C ages, aquifer depth and porosity (Vogel, 1967):

$$R = \frac{nH}{t} \quad (3.12)$$

where:
n = porosity
H = saturated aquifer thickness (m)

The parameters required for equation 3.12 is difficult to determine in basement aquifers because groundwater occurs within the weathered zone and the fractured bedrock aquifers.

The sampled water would represent a mixture of different ages if the water is stratified or the borehole intersects different flow lines arising from the presence of fracture, bedding and joint planes. Verhagen (2003) noted that the use of the effective porosity in a dual porous medium could be used. The assumption is that the isotope tracer would label all the water in the aquifer by advection or diffusion.

3.4.2 Physical methods

Saturated Volume Fluctuation (SVF)

This method comprises an inventory of inputs in relation to outputs over a specific time period of the water balance. It also comprises the change in the system caused by an imbalance between components. This is important, as one has to relate the input to rainfall that occurred over the same period. The responses (i.e. run-off, base flow or groundwater level change) are assumed to occur within the selected time interval. However, this response can be delayed and needs to be incorporated. Variable rainfall, delayed response (e.g. due to catchment features) and drainage due to soil type, thickness and geology, often makes it difficult to link hydrological output to specific rainfall events.

The SVF-method gives a combined picture of the water level response of an aquifer. This method determines effective recharge and aquifer storativity and allows these to be quantified reliably as lumped parameters. The methods presents one of the most valuable contributions to water balance interpretations, in that it determines average annual rainfall and annual variability of recharge. It also derives aquifer storativity from linear plots of SVF versus Q graphs. It is suitable for most hydrological analysis and aquifer management applications (Bredenkamp et al., 1995). It is based on the saturated water balance, with the following formula:

$$I - O + \mathrm{Re} - Q = S\frac{\Delta V}{\Delta t} \tag{3.13}$$

where:
S = storativity/specific yield
ΔV = saturated volume of aquifer
I = lateral inflow
O = lateral outflow
Re = recharge
Q = net discharge.
Δt = time

The status of the aquifer, based on the water level fluctuations of the monitoring boreholes, is combined and its variation with time is analysed. The water levels from the different observation boreholes are combined to produce the saturated volume status for the entire aquifer. This can be achieved by means of a network of finite elements, which is constructed using the monitoring boreholes or points of abstraction as nodal points for the grid network (Van Tonder and Kirchner, 1990). A random value for the base thickness of the aquifer is given, allowing the saturated volume values to be positive.

The SVF change can also be derived from contours of water levels in relation to an uncertain base. The following simplifying assumptions apply:

- The base is impervious; no losses or inflow via the base is considered; and
- If evapotranspiration losses are included, they have to be added to the abstraction, but if not, the estimated recharge will represent the effective percolation to groundwater (i.e. the recharge after evapotranspiration losses have been included).

In the simplest form, this saturated water balance is represented by the general formula:

$$I - O = S\frac{\Delta V}{\Delta t} \tag{3.14}$$

The balance between the inflow and outflow effects the change in volume of stored water over a specific time interval. The inflow represents both recharge and lateral inflow. The outflow represents abstraction, flow of springs, evapotranspiration and lateral outflow.

Hydrological processes react to rainfall almost immediately, but their combined cumulative response, affecting groundwater levels, may not. Even on a daily basis, the input-output balance could be unacceptable. This is because even though groundwater levels often rise quickly in response to a rainfall event, the effect could remain for many months.

S - values calculated during periods of no recharge, using the saturated volume fluctuation method, are expressed as:

$$S = \frac{(I - O - Q)}{\frac{\Delta V}{\Delta t}} \tag{3.15}$$

Cumulative Rainfall Departures (CRD)

Wentzel (1936) demonstrated that the cumulative rainfall departure (CRD) series correspond to fluctuations of the ground water level. According to Bredenkamp et al. (1995), “the CRD method conforms to the concept that equilibrium conditions develop in an aquifer over time until the average rate of losses equal the average recharge of the system”. The rationale behind the departure method is that in any area, despite large annual variations in precipitation, equilibrium is established between the average annual precipitation and the hydrological response (Bredenkamp et al., 1995). The CRD method is represented by the following equation:

$$ {}_{av}^{1}CRD_{i} = R_{i} - kR_{av} + {}_{av}^{1}CRD_{i-1} \tag{3.16}$$

where:

CRD_i = accumulated rainfall departures from the mean at time ***i***

R_i = rainfall at time ***i***

k = 1 indicate natural conditions and k > 1 indicate that the aquifer system is being exploited

R_{av} = average rainfall.

This equation responds remarkably well with ground water level fluctuations. However, it does not determine aquifer statistics and does not relate water level trends and the CRD. The water balance equation can be used to calculate storativity of an aquifer.

$$S.\Delta V = (I - O) + \mathrm{Re} - Q \tag{3.17}$$

Re or S can be obtained by correlating V with CRD. The aquifer responds differently during prolonged wet and dry rainfall cycles and the system adapts to the prevailing conditions. A 'long term – memory' is introduced to the natural losses from an aquifer. This is dependent of the status at the present time over ***n*** months. Most aquifers indicate a delayed recharge response, which correspond to the antecedent rainfall. Recharge in a specific month depends on the average of more than one month proceeding the current month. Introducing the long and short antecedent conditions the CRD can be calculated (Bredenkamp, 2000):

$$ {}_{n}^{m}CRD_{i} = \frac{1}{m}\sum\nolimits_{j=i-(m-1)}^{j=i} R_{j} + {}_{n}^{m}CRD_{i-1} - \frac{k}{n}\sum\nolimits_{j=1-(n-1)}^{i} R_{j} \quad (3.18) $$

where:

m = number of months denoting the short memory antecedent effective rainfall

n = period signifying the long term average condition of the system

k = exploitation factor which is dependent on abstraction /pumping:

$\frac{1}{m}\sum\nolimits_{j=i-(m-1)}^{i} R_{j}$ = short term average rainfall (3.19)

$\frac{k}{n}\sum\nolimits_{j=1-(n-1)}^{i} R_{j}$ = long term average rainfall (3.20)

Xu and Van Tonder (2001) derived a new formula for the CRD method. The k parameter applied in the Bredenkamp et al. (1995) formula is important to mimic groundwater flow. An appropriate value for k must be selected to adequately mimic the water level fluctuation in boreholes. The physical value of k is still unclear (Xu and Van Tonder, 2001). If only a short series of data is available, it often tends to be bias to a certain degree. Especially if the rainfall varies over short time scales, the Xu and Van Tonder (2001) formula can be applied:

$$ {}_{t}^{1}CRDi = \sum_{n=1}^{i} R_{n} - \left(2 - \frac{1}{R_{av} i}\sum_{n=1}^{i} R_{n}\right)\sum_{n=1}^{i} R_{t} \quad (3.21) $$

R_t often ranges from 0 to R_{av}, where 0 = aquifer being closed and R_{av} = open aquifer system. The cumulative rainfall average would conform to R_{av} if R_i does not show a trend

($R_t = k\,R_{av}$). It is assumed that the CRD is the driving force behind the monthly water level changes if the other stress is relatively constant. The groundwater level will rise if the cumulative departure is positive and will decline if it is negative.

Since CRD ∝ ($\Delta h + (Q_p + Q_{out})/(AS)$), making rCRD = $S(\Delta h + (Q_p + Q_{out})/(AS))$. After rearrangement of the formulas the following formula is obtained:

$$\Delta h_i = \left(\frac{\mathrm{Re}}{S}\right)\left({}_{t}^{i}CRDi\right) - \frac{\left(Q_{pi} + Q_{outi}\right)}{AS} \qquad (3.22)$$

where:
Δh = water level change
Re = recharge
Q_{pi} and Q_{out} = pumping and out flow rates
A = recharge area

The Xu and Van Tonder (2001) formula can account for changing pumping and outflow rates ($Q_p + Q_{out}$). This is an important factor to estimate recharge rates to the basement aquifers of Namaqualand as most of the data that is available for the area is from community water supply boreholes. The method also incorporates a time lag function that can be used if recharge is delayed. Time lags may be brief for macropore recharge and longer for matrix recharge depending on the unsaturated zone characteristics and the depth to water table.

3.5 Statistical approach using factor analysis

The statistical approach involves using groundwater chemistry to delineate areas of recharge and discharge. Lawrence and Upchurch (1982) and Tarvainen and Paukola (1998) used geochemical databases to delineate recharge areas and risk areas for contaminated groundwater, respectively. This approach can also indicate regions were direct rainfall recharge occurs to the hard rock aquifers. Due to climatic factors, topography and the heterogeneity of the aquifers the crystalline basement aquifers are generally yielding poor qualities and quantities of groundwater. Groundwater in the recharge areas is usually of a better quality than that of discharge areas and areas intermediate between these two regimes. The basic assumption is that in areas receiving direct recharge the water chemistry would not show large deviations from the rainfall chemistry as opposed to water that have undergone significant chemical changes as a result of evapotranspiration, “old” water and stagnant waters with no “refreshening” from recharging rainwater.

If the chemical character of the groundwater in recharge and discharge areas are known, then the processes involved in producing the specific groundwater chemistry can be used to delineate recharge areas using factor analysis. Factor analysis is a tool used to rearrange data to present it in a manner that better explains the structure of the underlying system that produced the data (Dawdy and Feth, 1967). Thus, a set of factors is created in a simple structure to explain the interrelations of the chemical parameters. Two types of factor analysis are used, R-mode analysis and the Q-mode of analysis. R-mode analysis describes the similarities between different variables and Q-mode analysis show correlations between sampling sites.

Factor analysis has proved useful as an aid in the interpretation of geohydrochemical data (Lawrence and Upchurch, 1976; Ashley and Lloyd, 1978; Dalton and Upchurch, 1978; Usunoff and Guzman-Guzman, 1989; Schot and Van der Wal, 1992; Adams et al., 2001). The purpose of factor analysis is to find groups of variables with shared common variances (Johnston, 1989). Factor analysis has several advantages over classical graphical approaches. It can be used to interpret neutral chemical species and non-chemical data (e.g. altitude, temperature, etc.) and secondly, variations in ions present in small concentrations are not masked by chemically similar ions in greater concentrations (e.g. Cl) in the data sets (Usunoff and Guzman-Guzman, 1989).

3.6 Geographical Information Systems (GIS)

In semi-arid rural areas, the paucity of data necessitates the use of techniques that can present recharge spatially. Redistributing point estimates are still a complex subject due to different, among others, climatologic, geologic, land cover and topographic conditions. GIS techniques are powerful in that it can give a qualitative assessment of recharge, if combined with other estimation methods a semi-quantitative estimation can be obtained over a specific area. GIS aids in the integration of different thematic layers, manipulation and visualisation of data that may aid in the conceptualisation of recharge processes and rates.

Krishnamurthy et al. (2000) describes the use of remote sensing and GIS to assess groundwater resource development in hard rock terrain, with special emphasis on the demarcation of areas for artificial recharge. GIS approaches have mainly been used to integrate various factors spatially to assess aquifer development potential and vulnerability (e.g. Kamaraju et al., 1996; Smith et al., 1997; Edet et al., 1998; Kellgren et al., 2000; Sophocleous, 2000 and Lachassagne, 2001).

The GIS approach involves the evaluation of different surface and subsurface features and its influence on natural groundwater recharge. The approach is mainly of a subjective nature where probability ratings are assigned to features that may have a positive or negative effect on groundwater recharge. The different layers are then weighted. The approach is similar to that applied in generating groundwater vulnerability maps. Different data sets may be used in defining a recharge potential map. The data sets are shown in Table 3.2, with the overlays that can be derived from these data sets. Some of the factors listed in Table 3.2 are discussed in order to evaluate their effect on water movement that may become available as recharge, derived mainly from existing literature. The most important factors that influences recharge are then identified to generate a recharge potential map.

Table 3.2: A listing of the data sets that is often available

Thematic maps	Derivatives	Typical sources
Lithology	Rock types	Geological maps, Remote Sensing
Soil	Clay, Thickness	Soil survey maps, Remote Sensing
Landform	Physiographic disposition, areal extent	Remote Sensing
Land cover/use	Vegetation, urban infrastructure, dams	Remote Sensing
Lineaments	Densities, intersections	Remote Sensing
Slope		Remote Sensing – DEM
Drainage	Density, length, bifurcation ratio	Topographic maps, Remote Sensing
Rainfall	Distribution, amount	Weather Bureau, Radar
Evapotranspiration	Amount	Weather Bureau, Remote Sensing
Water levels		Hydrocensus
Hydraulic properties	Conductivity, storage, transmissivity	Field and laboratory testing
Well Yield	Distribution, amount	Hydrocensus, Field testing

The method used to determine potential recharge areas using available spatial data in a GIS database is similar to the DRASTIC approach developed for aquifer vulnerability (Aller et al., 1987). DRASTIC is an acronym for:

- Depth to groundwater;

- Recharge rates;
- Aquifer media;
- Soil media;
- Topography;
- Impact of the unsaturated zone; and
- Conductivity (K) of the aquifer.

The Drastic Index (DI) for an area is determined by:

$$DI = \left(D\lambda_D + R\lambda_R + A\lambda_A + S\lambda_S + T\lambda_T + V\lambda_V + K\lambda_K\right)$$

where:
λ = weighting factor

The objective of the GIS exercise will enable the selection of the fewest and most important variables to define potential recharge areas. Point or local estimates calculated from other techniques can be used to distribute the estimates to all other areas with similar conditions.

Topography and slope

Topography is probably the most significant factor that drives both surface water and groundwater flow. The topography links most of the variables discussed later. As topography can:

- Distribute rainfall over an area by effects of orography;
- Determine the catchment configuration and thus influence runoff, ponding and infiltration;
- Determine the rate of development, accumulation and transport of soils;
- Determine the distribution of vegetation;
- Determine the drainage densities of streams;
- Influences the configuration of the water table (i.e. in unconfined conditions the water table elevations will mimic the surface topography); and
- Determine the land use of a particular area.

Scanlon et al. (1999) have shown with the aid of chloride data that topographic depressions as a function of geomorphic settings have high water fluxes in the Chihuahuan Desert, Texas.

Interflow and overland flow reduces groundwater recharge and the main drivers of these two processes are the physical configuration of the catchment. A catchment is made up of interconnected slopes and the channel network draining these slopes. The slope angle affects the moisture content of the unsaturated zone by governing the proportion of surface runoff to infiltration. The strongest flow-inducing gradients are mainly vertical in the unsaturated zone and lateral variations occur under saturated conditions. Troch et al. (2002) characterized the drainage response functions of the basic nine-hillslope functions derived from plan and profile curvatures (Figure 3.5). Plan and profile curvatures are the most dominant topographic controls on flow along hillslopes. The main limitations of their analyses are (Troch et al., 2002):

- The kinematic wave assumption of subsurface flow;
- The assumption of spatially homogenous hydraulic characteristics of the hillslopes;
- The assumption that capillarity effects of the unsaturated zone above the phreatic layer can be neglected; and
- Recharge is spatially uniform.

Slopes in the Namaqualand areas have basically the shape of no. 9 and 8 in Figure 3.5. Troch et al. (2002) modeled the subsurface flow rates and soil moisture storage for the nine hillslopes during free drainage at a constant depth of 2m (Figure 3.6 a-b). Zones with a concave topography will produce more subsurface flow (Dunne, 1983; Troch et al, 2002).

Troch et al. (2002) also evaluated the drainage response functions under a constant rainfall recharge event; the results are shown in Figure 3.7a-b.

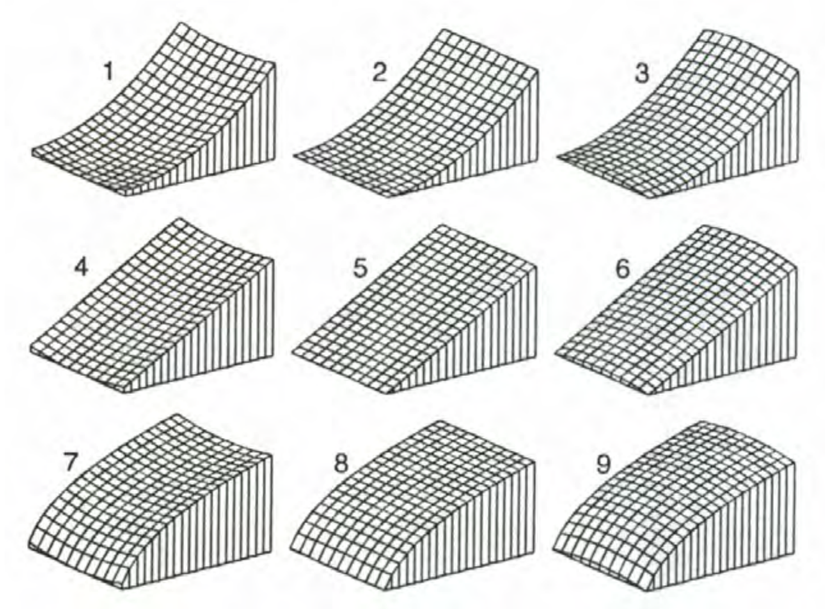


Figure 3.5: **3D view of the nine different hillslopes (Troch et al., 2002).**

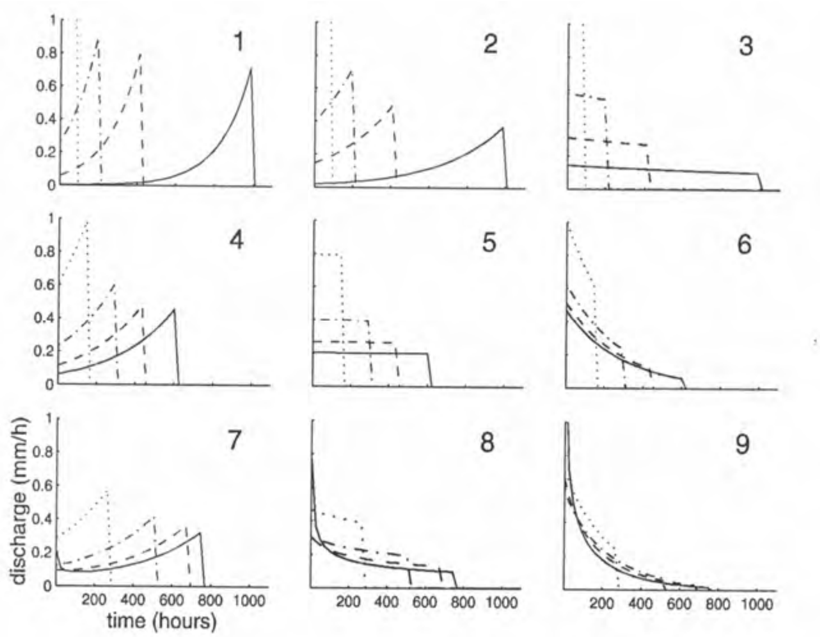


Figure 3.6a: **Normalised subsurface flow rates at different locations along the nine hillslopes (dotted line: x = 25m; dash-dotted line: x = 50m; dashed line: x= 75m; solid line: at outlet, x = 100m) (Troch et al., 2002).**

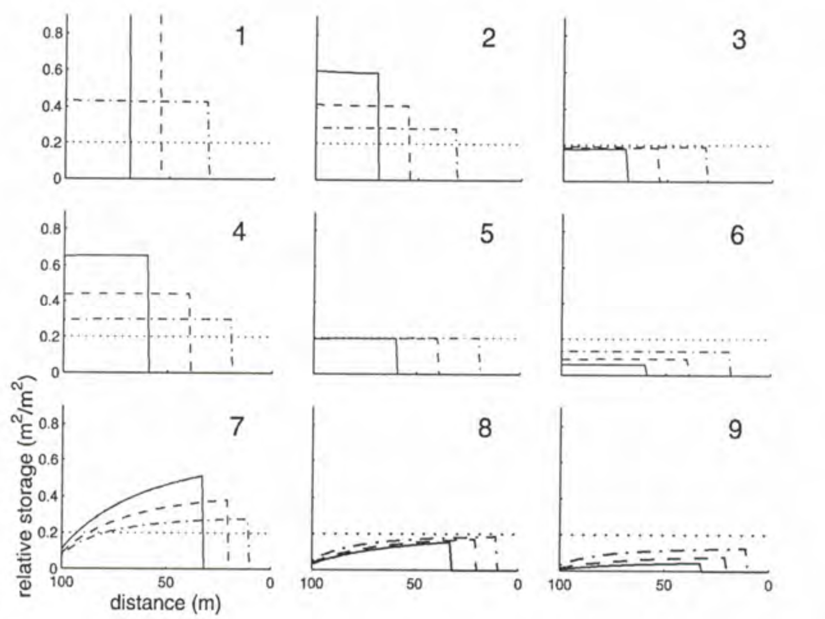


Figure 3.6b: **Relative soil moisture storage for characteristic time steps (dotted line: initial time, t = 0; dash-dotted line: t = 5 days; dashed line: t = 10 days; solid line: t = 15 days) (Troch et al., 2002).**

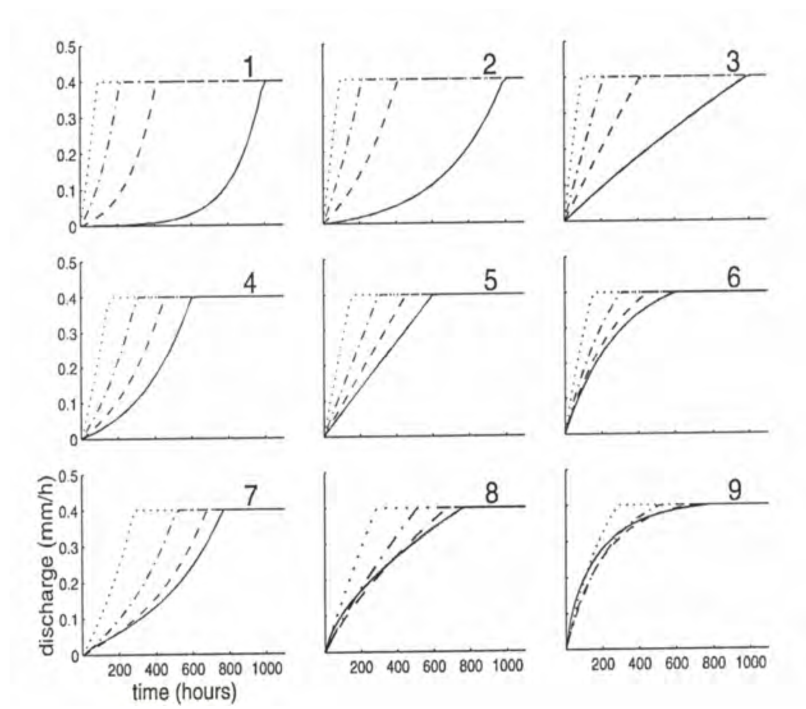


Figure 3.7a: **Normalised subsurface flow rates at different locations along the nine hillslopes during a constant recharge event of 10mm/day (dotted line: x = 25m; dash-dotted line: x = 25m; dashed line: x= 50m; solid line: at outlet, x = 100m) (Troch et al., 2002).**

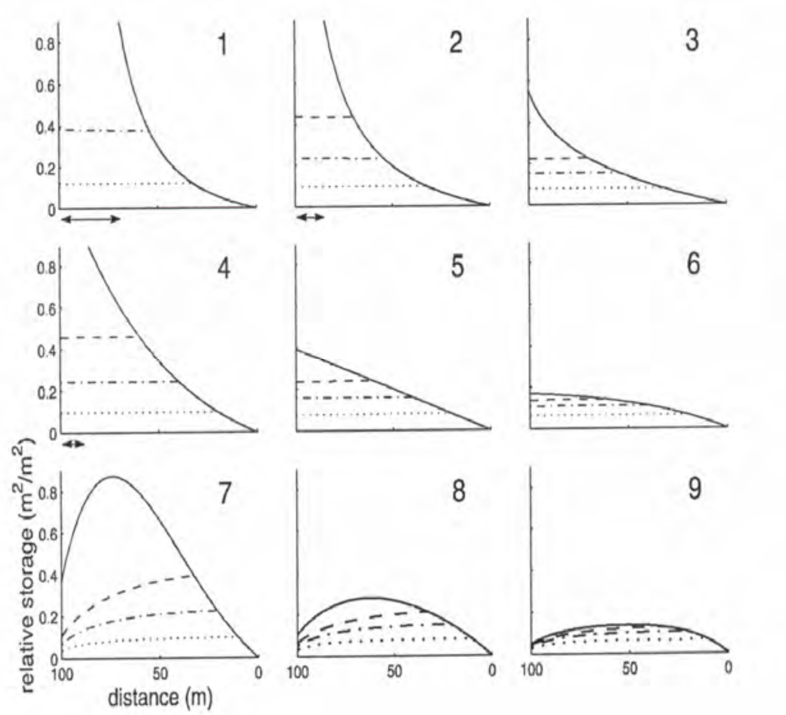


Figure 3.7b: Relative soil moisture storage for characteristic time steps during a constant recharge event of 10mm/day (dotted line: t = 5; dash-dotted line: t = 10 days; dashed line: t = 15 days; solid line: steady state). Arrows indicate saturated area of the respective slopes (Troch et al., 2002).

Soils

Soil texture and thickness greatly affects the infiltration of water (Scanlon et al., 1997). The pre-existing soil water conditions and the thickness and nature of the unsaturated zone determines the amount of water being recharged (Sophocleus, 1992). Holman et al. (2000) have used soil and geological information to generate groundwater vulnerability maps of shallow aquifers. Layering of different sediment types will introduce heterogeneities on different scales. Spatial heterogeneity of the soil moisture and fluxes along the land surface may be caused by (Kim et al., 1999):

- Spatial variation of the soil and vegetation characteristics;
- Spatial variation of the atmospheric boundary conditions such as precipitation and potential evapotranspiration; and
- Lateral topographic distribution of water.

The clay content of soils will significantly reduce recharge. Cook et al. (1992) negatively correlated recharge with the clay content of the top 2m of sediments. Distribution of water in a coarse textured soil occurs more rapidly than in a fine textured soil. Gravel has a higher hydraulic conductivity than a clayey soil (Table 3.3). Infiltration is quicker and higher through gravel than through clays. Macropore flow or preferential flow is an important factor to consider in arid soils. Soils along a slope will have the following characteristics (White, 1987):

- At the top of a slope soils tend to be freely drained; and
- At the valley bottom soils are generally poorly drained.

Table 3.3: Typical values of porosity (Freeze and Cherry, 1979)

Material	K (cm/sec)
Gravel	10^{-1} to 100
Clean sand	10^{-4} to 1
Silty sand	10^{-5} to 10^{-1}
Silt	10^{-7} to 10^{-3}
Clay	10^{-10} to 10^{-6}

Wakatsuki et al. (2002) have shown that granite and gneiss bedrock slopes with almost the same mineral compositions will produce different soil properties and dimensions of soil slips (Figure 3.8). Granitic rocks tend to break down to coarse-grained soils and gneissic rocks to a finer soil. The infiltration capacity for "granitic" soils will be larger than "gneissic" soils. Weathered profiles of granite are less clayey than that of schists.

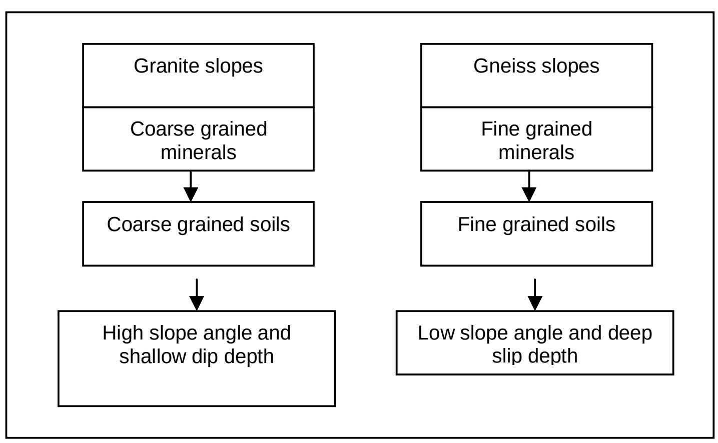


Figure 3.8: Relations between lithological properties of bedrock, soil structure and dimensions of soil slips for granite and gneiss slopes (adapted from Wakatsuki et al., 2002).

__Lineaments__

Lineaments can be traced from remotely sensed data and aerial photographs. Lineaments are easily identified in areas of thin overburden and outcrops. Fractures observed at outcrop scale can be correlated to the lineaments by applying a buffer analysis. Degnan and Clarke (2002) state that a lineament is fracture correlated, if fractures in bedrock outcrops have strikes similar to the trend of the individual lineament within a specific buffer zone. Fractures need to be interconnected in order for groundwater flow to occur. Fracture connectivity increases with fracture densities and length (Cook, 2003). Koch and Mather (1997) state that in order for the fractures to be hydrogeologically significant it must be significantly extensive to provide hydraulic connectivity between adjacent watersheds to increase the total recharge area. Minor fractures may provide only storage if not hydraulically connected to the larger fracture network. Lineaments are described in terms of its length density (Ld) and frequency (Lf), where (Greenbaum, 1985):

$$Ld = \frac{\sum_{i=1}^{i=n} Li}{A}$$
$$Lf = \frac{\sum_{i=1}^{i=n} Ln}{A} \qquad (3.23)$$

where:

$\sum_{i=1}^{i=n} Li$ = total length of all lineaments

$\sum_{i=1}^{i=n} Ln$ = total number of lineaments

A = area

The following factors must exist to create favourable conditions for groundwater targets (Walls and Kalinauskas, 2000):

- Brittle host rocks;
- Dilatant stresses to create open fractures;
- Conjugate fractures to enhance interconnections;
- Structural traps to retain water;
- Intersections with the surface to allow recharge; and
- Fracture and void enhancement by dissolution.

Drainage

Scanlon et al. (1999) concluded that higher recharge rates in arid basins are associated with drainage areas. High drainage densities are associated with areas covered by low permeability bedrock with appreciable runoff. Low drainage densities are common in regions with permeable soils and a low relief, resulting in increased infiltration capacities (Smith et al., 1997). Drainage are described in terms of length-density (Dld) and frequency (Df), where (Greenbaum, 1985):

$$Dld = \frac{\sum_{i=1}^{i=n} Si}{A} \qquad (3.24)$$

$$Df = \frac{\sum_{i=1}^{i=n} Sn}{A}$$

where:

$\sum_{i=1}^{i=n} Si$ = cumulative length of all streams

$\sum_{i=1}^{i=n} Sn$ = total number of streams

A = area

Vegetation

Due to the limited rain supply, vegetation in arid and semi-arid regions are sparse and often occur in geomorphic and surface drainage zones with a high moisture content. However, plants are opportunistic and will populate an area where water is easily accessible. Phreatophytes are the most reliable groundwater indicator.

Vegetative canopies exert a significant control on the rainfall reaching the ground surface and contributing to evapotranspiration. Berndtsson and Larson (1987) states that vegetation cover tends to increase infiltration as opposed to areas with bare soil in arid and semi-arid areas. Vegetation increases infiltration by (Berndtsson and Larson, 1987, Dunne, 1983):

- Retarding surface water movement;
- Reducing raindrop compaction; and
- Increasing organic matter content, bulk density and surface horizon depth.

Scanlon et al. (1997) states that vegetation is most probably the most important control on unsaturated water movement. Areas of coarse and bare soil have higher rates of water movement then vegetated areas. Vegetation tends to decrease the volumetric water content for sand, loamy sand and silty loam in arid regions (Dong et al., 2003). On remotely sensed data vegetation found in areas of excess moisture, with groundwater occurring close to the surface or at discharging areas, the vegetation is characterised by low spectral brightness coefficients in the red part of the spectrum and maximal values in the near infrared zone (Ob'yedkov, 1992).

Rainfall

Rainfall in arid and semi-arid areas produces sporadic runoff that seldom reaches the valley bottom. Rainfall in topographically distinct areas will be higher in areas of higher altitude (orographic effect). Bare rock outcrops produces runoff under most rainfall conditions and only infiltrates once it reaches alluvial or colluvial cover (Van Wesemale et al., 1998).

Water table depth

Infiltration and evapotranspiration are related to water table depth. Recharge is related the distribution of rainfall into infiltration, runoff and evapotranspiration (Kim et al., 1999). Recharge will be less if the water table is deep and higher when water tables are shallow in arid to semi-arid areas. Evapotranspiration will dominate under both cases but will be significantly higher if the water table is close to the surface. When the water table is shallow, infiltration reaches the saturated zone fairly fast, so that most of the individual rainfall events correspond to isolated infiltration events with small time lags (Wu et al., 1996). As the depth to groundwater increases the potential for rainfall to percolate to the saturated zone decreases (Wu et al., 1996). Wu et al (1996) also state that for groundwater at intermediate depth the recharge events produced by individual rainfall events merge into one single annual process although a few peaks of recharge correspond to large rainfall events or concentrated rainfall clusters. Sophocleus (1991) states that time lags may be brief for macropore recharge and longer for matrix recharge depending on the unsaturated zone characteristics, depth to water table and other factors.

Land use

Intensive land use in arid and semi-arid areas is focused near the channels of ephemeral rivers, valleys and areas adjacent to streambeds. Urban or peri-urban areas that have impermeable surfaces will tend to reduce direct recharge but recharge rates may increase in areas where infrastructure (e.g. leaking pipes, septic tanks, etc) creates pathways for recharge (Lerner, 1990). This is mainly applicable to dense settlements and may not be a significant in rural areas. The major land use activities that may impact on groundwater recharge processes are tillage and irrigation of farmlands as well as overgrazing.

Problems of scale

Hierarchy theory suggests that at a regional scale only a limited number of variables should be able to describe any relationships between recharge and rainfall over an area. At finer scales more variables must be incorporated in the model. The methodology proposed for the GIS approach involves knowledge acquisition and identification of variables favourable for recharge and then using GIS and remote sensing techniques to integrate, rate and weigh the variables to generate a recharge potential map. The recharge potential map can be calibrated with point and area estimates. It is thus obvious that scaling up or down is a major factor that needs to be evaluated.

The issue of temporal and spatial scales and its impact on hydrological studies has been well documented (e.g. Blöschl and Sivapalan, 1995; Bergström and Graham, 1998; Bergkamp, 1998; Western and Blöschl, 1999; Schulze, 2000; Brunsell and Gillies, 2003). Bergström and Graham (1998) make the point that hydrological modelers have different views on the scale problem depending on their perspectives and scientific viewpoint. As an example, a small lysimeter study of 1km^2 may be considered large and heterogeneous and a forecaster may consider a basin of several thousand km^2 as small and heterogeneous. A water resource evaluation study often assumes uniform rates of water movement throughout an area. According Scanlon et al. (1997), this assumption does not greatly affect resource estimates. However, contaminant transport studies require more detailed analysis of the spatial variability of water movement. Large spatial and temporal variations of recharge to arid zones are the rule. Six causes of scale (temporal and spatial) problems in hydrological responses have been identified (Schulze, 2000):

- Spatial heterogeneity in surface processes;
- Non-linearity in responses;
- Processes require threshold scales to occur;
- Dominant processes change with scale;

- Development of emerging properties; and
- Disturbance regimes.

The use of point recharge estimates to define recharge on a regional or even a local scale is fraught with uncertainties. Various geostatistical techniques exist to aggregate or "upscale" point estimates to regional estimates. These geostatistical techniques require regular closed spacing of data and must take into account the spatial heterogeneity of the area. Spatial scaling either up or down via different linkages across scales are illustrated in Figure 3.9.

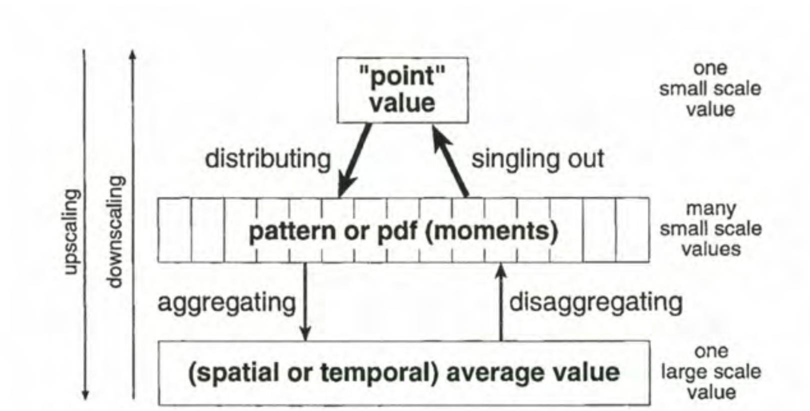


Figure 3.9: Processes involved in upscaling and downscaling (Blöschl and Sivapalan, 1995).

CHAPTER 4

Measurement and experimental techniques

4.1. Introduction

To complement the existing data from the operational borehole monitoring programmes, chemical and isotope data were collected from the rainfall and groundwater sampling programme. A bulk rainfall-monitoring network and later an event based monitoring programme was developed for the area for the application of the CMB method and the isotope characterisation.

4.2 Precipitation monitoring and sampling

Precipitation is often measured for hydro(geo)logical and meteorological studies. Specifically in recharge studies precipitation is important to determine the rate and mode of groundwater recharge. The chloride and stable isotope chemistry of the precipitation are compared with that of the groundwater and/or soil moisture. These methods are widely applied and literature on the subject is extensive (e.g. Eriksson and Khunakasem, 1969; Allison and Hughes, 1978; Sharma and Hughes, 1985; Bazuhair and Wood, 1996, Edmunds and Gaye, 1994; Gaye and Edmunds, 1996). Currently, no national programme exists in South Africa to sample rainfall chemistry. Bredenkamp (2000) also noted that specific measurements of chloride in precipitation are lacking in South Africa and a representative monitoring program needs to be initiated. The establishment of such a program would have to rely heavily on the collection of chemical and isotopic measurements that are representative of the atmospheric inputs. Rainfall sampling occurs on a project basis and is usually abandoned after the completion of the project. In South Africa, it is often not practical to empty rainfall collectors after each rainfall event, due to great distances and the inaccessibility of certain areas. Automated systems are expensive and require regular maintenance. A need exists in the southern African region to develop a regional precipitation monitoring programme. Several methods exist for the collection of rainfall for chemical analysis:

- Manually collecting daily or event rainfall;
- Bulk rainfall collectors;
- Automatic continuous analysers; and
- Ion exchange resins.

The first two methods listed above are the most cost effective. The bulk rainfall samplers (BRS) are often used in groundwater recharge studies to collect rainfall for chemistry and stable isotope analyses over extended periods, usually six to twelve months. The most important data derived from such sampling exercises are the concentration of chloride and the ratios of the stable oxygen and hydrogen isotopes. The amount of rainfall is also determined and compared with rainfall totals at the nearest weather observation station. The amount of rainfall is also important for the weighting of the chemical parameters. The chloride data obtained from such collectors need to be representative of the atmospheric deposition as the methods used to calculate recharge are very sensitive to variations in chloride concentrations in rainwater. An error in the concentration of chloride will yield significant over- or underestimation of recharge. Bulk samplers are open continuously and collect both wet and dry depositions. During periods of no rainfall aerosols deposit on the funnel and are washed into the sampling vessel during the next rainfall event (Appelo and Postma, 1993). The integrated O- and H isotope ratios are used to determine the local meteoric water line (LMWL) and the ratios of the input water and the deviation of the groundwater from this input water.

The current bulk rainfall samplers used in South Africa, sometimes called totalisers or cumulative rainfall samplers, are evaluated and compared with a new bulk rainfall sampler developed and tested during this research.

4.2.1 Bulk Rainfall Samplers

Several totalisers were purchased from the Council for Scientific and Industrial Research (CSIR) for rainfall monitoring in the Namaqualand region. The CSIR uses these rainfall samplers or totalisers, called the standard bulk rainfall samplers (SBRS), at various sites as part of their research activities (Weaver et al., 1999; Weaver and Talma, 2002). Gieske (1992) also used totalisers in his recharge study in Botswana and came to the conclusion that this method of sampling is worthwhile. The SBRS depicted in Figure 4.1a is typically a cylindrical collection vessel, constructed with unplasticised polyvinyl chloride (uPVC), with a funnel and bird protection wiring at the top. Unplasticised polyvinyl chloride is the preferred material for the construction of totalisers due to the fact that it is easily available, cuts and joins easily, is lightweight and impact resistant. The SBRS is usually constructed from commercially available blue uPVC piping. The totaliser is a singular structure that is either glued or cemented together which make it difficult to empty and maintain. This flaw may create contamination problems when the totaliser is emptied. The totalisers are often filled (250 – 500 ml) with silicon oil to prevent evaporation.

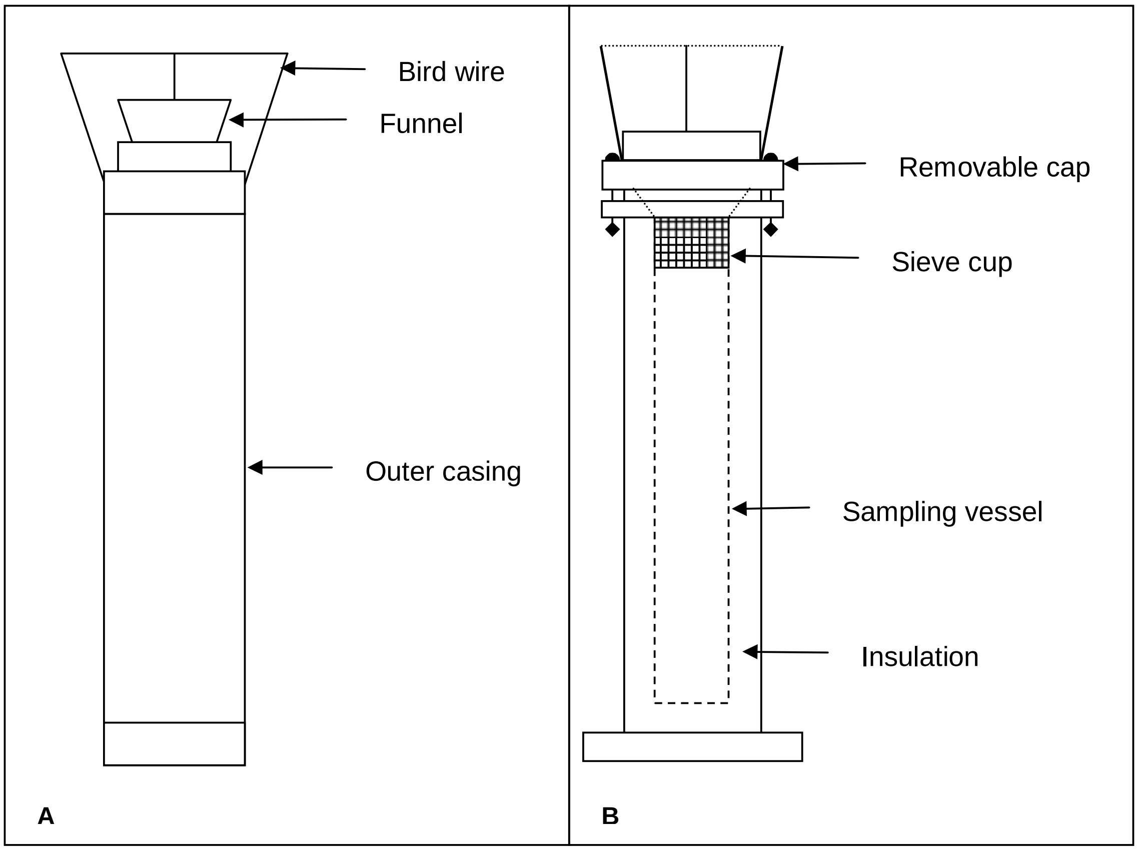


Figure 4.1a-b: The standard bulk rainfall and UWC bulk rainfall sampler designs.

The results obtained from the totalisers were found to be highly irregular. Values for 2000 ranged from 12.9 – 66.6 mg/l and in 2001 the values seemed to have decreased to 2.6 – 86.06 mg/l for the area (Table 4.1). The lower values measured in 2001, except for Langhoogte, can be explained by the fact that most of the leachable chloride of the PVC material have been removed during the 2000 season.

Table 4.1: Chloride concentrations (mg/l) of precipitation collected from bulk rainfall samplers.

Site	Cl_p (2000)	Cl_p (2001)
Kamieskroon	20	6.03
Spoegrivier	66.6	8.6
Buffelsrivier	21.7	10.3
Kommagas	22.4	12.9
Steinkopf	21.4	NA
Paulshoek	30.4	11.2
Langhoogte	52.15	86.08
Soebatsfontein	32.2	25.9
Springbok	NA	3.4
Wallekraal	48.8	NA
Leliefontein	12.9	2.6

NA = not analysed

It is evident that the bulk collectors have overestimated the total chloride deposition. A survey of international literature revealed a minimum and maximum chloride concentrations of 0.32 and 36 mg/l, respectively. The high chloride values are from samples taken very close to the coast and from islands. South African literature shows minimum and maximum chloride concentrations of 0.28 and 26 mg/l (the latter was collected in a similar bulk rainfall collector), respectively. Several factors may add to these erroneous results, they are:

- Anthropogenic activities;
- Environmental conditions; and
- Problems associated with the construction and materials used.

The effects of anthropogenic activities on the chloride concentration of the samples are probably very limited in the area. However, the influence of the various mining activities in the area on the rainwater chemistry was not established. The effects of dust are also limited, as the visual examination of the water did not reveal any visible turbidity. The effect of the sampler itself was tested and the experiments are outlined below.

The SBRS was redeveloped in order to make it more practical to sample and to enhance the quality of the data obtained. The UWC Bulk Rainfall Sampler (UWCBRS) was developed and is shown in Figure 4.1b. The construction of the UWCBRS is practical, with components that can be replaced over time. The UWCBRS has an inner high-density polyethylene (HDPE) sampling vessel that can be removed and capped in the field and transported as is to the laboratory. Reimann et al. (1999) have shown that factory new

HDPE bottles are excellent for storing water for ultra trace analysis. The inner sampling vessel is weighed and marked for conversion purposes. The inner sampling vessel is separated from the casing and the ground by polystyrene in order to minimise the transfer of heat from the environment to the water. A stainless steel or HDPE sieve cup can be inserted beneath the HDPE funnel in areas where insects are prevalent. The sieve cup can be easily replaced or cleaned and its position in the sampler minimise splashing. The funnel section of the UWCBRS can be retrofitted with a rainfall recorder. The two samplers were compared for practicality.

The Experiment

Temperature variations

The effect of air temperature variations inside the rainfall samplers was measured using MC Systems temperature loggers. The effects of environmental radiation on the air temperature within the samplers and the water temperature were investigated. The temperature within the loggers is important when the samplers are primarily used for stable isotope sampling. The loggers were calibrated and tested for a 5-hour period prior to usage. Drift between temperatures was corrected for all loggers and compared with a standard 0.1^{o}C calibrated mercury thermometer. An outside logger was set up to measure the ambient atmospheric temperature using a MC Systems logger with a radiation shield. The samplers were placed in an open space with no hindrances within 15 m of the rainfall samplers. The loggers were placed at the same depth in the center of the samplers, suspended over the water for the air temperature measurements within the loggers. The loggers were programmed to measure temperature at 20-minute intervals over 4.5 days. The second approach involved submerging the temperature loggers within 5 liters of water in both samplers in a second experiment. The logging time was set to 30-minutes. The samplers were again left in an open space for 3.5 days.

Water chemistry

The influence of uPVC, HDPE and silicon oil on the chemistry of water was tested as follows:

1. Four distilled water samples were collected in two new, pre-rinsed HDPE bottles and two uPVC bottles;
2. 200 ml distilled water was added to all bottles;

3. 30 ml of polydimethylsiloxane (silicon oil) was added to an HDPE and uPVC container. Distilled water (using a kettle type distiller) was used instead of deionised water as the distilled water contained traces of ions;
4. Samples were kept at room temperature for approximately one year and occasionally agitated; and
5. Analysed for major and trace elements using an ICP-MS.

Results

Temperature variations

It is evident from Figure 4.2 that the temperature of the air in the SBRS increases significantly from the temperature of the air outside. The temperature of the environment fluctuated between 4.4 -28.1 ^{o}C, while the temperature within the SBRS and the UWCBRS fluctuated between 3.1-32.6 ^{o}C and 3.1-26.5 ^{o}C respectively. The UWCBRS unit is more or less equal to the ambient air temperature. The temperatures for both units are more or less the same for temperatures below 10 ^{o}C. If the temperature of the environment rises during the day, the temperature inside the SBRS unit increases on average by 8.1 ^{o}C and by 1.6 ^{o}C in the UWCBRS over the recorded period. The SBRS is on average 8.1 ^{o}C warmer than the UWCBRS. The differences will be much higher during the summer months when the maximum air temperature fluctuates between 25-35 ^{o}C in most parts of South Africa.

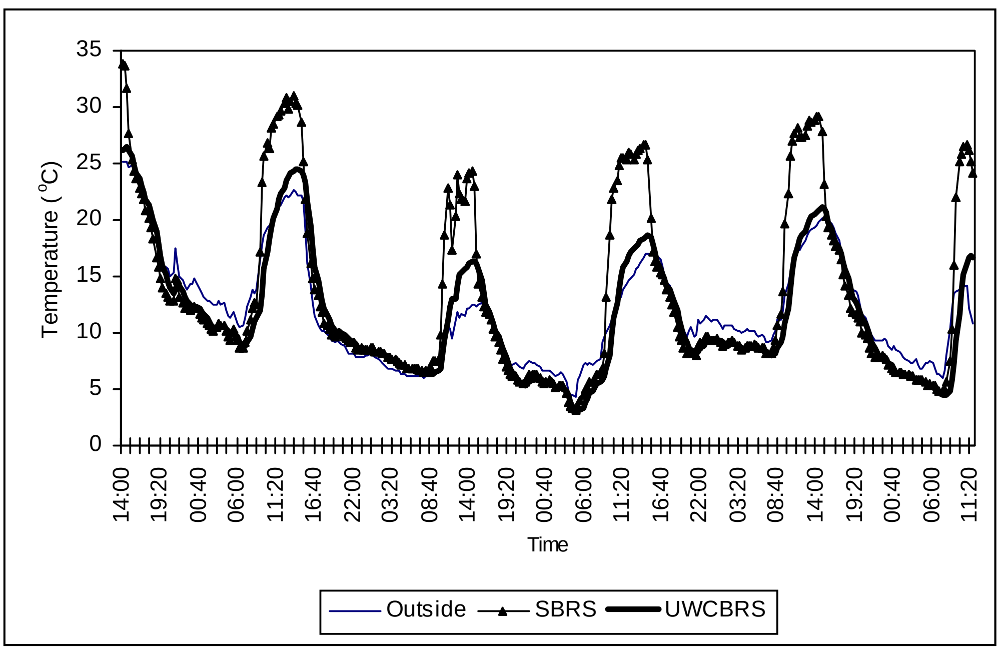


Figure 4.2: Comparison between temperature changes inside the two rainfall samplers and the temperature of the environment (without water).

The temperature of the water inside the samplers reacts differently to that of the environment as shown in Figure 4.3. The water temperature of the SBRS increased significantly during the day and attains temperatures higher than that of the ambient air temperature. The temperature of the air fluctuated between 9.5-32.2 ^{o}C, while the temperature of the water in the SBRS and the UWCBRS fluctuated between 12.5-36.6 ^{o}C and 14.9-22.7 ^{o}C respectively. On average the water in the SBRS is 4.4 ^{o}C warmer than the environment and the UWCBRS is 9.5^{o}C cooler than the environment. The water in the UWCBRS retains most of its heat during night time. The water temperature in the SBRS is on average 13.9^{o}C warmer than the water temperature of the UWCBRS unit. The fact that the inner sampling vessel is smaller in diameter than the SBRS prevents the formation of elevated temperatures above the water. Al-Malack (2001) has shown that uPVC pipes leach significant concentrations of calcium, barium and tin at temperatures above 35 ^{o}C.

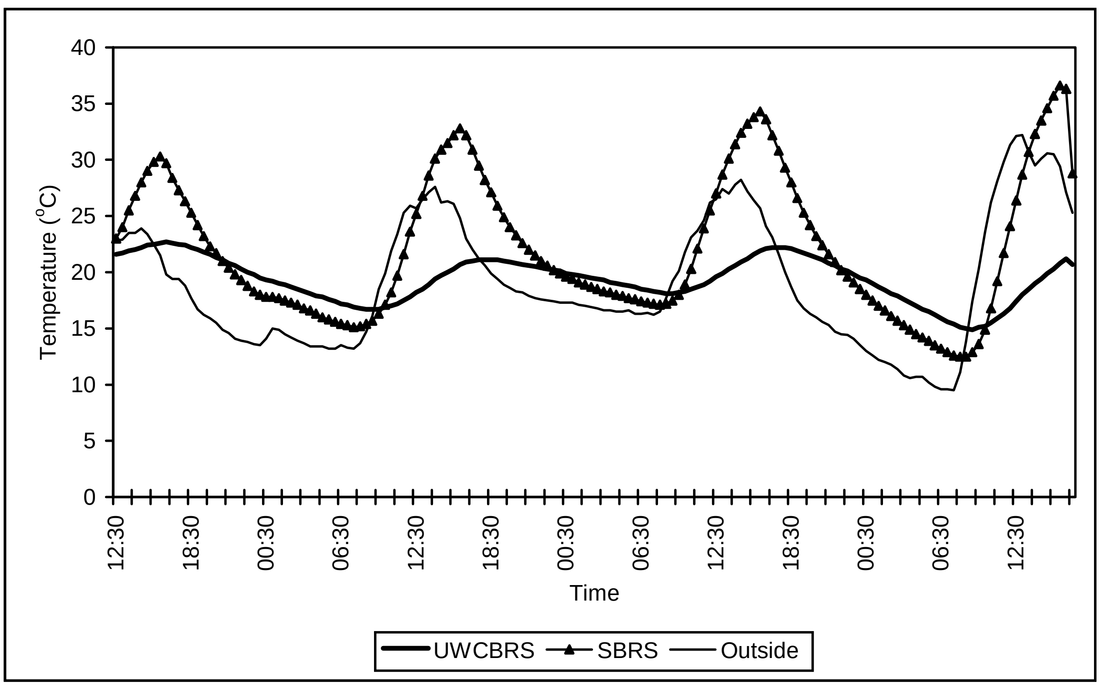


Figure 4.3: Comparison between temperature changes inside the two rainfall samplers and the temperature of the environment (with water).

Water chemistry

The water samples were analysed for major and trace elements. The chloride content of the water is shown in Figure 4.4. It is evident from the plot that the silicon oil and the PVC material increased the chloride content of the control sample. The control sample in the

HDPE bottle has a chloride concentration of 0.9 ppm. The silicon oil increased the chloride concentration to 1.8 ppm. Silicon oil is chemically inert and the increase in chloride concentration in the presence of the silicon oil is probably due to impurities in the oil. The uPVC added approximately 1.7 ppm of chloride and the uPVC and silicon oil sample added 2.6 ppm of chloride to the water. Beekman and Sunguro (2002) also found that PVC samplers overestimated the chloride concentrations in rainfall. This experiment was conducted at room temperature and the chloride values may be significantly higher under actual field conditions where large temperature fluctuations can occur (i.e. at higher temperatures more chloride can be leached). Leaching of chloride will be higher if the surface area of the uPVC receptor is greater. The reason for this effect is quite simple because PVC polymer is produced from vinyl chloride monomer. Two methods exist in the manufacturing of PVC. These methods are shown by the reactions:

$$HCl + C_2H_2 \rightarrow CH_2CHCl$$

or

$$2HCl + \tfrac{1}{2}O_2 + Cl_2 + 2C_2H_4 \rightarrow 2C_2H_4Cl_2 + H_2O$$

$$C_2H_4Cl_2 \rightarrow CH_2CHCl + HCl$$

The second reaction is mostly used because the first process is inefficient and expensive. To obtain a final PVC product the following are added: PVC resin, heat stabilisers, lubricants, special additives and colourants. It is evident that chloride, which is a major constituent in the polymer, can be leached. PVC is unstable at high temperatures and some kinds of radiation due to the formation of structural defects formed during polymerization (Abdel-Naby and Nouh, 2002). Labile chlorine atoms are associated with these structural defects and are easily detached by the effect of heat or sunlight to evolve HCl gas leading to the formation of polynes and discoloration of the PVC (Abdel-Naby and Nouh, 2002). Buxton et al (2000) have shown that the chlorine atom can, through reversible reactions, contribute chloride ions to an aqueous solution. Ranney and Parker (1996) and Al-Malack (2001) showed that ions such as barium, calcium, cadmium, lead, nickel, zinc and tin are leached from uPVC pipes.

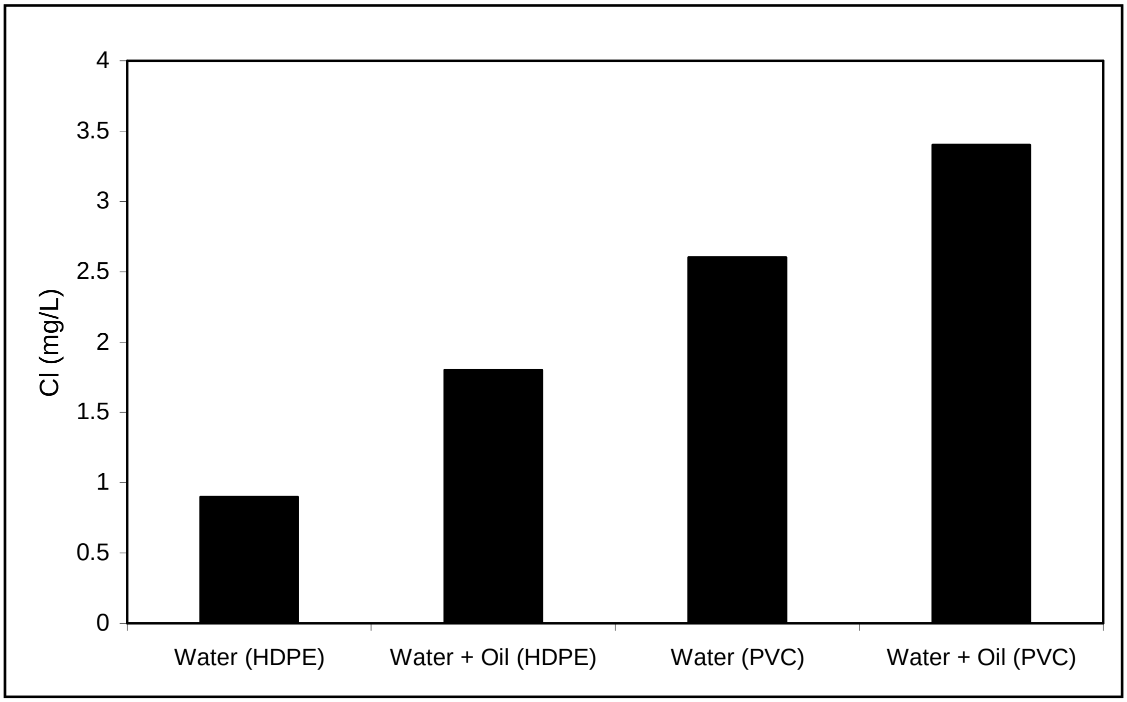


Figure 4.4. Chloride content of different samples collected in HDPE and PVC samples.

4.2.2 Event samples

Due to the uncertainties associated with the bulk rainfall samplers, an event basis rainfall sampling protocol has been developed to determine the chloride content of the rainfall occurring over the Springbok area. A standard plastic rainfall gauge was mounted 1.2 m above the ground. The gauge was emptied every morning and afternoon at about 09H00 and 16H00. Because the gauge was open during periods of no rainfall, the collection of dry deposition may have been possible. During extended periods of no rainfall, only the samples collected in the afternoon were analysed. The collected rainfall samples were transferred to new high-density polyethylene (HDPE) bottles. The samples were analysed by ICP-MS at the laboratory of the CSIR (Pretoria).

4.3 Groundwater

4.3.1 Chemistry and isotopes

Boreholes were sampled for chemical and isotopic analyses, each sample being analysed for the parameters listed in Table 4.2. The datasets are presented in Appendix A3. Parameters that were measured and recorded at the time of sampling were alkalinity, electrical conductivity (EC), pH, temperature and redox potential (Eh). Alkalinity was measured using a Hach® field titration kit. The EC, pH, temperature and Eh were measured using portable Orion EC and pH meters. When possible, the water level and discharge of the borehole were also recorded. Water was only taken from boreholes that were pumping for a significant amount of time. Samples were filtered in the field with a hand-held syringe using 0.45 µm membrane filters. Samples were collected in three new 250 ml polyethylene bottles. All sampling bottles were washed with de-ionised water and again with filtered sample water. Unfiltered samples were collected for isotope analyses. All samples were kept cool prior to despatch to the laboratory. Groundwater chemistry analyses were performed at the laboratories of Bemlab, CSIR and Infruitec.

Table 4.2: Physical and chemical determinants.

Group	Determinants
Physical determinants	EC, pH, Temperature, Eh
Major cations	Na, Mg, Ca, K
Major anions	Cl, SO_4, NO_x - N, F, HCO_3
Trace elements	Al, Ba, Ni, P, Sr, B, U, Cu, Mn, Zn
Isotopes	^{18}O, D, ^{14}C
Aggregate determinants	Alkalinity

The stable isotope analyses were performed at the Geochemistry Department of the University of Cape Town and the ^{14}C analysis at the Schonland Research Centre for Nuclear Sciences at the University of the Witwatersrand.. Stable isotope data are presented in “delta notation” where δ (‰) is defined as:

$$\delta = \left(\left(\frac{R_{sample}}{R_{standard}} \right) - 1 \right) * 1000 ‰ \qquad (4.1)$$

where:

R_{sample} and $R_{standard}$ = $^{18}O/^{16}O$ or $^{2}H/^{1}H$.

For ^{14}C sampling purged boreholes were sampled using the following procedures (Verhagen, pers. comm.):

1. Rinse container with sample water.
2. Fill container (with hose or bucket) – preventing aeration.
3. Empty a sachet of $BaCl_2$ into bucket and fill about ½ with sample water. Stir to dissolve.
4. Fill container, then:
   - 4.1 Pour a few ml of phenolphthalein suspension
   - 4.2 Pour in a ¼ of clean NaOH solution. Sample container should now be bright pink.
   - 4.3 Pour in the $BaCl_2$ solution (prepared in bucket). Sample should turn cloudy.
5. Fill container to near top. Ensure good mixture whilst filling and/or stirring. Screw on cap.
6. If pink colour disappears, more NaOH and $BaCl_2$ dissolved in sample water is added.
7. The precipitate is allowed to settle leaving clear, still pink solution for typically 1hour.
8. The supernatant is drained.
9. When draining stops, tip container until liquid begins to entrain precipitate.
10. Replace cap and gently swirl container.
11. Pour precipitate in 2-3 containers and label.
12. The next day precipitate would have shrunk. Pour off supernatant and transfer to smaller container (1-½ L) – top up with supernatant – seal and label.
13. When sample alkalinity is less than 1 meq/L or less – perform a second precipitation.

Based on the alkalinity of the water the amount of water needed for proper preciptation the following formula was used:

$$\frac{7500}{Alkalinity\ (mg\,/\,L\ CaCO_3)} = \textit{amount of water needed for precipitation of C} \qquad (4.2)$$

With each ^{14}C sample, a 1L sample of water was collected for chemical analysis. The usual wellhead measurements were also made (i.e. pH, alkalinity, temperature and EC).

4.3.2 Data quality

To determine the accuracy of the laboratory analyses duplicate samples was sent to two different laboratories using different analytical techniques. Duplicate samples were also sent to the same laboratory. Intercomparison of the data was considered necessary in order to ensure confidence in the results. Accuracy of the analyses of the ions can be interpreted from the electro-neutrality condition since the sum of the positive and negative charges in the water must balance. Samples that had ionic balance errors (IBE) above 10% were investigated. The ion balance error is expressed as (ions expressed in meq/L):

$$IBE = \frac{\left(\sum cations - \sum anions\right)}{\left(\sum cations + \sum anions\right)} * 100\,\% \qquad (4.3)$$

The quality of the data in the database was checked by simple 2D scatter plots and by sorting the data in Excel. By sorting the data (variables) either descending or ascending typographical errors can be identified. Extreme outliers on 2D scatter plots were investigated.

CHAPTER 5

Description of the Central Namaqualand area

5.1 Introduction

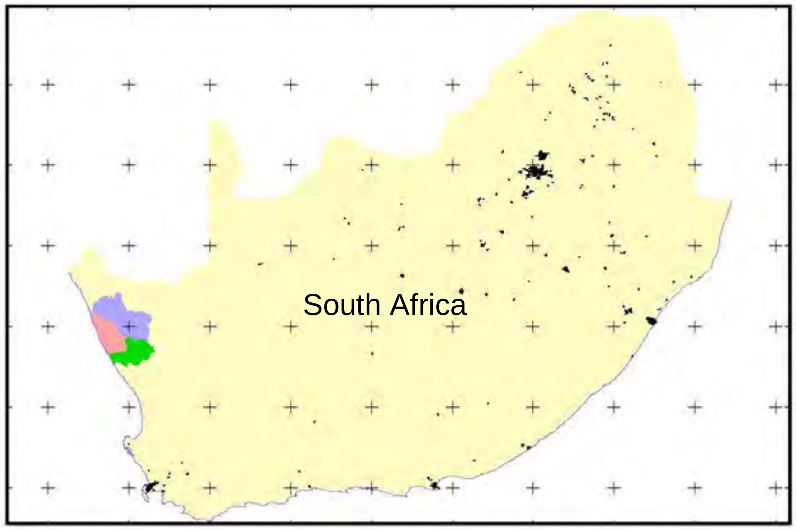
The study area is located in the Northern Cape Province of South Africa and is situated in an area called Namaqualand (Figure 5.1). The area is well known for its copper and diamond mining activities as well as for its annual mass flowering after the first significant rainfall. The place names given by the Nama Hottentots are often associated by the quality and quantity of the water and land resources because of its importance to the communities (Laidler, 1927). Most of the modern farm names are corruptions of the original Nama names.

5.2 Climate

The study area falls in the tropical desert arid, hot climatic region of South Africa, according to the Koeppen classification. The climate of the study area is controlled by altitude, topography and distance from the sea. Climatological data for the study area (i.e. precipitation, evaporation and temperature) were received from the South African Weather Bureau, Computing Centre for Water Research and data from the WR90 publication of Midgeley et al. (1994).

Precipitation

The region can be classified as arid to semi-arid. The mean annual precipitation (MAP) varies from 44 mm in the coastal zone area to 480 mm in the Kamies Mountains, for the period June 1999 to August 2001. Higher rainfall in the higher lying areas is a result of orographic rainfall. Rainfall mostly occurs during the winter months. High incidences of fog days on the West Coast of South Africa contribute significant moisture to the coastal areas of Namaqualand (Olivier and van Heerden, 1999). Climatological data (Midgeley et al, 1994) for the various subcatchments are shown in Table 5.1. Snow in the Kamies Mountains is not uncommon during the winter months.



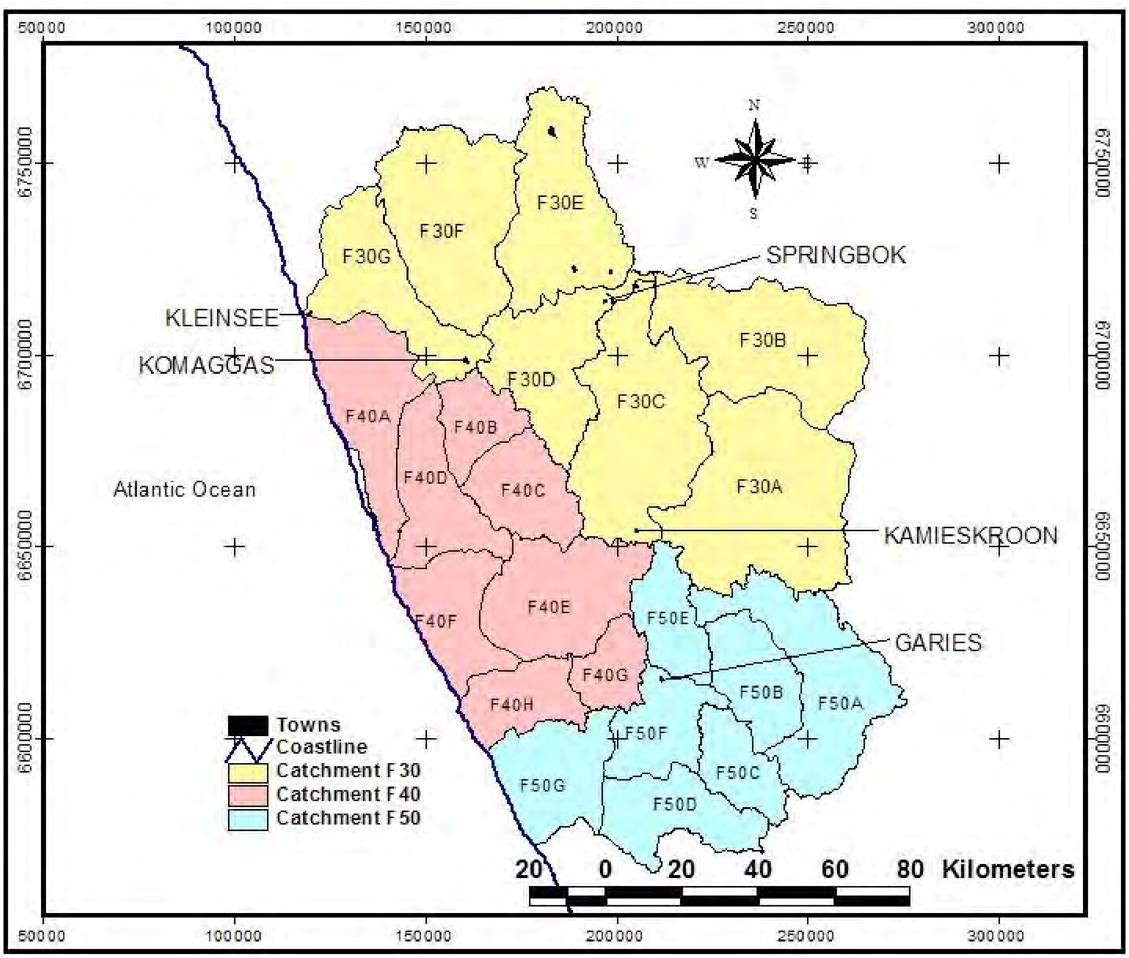


Figure 5.1: **The study area.**

Table 5.1: Climatological data for the various catchments that comprise the study area (source Midgeley et al., 1994).

Sub catchment	Area (km^2)	MAE (mm)	MAP (mm)	MAE/MAP
Catchment F30				
F30A	1954	2200	162	14
F30B	1462	2200	107	21
F30C	1655	2200	184	12
F30D	976	2200	162	14
F30E	1260	2200	153	14
F30F	1469	2200	112	19
F30G	980	2200	102	22
F30	**9756**	**2200**	**143**	**15**
Catchment F40				
F40A	984	1900	118	16
F40B	404	1900	130	15
F40C	608	1900	173	11
F40D	741	1900	123	16
F40E	1065	1900	186	10
F40F	682	1900	118	16
F40G	348	1900	168	11
F40H	514	1900	109	17
F40	**5346**	**1900**	**140**	**14**
Catchment F50				
F50A	1303	1900	179	11
F50B	603	1900	208	9
F50C	439	1900	159	12
F50D	687	1900	112	17
F50E	487	1900	246	8
F50F	575	1900	133	14
F50G	775	1900	96	20
F50	**4869**	**1900**	**159**	**12**

The quaternary catchment scale data are more representative of the areal precipitation occurring over the area. However, due to the strong orographic effects precipitation on higher altitudes can be considerably higher than the average quaternary catchment scale data. Average monthly rainfall for the three topographic zones is shown in Figure 5.2.

Mean annual precipitation (MAP) generally increases from west to east until it reaches the escarpment and decreases towards the interior. The higher lying areas within the study area receive much higher rainfall than the surrounding lower lying areas and the coastal plains (Figure 5.3). Figure 5.4 indicates how the precipitation increases from the sea to the interior (west to east), the topography also change from coastal lowlands to mountainous highlands in the same direction. The rain gauge station (Dabeep) that is situated on the Bushmanland plateau shows that a different climatic regime exists.

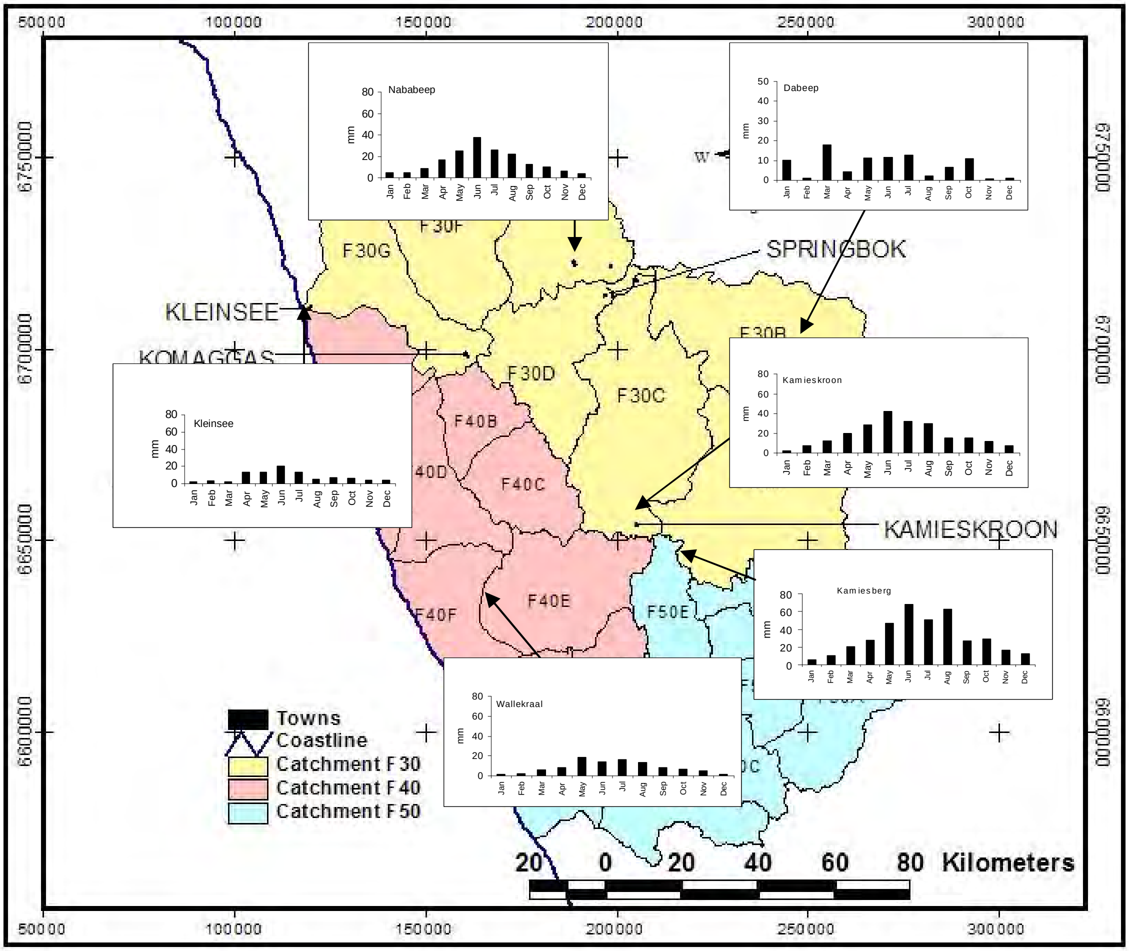


Figure 5.2: Average monthly rainfall for six rainfall stations.

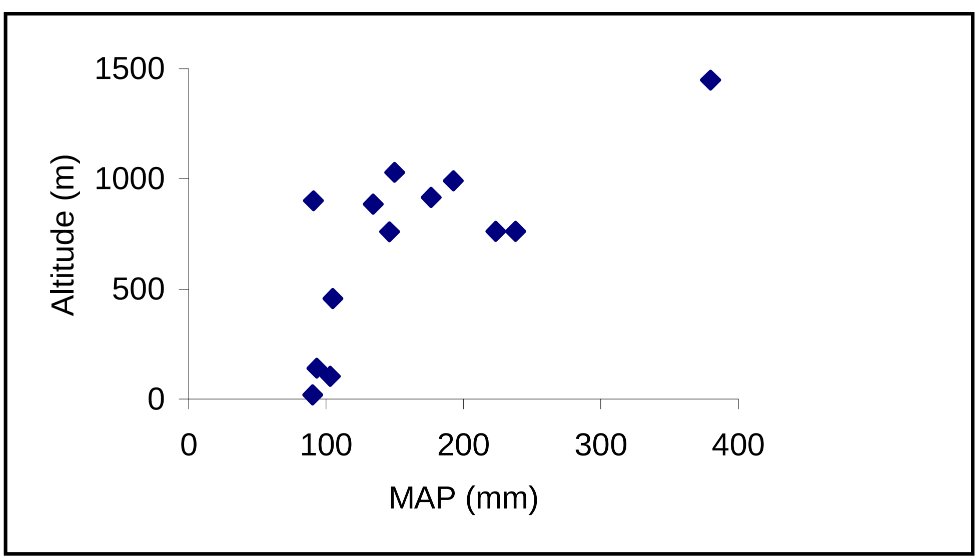


Figure 5.3: Altitude versus MAP.

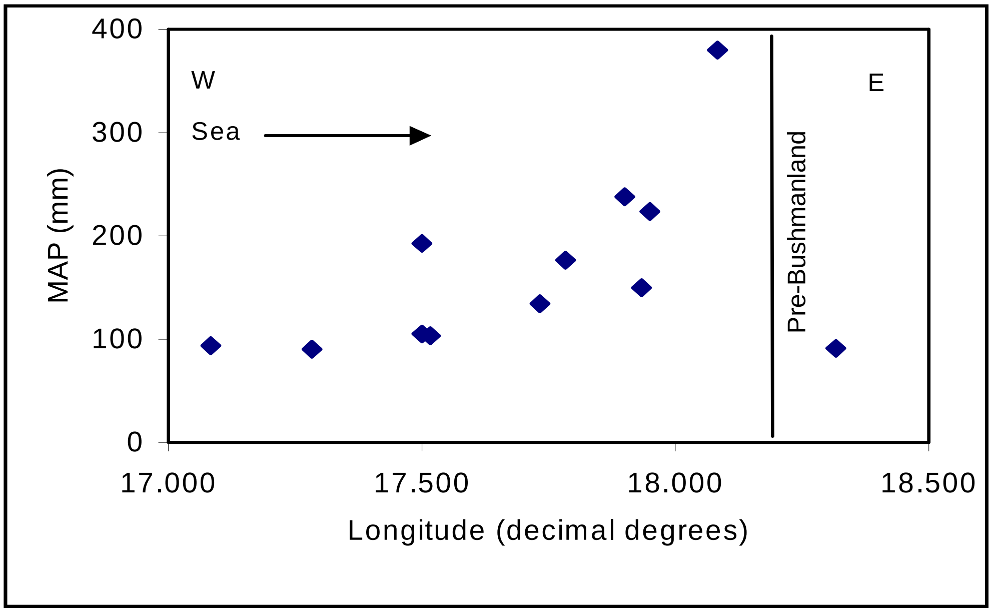


Figure 5.4: MAP versus distance from the sea.

Figure 5.5 shows that, for data obtained from the Springbok weather station, there is a large variation in rainfall over the 120-year period. The graph is plotted as the annual rainfall over the period minus the MAP over the period (217 mm). An oscillation between wet and dry years seems to exist with a quasi-12 year return period. The wet and dry cycles have a significant impact on groundwater recharge. Periods of above average rainfall will contribute much more to recharge than the drier periods.

On a larger time scale major rainfall periods occurred between 1913-1918, 1939-1943, 1950-1955 and 1992-1997 lasting for 5 to 6 years. At the start of 1992 an 83-year return period of excessive rainfall (since ~1909) was observed peaking during the 1996-1997 seasons. These high rainfall periods produced several flood events. The main flood event occurred during the 1997 season, however, higher rainfall was recorded the previous year.

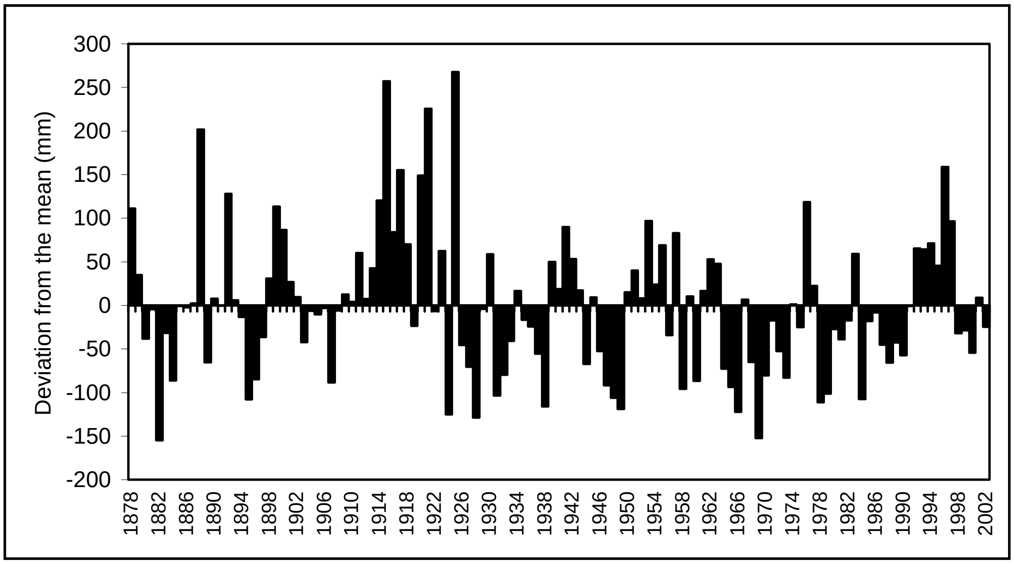


Figure 5.5: **Annual rainfall deviation from the average rainfall over a 120-year period, for the Springbok area.**

Temperature

Large variations between maximum and minimum, daily and seasonal characterise the temperature of the region. Table 5.2 shows typical temperature variations over the three topographic regions of the study area.

Table 5.2: **Temperature variations over the three topographic regions.**

	Summer		Winter	
	Max (°C)	**Min (°C)**	**Max (°C)**	**Min (°C)**
Lowveld	20	13	15	8
Escarpment Zone	30	17	16	8
Highveld	34	17	18	5

Evapotranspiration

Potential annual evapotranspiration is between 12 - 15 times the MAP. In some areas this factor is as high as 22 (Table 5.1). The high evaporation to precipitation ratio results in the formation of evaporitic salts at the surface as well as in the subsurface. In alluvium, Campbell et al. (1992) reported that evaporation occurred to a depth of 91 cm in the subsurface. Van der Sommen and Geirnaert (1990) found that in areas of dense vegetation and shallow water levels the actual evapotranspiration is much higher than in areas of sparse vegetation and deeper water levels. Potential evaporation tends to increase from the west to the east (Table 5.3).

Table 5.3: **Three evaporation stations with S-pan and A-pan MAE (mm) data Midgeley, et al., 1994).**

Gauge No.	Station name	S-pan	A-pan	Years
F3E001	Okiep		3193	1957-1979
F3E003	Grootmis	1939	2260	1964-1979
F4E001	Hondeklipbaai		1823	1964-1979

Controversy exists over the validity of pan experiments, considering that wind and temperature effects and humidity can vary considerably in micro-environments and for different surface types. The data obtained from pan experiments can be used for baseline considerations though. Potential evaporation is at maximum during the summer months and much lower during the winter months when rainfall is at its highest (Figure 5.6).

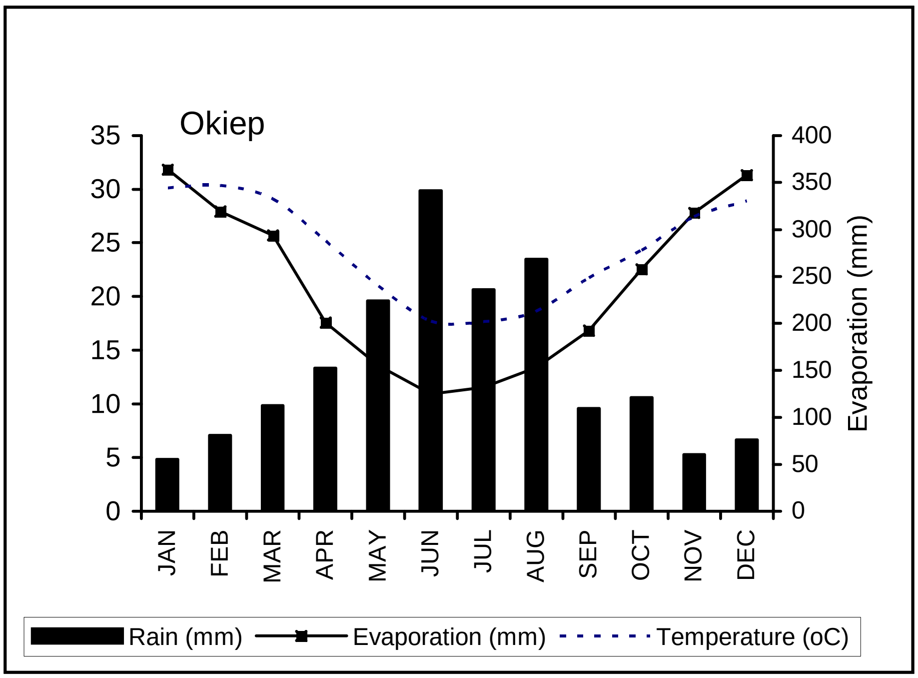


Figure 5.6: **Average monthly evaporation for the Okiep area and the relationship that exists with temperature and rainfall.**

5.3 Topography

The topography of the study area varies from a very low altitude and relief coastal zone to a rugged and high altitude escarpment zone. The different topographic zones are shown as cross-sections generated from a digital elevation model (DEM) (Figure 5.7a-b).

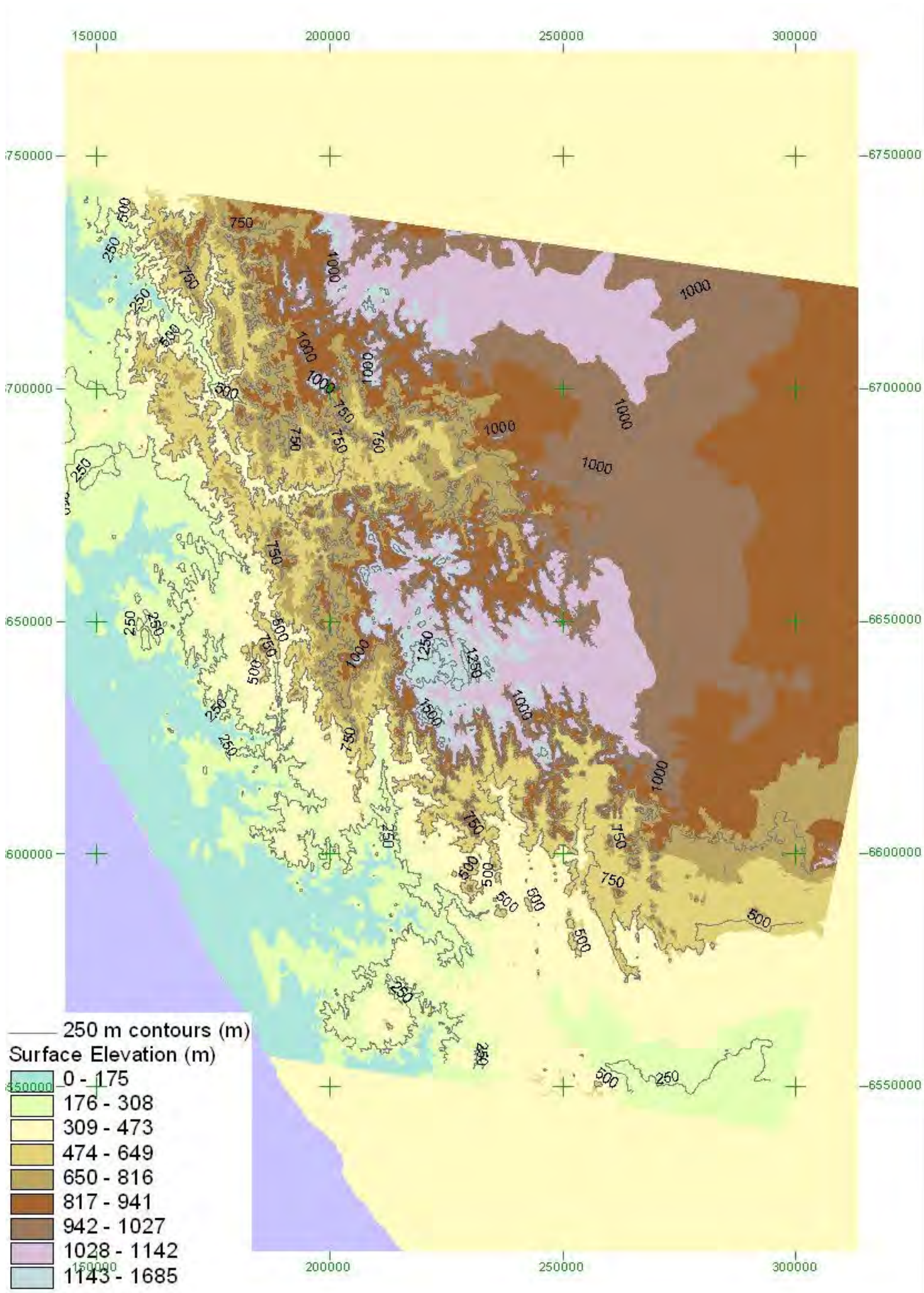


Figure 5.7a: Surface elevations and topography of the study area.

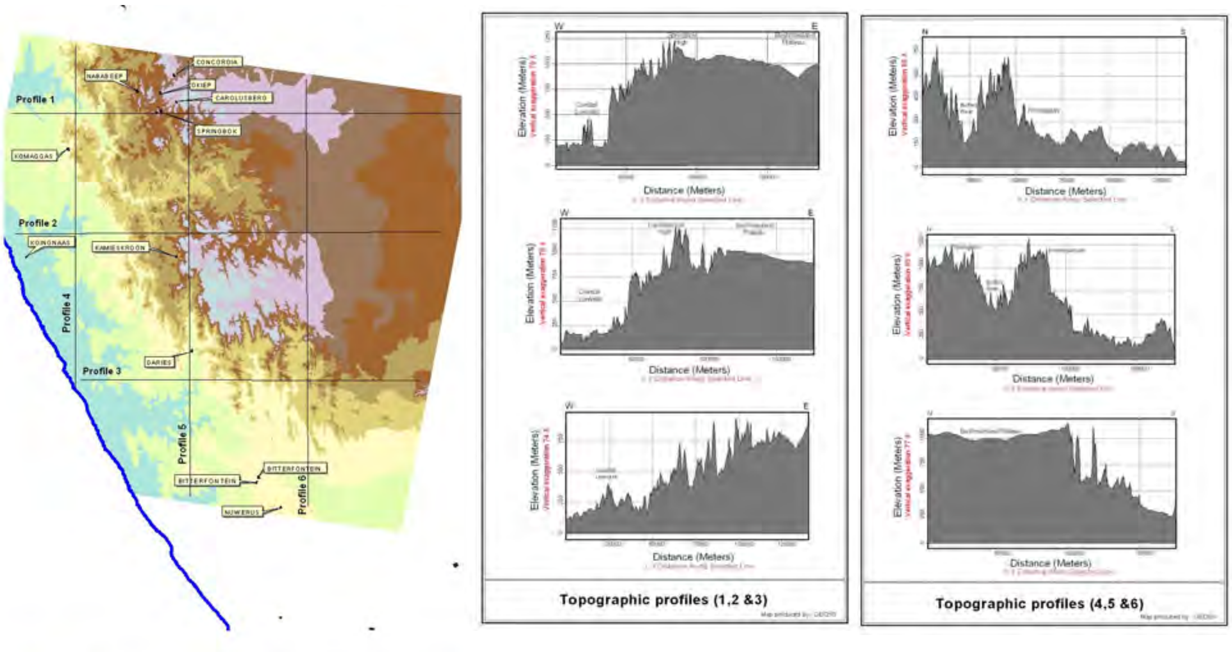


Figure 5.7b: Topographical profiles of the study area.

5.4 Geomorphology

The area is characterised by three geomorphologic regions, (1) a coastal lowland, (2) an escarpment zone, which comprises of highland and lowlands within this zone and (3) the Bushmanland Plateau as shown in Figure 5.8. These geomorphic zones are a result of several geomorphic cycles (Partridge and Maud, 1987). The distribution of the erosion surfaces and a cross section are shown in Figure 5.9. The coastal lowlands are underlain by crystalline basement rocks and overlain by recent sands. The escarpment zone is characterised by exposed domes, weathered material (extending to depths of approximately 54 to 60m), fractured rocks and alluvium filled valleys and paleorivers. Ellis (1988) classified the central mountainous regions as “closed mountains” and “open mountains”. The “closed mountains” is characterised by mountains with a high to moderately high relief with plains and hills that make up 12% of the area. The “open mountains” are characterised by hills of moderate to moderately high relief with uneven plains of low to moderate relief. The “closed mountains” have a thinner soil cover than the “open mountains”.

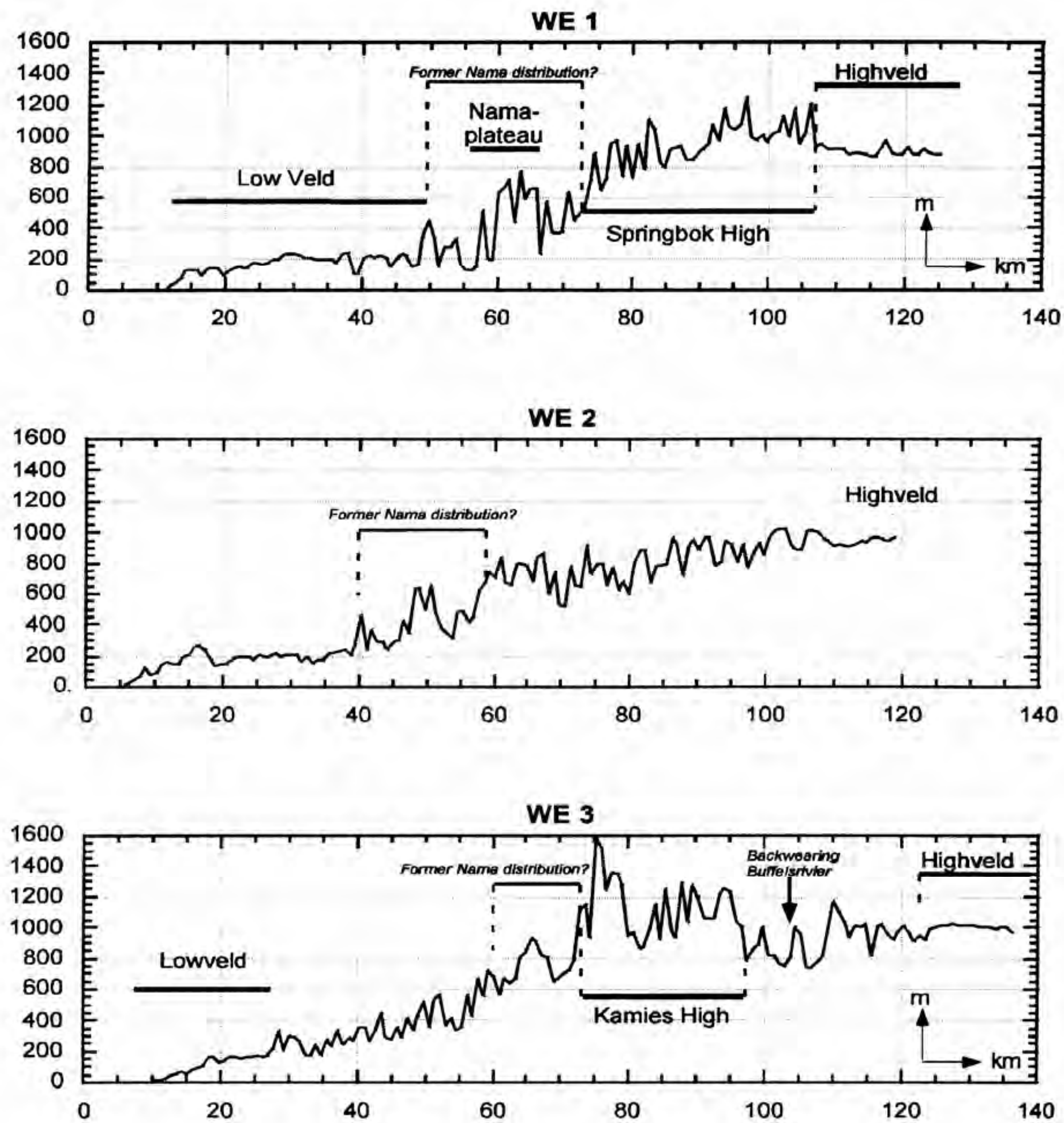


Figure 5.8: **Different geomorphic zones across the W-E profiles of the area (Bense et al., 1998).**

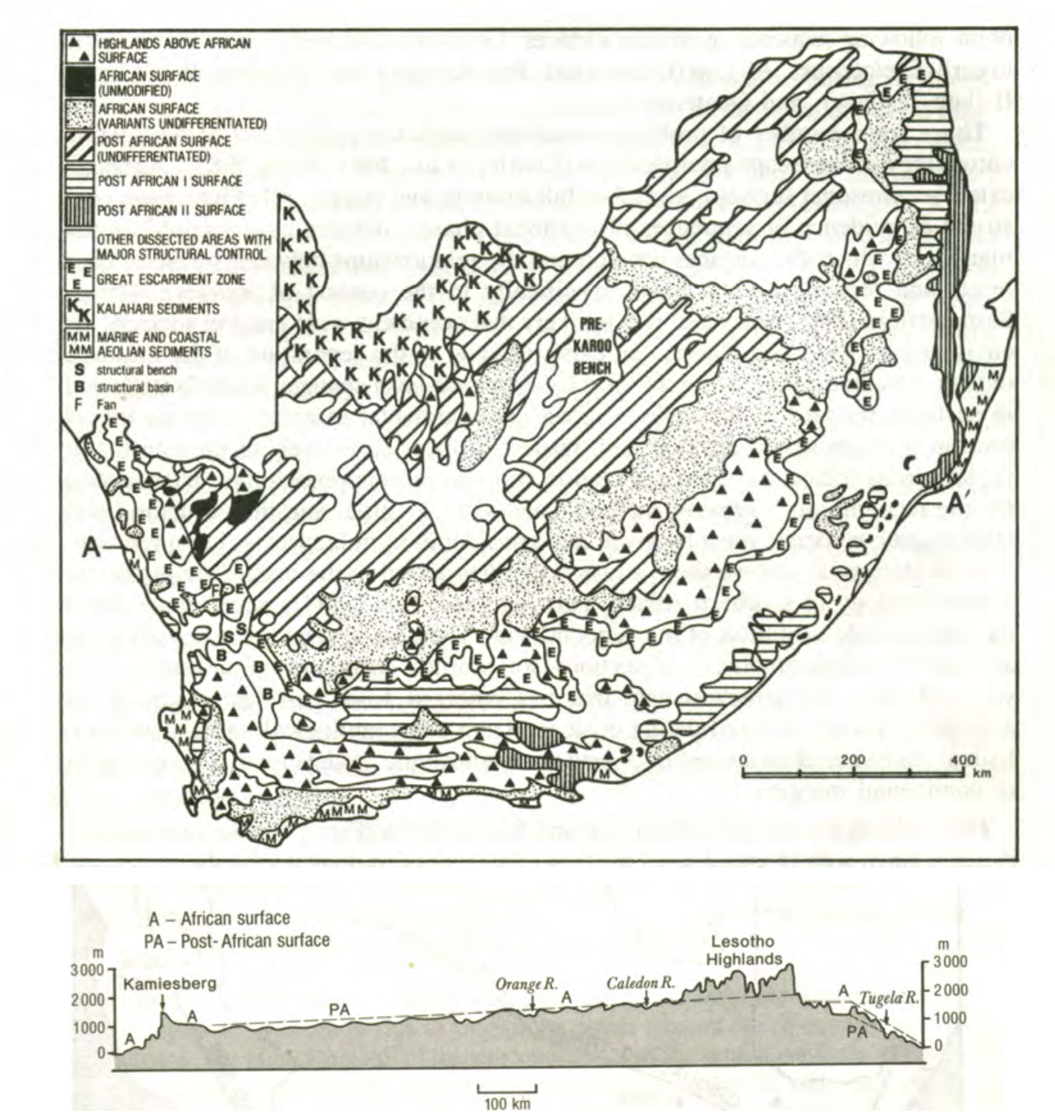


Figure 5.9: Distribution of erosion surface of the southern African subcontinent (Moon and Dardis, 1988).

Stripping of weathered material resulted in the exposure of the crystalline bedrock at the surface. A wide valley implies the occurrence of closely spaced joints and the steeper, narrow valleys are a result of low-density joints. The intersections of these joints would also create low gradient and relatively wide valley floors. The Namaqualand weathered zones indicate that wetter periods existed over very long periods. The groundwater plots in the kaolinite stability field, indicating that kaolinite is formed due to the incongruent dissolution of alumino-silicate minerals (Figure 5.10). The presence of kaolinite and montmorillonite indicates a relatively advanced weathering stage.

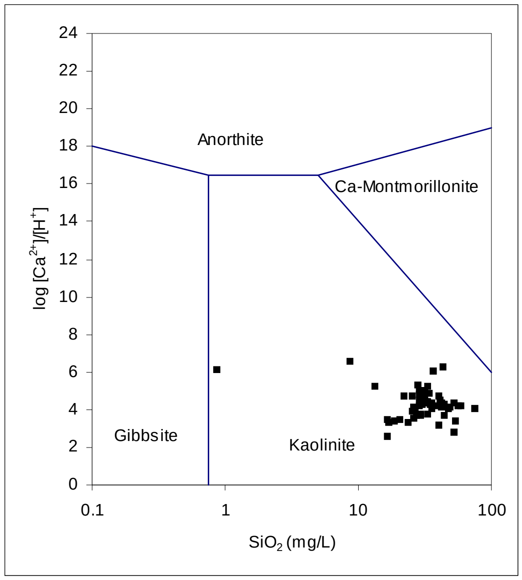


Figure 5.10: Log [Ca^{2+}]/ [H^+] vs. SiO_2 diagram for groundwater of the Namaqualand region.

The wider valleys should have deeper weathered zones than the steeper valleys. Deep weathered zones in the valleys indicate the presence and accumulation of moisture over large time scales. Weathering in these zones is still active because most of the surface runoff, if available, collects in these areas.

The thickness and character of the composite aquifer changes from one site to another, particularly in relation to petrographic composition of respective rocks, their type of tectonic deformations and type of weathering due to morphological and climatic conditions. On a regional scale the aquifer can be classified as a fractured crystalline basement aquifer but on a local scale two aquifer systems may exist (viz. a weathered zone or regolith aquifer underlain by a fractured crystalline aquifer). The depth of the weathering in Namaqualand extends in some cases to 54-60m below surface for both the metasediments and the gneissic rocks.

5.5 Vegetation

The vegetation is characterised by the Nama Karoo biome, which is dominated by a mixture of grasses and low shrubs (Low and Rebelo, 1996). The succulent Karoo biome dominates the western part of Namaqualand. Dwarf, succulent shrubs, dominates the vegetation. Mass flowering of annuals occurs in spring when the rainfall is sufficient. Most of the shrubs are classified as drought deciduous and tend to develop deep root systems.

In the alluvial plains and riparian zones vegetation is dependent on groundwater availability. Plant species such as *Prospis* (moderately drought tolerant, facultative phreatophytes) form extensive thickets in these zones, which indicates available groundwater (Low and Rebelo, 1996). *Acacia karoo* (riparian shrubs and trees) is found in the alluvial aquifers of the Buffels River. Succulent Karoo vegetation dominates at the coastal zones, ranging from subterranean, stemless dwarfs to 2.5 m high shrubs (Acocks, 1988).

Vegetation is an important component in any recharge study as vegetative cover intercepts precipitation before it reaches the surface. The water losses as a result of transpiration are also an important factor and are usually grouped with evaporation. Transpiration only takes place if the vapour pressure in the air is less than that in the leaf cells. Where the evaporating surface is the soil surface, the degree of shading of the crop canopy and the amount of water available at the evaporating surface are other factors that affect the evaporation process. Vegetation also influences the rate of runoff within a particular area.

5.6 Geology

Namaqualand can be subdivided into three major geological provinces (Tankard et al., 1982). These are the basement rocks of the Namaqua Province, the volcano-sedimentary rocks of the Gariep Complex (Visser, 1989) in the northwest and a Phanerozoic cratonic cover (Table 5.4). The geology of the area has been discussed in detail by Titus et al. (2002) and Titus (2003).

The Namaqua Province represents most of the crystalline basement in the northern Cape and southern Namibia (Tankard et al., 1982). In Namaqualand, the margins of the Namaqua Province are largely obscured by younger cover rocks of the Gariep, Nama and Karoo sequences, as well as with Cenozoic surficial sediments to the east and west (Figure 5.11). In the west and extreme north, rocks of the Namaqua Province and its correlatives are bordered by formations of the late Proterozoic Gariep Complex and in the east adjoin the Kaapvaal craton with marked structural discordance in both cases. In the south, rocks of the Nama Group, the Cape Supergroup and the lowermost units of the Karoo Supergroup cover the rocks of the Namaqua Province (Albat, 1984).

Table 5.4: Classification of major geological provinces (after Tankard et al., 1982; Visser, 1989).

Geological Province		Group	Age	Locality	OROGENIES & Subprovinces
Cover Rocks		Sand, Alluvium and Calcrete	Late Phanerozoic (Cenozoic)	Along coast. Most of WesternBushmanland	
Cover Rocks		Karoo Group 1. Prince Albert 2. Dwyka	Early Phanerozoic (Middle/Late Paleozoic)	Southeastern corner of Namaqualand	
Cover Rocks		Nama Group 1. Kuibis 2.Schwarzrand	Late Proterozoic (Late Namibian)	Isolated strip north of Springbok	
Cover Rocks		Gariep Complex Six Formations	Late Proterozoic (Early/Middle Namibian)	Central and Western Richtersveld	PAN-AFRICAN Gariep Sub-province
Namaqua Province	Central Zone	Namaqua Metamorphic Complex, (or Province)	Middle Proterozoic (Middle Mokolian)	Most of Namaqualand and parts of Bushmanland	NAMAQUAN Bushmanland & Gordonia Subprovinces
Namaqua Province	Western Zone	Vioolsdrif Intrusive Suite	Middle Proterozoic (Early Mokolian)	North-eastern and Eastern Richtersveld. Northern Namaqualand	EBURNIAN Richtersveld Subprovince
Namaqua Province	Western Zone	Orange River Group	Middle Proterozoic (Early Mokolian)	North-eastern part of Richtersveld	EBURNIAN Richtersveld Subprovince
Namaqua Province	Eastern Zone			Upington	

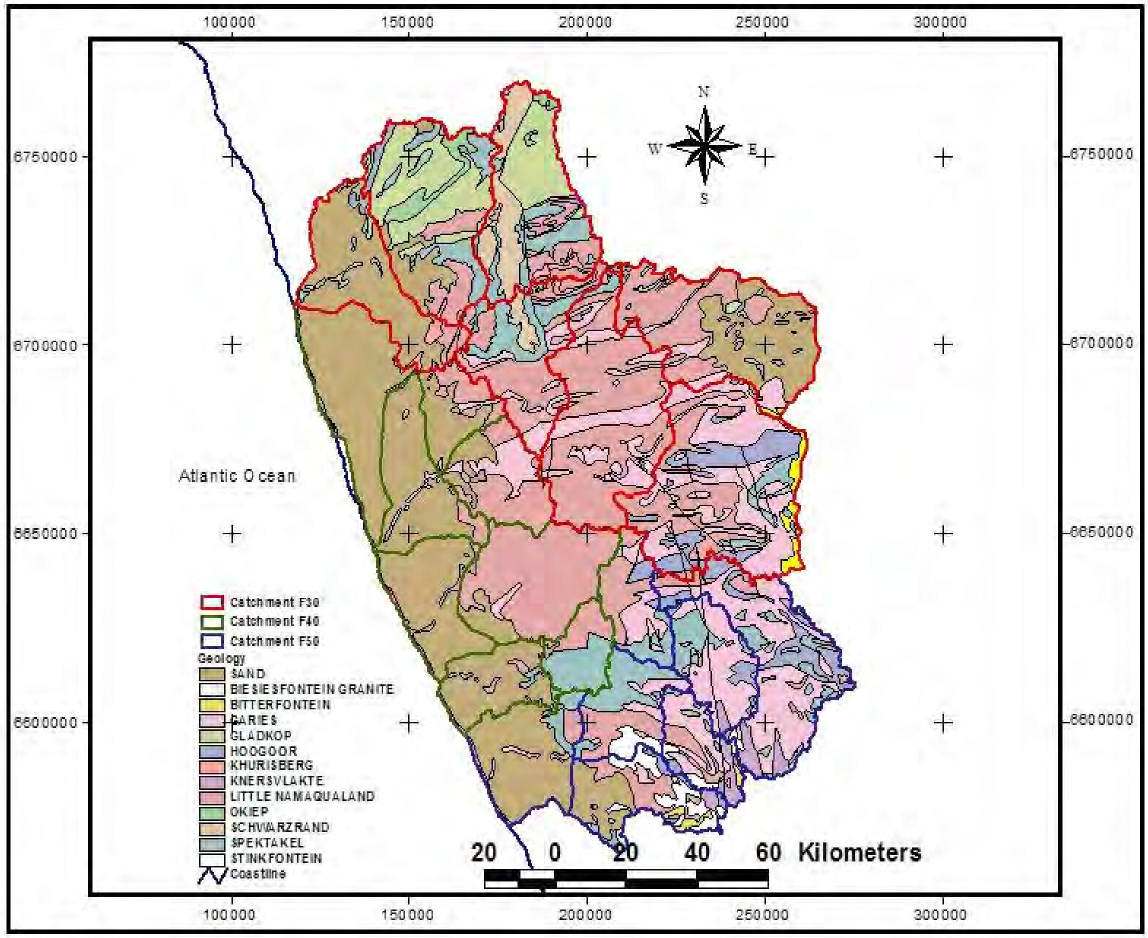


Figure 5.11: Geological map of the area.

Rocks of the Central Zone cover most of central Namaqualand and Bushmanland (including parts of northern and eastern Bushmanland), as well as the southwestern parts of southern Namibia (Tankard et al., 1982). Joubert (1971), Jack (1980), Theart (1980) and Albat (1984) carried out detailed mapping on a 1:100 000 scale, of areas mostly within Namaqualand. Rocks of the Western Zone (Table 5.4) occur mostly in the northeastern Richtersveld and northern Namaqualand regions (Tankard et al., 1982; Visser, 1989; Albat, 1984). Albat (1984) referred to both the Orange River Group and the Vioolsdrif Suite as the Richtersveld Province. The Eastern Marginal Zone, just east of Upington, is a NW/SE striking transitional boundary between the gneiss terrain and the older Kaapvaal craton.

The catchments are predominantly underlain by Proterozoic crystalline basement rocks of the Namaqua Metamorphic Province (Table 5.5). Cover rocks of the Nama group overlay the basement rocks to the north of the Buffels River catchment. The margins of the Namaqua Metamorphic Province are also obscured by younger cover rocks of the Gariep Complex to the north-west as well as by Cenozoic surficial sediments to the east and west. In the south, rocks of the Nama Group, the Cape Supergroup and the lowermost units of the Karoo Supergroup cover the rocks of the Namaqua Metamorphic Province (Albat, 1984).

Table 5.5: Namaqua Metamorphic Province (after Visser, 1989).

<table>
<tr><th rowspan="8">Namaqualand Metamorphic Province</th><th>Group</th><th>Subgroup</th><th colspan="2">Formations</th><th>Descriptions</th></tr>
<tr><td>Grunau</td><td></td><td colspan="2"></td><td>Meta-sedimentary</td></tr>
<tr><td>Okiep</td><td>Bitterfontein
Garies
Khurisberg
Aardvark
Een Riet</td><td colspan="2"></td><td>Meta-sedimentary
Meta-volcanic</td></tr>
<tr><td>Bushmanland
(1330 ± 170 Ma)</td><td>Aggeneys
Pella</td><td colspan="2"></td><td>Meta-sedimentary</td></tr>
<tr><td colspan="2"></td><td colspan="2">Toeslaan</td><td>Meta-sedimentary</td></tr>
<tr><td>Korannaland sequence</td><td></td><td>Goede Hoop
Rautenbach se kop
Biesje Poort
Piet Rooisberg</td><td>Sprigg
Eierdoppan
Jannelsepan
(1305 Ma)</td><td>Sedimentary
Meta-sedimentary</td></tr>
<tr><td>Geelvloer</td><td></td><td colspan="2"></td><td>Meta-sedimentary</td></tr>
</table>

Singer et al. (1995) discussed some of the soils of the Namaqualand region. They have sampled several localities to a depth of 100 cm and determined the physical characteristics of the soils. Data from Singer et al. (1995) were used to generate the ternary diagram, based on grain size analysis (Figure 5.12). It is evident from the ternary diagram that the soil can be characterised as mainly sandy and to some extent loamy sand. The coastal zone of the study area is overlain by sandy deposits (Table 5.6). Coastal dunes overlie beach and nearshore deposits, which indicate marine regression and transgression. (De Villiers and Cadman, 2001).

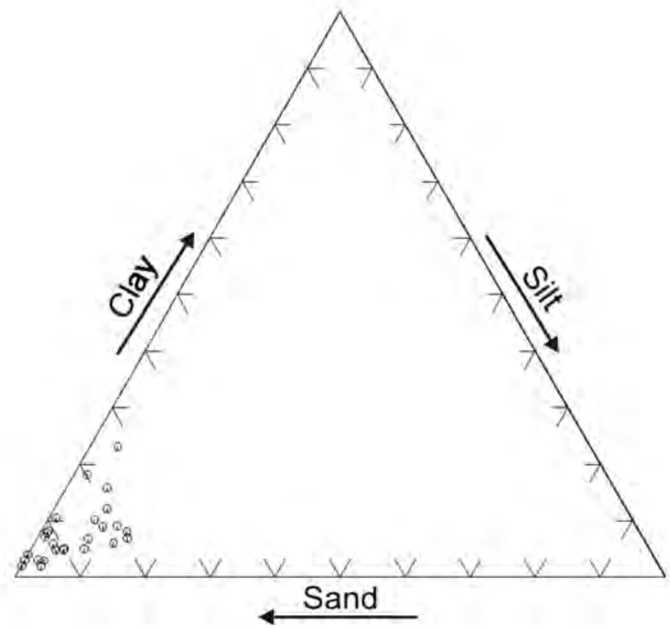


Figure 5.12: Ternary diagram of the soil classes found in Namaqualand (data from Singer et al., 1995).

5.7 Surface water drainage

Due to low rainfall over the semi-arid to arid region, most of the rivers are ephemeral. These ephemeral rivers only flow when rainfall is exceptional. Despite low annual runoff totals in arid regions, peak flood discharges are often high in periods of peak rainfall (Tooth, 2000). This was the case during the 1997 rainy season when the rainfall for the period was extremely high in the higher lying regions of the area.

Due to various stages of tectonic and eustatic events the main drainage routes of the rivers in the Central Namaqualand area have changed several times during the Tertiary period. These changes led to the deposition of various paleochannels. De Wit (1993) gives an account of the evolution of the drainage patterns in the NW Cape. The main ephemeral rivers in the area are the Buffels River, Groen River and Swartlyntjies River (Figure 5.13). The largest river in the area is the Buffels River with a length of approximately 250 km. The Buffels River has its origin in the Kamies Mountains (1317 mamsl) and discharges in the Atlantic Ocean near Kleinsee. The catchment is further fed by the western part of the Bushmanland Plateau at an elevation of 900m. The drainage system of the Buffels River catchment shows a large variation in drainage characteristics, channel width, depth, sediment thickness, drainage density and the development of river terraces. Negligible soil cover exists in the tributaries, a major pathway of direct groundwater recharge. In the lower lying areas the alluvial thickness' increase due to the change in topography (i.e. flat topography) and the concomitant decrease in sediment transport.

Table 5.6: Stratigraphy of the western coastline of southern Africa (after De Villiers and Cadman, 2001).

Mya	Geological Age		Geological Unit	Events
2		Holocene		Major transgression
	NEOGENE	Pleistocene	Prograding lenses of sediment	Several eustatic events
			Hondeklipbaai Sandy Gravels	
				Strong erosion
5		Pliocene		
			Channel deposits (Koingnaas)	Major regression
			Marine sediments (Upper Bredasdorp and Alexandria Formation)	Prograding (on continental shelf)
				Major transgression
			Shallow marine	Local erosion and fill
		Miocene	Marine sediments (Basal Bredasdorp and Alexandria Formation)	Major regression
				Seaward thickening of continental shelf deposits
				Major transgression
25	PALAEOGENE	Oligocene	Fluviatile/shallow marine deposits	Local erosion and fill
36		?Eocene / ?Palaeocene	Local deltaic sediments	Major regression
55			Thick marine sediments	Local regression
				Strong upbuilding of continental shelf
				Major transgression
65				

= unconformity

Rivers in semi-arid to arid regions generally show a decrease in volume downstream as a result of mainly evaporation and infiltration into the alluvium and channel boundaries (Tooth, 2000). In the Buffels River, for example, most of the water flows along the base of the alluvial aquifer and is stored in the channel banks during the drier months. This was confirmed by the interpretation of drillers logs and geophysical information. Geophysical profiles, using the electromagnetic tool, show anomalies in the channel banks due to the presence of groundwater during the dry summer months (Figure 5.14). A more detailed description of the geophysical surveys is given in the next section.

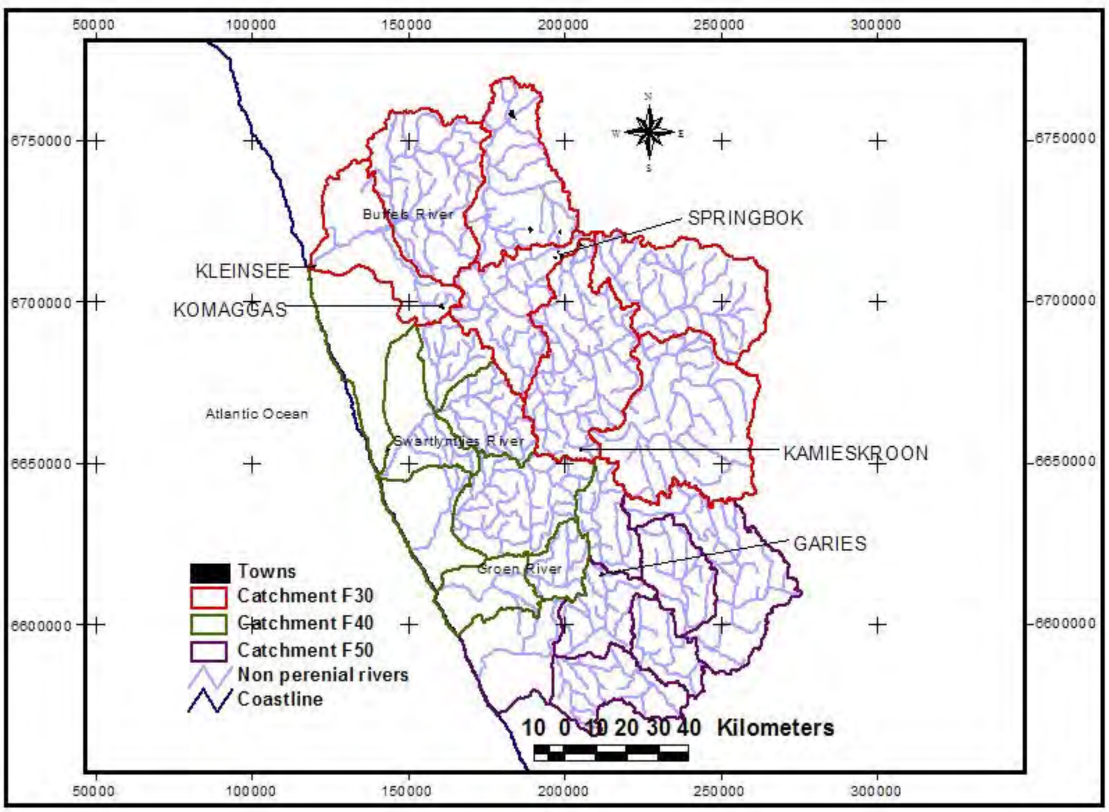


Figure 5.13: **Distribution of the rivers in the study area.**

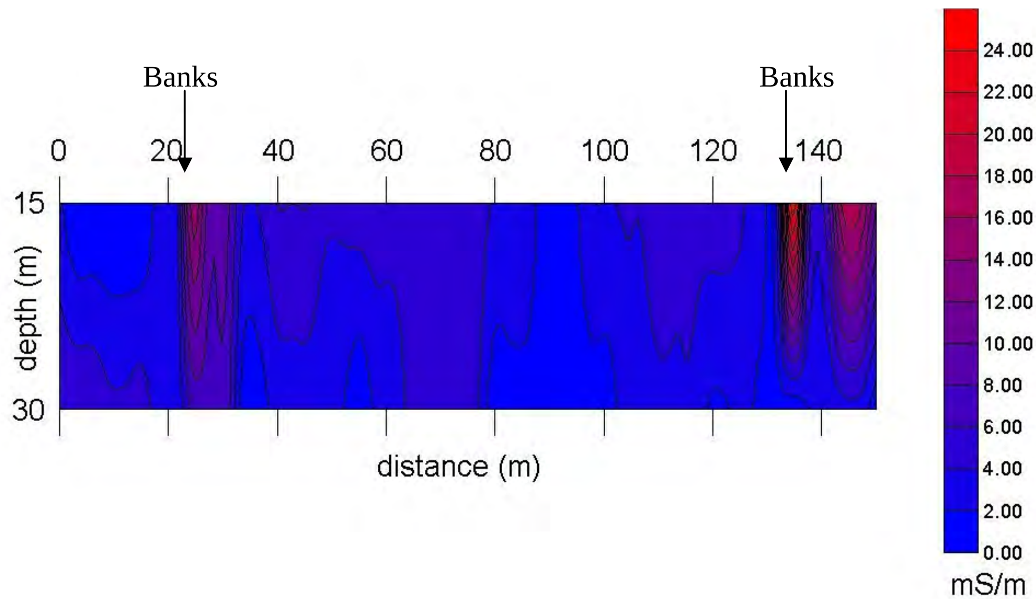


Figure 5.14: Electromagnetic geophysical profile across the Buffels River near the town Kamassies.

5.8 Hydrogeology

5.8.1 Aquifer types and conditions

Groundwater occurs in three different aquifer systems in the Namaqualand area, they are; (1) fractured bedrock, (2) the weathered zone or regolith and (3) the sandy/alluvial aquifers. These aquifers are closely interlinked.

Fractured and weathered zone aquifers

Fractured bedrock and weathered zone aquifers are hydraulically interlinked, where the weathered zone act as a reservoir that is able to recharge the bedrock aquifers. This process may be lacking in areas of extensive clay formation between the two aquifers, whereby the clay would form a hydraulic barrier. The weathered zone aquifers are generally considered to be the most productive groundwater zones (e.g. Tindimugaya, 1995; Acworth, 1997).

Alluvial aquifers

Superimposed on the basement aquifers are the alluvial aquifers associated with the ephemeral rivers, paleochannels and the coastal plain. Alluvial aquifers associated with the river systems are usually very shallow 1 - 15m and in the coastal areas tens of metres. Boreholes and large diameter wells drilled in Namaqualand are usually found in river courses and alluvium filled valleys. The alluvial aquifers are the main source of water supply for most villages (e.g. Buffels River, Twee River, Kammasies, Nou River, Rooifontein).

The alluvial aquifers are efficiently recharged during the rainy months. The alluvial aquifers in turn recharge other hydraulically connected aquifers. As part of this study the Groundwater Group at UWC and the Geophysics and Geology Department at the University of Missouri-Rolla did geophysical profiles over several alluvial aquifers using the GEM-300 (Geophysical Surveys Systems Inc.) and EM34-3 (Geonics) electromagnetic instruments. The studies were conducted over the dry and wet season. The results indicated that during the dry seasons most of groundwater was stored in the channel banks and during the wetter seasons groundwater occurred in the alluvium and channel banks. During the dry season little groundwater occurred within the weathered zone below the alluvium as opposed to the wet season where distinct anomalies were recorded. The “dry” survey was conducted perpendicular to the riverbed and the “wet” survey along the riverbed. The GEM 900 Hz survey is at shallow depth and the GEM 330 Hz penetrated much deeper into the subsurface. The results of the surveys are shown in Figure 5.15a-d.

5.8.2 Piezometry and groundwater flow

Groundwater levels (measured from the surface) vary from being shallow to very deep (Figure 5.16) and are a function of the settings in which the boreholes were drilled, as well as the fracture systems that the borehole intersects. A plot of the water levels, Figure 5.17, shows that the 0-10 mbgl range occurs throughout the study area. A dense cluster of 0-10 mbgl water levels occurs in the escarpment zone. Deeper groundwater levels >50 mbgl dominate in the lower lying coastal areas. In arid and semi-arid zones, shallow water levels increase the potential for recharge.

The average depth of the boreholes, recorded in the NGDB, for the area is 60 m, with a maximum of 353 m. Most boreholes have been sited on fracture zones, based on geophysical or geological information, with variable yields. Figure 5.18 shows the relationship between borehole depth and discharge (note the clustering of data below 0.5 l/s). The most productive boreholes are those that occur between the depths 25-100 m. Below 100 m isolated cases of high yielding boreholes occur.

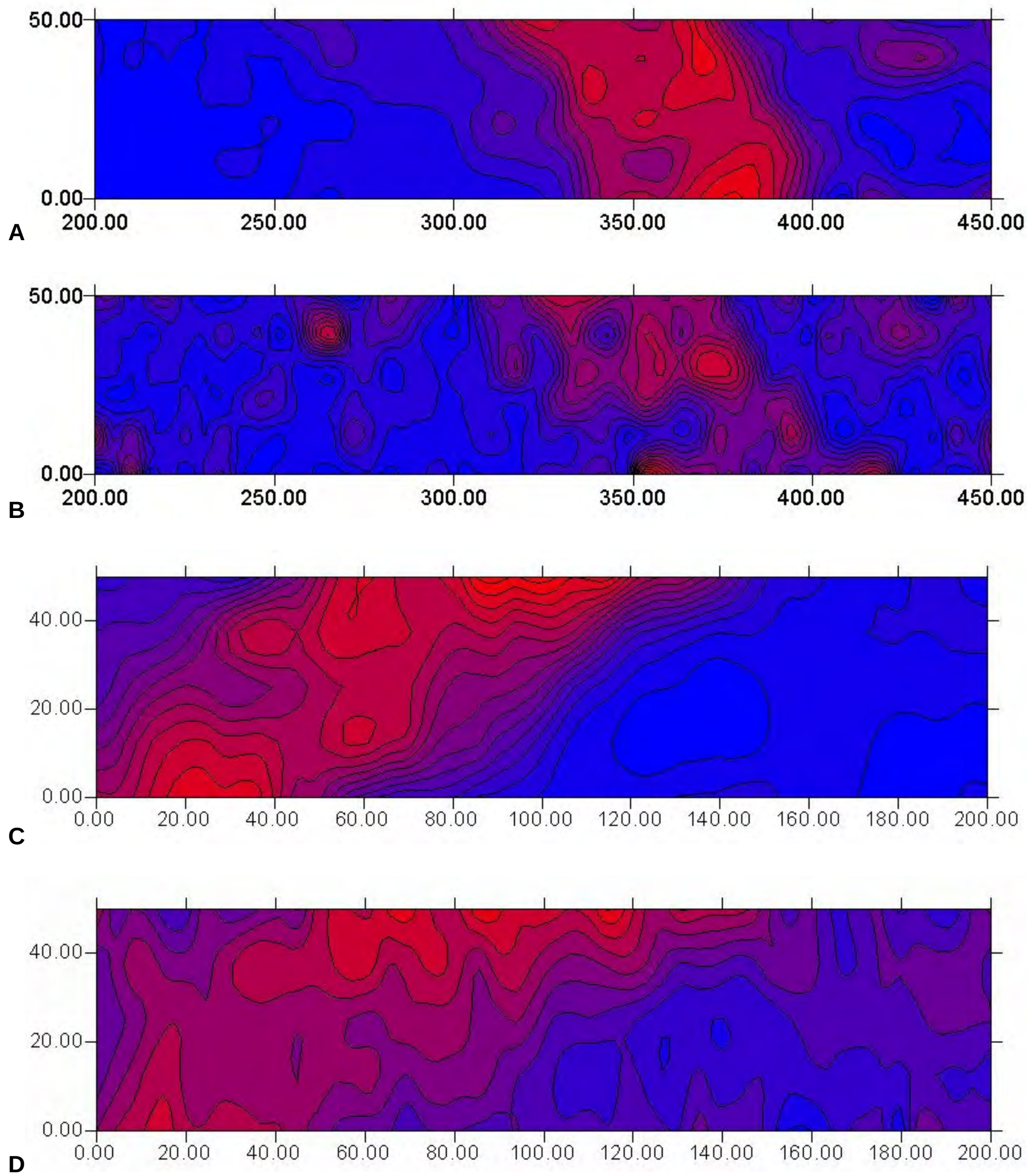


Figure 5.15: **Dry and wet season profiles of the Buffels River near the town of Buffels River (Strohmeyer, 2001) – *red = higher water content; blue = lower water content*.**

A: Dry season: 930 Hz GEM-300 data, north is down

B: Dry season: 330 Hz GEM-300 data, north is down

C: Wet season: 930 Hz GEM-300 data, north is to the left

D: Wet season: 330 Hz GEM-300 data, north is to the left

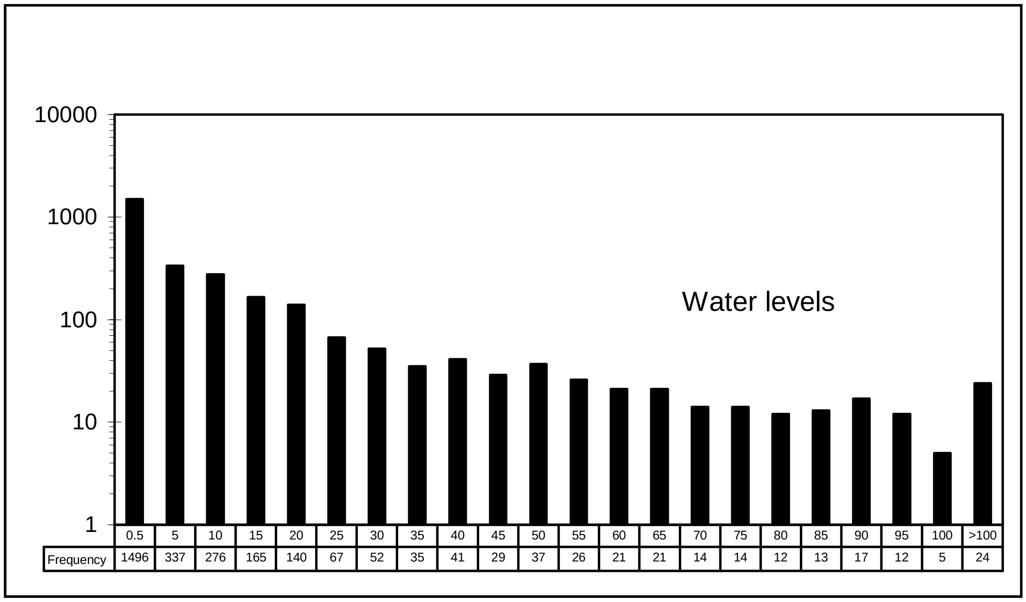


Figure 5.16: Frequency diagram for water levels of the central Namaqualand area (source NGDB).

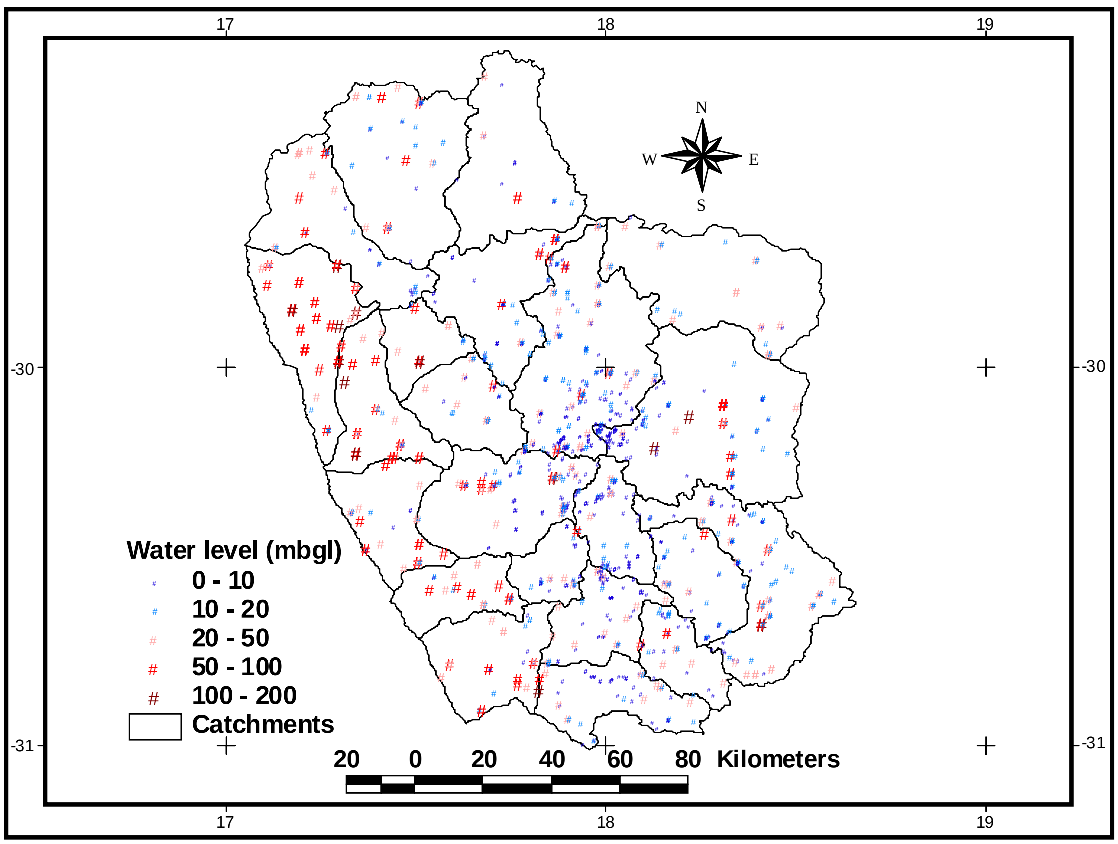


Figure 5.17: Regional distribution of groundwater levels.

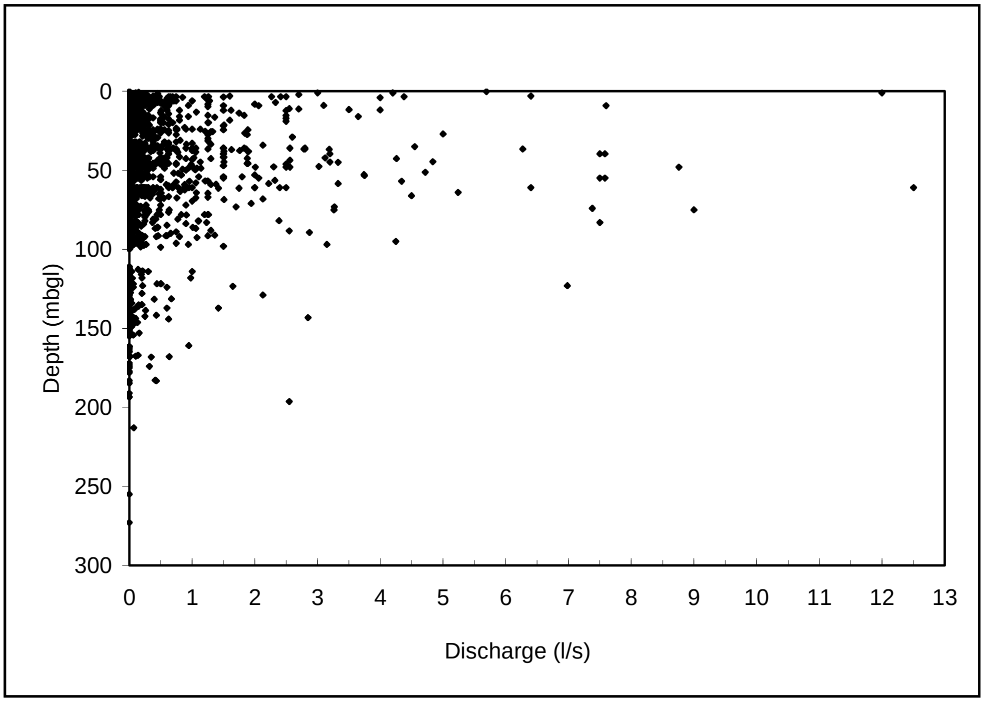


Figure 5.18: Borehole depth versus yield for boreholes contained in the NGDB.

Yield data from the NGDB indicate that of the 2605 boreholes with data, 1436 have a yield of zero. That is, 55% of boreholes drilled are dry boreholes, 33% gave a yield of less than 1 l/s and boreholes with yields >1 l/s make up 10% of the total as shown in Table 5.7. It is not indicated in the NGDB whether zero (0) indicates no value.

Table 5.7: Yield data obtained from the NGDB.

	Yield = 0 l/s	**Yield <1 l/s**	**Yield >1 l/s**
Number of boreholes	1436	892	277
%	55.1%	34.2%	10.6%

Boreholes with relatively higher yields are often associated with areas with high lineament frequency densities (HLFD). Areas on the periphery of high the HLFD areas show higher borehole yields (Figure 5.19). This may be explained by the fact that areas that are easily discernable on the satellite images are usually on the higher bare crystalline outcrops. These areas are usually inaccessible and are often not drilled. Due to the different tectonic events that occurred, not all fractures may be open (i.e. can conduct water). A striking feature of the map, shown in Figure 5.19, is that most of the drilling occurred relatively close to the HLFD areas.

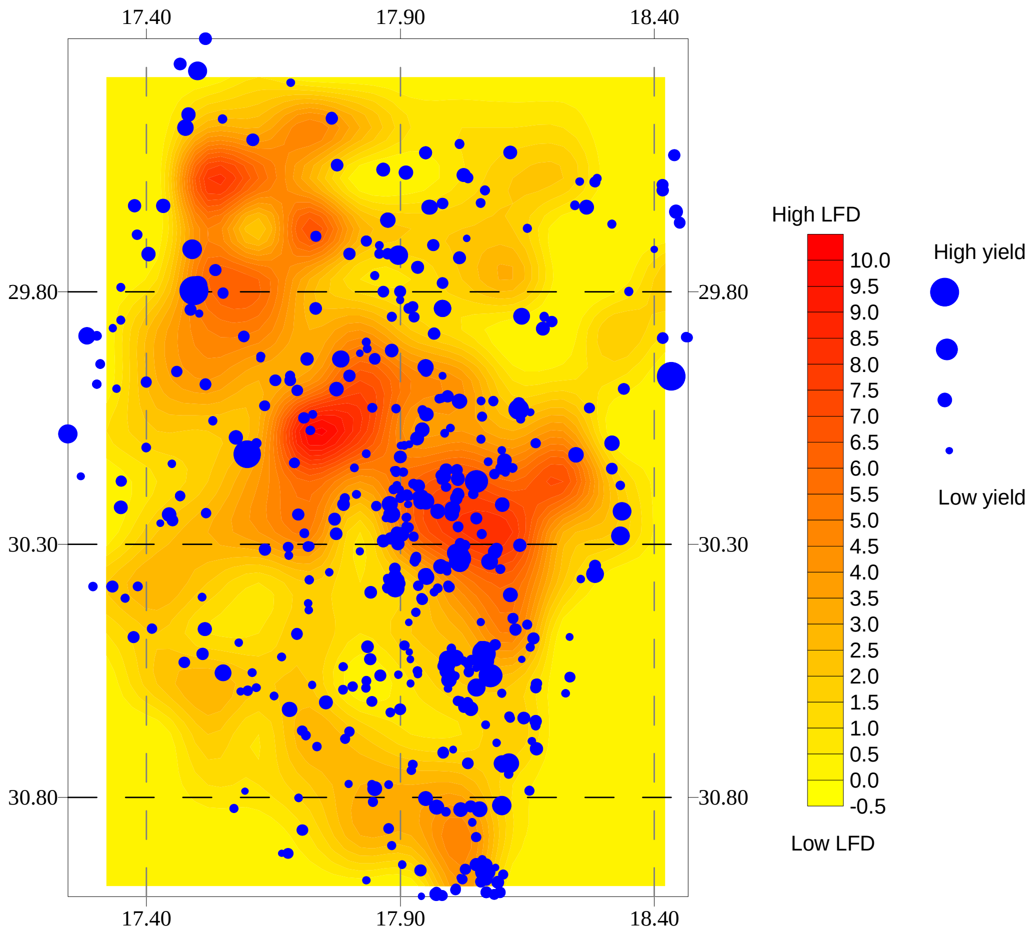


Figure 5.19: Comparison between lineament frequency densities and borehole yield density contour map of Namaqualand (De Gita, 2002).

Infiltration into the fractured crystalline rocks in Namaqualand occurs along the vertical to sub-vertical fractures, with lateral flow predominantly along horizontal to sub-horizontal fractures. Downhole geophysical logging were performed for two boreholes in the Garies area. The results indicate that the major groundwater flow patterns are controlled by horizontal fractures. Borehole water electrical conductivity profiles show clear step like transitions in the log (Figure 5.20), which is indicative of major flowing fractures. The hydraulic gradient is from the higher lying regions to the lower lying regions across the different scales. Groundwater occurring at depth is associated with a reduction of hydraulic gradients and hydraulic conductivity. This results in the stagnation of the groundwater with enhanced water-rock interaction. The high salinities associated with the groundwater indicate that the area experiences insignificant recharge under present climatic conditions.

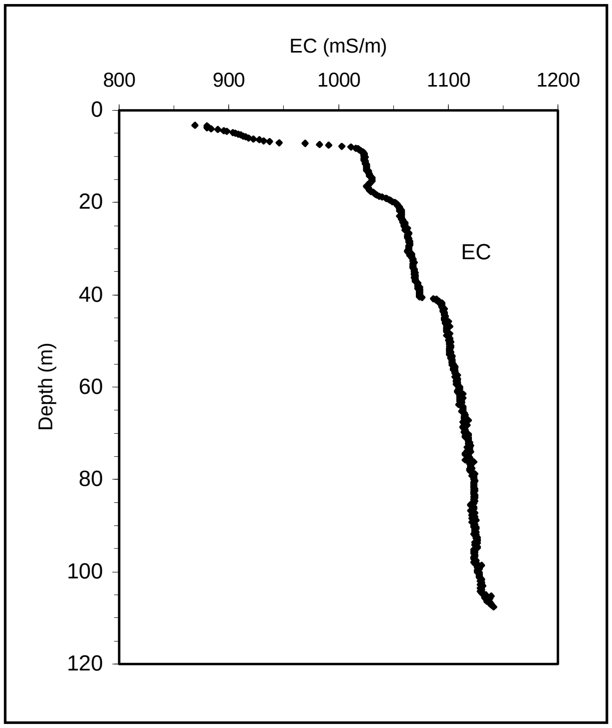


Figure 5.20: Electrical conductivity logs for borehole G45772 in the vicinity of Garies.

The main source of recharge to alluvial aquifers is the infiltration of surface water as the water drain towards areas of lower topography. Groundwater also discharges directly from the hard rock aquifers to the alluvial aquifers. It is often found in the area that groundwater exploited from the alluvium has elevated levels of fluoride. The high fluoride water is mainly found in the fractured rock aquifers and is a result of long residence times and the mineralogical compositions of the crystalline bedrock. Groundwater in alluvial aquifers will follow the surface topography of the ephemeral rivers where it may infiltrate to the underlying basement aquifers through fractures.

Figure 5.21 illustrates the possible interactions between the various aquifer types found in the area. Conceptually, recharge can occur both vertically and laterally depending on the interconnectivity of the different aquifer units occurring within an area. These interactions are dependent on, among others, the local geomorphology, geology (structural and lithological), hydraulic gradients, and water table depths. Groundwater flow in topographic highs occurs along major fractures as a function of the naturally high hydraulic gradients in these regions. Groundwater that circulates at depth is associated with a reduction of the hydraulic gradients and hydraulic conductivity with depth. This results in the stagnation of the groundwater with enhanced water-rock interaction. The high salinities associated with these groundwater probably experience insignificant recharge under present climatic conditions. The groundwater flow in the three sub-aquifer systems is divided according to “typical” depths. Alluvial aquifers associated with the river systems are usually very shallow: 1- 15 m, and in the coastal areas tens of metres; the weathered zones to depths of a few metres to recorded depths of up to 60m m, and the fractured rock aquifers to depths of several hundred meters.

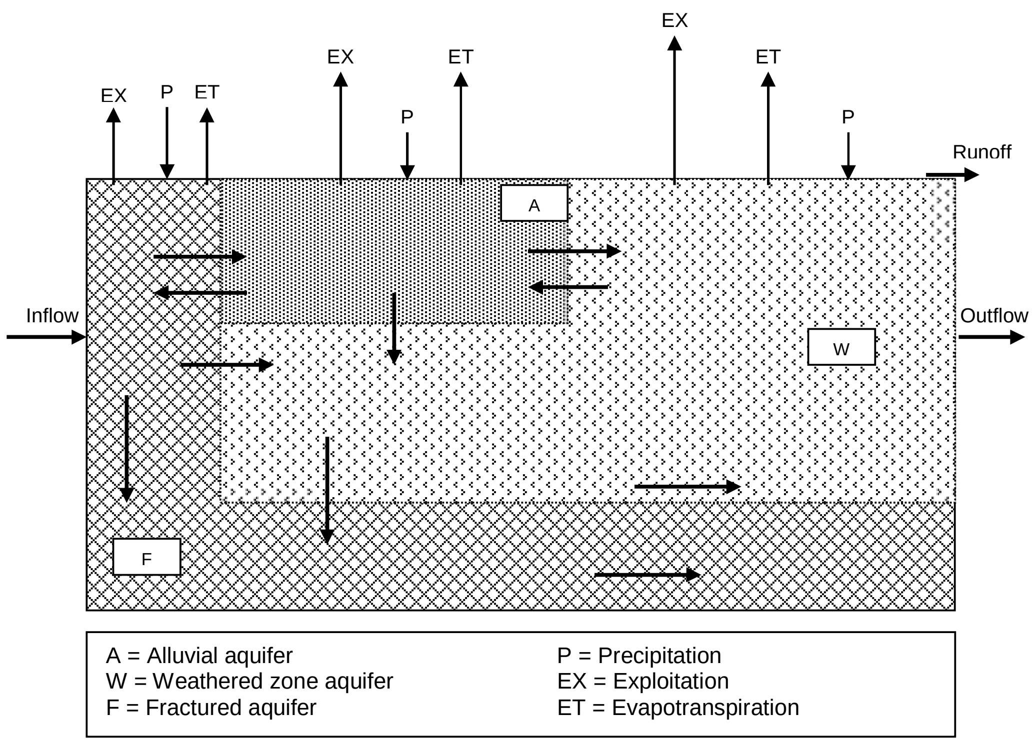


Figure 5.21: Conceptual model of the flow processes in the three aquifer types found in the study area.

5.8.3 Hydrogeochemistry

The hydrogeochemistry of the area is discussed in detail by Titus et al. (2002) and Titus (2003). On a Piper diagram, the samples plot mainly as a Na-Cl dominant type water (Figure 5.22). The NaCl character of the water is a result of a Na-Cl dominant rainfall chemistry as well as the preferential dissolution and leaching of the more evaporitic salts during infiltration. Recently recharged groundwater also shows a Na-Cl character. Salt is deposited in small concentrations in precipitation and are concentrated in the soil zone due to evaporation and transpiration as it moves through the soil zone to the groundwater. In areas of low or no soil cover, the salt deposited on the surface is transported to the groundwater via fractures and joints. A direct correlation exists between groundwater quality and altitude. Where altitude refers to topographically higher elevations with negligible soil cover. In the higher lying regions of the study area the dilute and aggressive infiltrating water controls the weathering of the mineral phases (Titus, 2003). Whilst the dynamic chemical characteristics of the groundwater suggests active flow systems, where equilibrium between the groundwater and mineral phases is rarely attained. In the lower lying flat areas higher salinity water dominates, caused by the leaching of soluble salts during periods of infiltration into the aquifer as well as the effect of long residence times.

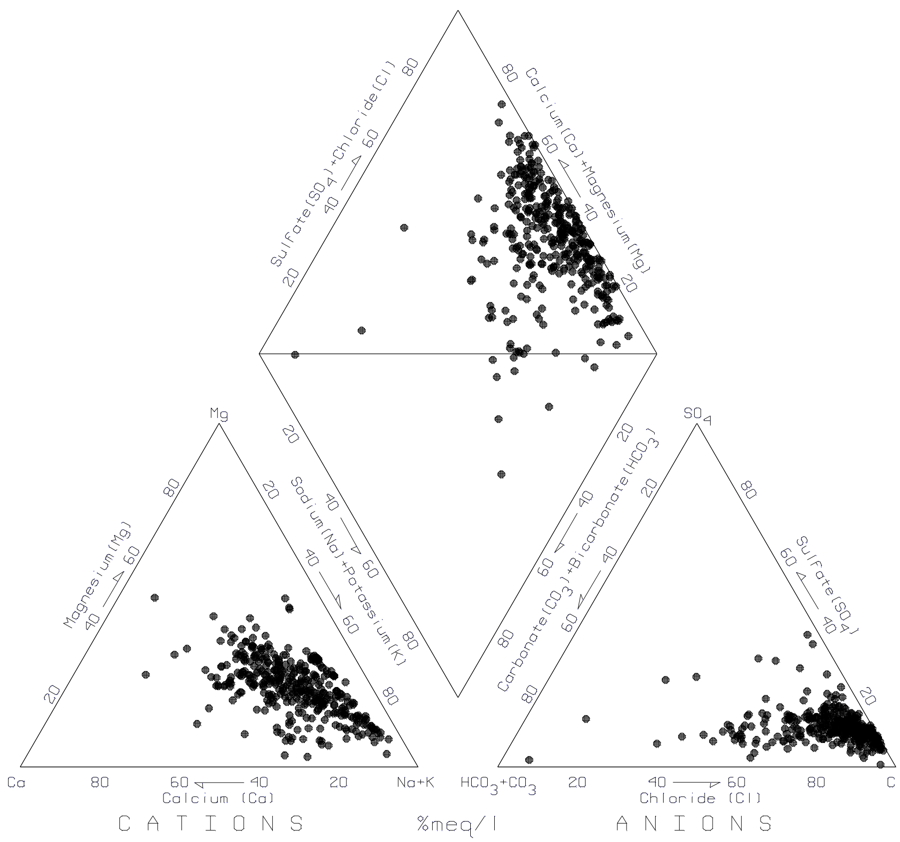


Figure 5.22: Piper diagram of the groundwater sampled in the study area.

Titus et al. (2000) have shown that the groundwater chemistry at any locality is indicative of where the borehole intersects the groundwater flow paths. Three distinct flow patterns have been identified viz. localised flow, intermediate flow and regional flow. The flow systems may be stacked and a borehole may often exploit water that is a combination of two or more flow patterns, producing groundwater that may be chemically distinct from water exploited from a borehole tens of meters apart.

The quality and quantity of the groundwater is often a limiting factor for development in the region. Based on electrical conductivity measurements most communities use groundwater that do not comply with local and international water quality standards and guidelines. Several areas make use of desalinisation technology to produce groundwater of an acceptable quality for domestic use. Murray and Tredoux (2002) suggest that the groundwater quality can be improved by rerouting excess surface water to the subsurface in the Kharkams area.

5.8.4 Aquifer characteristics

Intrinsic properties of the rocks

Crystalline rocks have very little to no primary porosity and the porosities found in these rocks are a result of secondary processes such as weathering and tectonic activities. Hydraulic conductivities and effective porosities of cores, obtained from the Okiep Copper Company, were determined using a gas permeameter and porosimeter as well as a mercury pump (Table 5.8). The porosities of the measured cores decrease with depth (Figure 5.23). The porosities of the cores range between 1-21.4%, the higher porosities occur in samples where large mineral clasts occur within the dense crystalline rocks and weathered rocks. The average and harmonic mean of the samples are 3.2% and 2.3%, respectively. A plot of hydraulic conductivity against the core sample depth indicates that the permeability or hydraulic conductivity of the rocks are generally similar except for the higher values obtained from partially weathered rocks that are usually encountered in the top few meters of the vertical section (Figure 5.24). Higher values were also obtained in two samples, A10 and A14, which occur at 110 m and 165 m, respectively. They are a result of mineral alteration processes. Unweathered and unfractured crystalline rocks have hydraulic conductivities in the range of 1.36×10^{-9} to 1.57×10^{-5} m/day. The weathered rocks have hydraulic conductivities in the range of 8.94×10^{-7} to 2.07×10^{-3} m/day.

The values obtained for the hydraulic conductivities of the core plugs are in good agreement with the reported values of Clauser (1992) and Clauser (2001). The hydraulic conductivity values obtained by laboratory analyses are at least three orders of magnitude smaller than that obtained from borehole data (Figure 5.25).

Table 5.8: Permeability and porosity values for the different rock types (Flanagan, 2003).

Sample ID	Depth (m)	Lithology	Intrinsic Permeability (mDarcy)	Hydraulic Conductivity (m/day)	Porosity (%)
A01	1	Weathered Concordia Granite zone	-	-	-
A02	8	Weathered Concordia Granite zone	2.61E+00	1.91E-03	3.73
A03	15	Contact between weathered and fresh zones	3.48E-06	2.55E-09	2.57
A04	20	Concordia Granite	3.92E-06	2.87E-09	1.71
A05	31	Minor pegmatite intrusive zone	0.00E+00	0.00E+00	1.88
A06	50	Concordia Granite	4.93E-06	3.61E-09	2.36
A07	62	Concordia Granite	6.27E-06	4.59E-09	1.74
A08	80	Concordia Granite	5.65E-06	4.14E-09	1.60
A09	99	Contact between Concordia Granite and diorite (Koperberg Suite)	4.12E-06	3.02E-09	1.83
A10	112	Concordia Granite; concentration of dark minerals	1.44E+01	1.06E-02	21.36
A11	134	Concordia Granite	1.49E-05	1.09E-08	1.63
A12	143	Contact between Concordia Granite and Steinkopf Gneiss	5.87E-06	4.29E-09	2.18
A13	151	Contact between anorthosite and plagioclase (Koperberg Suite)	4.05E-06	2.96E-09	1.67
A14	165	Alteration of plagioclase (dark minerals); concentration of sulphides	1.11E+00	8.12E-04	9.49
A15	188	Concordia Granite fracture zone	9.70E-06	7.10E-09	1.47
B01	1	Weathered Concordia Granite zone	2.83E+00	2.07E-03	3.08
B02	7	Weathered Concordia Granite zone, presence of garnets	4.55E-02	3.33E-05	2.78
B03	33	Wolfram Schist	1.85E-06	1.35E-09	1.04
B04	44	Contact between Concordia Granite and Wolfram Schist	5.93E-06	4.34E-09	1.69
B05	48	Contact between Concordia Granite and Wolfram Schist	8.78E-06	6.43E-09	1.60
B06	64	Concordia Granite	1.94E-05	1.42E-08	1.80
B07	82	Wolfram Schist	6.05E-06	4.43E-09	2.43
B08	104	Concordia Granite; presence of garnets	5.41E-06	3.96E-09	2.40
C01	7	Nababeep Gneiss	5.23E-06	3.83E-09	2.98
C02	10	Nababeep Gneiss	5.63E-06	4.12E-09	2.33
C03	30	Nababeep Gneiss	4.59E-06	3.36E-09	2.28
C04	40	Aplite zone (fined-grained granite)	6.14E-06	4.50E-09	2.56
C05	50	Nababeep Gneiss	4.87E-06	3.57E-09	2.53
C06	60	Nababeep Gneiss	5.21E-06	3.81E-09	2.42
C07	70	Pegmatite zone	2.49E-05	1.83E-08	2.53
C08	78	Nababeep Gneiss with minor joints	3.71E-06	2.71E-09	2.05
C09	80	Nababeep Gneiss	8.02E-06	5.87E-09	2.00
D01	1	Weathered Concordia Granite	2.15E-02	1.57E-05	4.89
D02	6	Weathered Concordia Granite	1.22E-03	8.94E-07	4.47
D03	20	Contact between Concordia Granite and Shonkinite Gneiss	2.39E-05	1.75E-08	3.56
D04	24	Shonkinite Gneiss	1.39E-05	1.01E-08	3.49
D05	28	Shonkinite Gneiss	1.82E-03	1.33E-06	10.04
D06	55	Concordia Gneiss	4.74E-06	3.47E-09	1.86
D07	64	Concordia Granite	1.19E-05	8.68E-09	2.79

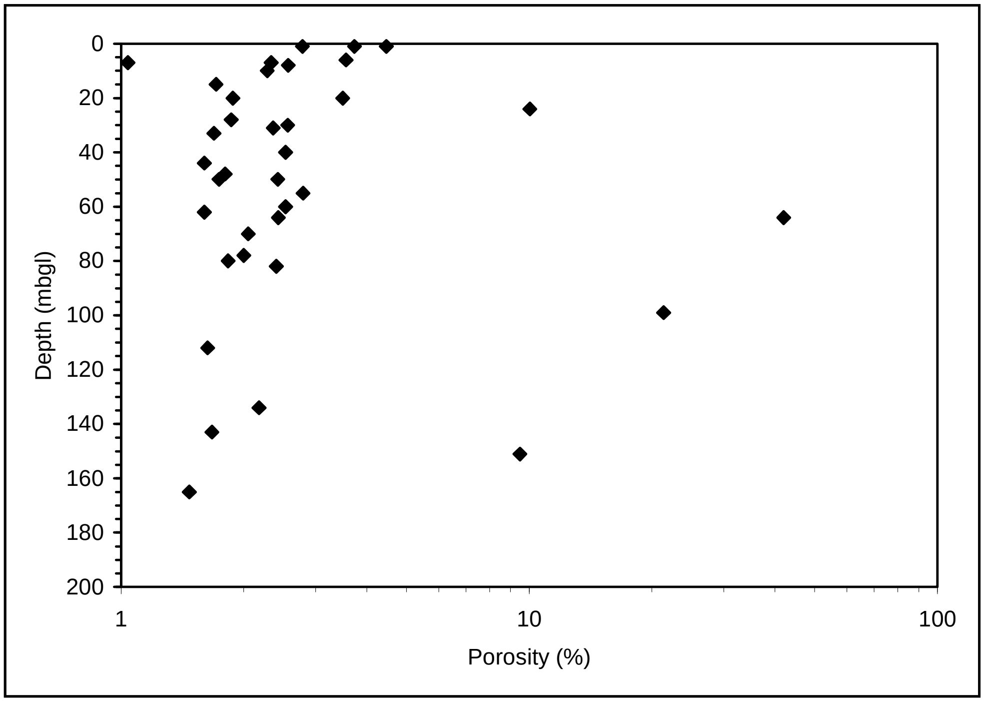


Figure 5.23: Porosity versus depth below ground level.

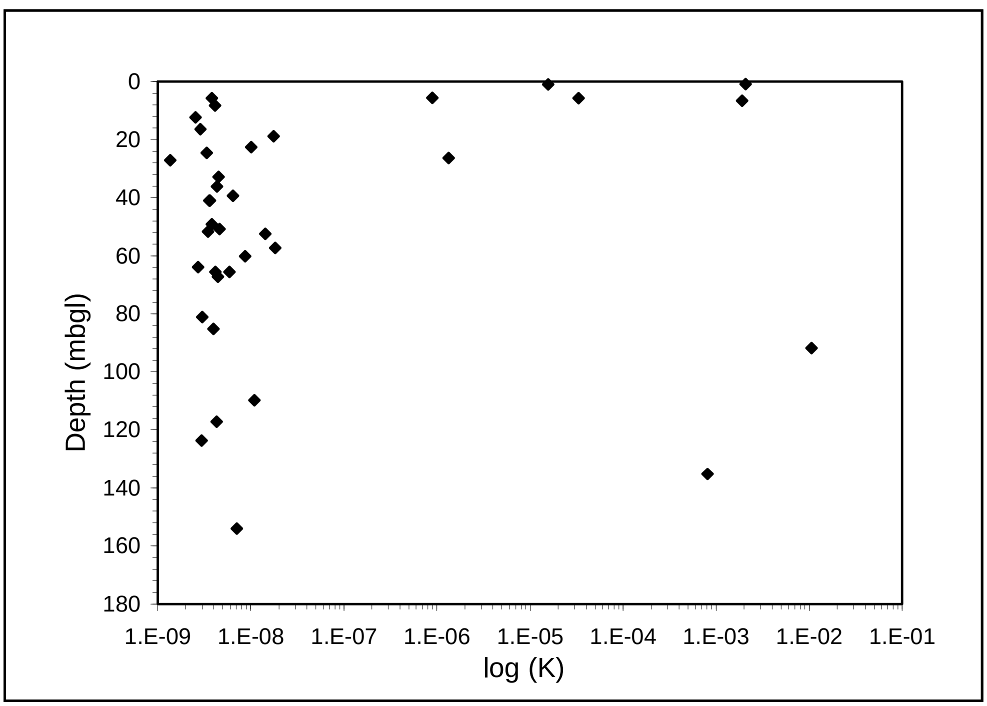


Figure 5.24: Hydraulic conductivity versus depth below ground level.

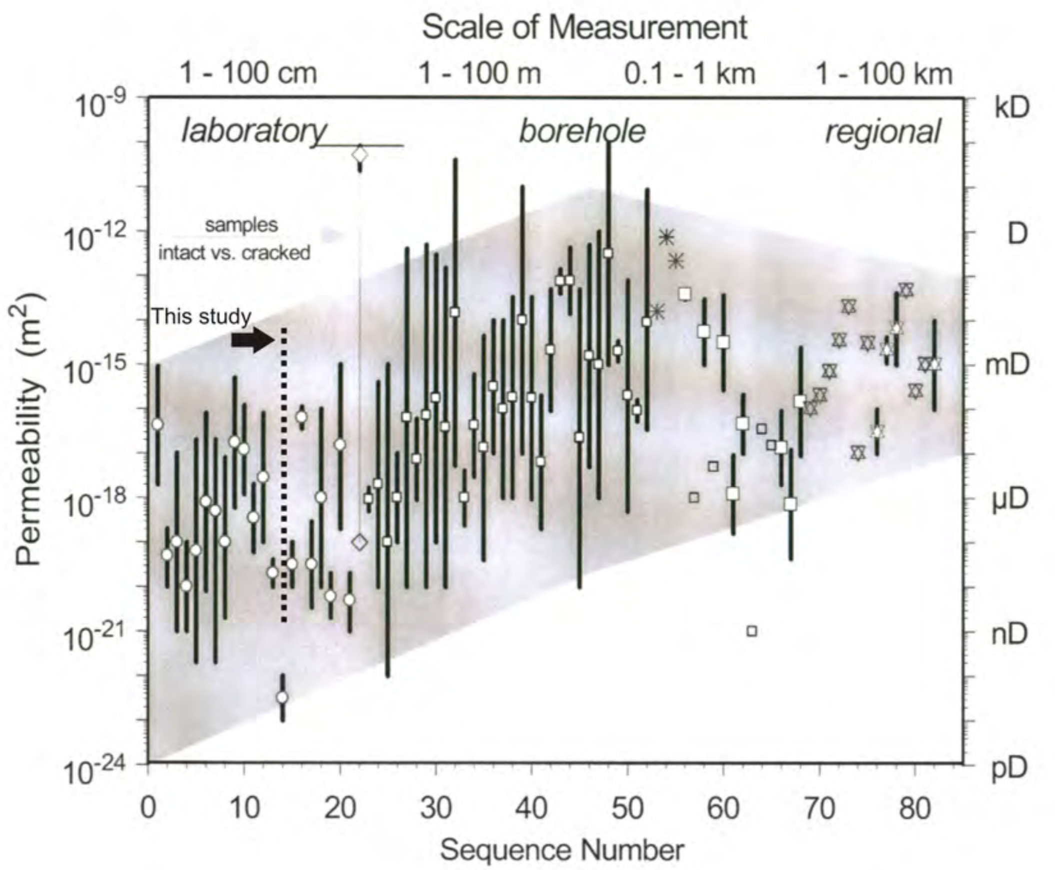


Figure 5.25: Range of measured or inferred permeability of basement and metamorphic rocks as a function of the characteristic length scale (after Clauser, 2003) the broken line indicate ranges of intact and weathered values for the Namaqualand region.

Transmissivity and storativity

Aquifer test data sets were collected from 28 pumping and 12 observation boreholes (Table 5.9). The data were obtained from DWAF (Department of Water and Forestry) as well as from Toens and Partners. Data were recorded from reports that had calculated transmissivity (T) and storativity (S) values for different areas in Namaqualand. These values have been calculated using well-known analytical methods, mostly Theis and Cooper-Jacob.

Table 5.9: T and S values extracted from reports (DWAF and Toens and Partners).

Town	Borehole number	Transmissivity (m^2/d)	Storativity
Tweerivier	LF 90/201	9.5	5.05 E-04
Steinkopf	Steinkopf aquifer		2.1 E-07
Steinkopf	SK 103 (confined)	1505; 260	1.95 E-05
Steinkopf	SK 102 (semi-con.)	*Various T values	7.9 E-02
Steinkopf	SK 93/106 (unconfined)	2	
Steinkopf	93/107 (unconfined)	29.5	
Steinkopf	93/108 (unconfined)	38.8	
Steinkopf	SK 91/102 (con. To semi-con.)	4720	
Steinkopf	91/103 (con. to semi-con.)	1254	
Steinkopf	91/104 (con. to semi-con.)	922	
Steinkopf	91/105 (con. to semi-con.)	27.15	
Komaggas	KG 91/100 (con. to semi-con.)	52	
Komaggas	KG 91/101 (con. to semi-con.)	2.1	
Komaggas	KG 91/102 (con to semi-con)	15.04; 0.95	
Leliefontein	LF 90/201 (confined)	40	
Garies	GA 91/1 (uncon. to semi-con.)	10.3	2.0 E-04 to 7.2 E-04
Karkams	G37133 (semi-con.)	1193	
Karkams	G37152	1170	
Karkams	G37159	816	
Karkams	G37166	6426	
Karkams	G37174	12040	

The T-values, for some areas, are unrealistically high for this type of aquifer. The in house Excel programmed software, AQUATEST, was used for the interpretation of pump test data. This program makes use of step test data when calculating transmissivity and storativity values. The transmissivity and storativity values, without considering boundary conditions, calculated using AQUATEST are presented in Table 5.10.

Table 5.10: T and S values calculated using AQUATEST.

Town	Borehole number	Transmissivity (m^2/d)	Storativity
Kommagas	KG 93/114	0.28	2.66 E-03
Kommagas	KG 93/113	14.61	6.07 E-04
Kommagas	KG 93/111	0.10	1.27 E-03
Kommagas	KG 93/106	0.31	4.71 E-03
Kommagas	KG 93/107	0.68	1.00 E-02
Kommagas	KG 93/217	0.11	1.00 E-02
Kommagas	KG 93/216	0.08	1.00 E-02
Kommagas	KG 93/218	0.11	1.00 E-02
Kommagas	KG 93/108	1.62	8.48 E-04
Kommagas	KG 93/115	3.57	2.62 E-03
Klipfontein	LF 98/312	0.08	9.54 E-04
Klipfontein	LF 98/311	0.24	1.00 E-02
Spoegrivier	G 45805	0.38	1.42 E-04
Garies	G 45779	0.38	1.42 E-04
Garies	G 45781	1.43	1.67 E-04

The storativity (S-value) has been determined by using the Theis and Jacob method. Most of the times only one observation borehole is used that disregards the fact that the S-value produced by the pumping tests becomes smaller as the distance of the observation borehole from the pumping borehole increase. Evidence indicates that for large values of r, the inferred S values become unrealistically small (Bredenkamp et al., 1995).

Comparison of results between FC and AQUATEST

Another common software program called FLOW CHARACTERISTICS (FC) was used to analyse aquifer test data (Van Tonder and Xu, 1999). The data was interpreted with the FC Excel programmed software. For the illustration of the differences in T and S values, between these two methods, pump test data collected at Paulshoek, Kammasies, Nourivier and Leliefontein was analysed (Table 5.11).

Table 5.11: FC and AQUATEST displays different T and S values for Paulshoek (Hassan, 2002).

Method	Locality	Transmissivity (m^2/d)	Storativity
FC	**Paulshoek (G 45816)**	Early – 3.27 Late – 1.32	1.43 E-02
AQUATEST		2.23	9.85 E-03
FC	**Paulshoek (G45815)**	T (Early) = 36.72 T (Late) = 6.58	6.6 E-03
AQUATEST		T = 17.03	1 E-04 (r_e = 0.9m)
FC	**Paulshoek (G45820)**	T (Early) = 10.00 T (Late) = 2.06	S = 4.4 E-04
AQUATEST		T = 6.79	9.8 E-04 (r_e = 0.3m)
FC	**Kamassies (91/1)**	T (Early) = 3.79 T (Late) = 1.33	5.5 E-03
AQUATEST		T = 2.23	9.85 E-03 (r_e= 0.08m)
FC	**Nourivier (G45839)**	T (Early) = 0.40 T (Late) = 0.35	4.4 E-03
AQUATEST		T = 0.23	1 E-03 (r_e = 0.19 m)
FC	**Leliefontein**	T (Early) = 1.13 T (Late) = 0.57	2.2 E-03
AQUATEST		T = 1.45	1.5 E-03 (r_e = 0.4m)

In terms of the S-value, low values could be expected due to the fractured nature of the aquifer. For fractured aquifers S-values ranges from 10^{-4} to 10^{-7} (Kruseman & de Ridder, 1991). Therefore, the S-value calculated using AQUATEST could be seen as a better estimate for storativity of this aquifer system, although the results seem to be in relatively good agreement. The transmissivity values do not vary significantly for both programs, whereas there are differences in the storativity values. With the use of AQUATEST more emphasis is placed on the use of the effective radius to calculate the S-value. The FC program depends more on the use of the aquifer thickness for the calculation of the S-value. For hard rock aquifers a value of < 40m is recommended by this program (Hassan, 2002). Storativity values seem to be on the high end of the ranges for hard rock terrains. It is postulated that the S values will be smaller if integrated over a larger area.

CHAPTER 6

Groundwater recharge assessment

6.1 Introduction

Quantitative and qualitative information on aquifer recharge rates and storage are needed to manage the groundwater resources of the Namaqualand region. General information on recharge rates and aquifer storage are lacking for the area. This systematic approach to assess groundwater recharge is the first for the area. The results contained in this chapter are a foundation on which future work can be based. The assessment of recharge rates for such a large area requires evaluation on a regional scale, often using local scale data.

The chloride mass balance (CMB) method is used to estimate recharge on a local and regional scale using the saturated zone approach. The stable isotopes oxygen-18 and deuterium as well as the radiogenic isotope ^{14}C are used together with factor analysis and the GIS assessment method to delineate and constrain recharge areas and processes. The saturated volume fluctuation (SVF) method is used to estimate storage coefficients and recharge. The cumulative rainfall departures (CRD) method is used to estimate the recharge rates to the aquifers. A numerical model was developed, as a case study, of the Buffels River alluvial aquifer. The sites described in this chapter are shown in Figure 6.1.

6.2 Chemical and isotope tracer methods

6.2.1 Chloride mass balance

The method is attractive to obtain a first estimate of total recharge. This section will highlight the use of the CMB method to characterise and estimate groundwater recharge both on a local and regional scale by using the chloride concentration in rainfall and comparing it to that of the groundwater chloride concentrations.

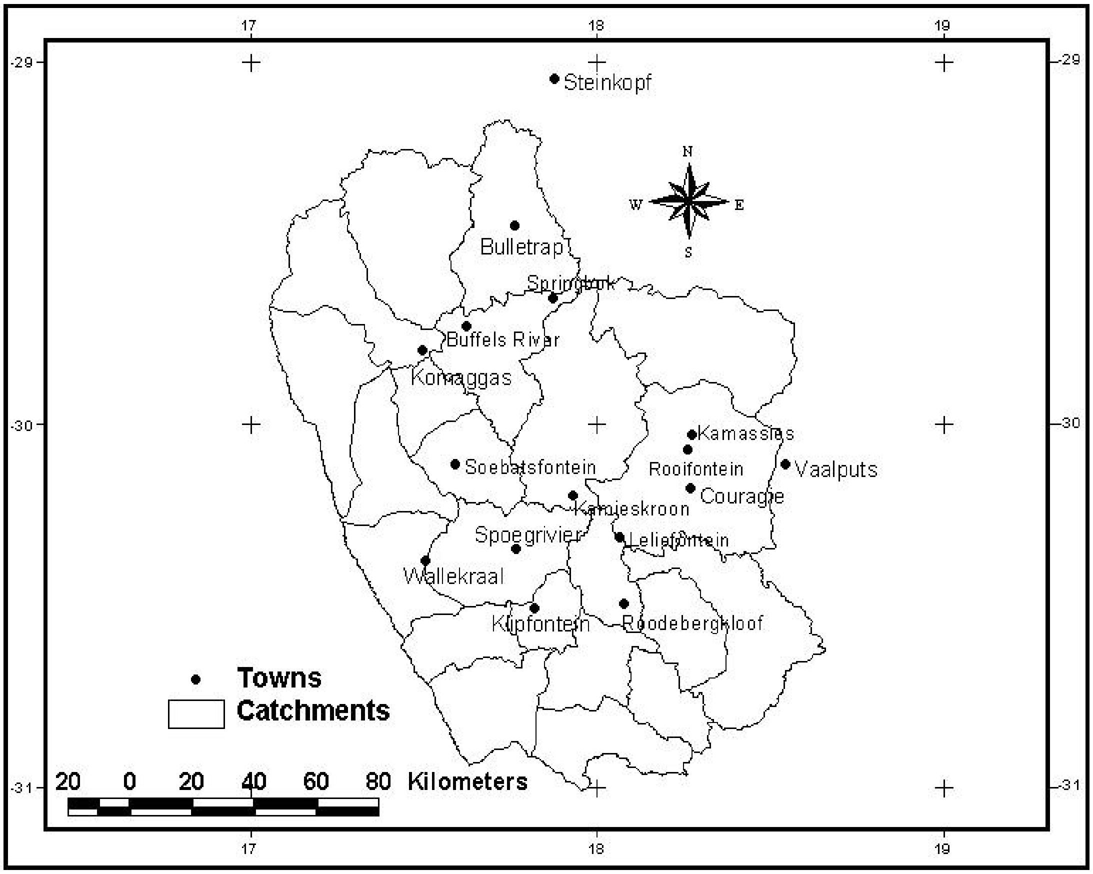


Figure 6.1: Map showing localities described in this chapter.

Precipitation composition

The chloride concentration in rainfall measured over the Springbok area is highly variable. Seventy percent (70%) of the rainfall that occurred in 2001 over the area was collected for chloride analysis. Table 6.1 shows the chloride and bromide values, of the sampled rainwater, of the individual rain events. The values range from 0.17– 8.59 mg/l with a volume weighted concentration of 2.42 mg/l (Table 6.2).

An initial bulk rainfall sampling program for chloride deposition was abandoned due to problems with the sampler as discussed in Chapter 4.

Table 6.1: Chloride and bromide concentrations of event based sampled rainwater.

Station	Date	Time	Rain (mm)	Cl (mg/l)	Br (mg/l)
SPK 2	29/06/01	14H00	1.8	4.86	<0.05
SPK 1	4/7/01	16h00	7	0.88	<0.05
SPK 3	4/7/01	09h00	20	0.17	<0.05
SPK 2	5/7/01	08h30	13	4.31	<0.05
SPK 2	8/7/01	09h30	5	8.59	<0.05
SPK 2	10/7/01	08h30	2.5	3.22	<0.05
SPK 2	18/07/01	08h15	11	2.05	<0.05
SPK 3	18/07/01	17h00	4	4.65	<0.05
SPK 2	19/07/01	08h15	11	4.05	<0.05
SPK 3	20/07/01	08h30	18	3.18	<0.05
SPK 2	22/08/01	11h15	3.5	5.55	<0.05
SPK 2	24/08/01	12h15	10	0.54	<0.05
SPK 3	24/08/01	13h00	9	0.45	<0.05
SPK 2	30/08/01	10h55	14	1.2	<0.05
SPK 2	31/08/01	12h05	10	0.97	<0.05
SPK 2	6/9/01	10h00	4	6.03	<0.05
SPK 1	11/9/01	14H15	7	2.99	0.05
SPK 1	19/09/01	8H45	3.5	0.88	<0.05
SPK 1	24/09/01	14h00	1	2.7	0.07
SPK1	3/10/01	8H30	2	3.41	0.05

Table 6.2: Summary statistics of the chloride concentrations of the event samples.

Statistics	Cl (mg/l)
Mean	3.03
Standard Deviation	2.23
Minimum	0.17
Maximum	8.59
Weighted Average	2.42

Bromide was included in the analyses to determine the main sources of the rainwater. Bromide and chloride are conservative tracers and they do not share in oxidising or reducing environments and do not form insoluble precipitates. Most of the Br ion concentrations are below the detection limit of the analytical equipment of 0.05 mg/l. The three samples where Br was detected gave Br/Cl ratios of 1.5%, 2.6% and 1.7%. In the case of evaporation or mixing with fresh water the Br/Cl ratio remains constant (Hsissou et al, 1999). Two of the samples have Br/Cl ratios of that of seawater (1.5-1.7%) and the sample that has a higher Br/Cl ratio indicate that another source of Br exists in the area. A possible source of aerosols may be as a result of anthropogenic activities such as the mining activities in the area.

A very weak correlation exists between the rainfall amount and chloride concentration in rainwater for the individual samples (Figure 6.2). On a local scale, chloride concentrations decrease with increasing rainfall. During periods of low rainfall, more aerosol particles are incorporated into the rainfall occurring over a particular area.

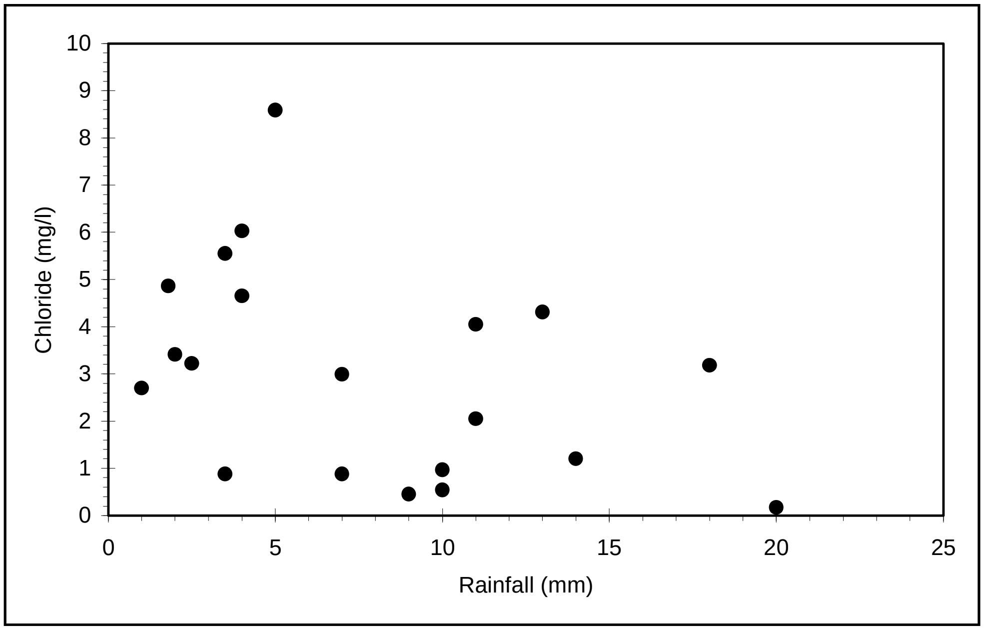


Figure 6.2: Chloride versus rainfall amount relationship for individual samples.

On a regional scale, chloride concentrations increase with increasing rainfall. This is based on available chloride data for the near coastal areas of South Africa (Figure 6.3). Based on a linear regression the relationship between chloride and the amount of rainfall occurring near the coastal sites of Southern Africa at a distance >15km away from the coastline, chloride in precipitation can be estimated as (see Appendix A1 for data):

$$Cl_P = 0.0043(P) + 1.1214 \qquad (6.1)$$

Where Cl_P (mg/l) is the chloride concentration of the rainfall and P is the precipitation in mm. The relationship provides a best estimate of chloride in rainfall in the absence of data. The relationship can be improved when more data becomes available.

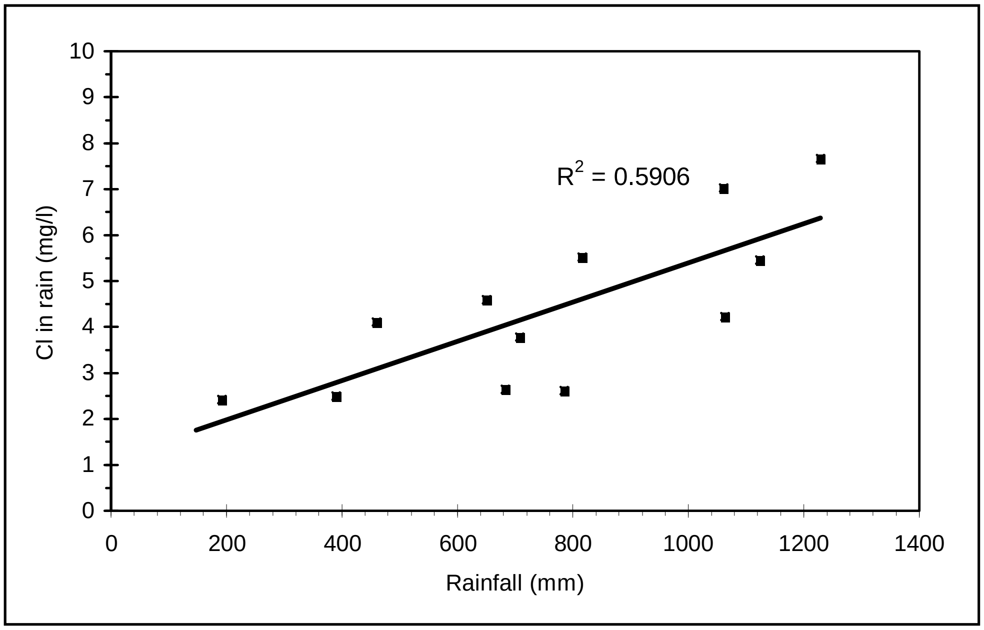


Figure 6.3: Chloride versus rainfall amount relationship for the coastal areas of South Africa.

The data also show a power relationship between chloride concentration in rainfall with elevation (Figure 6.4) and distance from the sea (Figure 6.5), although the latter is not a strong relationship.

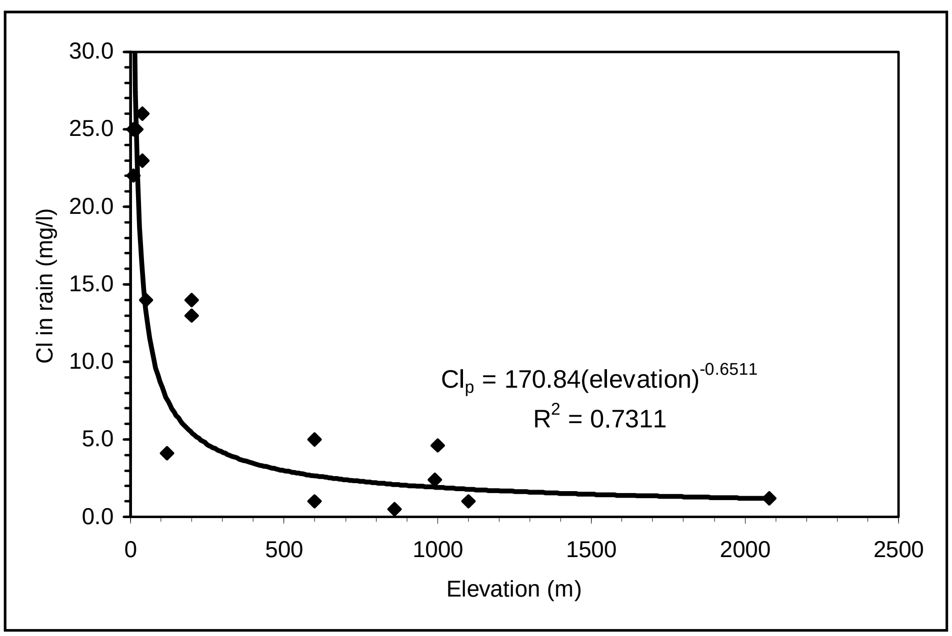


Figure 6.4: Chloride versus elevation relationship for the coastal areas of South Africa.

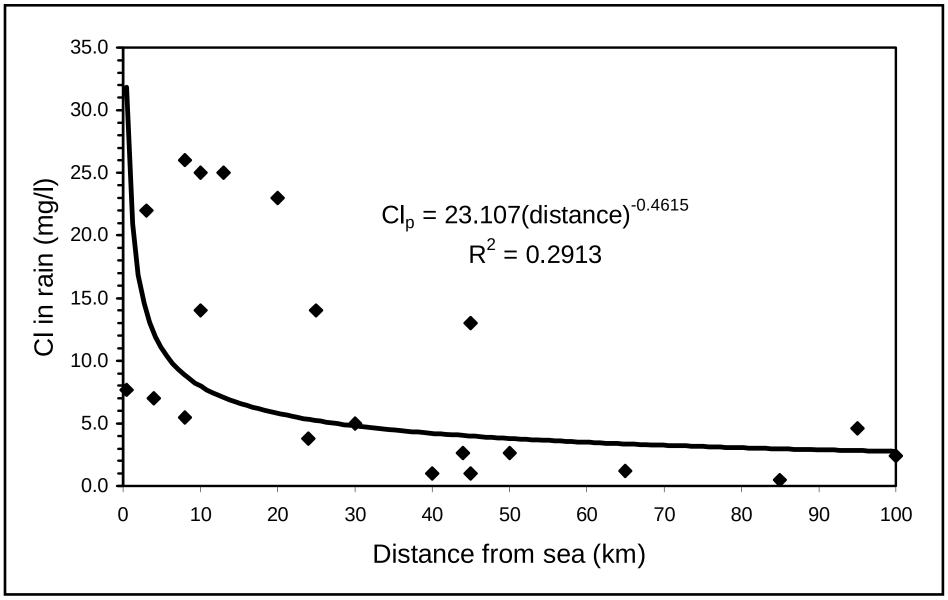


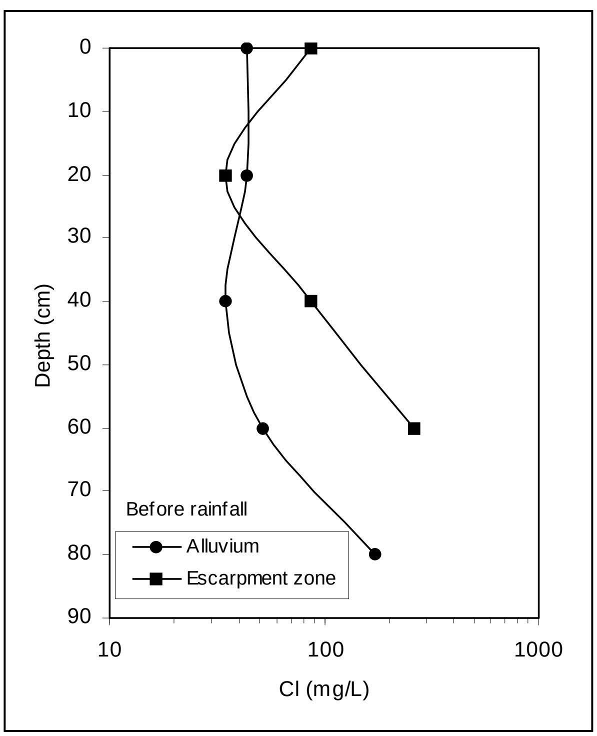
Figure 6.5: **Chloride versus distance from the sea relationship for the coastal areas of South Africa.**

The chloride concentrations were estimated for the other sites in the study area based on the linear relationship between the chloride in rain and the rain amount, by applying equation 6.1. The CMB method will not give reliable estimates very close to the coastal sites of the study area because of:

- The high chloride concentrations in the soils and groundwater, as a result of marine regression and transgression;
- The difficulty in accurately determining the chloride deposition flux in these environments due to the recycling of dust in the environment by open cast mining activities and the high incidences of fog (Olivier and Van Heerden, 1999) that may introduce additional chloride; and
- The high variability of chloride in rainfall very close to the sea, as a result of non-rain deposition of chloride. The area behind the escarpment is also controlled by a different climatic regime with a different weather pattern and rainfall distribution and will also give unreliable estimates due to the lack of data. The chloride concentration of the rainwater will be much less than that of the Springbok area in the plateau region following the chloride versus rainfall amount trend.

Bredenkamp et al. (1995) showed that two different chloride versus rainfall amount trend lines exist for the coastal and inland rainfall samples in South Africa.

Soil samples were taken from two localities in the study area, from alluvium associated with the Buffels River and soil from the escarpment zone. The same day it started to rain and after the rainfall (two days later) a second group of samples were taken close to the first augered holes, as well as from a site on the coastal lowland. The rainfall amount was not captured. The soil was sampled at 20 cm intervals, by hand augering, to a maximum depth of 80 cm. The salts in the soil was analysed through elution with deionised water; the supernatant was then analysed for major ion chemistry (Appendix A2). The profiles clearly show the high chloride content of the soils of the coastal lowlands (Figure 6.6). The concentration of the salts may indicate that the soils are of marine origin or as a result of concentration by evapotranspiration with negligible recharge. The before and after rainfall profiles indicate that the chloride bulges at 20 cm before the rainfall event has moved to 40 cm after the rainfall event. This indicates infiltration of water into the subsurface but it did not infiltrate deeper than 50 cm. Verhagen and Levin (1986) have shown using isotope profiling in the Vaalputs area that soil moisture do not penetrate beyond a depth of 3 m. The main recharge mechanism is probably via preferential flow paths if it exists.



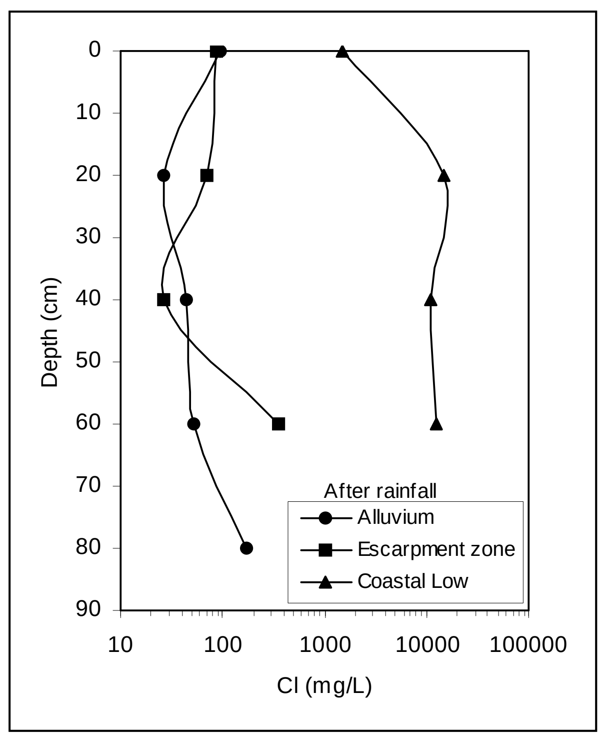


Figure 6.6: Chloride concentration in the soils of three geomorphic areas.

The chloride concentration of the rainfall in the study area, excluding the coastal strip and the area behind the escarpment, will range between 2 and 3 mg/l. The area also falls in relatively homogenous rainfall regions (Figure 6.7) as defined by Dent et al. (1990). The homogenous zones were delimited according to (Dent et al., 1990):

- Mean annual precipitation;
- Altitude;
- Aspect;
- Topographic complexity; and
- Agricultural population distribution.

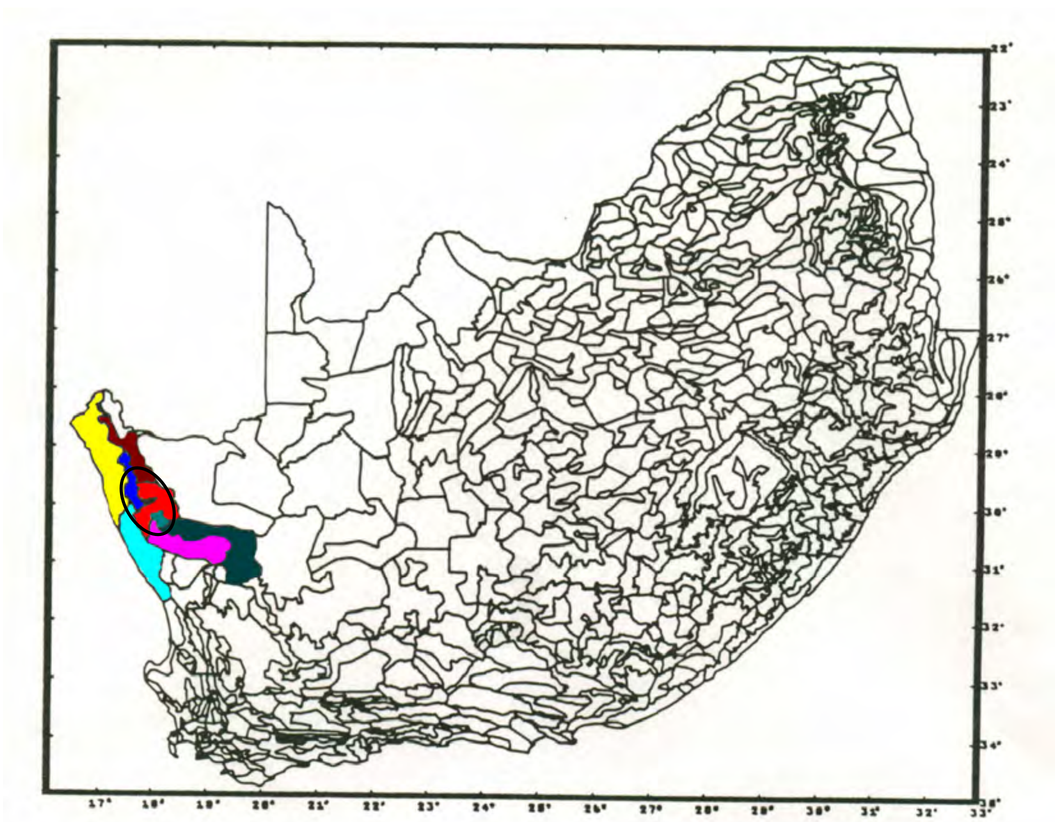


Figure 6.7: Homogenous rainfall regions of South Africa and the regions overlapping with the study area (after Dent et al., 1990).

Groundwater composition

Two data sets are used to describe the chloride content in the groundwater of Namaqualand. One data set stems from a hydrocensus conducted between 1996-2000 and the second is from the NGDB (Appendix A3). The NGDB data covers a more extensive area than that of the hydrocensus. The groundwater in the Central Namaqualand area is generally of a very poor quality and is dominated by Na-Cl type water. Chloride concentrations are generally a good indicator of groundwater quality in the study area. The descriptive statistics of the chloride concentrations in the groundwater is shown Table 6.3.

Table 6.3: Summary statistics of the chloride concentrations (mg/l) found in the groundwater samples of the NGDB and hydrocensus database.

Statistics	Cl NGDB	Cl Hydrocensus
Count	434	258
Mean	1703	1078
Standard Deviation	2179	1195
Minimum	30	13
Maximum	23644	9063
Harmonic Mean	444	297

The distribution of the chloride ion in the groundwater of Namaqualand clearly indicates that lower concentrations occur in topographically steeper areas and chloride rich groundwater occurs in topographically flat areas (Figure 6.8). The coastal aquifers are characterised by highly saline groundwater, a result of the influence of the sea (e.g. marine regression and transgression and the effect of sea spray).

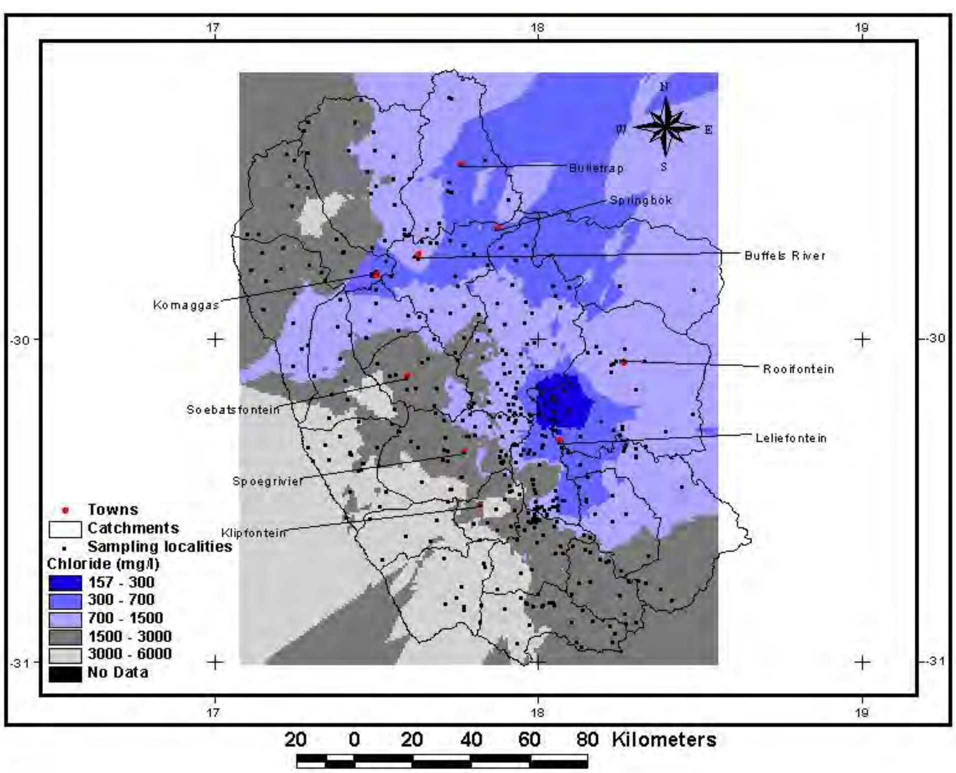


Figure 6.8: Chloride distribution in the aquifers of the three catchments.

Recharge estimation

The fundamental basis of the CMB method is that the water mass flux crossing the plane of the water table can be calculated if most of the assumptions outlined in Table 6.4 are met (Bazuhair and Wood, 1996; Wood, 1999). Because not all of these conditions are met, the method does not permit accurate quantification of recharge rates. However, it is still a suitable method for a first approximation of recharge. Cook (2003) also warns about the use of the CMB method in fractured rock aquifers due to the effects of the different types of porosities of the aquifer media, but also states the method can give reliable estimates of recharge to fractured rock aquifers over other methods. Understanding and knowing the area in which the method is being applied is essential when interpreting the results. Applying the method on its own to determine recharge rates is often not recommended, as it is with most other methods, due to the uncertainties of the input data for the method.

Table 6.4: Assumptions when using the CMB method and the situation in Namaqualand.

Chloride in groundwater originates only from precipitation (no unmeasured chloride mass from overlying, underlying or adjacent aquifers and no unmeasured run-on occurs).	×
Chloride is conservative in the system.	✓
The chloride mass flux has not changed over time.	?
There is no recycling or concentration of chloride within the aquifer.	×
No evaporation of groundwater occurs upgradient from the groundwater sampling points.	?
The adsorption of chloride in soils and the vegetation uptake is considered negligible.	✓

Site-specific results were obtained using the CMB method by using groundwater chloride data from both the NGDB and hydrocensus database. The chloride in precipitation versus rainfall amount was used to predict the chloride in precipitation value for the whole area (equation 6.1). The results are shown in Table 6.5. The average, maximum and minimum chloride concentrations of the groundwater at the specific localities were used to determine the average, minimum and maximum rate of recharge. In the hard rock areas, higher chloride values may indicate very old water and in the alluvial aquifers high chloride values may indicate leaching of evaporitic salts during infiltration and leakage of groundwater from the adjacent hard rock aquifers. However, low chloride groundwater is also associated with the higher lying areas and alluvial zones receiving active recharge.

Table 6.5: Recharge estimation using the CMB method.

Site	Cl_{gw}			MAP (mm)	Cl_P (mg/l)	Re (mm/yr)			*Re (%)
	Mean	Max.	Min.			Mean	Min	Max	
Buffels River	512.1	747.9	369.6	188	1.93	0.71	0.49	0.98	0.38
Bulletrap	281.4	283.7	279.0	172	1.86	1.14	1.13	1.15	0.66
Kamieskroon	592.4	2229.2	99.1	212	2.03	0.73	0.19	4.36	0.34
Klipfontein	1683.0	1859.0	1393.0	196	1.96	0.23	0.21	0.28	0.12
Komaggas	465.5	1481.3	186.4	229	2.11	1.04	0.33	2.59	0.45
Leliefontein	105.4	209.0	34.8	395	2.82	10.57	5.33	32.01	2.68
Rooifontein	607.5	1907.5	54.0	138	1.71	0.39	0.12	4.38	0.28
Spoeg River	1773.0	1970.8	1575.1	200	1.98	0.22	0.20	0.25	0.11

*average value

The chloride method was applied over the study area using GIS. Rainfall and chloride concentrations in rainfall and groundwater grids were generated in Surfer®. Interpolations were performed using the Kriging technique. The data from the NGDB was used for the groundwater chloride as it had more spatial coverage. The Namaqualand hydrocensus data was also used to derive recharge rates to determine if any differences exist. The NGDB data was collected prior to the onset of a wetter period in which the hydrocensus data was collected. Using the math function in Surfer®, the grids were recalculated to give the recharge estimates in mm/yr. The grid was converted to XYZ data file format and imported into ArcView where the catchment boundaries were overlain to obtain the CMB estimates over the area (Figure 6.9). The spatial configuration of the CMB estimates depends on the spatial distribution of the sampling points. However, the map gives an indication of the main recharge areas over the area. The highest recharge rates coincide with areas of high elevation. The highest rate, however, occurs, away from the highest elevation and coincides with the intersection of three major regional lineaments.

The data from the hydrocensus shows a different recharge pattern to that of the NGDB data. The hydrocensus data was collected from 1996 – 2001. The hydrocensus data give a higher estimate for recharge in the higher lying areas, assuming that the chloride input remained the same. The hydrocensus data was collected during a period of above average rainfall, with increased recharge. The recharge rates calculated from the two data sets represent more or less the minimum and maximum recharge in Table 6.5 for the NGDB and hydrocensus data, respectively.

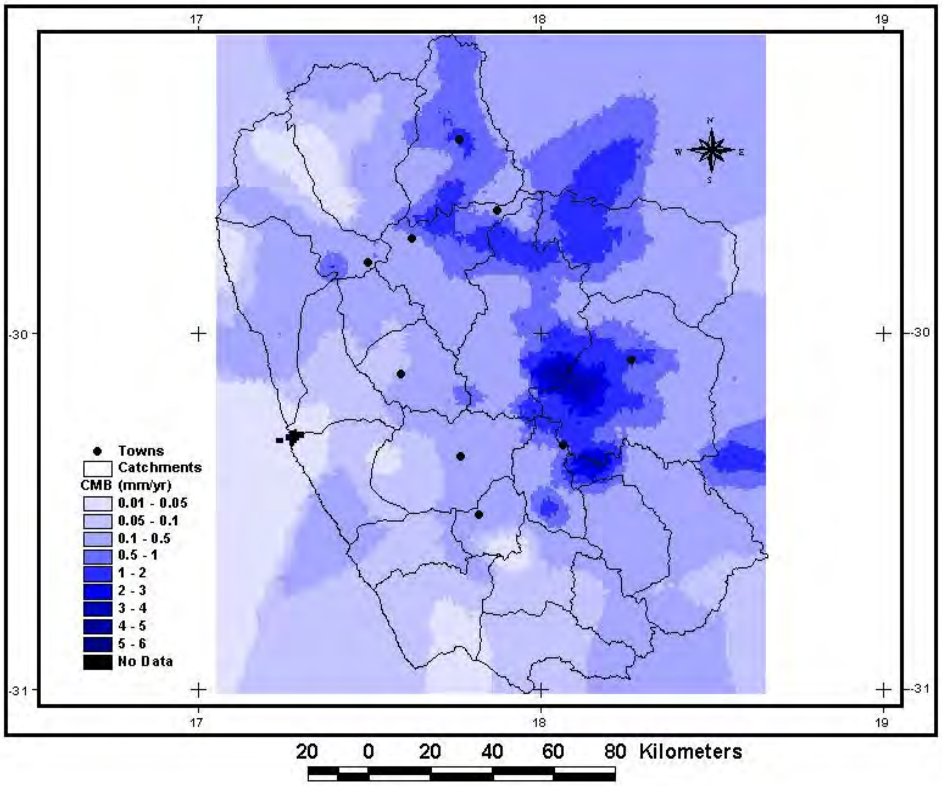


Figure 6.9: **Annual recharge (mm/yr) for the central Namaqualand area using NGDB data.**

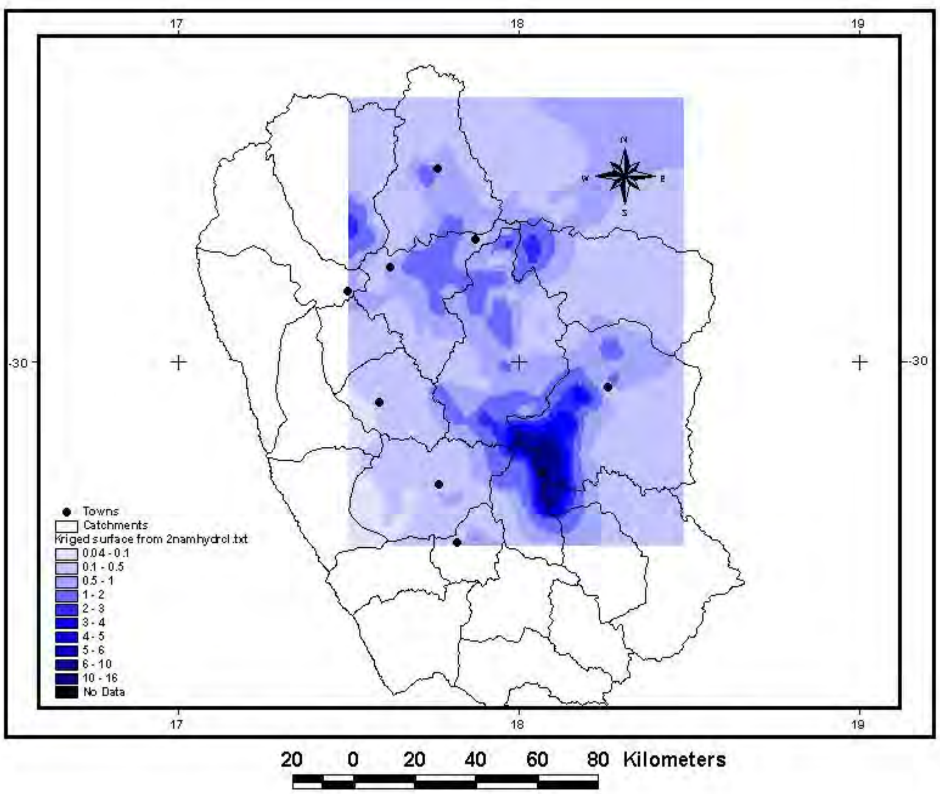


Figure 6.10: **Annual recharge (mm/yr) for the central Namaqualand area using hydrocensus data.**

6.2.1 Stable isotopes (deuterium and oxygen-18)

The stable isotopes deuterium and oxygen-18 can be used to differentiate between water that recharged directly and water that was added indirectly to the saturated zone. The isotope approach gives a qualitative indication of the recharge processes. Samples from the bulk rainfall samplers and groundwater from selected sites were analysed for the stable isotopes oxygen-18 and deuterium (Figure 6.10).

Precipitation composition

Rainfall mainly occurs during the months May to August. Rainfall gradually increases from west to east, due to the distance from the sea and change in altitude (orographic effect). Rainfall decreases again after the escarpment (Pre- Bushmanland). This is a direct result of a different circulation pattern operating over the Bushmanland Plateau, which receives summer rainfall. Variations in δD and $\delta^{18}O$ can be used to study recharge due to the isotope variations inherent in precipitation. Dansgaard (1964) identifies temperature, latitude, altitude and seasonality as the main factors that control the isotopic variations in precipitation.

The δD and $\delta^{18}O$ values of rainwater, collected in the totalisers indicate that both the δD and $\delta^{18}O$ values decrease from the coast to the interior. This may be due to the altitude effect and the process of rainout whereby the δD and $\delta^{18}O$ values in clouds decrease as the fraction of vapour remaining in the cloud decreases as the cloud front moves inland. The stable isotopes, plotted on an $\delta^{18}O$ versus longitude diagram (Figure 6.11), indicate that the different sampling stations receive rainfall with distinct isotopic compositions. The outlier is a sampling station (Wallekraal) that is situated at the lowest point of all the stations and has the lowest rainfall for the measured period. It is postulated that this area only received one rainfall event during the sampling period.

The samplers were set up to determine if the isotopic composition of the rainfall is similar or different from the Global Meteoric Water Line (GMWL) of Craig (1961). The GMWL is characterized by a linear relationship between δD and $\delta^{18}O$ of precipitation and is given by:

$$\delta D = 8\delta^{18}O + 10 \quad (6.2)$$

This relationship is based on precipitation data from different locations around the world. Individual locations have lines of best fit with slightly different equations to the GMWL, which are termed local meteoric water lines (LMWL). The Local Meteoric Water Line for the study area was determined by using data from the bulk rainfall samplers (Figure 6.12). The data is shown in Table 6.6. The LMWL is defined by the following equation:

$$\delta D = 7\delta^{18}O + 8 \tag{6.3}$$

The bulk rainfall samplers collected rainfall over a one-year period, the rainfall represents the weighted average of the annual rainfall. It is assumed that minimal evaporation from the bulk rainfall samplers occur due to the silicon oil layer. However, the amount of evaporation from the bulk rainfall samplers with the silicon oil layer is directly related to the depth of the floating silicon oil layer (Weaver and Talma, 2002). Ideally, rainfall amounts from the bulk rainfall samplers should be compared with rainfall amounts from another rainfall gauge at the same site. The weighted average annual δD and $\delta^{18}O$ values of precipitation would be expected to remain constant from year to year (Kendall et al, 1995). It may be lesser in an area of sporadic rainfall such as Namaqualand. The LMWL of Namaqualand is similar to the Western Cape LMWL of Diamond and Harris (1997). The precipitation of the Western Cape is defined by a meteoric water line with the approximate equation $\delta D = 6.1\delta^{18}O + 8.6$ (Diamond and Harris, 1997). Rain, for both areas, is derived from the same Atlantic Ocean frontal system.

Evaporated water generally forms an array on a δD versus $\delta^{18}O$ diagram, which has a shallower gradient than the LMWL. The slope of this line depends on the humidity at the place of evaporation (Gat, 1980). The lower the humidity, the less steep the gradient of the “evaporation line”. The samples taken from large diameter wells were removed from the data set because of the isotopic enrichment of the water within the wells, due to the high humidity above the water in the large diameter wells.

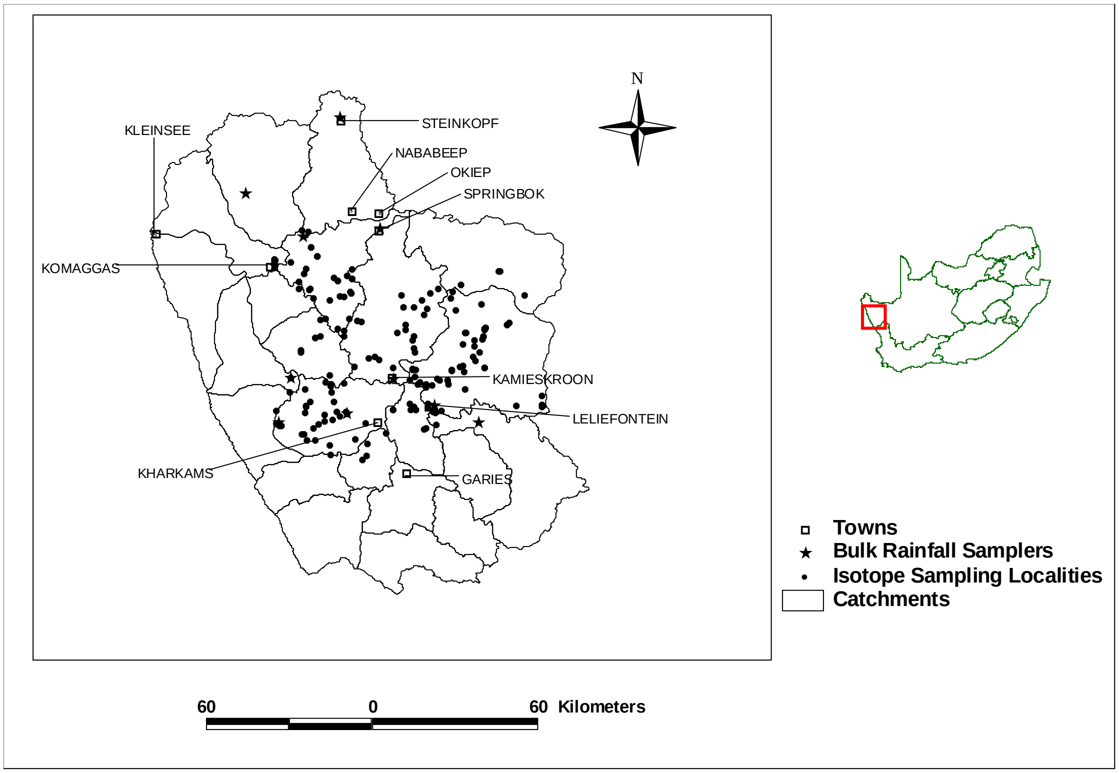


Figure 6.10: Sampling localities for stable isotopes.

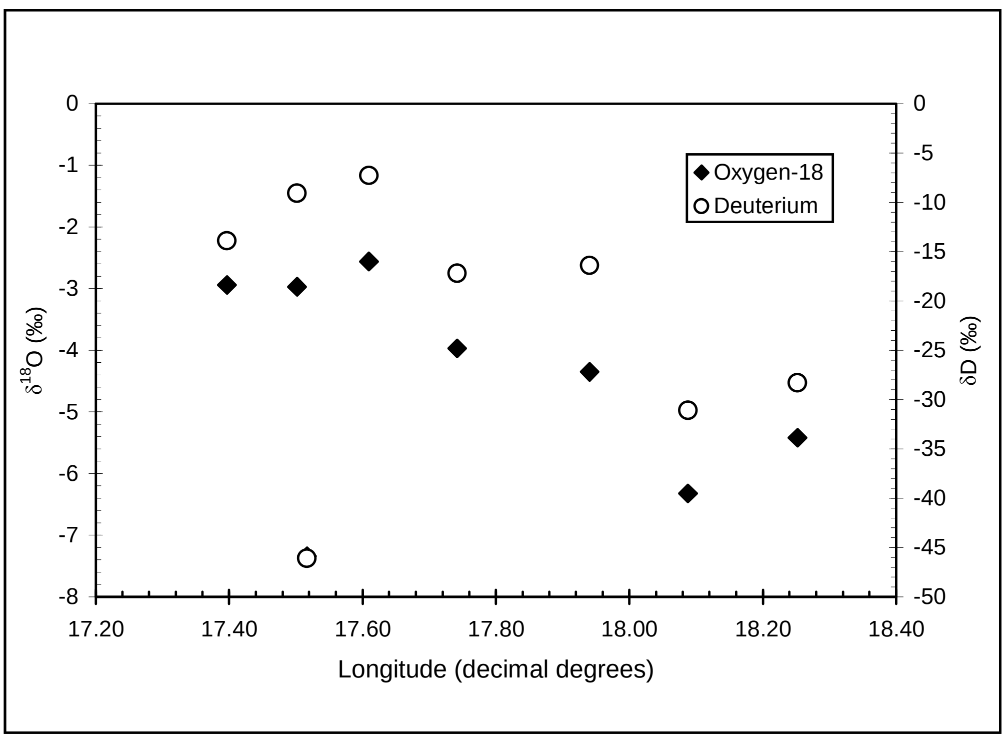


Figure 6.11: Plot of rainfall $\delta^{18}O$ and δD versus longitude.

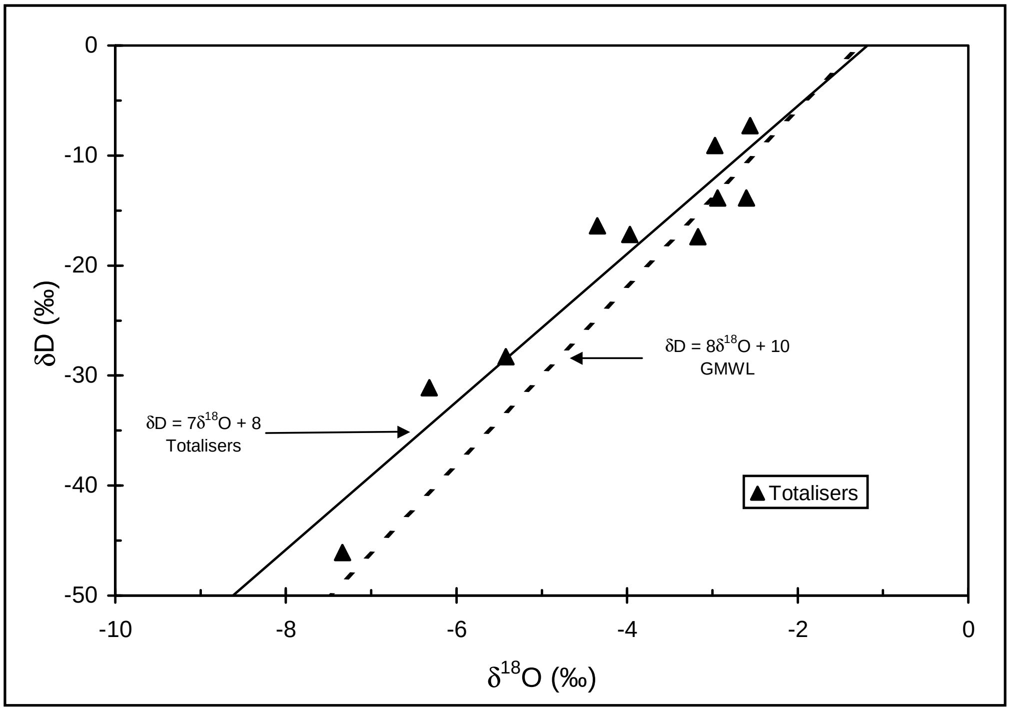


Figure 6.12: Plot of rainfall δD versus $\delta^{18}O$ data.

Table 6.6: Stable isotope data collected in bulk rainfall samplers.

Gauge	Site	δ^2H (‰)	$\delta^{18}O$ (‰)
G3	Buffelsrivier	-7	-2.56
G1	Kamieskroon	-16	-4.35
G4	Kommagas	-9	-2.97
G8	Langhoogte	-14	-2.94
G15	Leliefontein	-31	-6.32
G7	Paulshoek	-28	-5.42
G10	Soebatsfontein	-14	-2.6
G2	Spoegrivier	-17	-3.17
G6	Steinkopf	-17	-3.97
G13	Wallekraal	-46	-7.34

Groundwater composition

The isotopic composition of the groundwater in the study area will be used here to determine whether recharge is immediate or delayed. The δD and $\delta^{18}O$ values of the precipitation and the derived LMWL will be used to determine the processes that might have altered the isotopic composition of the recharging precipitation to the composition of sampled groundwater contained in the database for the area. The isotopic composition of groundwater in arid regions can be considerably modified from that of the local precipitation, as opposed to temperate regions (Clark and Fritz, 1997).

A diagram of δD versus $\delta^{18}O$ (Figure 6.13) shows the scatter of sampling points for all the groundwater sampled for the stable isotopes, the data is given in Appendix A4. The groundwater of the study area generally lies on the line:

$$\delta D = 4\delta^{18}O - 5 \qquad (6.4)$$

The groundwater of the region has a general slope of 4 indicating that most of the water has undergone some degree of evaporation. This is expected, as the current potential evapotranspiration rates are 12-15 times the precipitation. However, there are samples that follow the LMWL closely indicating little or negligible enrichment by evaporation.

The groundwater sampling points near the town of Leliefontein are also shown. Leliefontein is situated at about 1527 mamsl on the Kamies Mountains with a MAP of approximately 395 mm. Precipitation that falls in the Leliefontein region is immediately recharged due to both the high rainfall as well as the favourable conditions for recharge. Groundwater from higher lying areas, characterised by the Leliefontein samples in Figure 6.13, have depleted isotope ratios. The higher lying areas receives direct recharge as a result of:

- High rainfall;
- Exposed bedrock with little soil cover;
- Exposed fractures; and
- Fast runoff from the surface.

Topographically flat areas have the opposite characteristics and hence increase the chances for evaporation and the concurrent enrichment of the δD and $\delta^{18}O$ values.

The LMWL seems to be more dynamic and probably changes between seasons but can only be proved with the collection of additional data. This is indicated by the distribution of the groundwater sampling points and their distribution along the GMWL and LMWL.

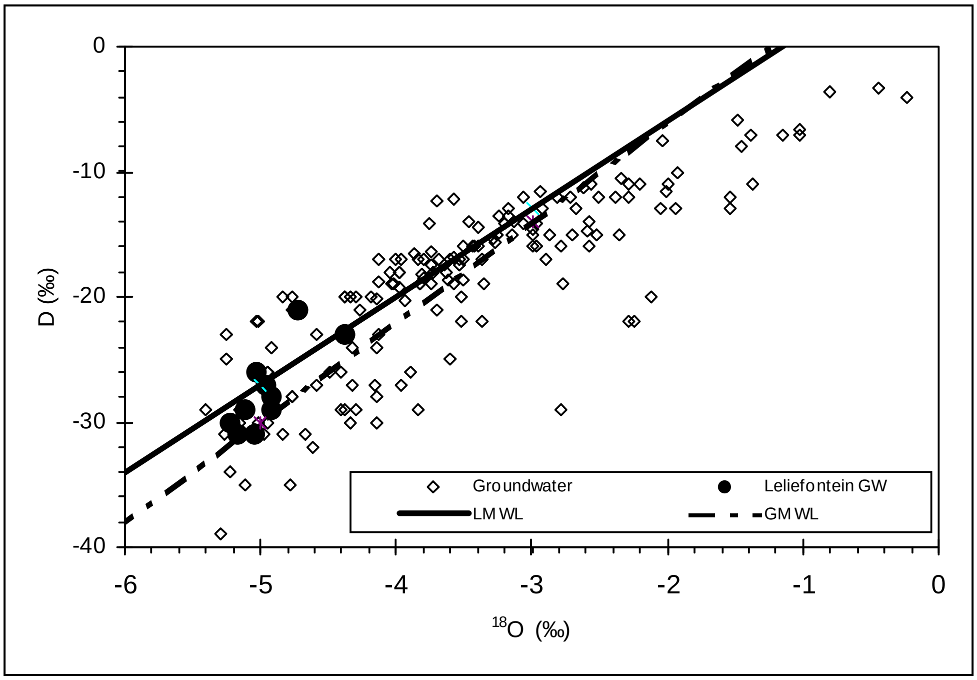


Figure 6.13: δD versus δ^{18}O diagram for the groundwater of the study area.

6.2.2 Radiogenic isotope (carbon-14)

Recharge areas, recharge rates, groundwater flow patterns and identifying non-renewable water resources can be defined by using the mean residence time of groundwater, derived from ^{14}C measurements. It is important that the combined inorganic and isotopic geochemistry be used with the conceptual understanding of the groundwater system when interpreting the radiocarbon results.

Mean residence times of the groundwater

Measured ^{14}C activities for groundwater samples, taken from 10 boreholes, range from 119.6 to 1.6 percent modern carbon (pmC). Table 6.7 shows the ^{14}C and chemical data for these boreholes. The sampled boreholes are not indicative of the area in which the borehole is located but more indicative of the position of the sampled borehole. As an example, the Komaggas sample was taken at a borehole within the vicinity of a streambed. Similarly, near Kamassies a borehole was sampled in the basement aquifer, whereas the town mostly uses water from the alluvial aquifers. ^{14}C activities may exceed 100 pmC in areas where groundwater contains tritium (Izbicki and Martin, 1997). Two samples in the Garies area have tritium data of 0.5±0.2 TU and 0.2±0.2 TU with ^{14}C values of 35.2±0.4 pmC and

59.9±0.5 pmC (DWAF, pers. comm.). Samples with high ^{14}C values are associated with sites where groundwater is abstracted from the alluvium. Two sampling groupings are identified, the basement and the alluvial aquifers (Figure 6.14). There is a direct correlation between ^{14}C values and chloride between the basement and alluvial aquifers, with the high salinity water having high ^{14}C values.

Table 6.7: Environmental isotope and chemistry data for the ten selected sites.

Site	^{14}C (pmC)		^{13}C	^{2}H	^{18}O	Alkalinity	EC (mS/m)	Cl (ppm)	HCO_3 (ppm)
Buffels River Town	114.8	±2.7	-13.33	-19.1	-3.95	143	216	34.5	229.6
Couragie	102.7	±2.6	-11.92	-24.8	-4.2	177	498	1555	244.7
Kamieskroon	103.9	±2.6	-14.67	-16.9	-3.83	220	386	1214	269.9
Kammasies	10	±1.7	-7.15	-28.3	-5.18	298	272	611	318.8
Klipfontein	1.6	±1.6	-11.69	-18.2	-3.83	93	564	1878	140.9
Komaggas	119.6	±2.8	-7.15	-12.9	-2.99	394	198	92.2	570.1
Leliefontein	44.8	±2.1	-16.47	-26.9	-5.57	55	32.3	56.8	93.4
Soebatsfontein	*29.8	±1.9	-10.88	-14.5	-3.19	115	568	1801.6	182.1
Spoegrivier	64.8	±2.3	-12.43	-16.8	-3.68	160	387	37.9	253.4
Wallekraal	nm	nm	nm	-14.9	-3.17	27	1452	5112	63.3

* Insufficient CO_2

nm = not measured

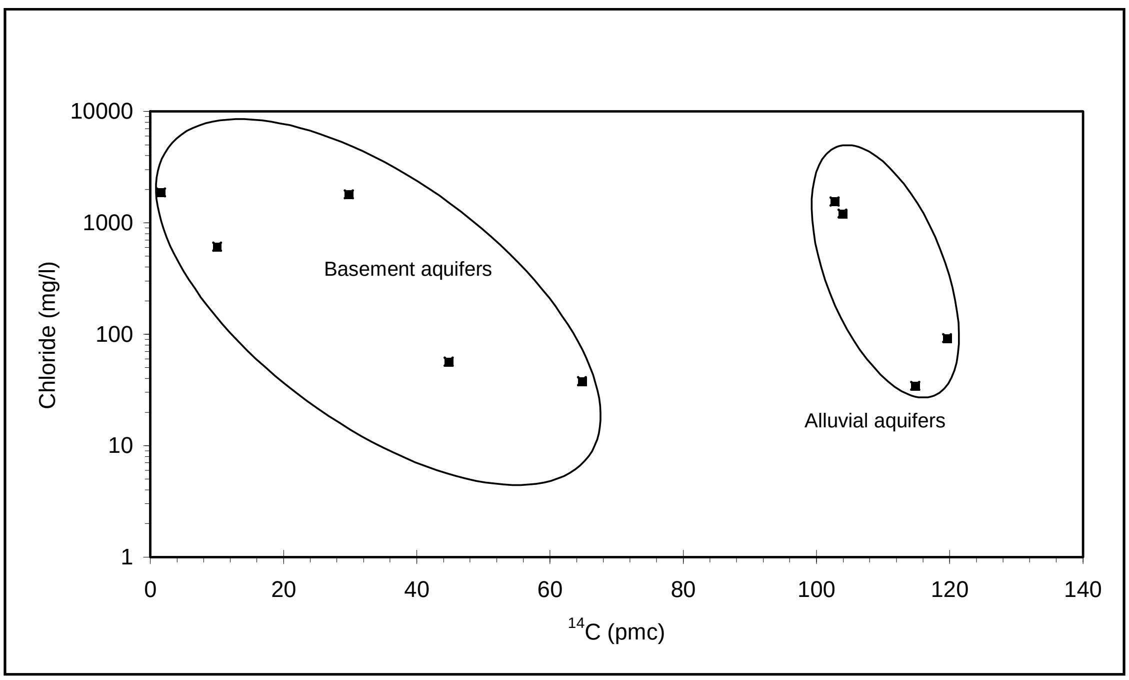


Figure 6.14: Plot of chloride versus ^{14}C for selected localities.

The initial ^{14}C activity was set at 100-90 pmC for data from the hard rock aquifers and the upper limit (120 pmC) of the measured ^{14}C for the alluvial aquifers (Table 6.7). A simplistic approach was followed to adjust the ages of the groundwater, as the objective of this study was to determine the relative ages of the groundwater since recharge using equation 3.11. The correction of ^{14}C data is fraught with uncertainties and the different correction methods do not give unique solutions (e.g. Plummer and Sprinkle, 2001). It is evident that the aquifers that are mainly recharged under current climatic conditions are the alluvial aquifers. These aquifers may recharge deeper hard rock aquifers or aquifers that are hydraulically linked with the overlying alluvial aquifers and visa versa. The Q values for the alluvial aquifers (>100 pmC) were assigned a value of 1 as lower values give negative ages and 0.85 is assigned to the hard rock aquifers (Hendry, 1988). The ^{14}C ages given here is used comparatively as it was taken over a large spatial area. Verhagen and Levin (1986) noted that no regional ^{14}C pattern exists in the area. In the Bulletrap area two samples show an age difference of about 12 000 years and in the Roodebergkloof area the difference is approximately 4000 yrs. (Table 6.8). Mixing of groundwater of different ages is probably the rule. Stacked flow patterns occur both on a local and regional scale. The groundwater "age" for the Leliefontein area is not realistic, based on the conceptual model and chemistry data. Conceptually, the Leliefontein area is situated in the escarpment zone with high rainfall and very low EC (averaging 35 mS/m) indicating fairly young and dynamic groundwater flow. The only plausible explanation is that there was a problem with the sampling or analysis at this locality.

Table 6.8: Unadjusted and adjusted mean residence times (MRT) of the groundwater in the study area.

Sample ID	A	Ao	MRT unadjusted	Q	Ave. MRT adjusted	Aquifer
Buffelsrivier	120	114.8	Modern	1	Modern	Alluvium
Couragie	120	102.7	Modern	1	Modern	Alluvium/Basement
Kamieskroon	120	103.9	Modern	1	Modern	Alluvium
Kammasies	100-90	10	19042-18171	0.85	17698	Basement
Klipfontein	100-90	1.6	34198-33327	0.85	32854	Basement
Komaggas	120	119.6	Modern	1	Modern	Alluvium/Basement
Leliefontein	100-90	44.8	6640-5769	0.85	5296	Basement
Rooifontein*	120	114	Modern	1	Modern	Alluvial
Soebatsfontein	100-90	29.8	10012-9141	0.85	8668	Basement
Spoegrivier	100-90	64.8	3588-2716	0.85	2244	Basement
Wallekraal	100-90	32.8	9219-8348	0.85	7875	Basement
Bulletrap*	100-90	76.1	2259-1378	0.85	500	Basement
Bulletrap*	100-90	17.2	14557-13686	0.85	12789	Basement
Roodeberg (G45781)**	100-90	35.2	8635-7764	0.85	6855	Basement
Roodeberg (G45783)**	100-90	59.9	4238-3367	0.85	2458	Basement

*** Toens and Partners (1990, 1991) ** Dwaf data (analysed by CSIR)**

6.2.3 Summary

The chemical and isotopic data of the study area can be used to characterise and delineate groundwater recharge. However, it is essential that the hydrogeology and aquifer characteristics be well understood in order to make any meaningful interpretations.

The use of the CMB method in this study is used to essentially delineate areas where direct recharge is occurring. Chloride concentrations in the saturated zone are a result of various processes and a mixture of various groundwater flow lines. The CMB method overestimate recharge due the fact that recharge in arid and semi-arid areas are event driven, with above average rainfall only occurring episodically. The rainwater chloride will be lower than that of the annual or wet season chloride input. Sami and Hughes (1996) came to the same conclusion for rainfall occurring over the Karoo. In addition, if there is runoff contributing to recharge over an area the CMB method will underestimate recharge. The CMB method will always underestimate recharge in the alluvial aquifers; they are recharged during events of significant runoff.

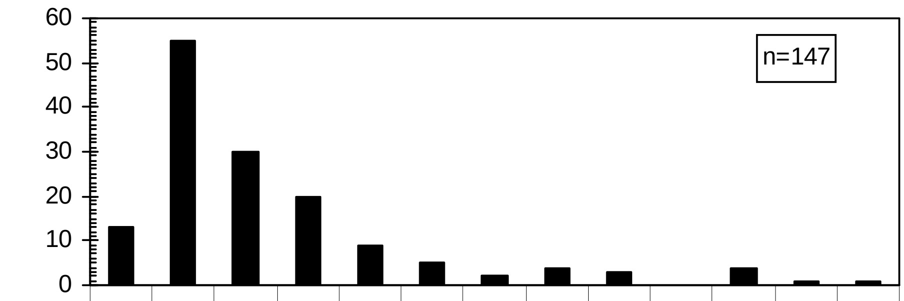
Rainfall over the study area varies in its isotopic composition. There is, as expected, a decrease in δD and $\delta^{18}O$ as the rain front moves from the sea towards the inland. The escarpment acts as a barrier for rainfall with the amount of rain rapidly decreasing behind the escarpment zone.

Groundwater level fluctuations show that recharge occurs mainly during the months of peak rainfall (May to August), as shown in the next section. The amount of rain is in turn related to the orographic effect (i.e. more rainfall in high lying areas). The higher lying areas are the main recharge zones for the basement aquifers, if favourable conditions exist. However, groundwater discharges directly from the aquifers as springs or seeps and can re-enter the subsurface, under favourable conditions, lower down the topographic profile. Often the water would evaporate prior to infiltration. Recharge is redistributed through the different aquifer systems, both laterally and/or vertically. The stable isotope signatures of the Leliefontein area are generally not the same as for the other higher lying areas (i.e. Springbok area) due to the effects of latitude (atmospheric circulation) and longitude (distance from the sea). Rainfall is further evaporated in areas where infiltration is delayed. In areas with thick soil cover (alluvial zones) infiltration is slow and as the water moves to the water table, it is evaporated through the unsaturated zone. Fractures and joints will act as conduits if they are open and well distributed. Recharge will be faster in unexposed areas where jointing and fracturing is dominant. Where stable isotope ratios do not appear to have been affected by evaporation, recharge must have infiltrated very fast due to the fact the annual potential evaporation is approximately 12-15 times the amount of precipitation.

The ^{14}C data shows that the alluvial aquifers host the most recently recharged water. This is a result of the local topography of the areas. The alluvial aquifers occur as narrow strips in the incised valleys. Runoff is channelled in most cases to these areas and hence the increased potential for recharge.

6.3 Physical Methods

Estimating recharge by correlating water levels, rainfall and aquifer storage was identified as the most promising method for application in the study area. Bredenkamp et al. (1995) and Bredenkamp (2000) have shown that the CRD and SVF methods are probably the most successful in estimating recharge in South Africa. Bredenkamp (2000) also developed the moving average (MA) method to estimate recharge using mainly rainfall and water level data. The methods involving water levels require a good knowledge of the S-values of the aquifers. Water level data are used to determine the spatial and temporal changes in water levels and apply these changes, whether it is anthropogenic and/or naturally induced changes, to estimate aquifer storativity and then recharge. Conversely, if recharge is known the storativity of an aquifer can be determined. Water level monitoring is mainly restricted to the boreholes incorporated into the rural water supply schemes of the study area. Water levels in the study area, extracted from the Namaqualand hydrocensus database, reveal that most of the water levels occur between 5-20 mbgl (Figure 6.15). Water levels can be measured with ease in shallow groundwater systems and the errors associated with water level measurements are considered minimal. Methods involving the use of water levels are sensitive to the depth to water level. As the water level becomes deeper, the relationship between rainfall and recharge becomes weaker. The area of influence is also an important parameter to determine. The area of influence is generally considered to coincide with areas that contribute to recharge.



	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	>60
Frequency	13	55	30	20	9	5	2	4	3	0	4	1	1

Figure 6.15: Water level data for the study area (hydrocensus database).

Rainfall is measured at most of the abstraction schemes using standard rain gauges. Errors in rainfall measurements are mainly derived from the collection method. Rainfall measurements are usually underestimated. Underestimation of rainfall in gauges due to wind field deformation, wetting on the internal walls and evaporation accounts for losses of 2-10%, 2-10% and 0-4%, respectively (Rubel and Hantel, 2001). Rainfall can thus be underestimated by 4-28%. Legates and Willmott (1990) estimated that the average global precipitation might be underestimated by about 11% due to systematic biases.

Aquifer response

Hydrographs from production and observation boreholes show that the water levels in the boreholes fluctuate in response to recharge, abstraction, hydraulic properties of the aquifer and the aquifer configuration. Boreholes are generally drilled in fracture zones, contact zones and highly weathered zones, as they are the most conductive zones in basement areas. Boreholes and large diameter wells are also drilled into the alluvial aquifers associated with valleys, paleochannels and ephemeral rivers. Four typical hydrograph responses for the different aquifer settings have been identified in the study area:

Type 1: Boreholes that are drilled in topographically high areas with little soil cover and high rainfall (Figure 6.16). There is a strong relationship between the amount of rainfall and groundwater abstraction and aquifer (water level) response. Steep drawdowns during pumping and the fast recovery thereafter is an indication of the low storativity and high transmissivity. The electrical conductivity (EC) of the water remains constant, thus indicating a short groundwater flow path within an actively recharged aquifer system. The limiting factor in this aquifer type is the storage. Cook (2003) states that if the water table rise in the fractures is very fast, relative to the matrix permeability, then the specific yield will be similar to the fracture porosity. Due to the lack of weathered overburden most of the storage is in the fractured bedrock, this produces the sharp fluctuations in the water level.

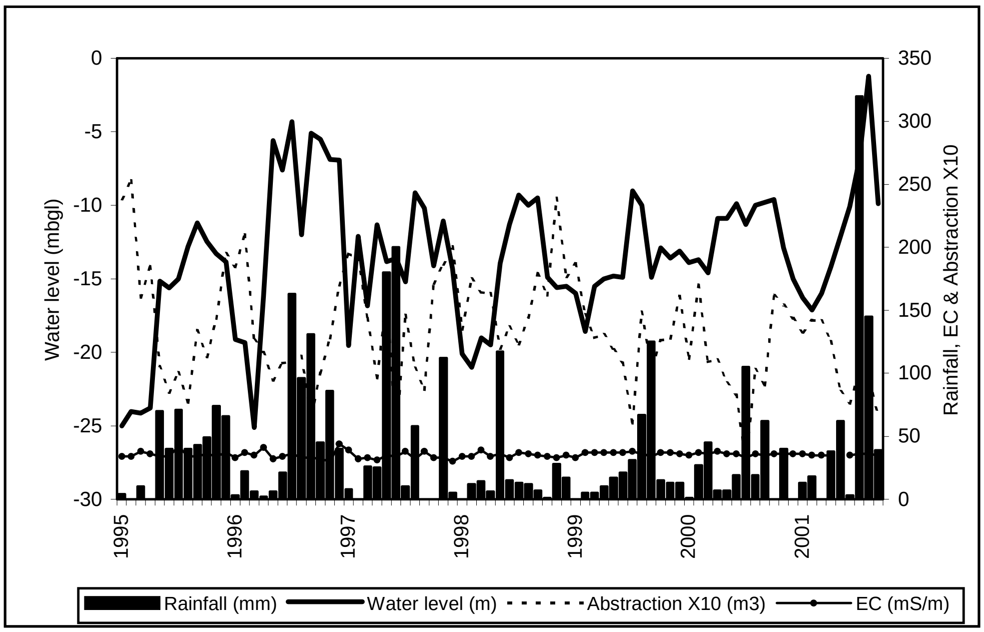


Figure 6.16: Type 1 hydrograph.

Type 2: This specific borehole is found in granite where a 2m thick-inclined brecciated fault zone, was targeted at 38 mbgl (Figure 6.17). The water levels are mainly controlled by abstraction and rainfall. The water levels recovered considerably after abstraction has been decreased. Again, this implies relatively low storativity. Recharge to the borehole is both from direct rainfall recharge and from recharge through the fault zone through lateral groundwater flow. Groundwater flow is controlled by recharge events in the upper reaches of the catchment. The water level is maintained by periods of low rainfall and abstraction, indicating the flow of water within the fault. This flow may be regional or localised. The constant EC values indicate that it may be recently recharged water flowing within the aquifer near the fault zone.

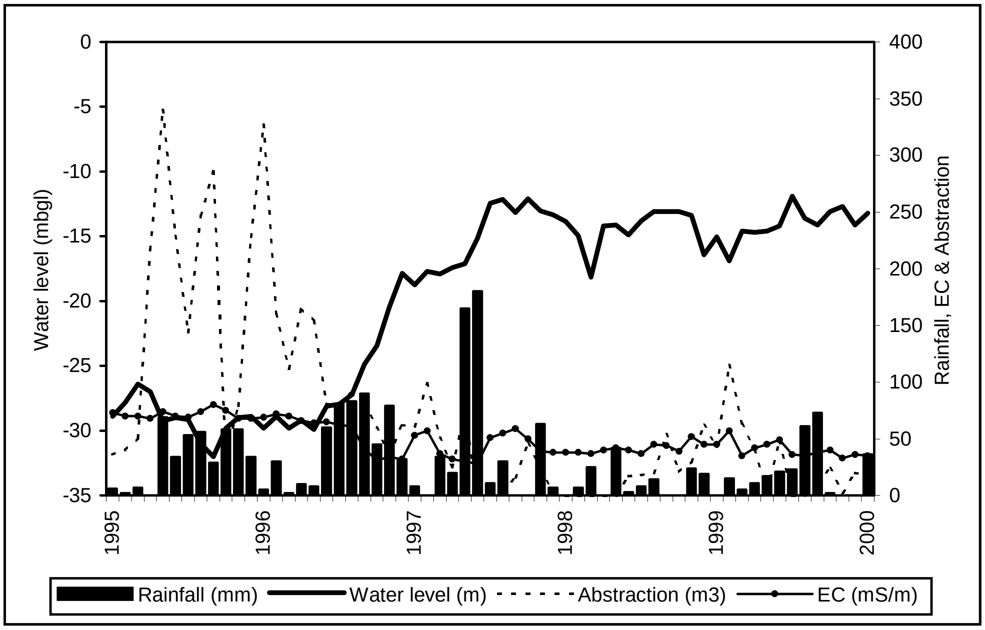


Figure 6.17: **Type 2 hydrograph.**

Type 3: Boreholes that are drilled in alluvium and the weathered zone (Figure 6.18). This water level responds to both rainfall recharge and abstraction. During periods of no rainfall, the water level declines significantly. The target is the alluvial aquifer associated with the Buffels River and the underlying weathered zone associated with a major fracture zone. Groundwater storage occurs both in the alluvium and the weathered zone in the wet months and during the drier months storage is primarily in the weathered zone. The two aquifers are often interlinked, resulting in relatively large storage. During the wet seasons, active recharge is taking place through the stream. The water levels were prevented from rising to the surface through increased exploitation of the aquifer. This is probably the best management practice in this situation; otherwise, water will be lost through evapotranspiration, runoff and subsurface flow in the alluvial zone. Recharge pulses is also manifested by the behaviour of the EC curve. Dilution of the groundwater by incoming meteoric water is the explanation for these phenomena.

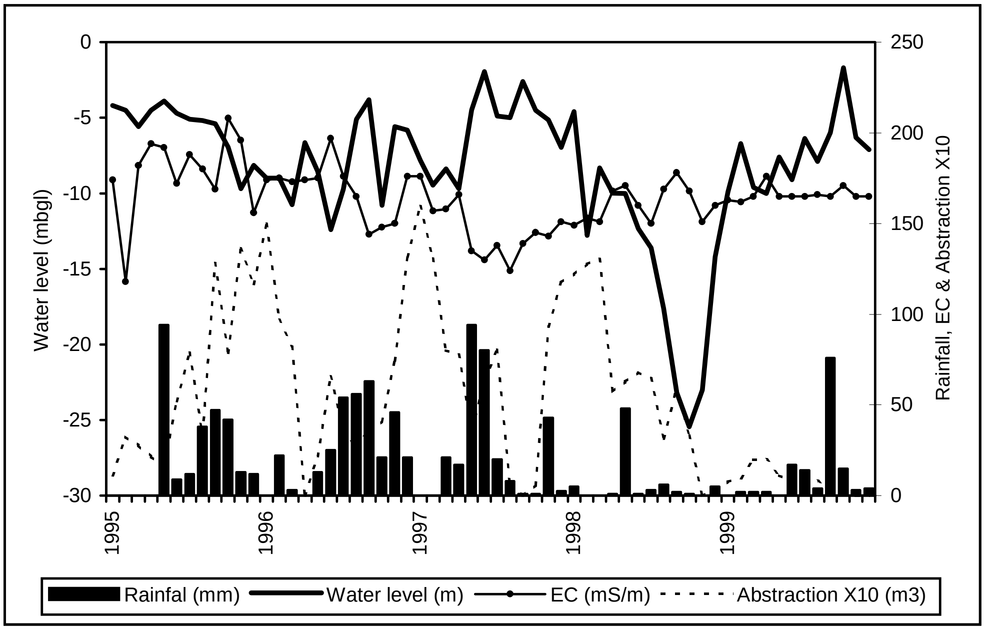


Figure 6.18: Type 3 hydrograph.

Type 4: Boreholes that are drilled in the alluvial aquifers associated with a ephemeral river (Figure 6.19). The alluvial systems associated with the major ephemeral rivers receive groundwater from the surrounding aquifers as well as from the upper reaches of the river. The water level dramatically responded to the above average rainfall events that occurred during the wet seasons of 1996 and 1997. The effect of the major response was a result of water movement from the upper parts of the catchment. Rainfall in the upper parts of the catchments reached record levels (1 in 80 year event). The major source of recharge in this environment was both vertical and lateral. The water levels are more affected by the lack of rain after the 1997 floods and the increased abstraction rates. If groundwater is not exploited the water table will gradually decline due to evapotranspiration and drainage. The system would probably return to pre- 1996 season levels if the lack of rainfall in the area continues. The EC of the groundwater decreased after the peak of the rainfall and water level rise, and generally rises as water from the upper parts of the catchments start to flow into the system. The CMB method will underestimate recharge in these settings, and must be applied with caution. During the dry season, water is stored in the banks of the stream (*see* Figure 5.14) and is released over time as depicted in Figure 6.20. A major NNW fault is present below the alluvial aquifer near the borehole.

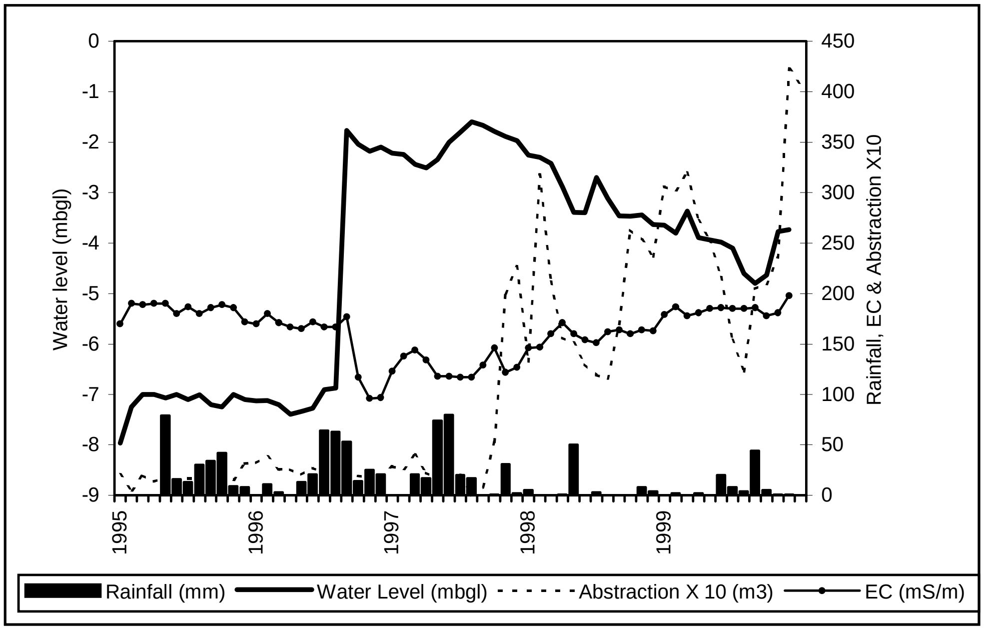


Figure 6.19: Type 4 hydrograph.

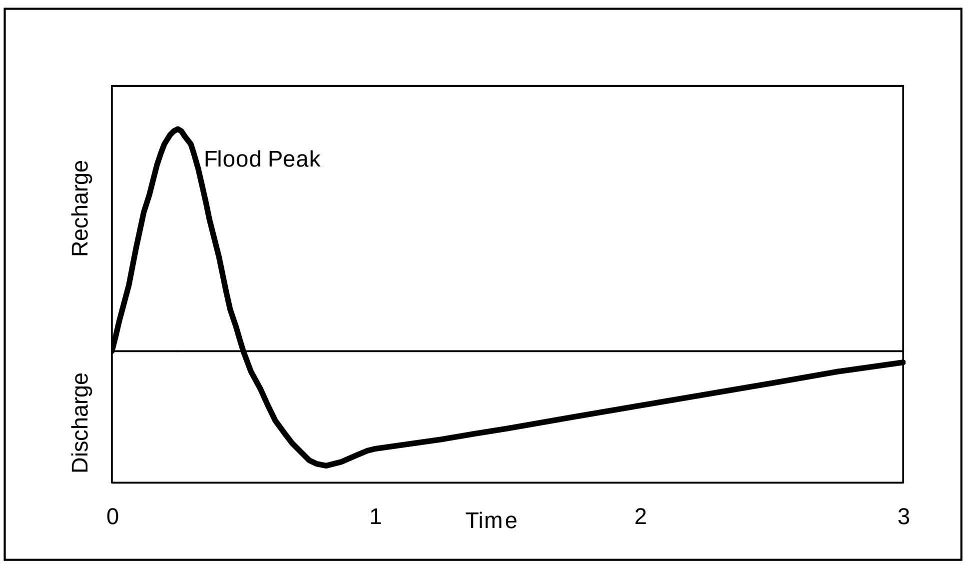


Figure 6.20: Bank storage response to periods of high recharge from a stream (after Todd, 1980).

Water level approach

SVF, equal volume and CRD simulations were developed for six areas where complete data sets were available for at least five years (1995-1999). The data used are given in Appendix A5. Unfortunately, data after this period could not be obtained. The data needed to develop the simulations are rainfall, water levels, abstraction, recharge area and storativity. The recharge areas were determined from 1:50 000 topographic maps. The boundaries were carefully selected and in most cases correspond to topographic boundaries. This assumption is probably doubtful in fractured rock terrain where flow occurs in regional structures across some of these boundaries. The simulations are all carried out using Excel based software. Observed water levels are converted to fluctuations from the mean water level for the revised CRD simulations.

Site descriptions

Buffels River

Two types of aquifers occur near the town of Buffels River, an alluvial and basement aquifer. The main water supply for the local community comes from the Orange River-Kleinsee pipeline. Groundwater is abstracted from mainly the alluvial aquifer unit. Deeper boreholes also occur in the area that targets a NNW striking fault (no water level and abstraction data is available for these boreholes). The alluvial aquifer unit (3 boreholes) is monitored on a monthly basis. The boreholes in the alluvial aquifer are drilled to the base of the alluvium. The thickness of the alluvial unit from borehole logs varies from between 6.1 - 14 m. From pumping test analysis the specific yield of the borehole was estimated to be 10^{-3} - 10^{-2}. Two of the three boreholes were destroyed during the 1997 rainy season when exceptional rainfall occurred over the area. The MAP for the area is 188 mm. Three boreholes have monitoring data available for analysis.

Bulletrap

This settlement is located approximately 26 km north of Springbok. The area is underlain by phorphyritic leukogranites, syenite and quartzitic layers in schist (Toens and Partners, 1996). Primary and secondary aquifers occur in the area with the main target zones for the boreholes being the brecciated fault zones and the joints cutting across the area. The MAP for the area is 172 mm. Six boreholes have monitoring data available for analysis.

Klipfontein

This settlement is located approximately 25 km southwest from the town of Karkams. Toens and Partners (1991) reported that the groundwater in the area is not suitable for domestic use. The water quality is being improved through desalinisation. The boreholes are located within a fault zone of the fractured gneiss aquifer. The ^{14}C data indicate that the water near Klipfontein is approximately 30 000 years old. The MAP for the area is 196 mm. Two boreholes have monitoring data available for analysis.

Komaggas

Groundwater is abstracted from the primary and secondary aquifers. Fault, joint and brecciated zones constitute the aquifer. According to Toens and Partners (1992), the metasediments occurring in the area is regarded as the “parent” source for water. The town is situated along an intermediate discharge zone, the coastal aquifers to the west. The MAP for the area is 229 mm. Fifteen boreholes have monitoring data available for analysis.

Rooifontein

The town of Rooifontein is located near the Buffels River in the escarpment zone. Both the alluvial and basement aquifers are used in the area. The alluvial aquifers are the main source of water for the community. The MAP for the area is 138 mm. Two boreholes have monitoring data available for analysis.

Spoeg River

This settlement is located approximately 15 km west from the town of Karkams. Both alluvial and basement aquifers occur in the area although the alluvial aquifers are not being exploited because of their limited extent. Groundwater is exploited from the numerous fault zones occurring in the area. A thin alluvial cover is located on the fault zone from which water of very poor quality was abstracted in the past. The poor water quality may indicate that the alluvial aquifer is in hydraulic contact with the basement aquifer and may be associated with a discharge zone for regional groundwater flow. ^{14}C ages give a age of 2000 years for the groundwater. The MAP for the area is 200 mm. Four boreholes have monitoring data available for analysis.

6.3.1 Saturated Volume Fluctuation

Aquifer storativity or specific yield is often used in hydrogeology to transform a change in groundwater level to an equivalent change in water storage and hence recharge (Sophocleous, 1991). The storage coefficient of an aquifer is defined as the volume of water that an aquifer releases or takes into storage per unit area of aquifer per unit change in hydraulic head. Several methods exist in determining aquifer storage these include the interpretation of hydraulic tests (e.g. aquifer test data), volume balance methods (e.g. saturated volume fluctuation (SVF) method), water budget methods, geophysical methods and field capacity tests (Healy and Cook, 2002). Storativity values were calculated for the study area using aquifer test data and values obtained by the SVF method. Values for S and T are routinely obtained from the analysis and interpretation of aquifer test data. S - values calculated during periods of no recharge, using the saturated volume fluctuation method

(Van Tonder and Kirchner, 1990), are expressed as:

$$S = \frac{(I - O - Q)}{\frac{\Delta V}{\Delta t}} \tag{6.5}$$

where:
I = inflow
O = outflow
Q = abstraction
ΔV = change in saturated volume aquifer material
Δt = time increment.

The SVF method is programmed in an Excel spreadsheet and includes additional tools to estimate S-values (SVF and recession period methods) and recharge (SVF and equal volumes). The results of the two methods are shown in Table 6.9. The S-values obtained by pumping test analyses are also included for the different areas for comparison. Recharge estimates from the SVF and equal volume methods are in close agreement.

Table 6.9: S-values calculated for the study area compared to the pumping test results.

Site	$S_{(SVF)}$	$S_{(PT)}$	R_{SVF} (%)	$R_{Equal\ volume}$ (%)	R_{SVF} (mm)	$R_{Equal\ volume}$ (mm)
Buffels River	$5X10^{-3}$	$1.0X10^{-2}$	2.8	2.5	5.3	4.7
Bulletrap	$5.43 X 10^{-5}$		0.2	0.2	0.3	0.3
Klipfontein	$3.86X10^{-5}$	$9.5X10^{-4}$	0.1	0.1	0.3	0.1
Komaggas	$7.83x10^{-4}$	$6.6X10^{-3}$	1.9	2	4.4	4.6
Rooifontein	$8.5X10^{-4}$		1.9	1.9	2.6	2.6
Spoeg River	$1.47X10^{-4}$	$1.4X10^{-4}$	0.1	0.1	0.2	0.2

The S-values obtained from the SVF method are an order of magnitude lower than that obtained from pumping test data. Bredenkamp et al. (1995) caution against the use S-values obtained from pumping test data, as the results can be unreliable in fractured rock environments. S-values calculated from the aquifer test data in crystalline basement aquifers are usually highly erroneous due to problems of non-uniqueness, the spacing of the observation boreholes and the connectivity of the observation boreholes with the pumping borehole. The values obtained from aquifer tests are averaged over the spatial zone of influence of the pumping borehole. The S-values obtained from the SVF method may also be subjected to the same errors as that of the pumping test data. The SVF value is probably closer than the true value because it integrates the S-value over a larger area. The values obtained using the two methods give a range in which simulations, using the CRD method, can be performed. The S-values can be relatively ascertained on the responses of the water level fluctuations. Rapid water level rises/drops indicate that the S-value is mainly associated with the fractures, indicating lower S-values. Slow water level rises/drops may indicate storage in the fractures and matrix, indicating higher S-values.

6.3.3 Cumulative Rainfall Departure

The CRD method uses the same data as the SVF method. The major advantages of using the CRD method in the Central Namaqualand region are: (1) the required simulation inputs are readily available (except the S-values); (2) the method can accommodate for variable pumping rates during simulation; and (3) the method can incorporate a lag time if water levels are deep and recharge is not immediate after a rainfall event. As the depth to the water table increases the correlation between rainfall infiltration and recharge decreases (Wu et al., 1996). Wu et al (1996) also state that for groundwater at intermediate depth the recharge events produced by individual rainfall events merge into one single annual process although a few peaks of recharge correspond to large rainfall events or concentrated rainfall clusters. The CRD method can also be used to determine the effects of pumping on a borehole hydrograph. Two versions of the CRD method is available, the Bredenkamp et al. (1995) and the Xu and Van Tonder (2001) methods.

The results of the CRD (2001) simulations are shown in Figures 6.21-6.26, the results for both are shown in Table 6.10. The approach was as follows:

- To calculate recharge by using both the SVF and aquifer test derived S-values; and
- To calculate recharge by using both the Bredenkamp et al. (CRD 1995) and the Xu and Van Tonder (CRD 2001) formulas.

Table 6.10: Recharge estimations using the two CRD methods and different S-values.

Site	Method	$Re_{SVF(S)}$ (%)	$Re_{PT(S)}$ (%)	Area (km^2)	$Re_{SVF(S)}$ (mm)	$Re_{PT(S)}$ (mm)
Buffels River	CRD (2001)	3.43	6.87	12	6.4	12.9
	CRD (1995)	6.56	13.11		12.3	24.6
Bulletrap	CRD (2001)	0.06		20	0.1	
	CRD (1995)	0.12			0.2	
Klipfontein	CRD (2001)	0.04	0.92	15	0.1	1.8
	CRD (1995)	0.07	1.78		0.1	3.5
Komaggas	CRD (2001)	0.29	1.64	25	0.7	3.8
	CRD (1995)	0.58	4.92		1.3	11.3
Rooifontein	CRD (2001)	0.54	3.06	8	0.7	4.2
	CRD (1995)	0.87	5.12		1.2	7.1
Spoeg River	CRD (2001)	0.04	0.04	25	0.1	0.1
	CRD (1995)	0.1	0.1		0.2	0.2

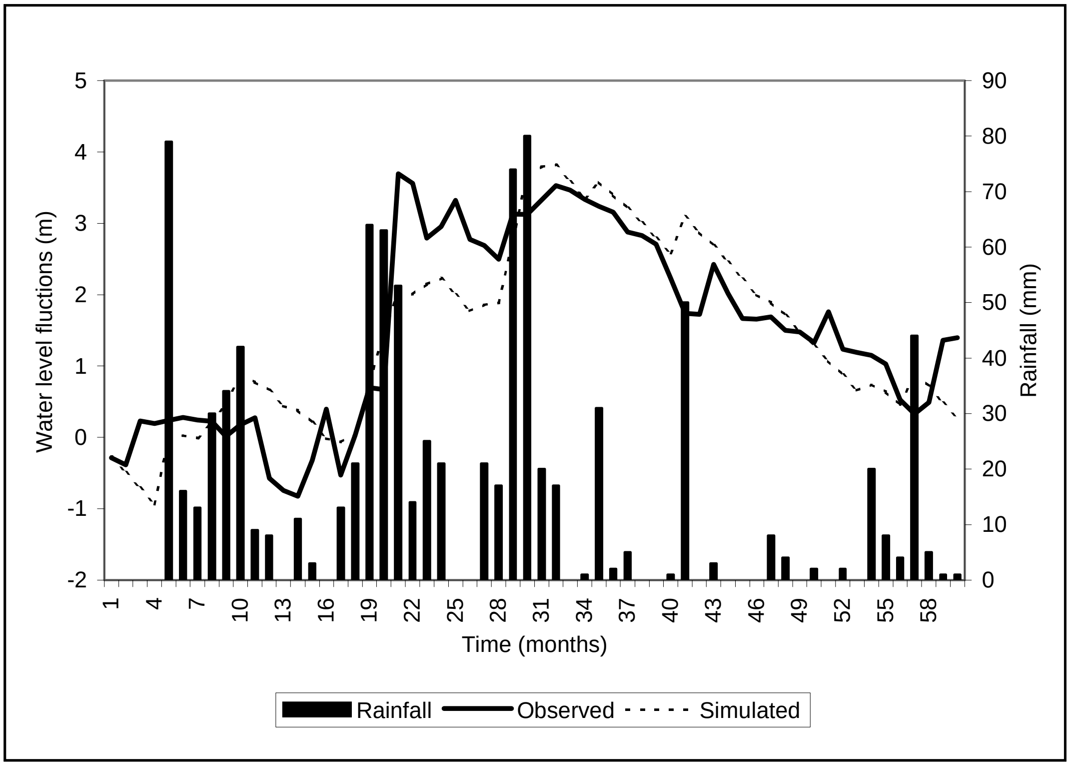


Figure 6.21: Observed and simulated water levels for the Buffels River town area.

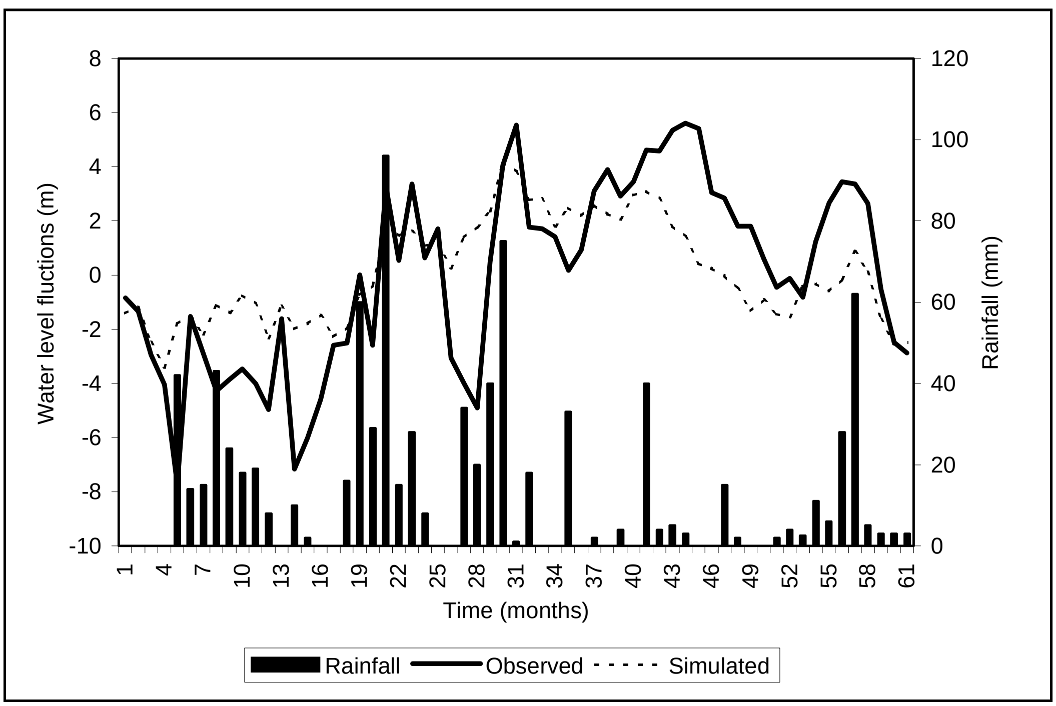


Figure 6.22: Observed and simulated water levels for the Bulletrap area.

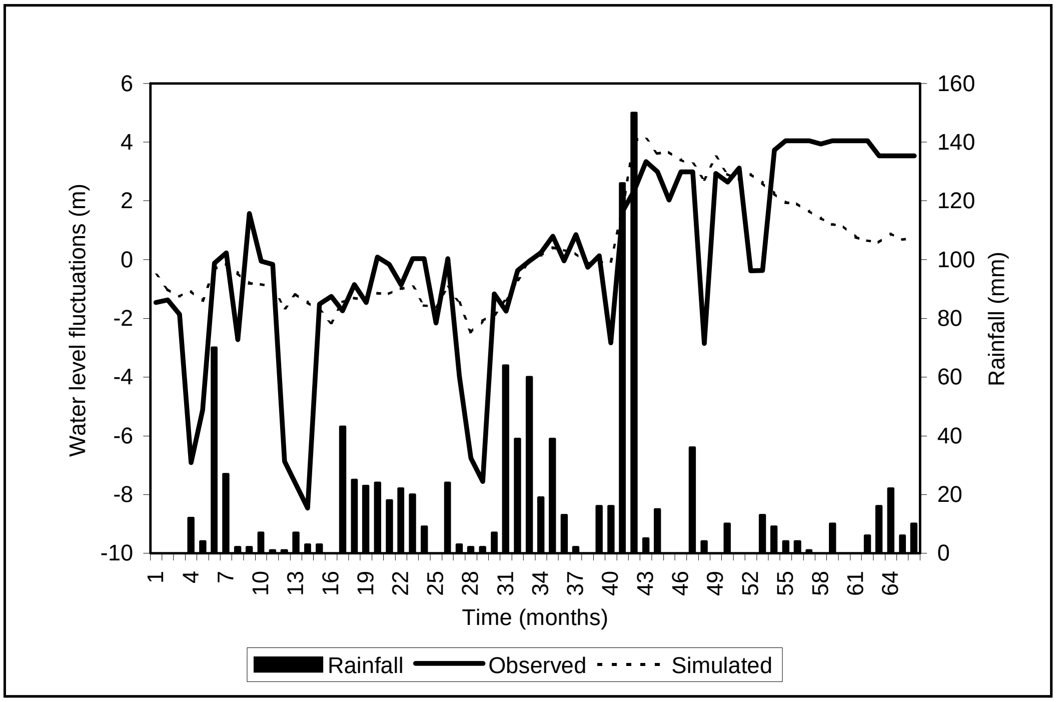


Figure 6.23: Observed and simulated water levels for the Klipfontein area.

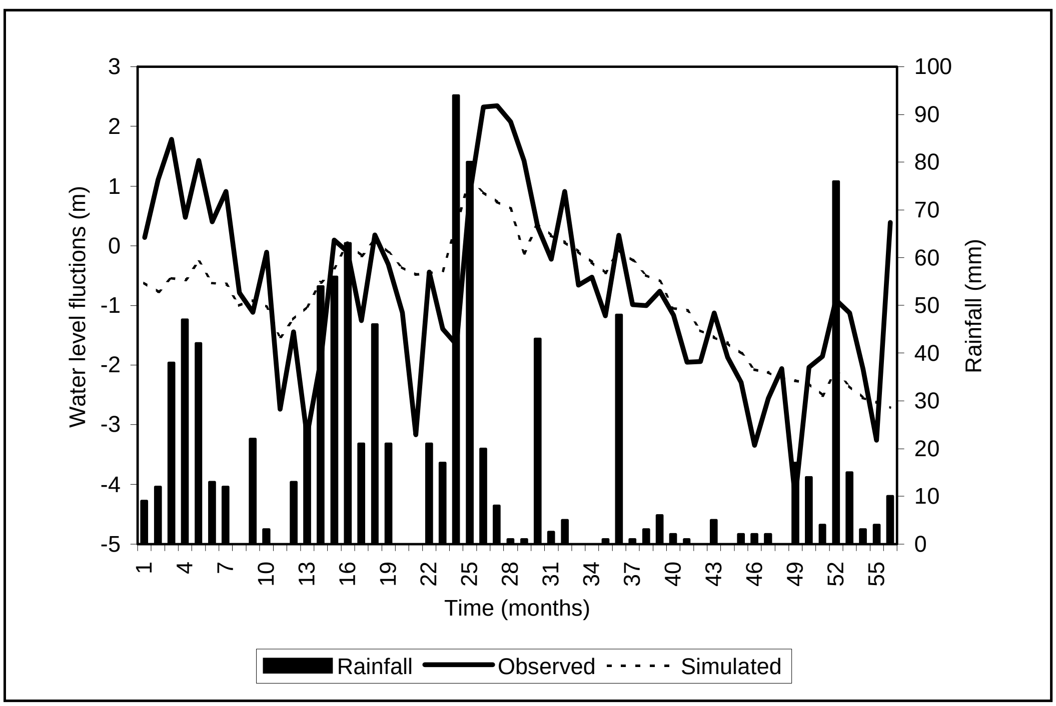


Figure 6.24: Observed and simulated water levels for the Komaggas area.

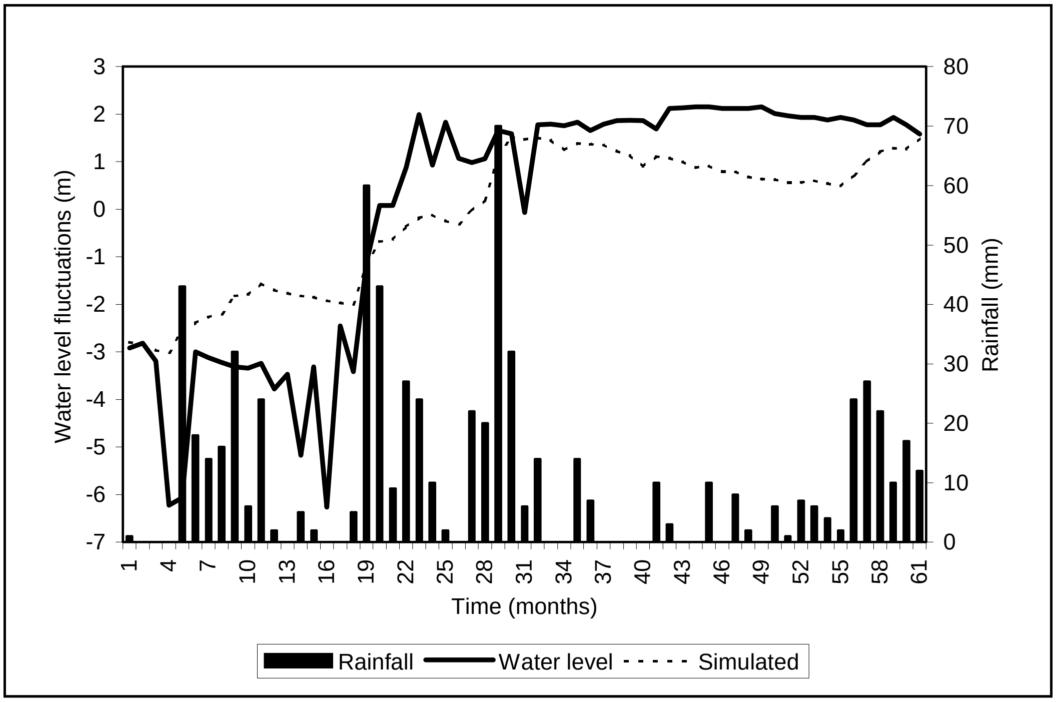


Figure 6.25: Observed and simulated water levels for the Rooifontein area.

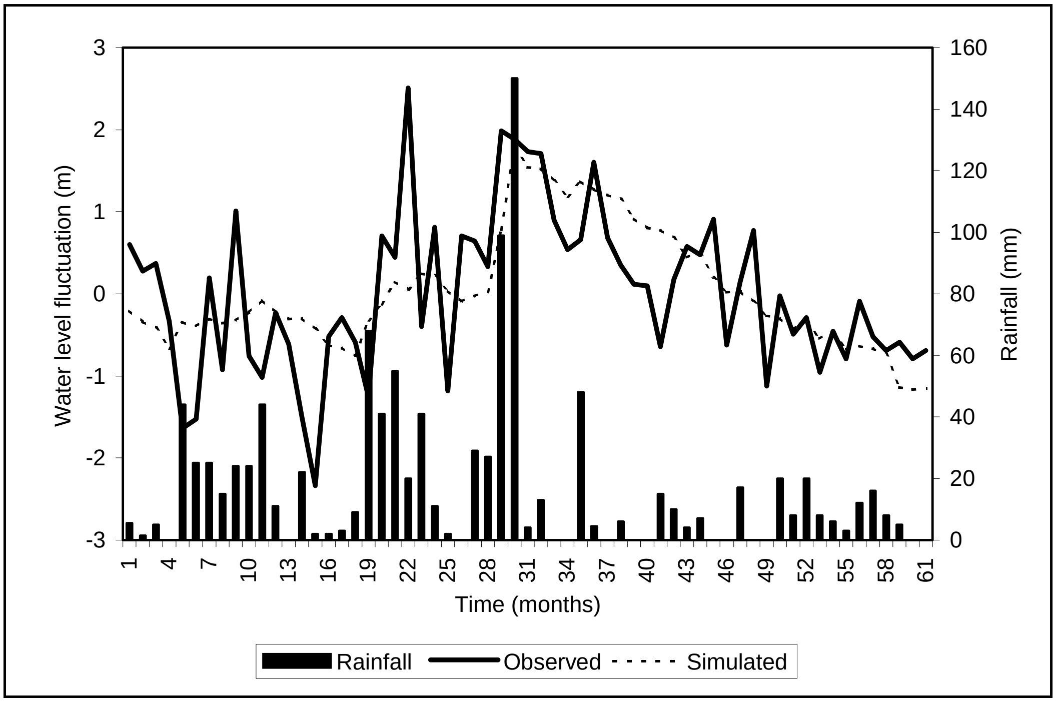


Figure 6.26: Observed and simulated water levels for the Spoeg River area.

Rainfall for the 1995, 1996 and 1997 periods were above average. Recharge, as seen by the water level responses, occurred over most of the area. However, because the method averages recharge over the whole period; periods of significant recharge may be masked. Simulations were also performed for periods of significant rainfall for the Buffels River town and Bulletrap areas (Table 6.11). Recharge occurring in the area was at a maximum during the 1996 rainy season. In 1997 when the flood occurred most of the water levels did not respond to the high rainfall as the 1996 rain event. This may be explained by the increased storativity at shallower depth. The flood event was probably linked to the high rainfall events that occurred during the 1996 as well as the intensity of the rainfall events of the 1997 season. The aquifers were recharged above the normal average annual recharge. The closest rainfall period that matched the 1995-1997 seasons occurred between 1950-1955 and the years 1976 and 1983 where rainfall was significantly above average (Figure 3.5). The average annual recharge decreased after the 1995-1996 rainfall seasons.

Table 6.11: Recharge values for different time steps for two sites.

Periods	Method	RE (%)	
		Buffels River	Bulletrap
1995-1996	CRD (2001)	7.93	0.15
	CRD (1995)	10.1	0.26
1995-1997	CRD (2001)	4.49	0.13
	CRD (1995)	6.84	0.28
1995-1998	CRD (2001)	4.23	0.08
	CRD (1995)	7.65	0.17
1995-1999	CRD (2001)	3.43	0.06
	CRD (1995)	6.56	0.12

6.3.4 Summary

The two CRD versions give in most cases different results, usually by a factor of 2. Xu and Van Tonder (2001) found similar variations when they applied both methods to the Grootfontein dolomitic aquifer. The results of the revised CRD (2001) is favoured because of the following (Xu and Van Tonder, 2001):

- The revised CRD method generally produces a better fit between the observed and simulated water levels;
- The method can account for variable pumping and outflow rates;
- It can account for trends in data; and
- The method does not require a large set of spatial data.

The disadvantages of the method are:

- The approach does not address parameter variations spatially; and
- Recharge is averaged over the simulated period and may be significantly higher than the average during periods of peak rainfall. It is well recognised that in drier climates that recharge events are associated with short periods of intense rainfall.

The simulations did not need time lag adjustments, as most of the responses were shorter than one month. Indicating that recharge from the surface to the groundwater is relatively fast if recharge occurs. The abstraction and the low S-values associated with the aquifers weaken the correlation between water fluctuations and rainfall. The simulated water levels deviate from the observed water levels due to the addition or removal of groundwater from the aquifer due to inflow and outflow. When water is flowing out of the aquifer the simulated fluctuation is higher than the observed fluctuation and if groundwater is being added via lateral flow or surface runoff from outside the recharge area the simulated water level will be lower than the observed water level. The spatial variability of recharge in the basement aquifers complicates the estimation of recharge and the relationship between the CRD and water levels due to the fact that spatial water levels are averaged. Bredenkamp (2003) indicates that the method works best in dolomitic aquifers where the highly permeable aquifers equalises the spatial differences in recharge. It has also been shown that the alluvial aquifers are receiving most of the recharge as opposed to the basement aquifers. Lumping the different water levels of basement and alluvial aquifers to estimate recharge may introduce discrepancies in the recharge rates calculated for different areas.

The recharge values estimated for the six areas indicate that recharge is not uniform over the study area. The variability of groundwater recharge is a function of the amount of rainfall, aquifer properties, geomorphology of the area and the geometry of the aquifer. Recharge, as a percentage of rainfall, is higher in areas where the main groundwater targets are alluvial aquifers or a combination of alluvial and basement aquifers. The Buffels River, Kamassies, Komaggas and Twee River communities are abstracting groundwater from the alluvium, which are fed by the surrounding hard rock and weathered aquifers. Areas underlain by fractured hard rock and weathered zone aquifers receive little recharge. Recharge to the fractured hard rock aquifers in the Spoeg River and Klipfontein areas receive very little recharge, manifested by the groundwater chemistry and ^{14}C data. The groundwater in these two towns are desalinised to make it fit for drinking. If groundwater is not exploited the water levels gradually decline after the main rainfall period due to evapotranspiration and drainage. Increasing abstraction prior to the main rainfall occurring months may increase storage and hence recharge rates under favourable conditions.

6.4 Statistical techniques

The statistical approach involves using groundwater chemistry and isotope data to delineate areas of recharge and discharge or negligible recharge. The method is attractive for application in the area, a large database with chemistry data exist. In South Africa, hydrochemistry data is readily available from the NGDB. This approach can also indicate regions where direct recharge occurs to the hard rock aquifers. The basic assumption is that in areas receiving direct recharge the water chemistry would not show large deviations from the rainfall chemistry as opposed to water that have undergone significant chemical changes as a result of evapotranspiration prior to infiltration and long residence times resulting in “old” and stagnant water with no “refreshening” from recharging rainwater. A statistical overview of the chemistry data is shown in Table 6.12 and the complete data set in Appendix A4.

Table 6.12: Namaqualand Hydrocensus chemistry database.

Namaqualand Hydrocensus Database			
Variable	**n**	**Mean**	**S. D.**
EC (mS/m)	232	327	305
pH	232	7.2	0.6
^{2}H (‰)	147	-18.8	10.4
^{18}O (‰)	147	-3.5	2.2
Ca^{2+}	232	161.15	172.65
Mg^{2+}	232	99.26	118.76
Na^{+}	232	454.49	582.99
K^{+}	232	9.37	21.69
HCO_3^-	232	144.90	72.33
Cl^-	232	938.17	1150.92
SO_4^{2-}	232	236.70	264.16
NO_3^-	221	23.41	39.45
PO_4^{3-}	120	0.23	0.34
F^-	231	2.18	1.30
Sr^{2+}	189	1.18	1.55
Al^{3+}	162	0.56	0.43
B^{3+}	161	0.46	0.56
Ba^{2+}	186	0.05	0.06
Cu^{2+}	125	0.01	0.02
Fe^{3+}	46	0.07	0.22
Zn^{2+}	178	0.35	1.42

All variables in mg/L unless otherwise indicated

The Statistica computer program was used to perform the factor analysis. Data was imported from the chemical database and missing data was casewise deleted. A correlation matrix was calculated for the different variables. Several variables, mainly the trace elements, were not included in the analysis due to missing data. The data was rotated (varimax rotation) to reduce the factor loadings to a simple structure by placing the highest possible loadings on the fewest number of variables, while preserving the independence of each factor and reducing the complexity further by allowing the factors to become slightly correlated (Levinson, 1980). In the data set, factor extraction was carried out by means of principal components. Varimax rotations are orthogonal and results in factors that are uncorrelated. During rotation, the Kaiser normalisation is applied, where only factors with eigenvalues greater than one are retained.

Numerical values are assigned to each factor, which can range from +1.00 to -1.00. These are commonly referred to as loadings, which are a measure of the extent to which each factor is associated with a particular value. If two loadings of the same factor have the same sign (either positive-positive or negative-negative) then they are positively correlated. If they have opposite signs then they are negatively correlated. Factor loadings and factor scores were extracted and interpreted. Only factor loadings greater than +3 and smaller than –3 are used in interpreting the factor loadings. These new combinations are then examined for significance in terms of process, types of samples, geological and geochemical information (Rose et al., 1979). Factor scores (Q-mode) are extracted for each sampling site for each factor. The factor scores for each sample were plotted and interpolated using Kriging over the study area. This process gives insight into the areal importance of the chemical processes represented by the different factors. The factor scores are related to the intensity of the chemical process described by any particular factor (Lawrence and Upchurch, 1982). Extreme negative values (< -1) indicates that an area is unaffected by the chemical process and positive scores (> +1) reflect areas most affected, whilst scores of zero (0) approximate areas affected to an average degree by the chemical process (Lawrence and Upchurch, 1982).

6.4.1 R- and Q-mode factor analysis

Four factors account for 70.4 % of the variance in the data set (Table 6.13). Factor 1 has a high loading of variables that contribute to the salinity of the groundwater in the area.

Included in this factor is the altitude of the sampling point. The altitude load weakly negative, indicating that salinity generally increases with decreasing altitude. Groundwater flow in topographically steep areas is dynamic resulting in water with low salinity. This factor has the highest eigenvalues and explained variance. The factors that influence factor 1 range from the aquifer, topographical, climatological and geological characteristics. It is assumed that areas with higher salinities occur in discharge zones and fresh water in recharge areas. However, the formation of saline soils as a result of evaporation, discharge and to a lesser extent irrigation return flow may during periods of high infiltration and subsequent recharge add to the salinity of the groundwater in recharge areas. Areas are also indicated where over abstraction leads to the upconing of poorer quality water. It is assumed that the poorer water qualities are old or fossil water. With the aid of downhole geophysics, it was shown that the water quality deteriorates with depth (Figure 5.20). The map of the factor scores, for factor 1, for each sample identifies possible recharge and discharge areas (Figure 6.27). The map of the factor score as expected would correlate well with an EC or TDS map of the area. Areas that fall in the zones defined by values (> +1) indicate highly mineralised water and are associated with discharge zones or zones that do not receive significant recharge under the current climatic regime. Areas that fall in zones of (0 to -1) are recharge areas and are characterised by fresher water. This zone is further subdivided into areas that receive direct recharge (<-0.5) and areas receiving indirect recharge (-0.5 to 0). Areas that occur between (0 to +1) are zones where mixing of fresh and saline water occurs these zones may also be overlapping recharge and discharge zones.

Table 6.13: Factor loadings for the 12 variables selected.

Variable	Factor 1	Factor 2	Factor 3	Factor 4
Altitude	-0.35	-0.51		
pH		0.38	0.50	
HCO_3	0.30		0.56	0.43
Na	0.87			
Cl	0.94			
Ca	0.91			
K	0.58			
Mg	0.89			
SO_4	0.76			
NO_3				0.88
F			0.88	
Sr		-0.87		
^{18}O		-0.86		
Eigenvalues	4.76	2.13	1.19	1.07
Cumulative % variance	36.62	53.02	62.21	70.41

All variables in mg/L unless otherwise indicated

Factor 2 includes pH, strontium, oxygen-18 and altitude (Table 6.13). The grouping has high negative loadings for strontium and oxygen-18. The exact explanation is not known for this loading. The crystalline basement rocks have high strontium concentrations. The presence of altitude within this factor indicates that the pH is controlled by the altitude and is a result of more acidic direct recharging precipitation. The strong strontium and oxygen-18 relationship dominates only in the northern part of the interpolated area (Figure 6.28).

Factor 3 includes pH, bicarbonate and fluoride (Table 6.13). The fluoride in the groundwater is generally high in the central Namaqualand area due to the influence of the geology. Elevated fluoride concentrations in the groundwater occur sporadically. The fluoride in the groundwater is mainly controlled by the pH of the groundwater. The processes that increase the fluoride and pH of the groundwater dominates at lower altitude or topographically lower lying areas. The presence of bicarbonate in this factor indicates localised recharge as HCO_3 is primarily derived from the dissolution of carbonate minerals by slightly acidic rainwater. The rainwater derives its acidity by atmospheric CO_2 and/or by biogenic processes in the soil zone. At higher altitudes or topographically steep zones fluoride concentrations are generally low. Areas receiving direct recharge seem to be unaffected but some distance away the process becomes significant. This is an indication of residence times and flow regimes. For this process to occur water had to be in contact with the rocks for some time. The <–1 contours delineates probable direct recharge areas. The factor scores (Figure 6.29) indicate that high fluoride concentrations are localised and seems to be enhanced by localised abstraction.

Factor 4 is characterised by a high nitrate and moderate bicarbonate loadings (Table 6.13). This factor is associated with pollution from agricultural activities. No geological origin for nitrate exists in the area. This factor indicates localised point recharge by nitrogen rich water resulting from animal drinking stations and possibly pit latrines. Livestock farming is the dominant agricultural activity and the planting of livestock feed. Fields are often tilled during the planting season. The factor scores (Figure 6.30) indicate that the process occurs only in localised patterns (i.e. point source pollution).

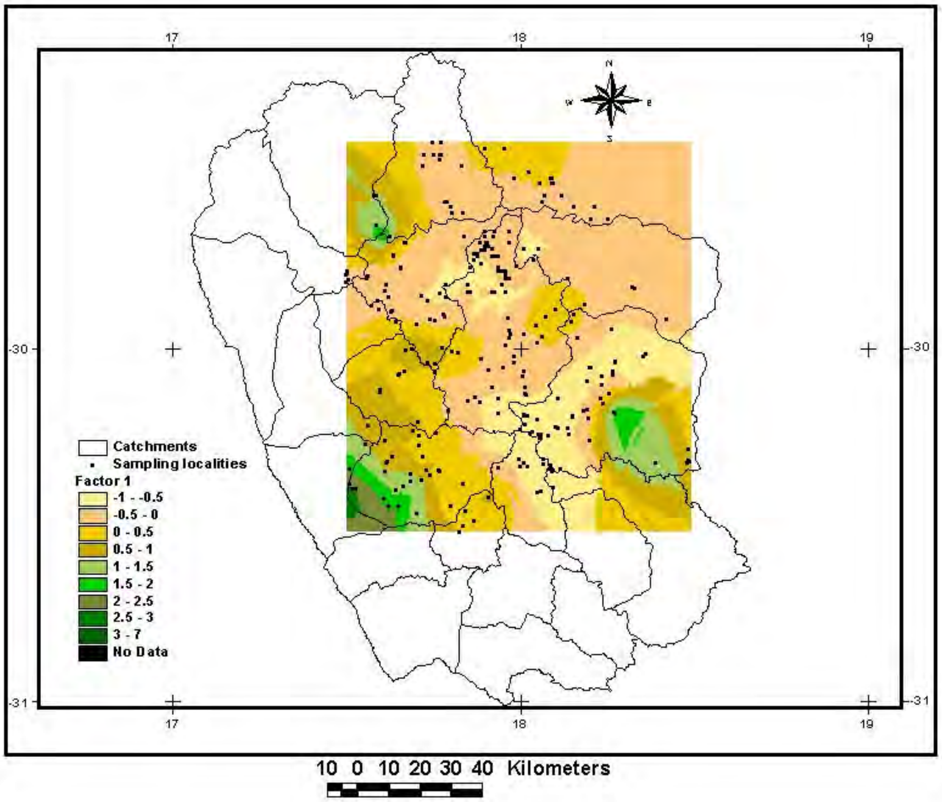


Figure 6.27: Distribution of factor scores for factor 1.

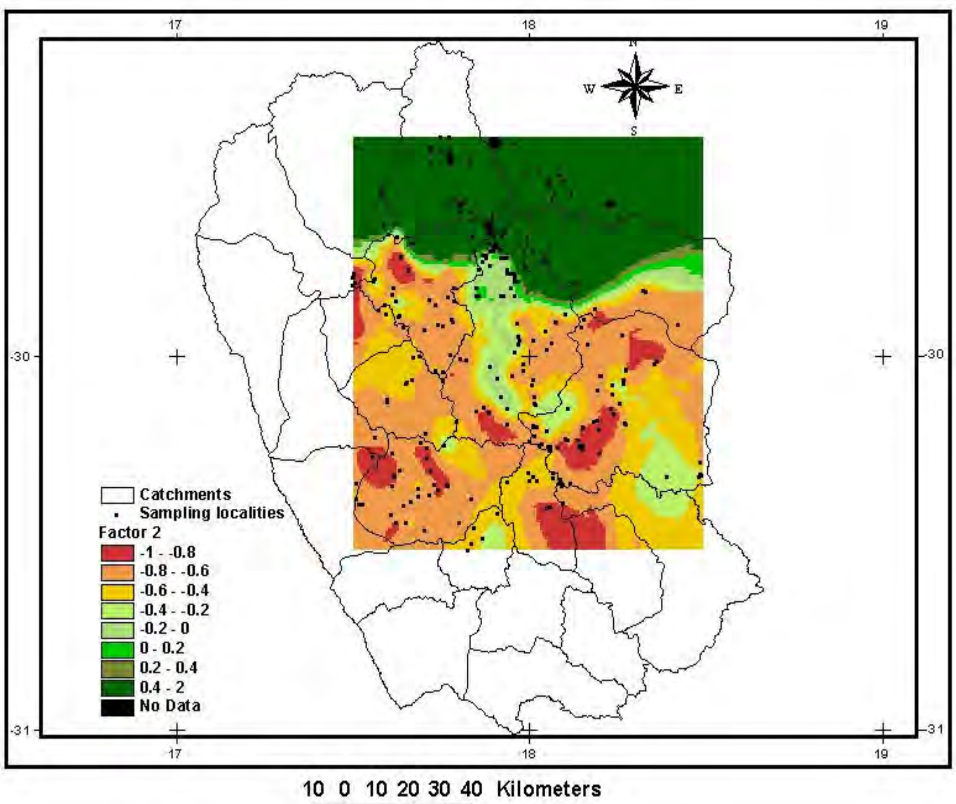


Figure 6.28: Distribution of factor scores for factor 2.

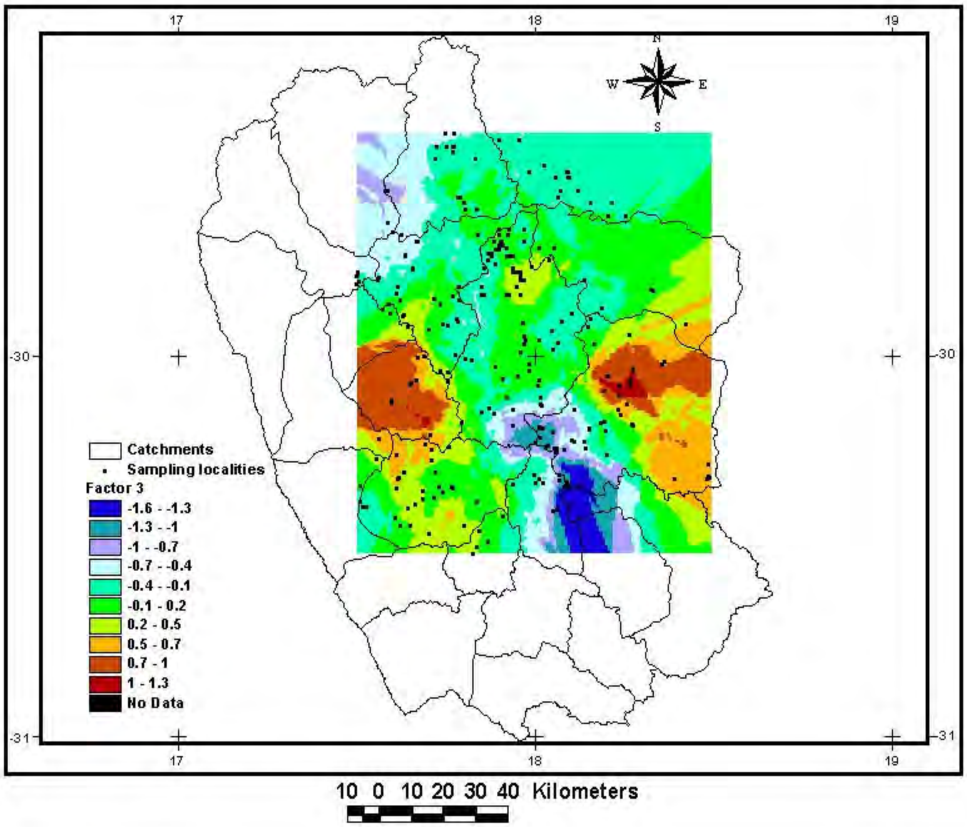


Figure 6.29: **Distribution of factor scores for factor 3.**

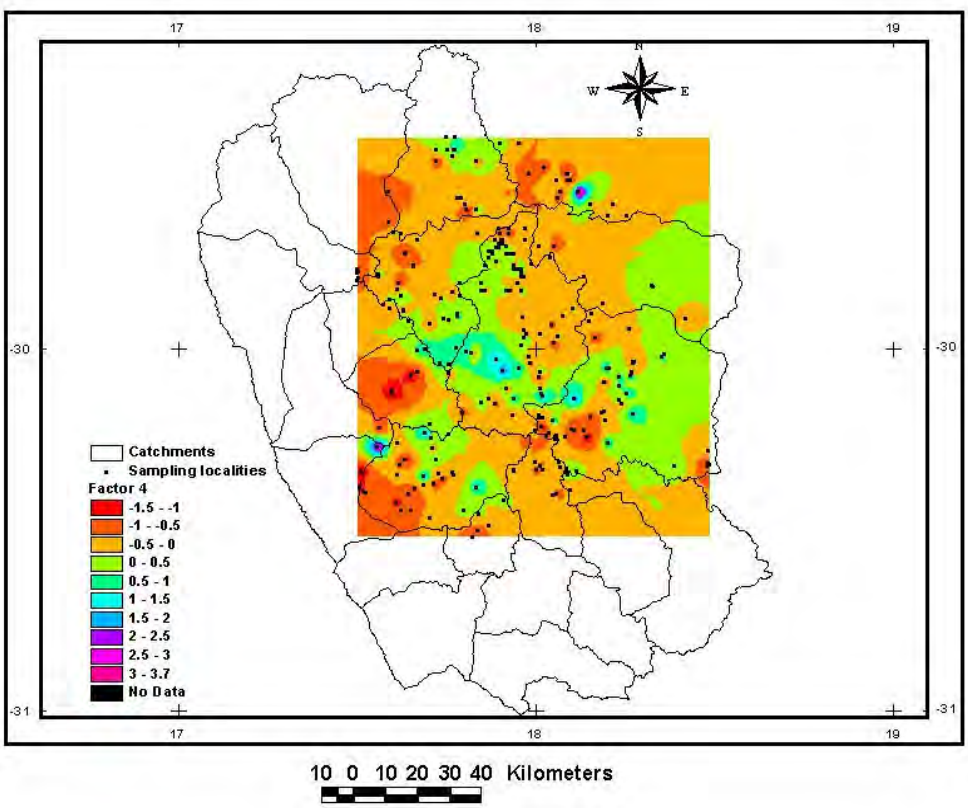


Figure 6.30: **Distribution of factor scores for factor 4.**

6.4.2 Summary

The statistical approach, using mainly the groundwater chemistry, indicates regions of relatively fresh water and highly mineralised water. Factor analysis is useful in the study area due to the fact that:

- Chemistry data are readily available;
- Factor analysis mainly describes the underlying processes and/or factors that produced the data;
- Variabilities of ions in small concentrations are not dominated by major ions (eg. chloride);
- Intermediate areas are delineated and not just the two extremities;
- Conventional methods, like the Piper diagram, would not indicate hydrochemical trends because of a dominant Na-Cl type water in the recharge and discharge areas; and
- Regional distribution and analysis of the different factors can be made.

The result of the statistical approach can aid in describing the regional groundwater and recharge trends. Direct recharge in the Central Namaqualand region is dominant in the higher lying regions. This is a direct result of the amount of rainfall over these areas due to the orographic effect. The rainfall is also recharged rapidly due to the favourable surface conditions. The hydraulic gradients in the higher lying areas are in the direction of structurally controlled surface depressions (valleys, alluvial plains, etc.). The water, both groundwater and surface water, collects in fracture controlled valleys, having a thick weathered zone. Rapid infiltration in the higher lying areas result in groundwater with a superior quality than groundwater occurring in topographically lower lying flat areas. The absence of significant soil cover is also a dominant factor in topographically steep zones. In the lower lying areas the soils generally have a high salt content due to the lower rainfall and high evapotranspiration rates and the fact that they act as sinks where groundwater accumulate. These areas may receive indirect recharge during periods of peak overland flow. Discharge is dominant in the lower lying areas and occurs as natural springs, evapotranspiration and aquifer exploitation. Overland flow occurs in the higher lying areas when the rate of vertical movement is slow. Discharge in lower lying areas is dominant along the horizontal to sub horizontal fracture and joint planes. Mixing zones, between modern (recently recharged) and older water, exist between recharge and discharge zones.

Recharge is also identified by the infiltration of nitrogen rich water from stock farming activities. Groundwater recharged in the Kamies Mountains flows to lower lying areas under steep hydraulic gradients. Water is transported out of the catchment along the ephemeral rivers, as well as through paleochannels. In the recharge zones groundwater percolation to the saturated zone are fast. Recharge in the lower lying areas, with significant soil cover, is much slower. If no significant rainfall occurs above a certain critical limit, no recharge will occur. This is attributed to the large soil moisture deficits, low rainfall and high evapotranspiration rates found in the area.

6.5 GIS based recharge assessment

The GIS approach involves the evaluation of different surface and subsurface features and its influence on natural groundwater recharge. The approach is mainly of a subjective nature where probability weights are assigned to features that may have a positive or negative effect on groundwater recharge. The approach is similar to the methodology of creating groundwater vulnerability maps. Different data sets were collated that may be used in defining a recharge potential map. The data sets are shown in Table 6.14 with overlays that can be derived.

Table 6.14: A listing of the data sets used in the GIS approach.

Data
Geology map (1: 1000 000) 1. Lithology
Land Type: 1. Soil type and clay content 2. Soil thickness 3. Land cover
Landsat TM image 1. Lineaments 2. Lineament intersections 3. Digital Elevation Model 4. Slope
Topographical maps 1. Drainage density
Climatological Data 1. Rainfall distribution and amount
Hydrogeological data 1. Water levels

All data sets were imported into ArcView GIS and standardised to the UTM 34 (WGS84 datum) projection. UTM was chosen as all directions, distances, shapes and areas are reasonably accurate within 15^{o} of the central meridian. As this projection is conformal, shape and angles within any small area are essentially true. The different components of the recharge potential map are subjectively weighted according to the probability of recharge occurring in the particular area.

Lithology

The geology of an area is considered the most important factor in that all the surface and subsurface features of an area is controlled by the different lithologies. The major drawback is the scale of the available geological map of the area (1: 1000 000) compiled by the Council of Geoscience. The lithological ratings are shown in Table 6.15.

Table 6.15: Lithology and recharge potential found within the study area.

Geology – Lithology	Recharge probability
Gneiss	65
Granite	65
Limestone	85
Quartzite	65
Sediments	90
Schist	65
Sedimentary	75
Shale	55

Soil characteristics

The characteristics of the soils are derived from a 1: 250 000 land type data set, obtained from the Institute of Soil Climate and Water. The land types incorporated terrain form, topography and microclimate. Although the data set does not include an actual soil map it does have information pertaining to the soil thickness, percentage clay and soil texture within each land type. The depth of the soil zone and its clay content is an important factor due to the high evapotranspiration rates. The soil layers over most of the coastal areas are not considered significant aquifers due to the poor quality and quantity of the groundwater. An exception is the alluvial aquifers associated with the main drainage systems. Thick soil covers will inhibit the movement of water to the water table. A linear relationship is assumed where no soil cover is ranked 100% probability and the maximum soil thickness of 1.2 m is weighed at 50%.

Due to the arid nature of the area soil moisture deficits are high and considerable amounts of rainfall are needed to initiate vertical groundwater recharge in thick soils. The soil characteristics over most of the area are a function of in situ weathering and transported material along rivers and paleochannels. The soil thickness map also indicates that the soil depths vary across the mountainous areas.

Lineaments

The process followed included a visual assessment of geological lineaments, mapped from the Landsat TM image (p176r081), acquired in December 1999. The Landsat TM scene did not cover the entire area of interest, but the bulk of the relevant lineaments did occur within the core region of the satellite image. The lineaments were mapped at a scale of 1:250 000. The classification used is listed in Table 6.16.

Table 6.16: The classification system used for lineaments.

Type of lineament	Code	Description
Lineaments	1	Any linear feature that could not be classified
Shear zones	2	A wide zone where lithological displacement is evident
Dykes	3	Zones of igneous intrusion
Faults	4	A narrow zone where lithological displacement is evident
Geological contacts	5	Where differing lithologies come into contact, yet no displacement is apparent

Once the lineament mapping had been completed, the entire image was reviewed at a scale of 1:125 000 and lineaments missed, inaccurate or misclassified were updated. Only visible lineaments were mapped and no inferences were made if the lineament could not be seen. Many of the valley floors are filled with cover alluvial material and the linear nature of such valleys suggests that they are fault controlled. However, if the lineament could not be seen it was not mapped.

In an attempt to assess the groundwater flow potential of each lineament, a normalized difference vegetation index (NDVI) and a soil adjusted vegetation index (SAVI) was generated from the Landsat TM image. The SAVI was suggested by Kellgren et al. (2000) as a better method for this purpose, however for this particular scene the difference between the NDVI and the SAVI was minimal. Lineaments associated with higher NDVI values were assumed to be having more groundwater that is available for plants. The lineaments were also visually assessed in terms of groundwater flow potential and in conjunction with the NDVI, a qualitative value of high, medium and low were assigned to the lineaments. For the high flow lineaments a buffer distance of 200 m was assigned and this zone given a 90% probability for recharge potential. The medium flow lineaments were buffered by 100 m and assigned a 70% recharge probability and the low flow potential lineaments buffered by 50 m and given a 50% recharge probability.

The occurrence of lineament intersections is considered important, as the probability of recharge occurrence is higher at these zones. An additional shortcoming of this current study was the difficulty in determining lineament intersections and allocating an associated recharge probability value. The process could be carried out manually with the assigned lineament flow characteristics being taken into account. A proposed rating for the intersections is shown in Table 6.17.

Table 6.17: Lineament intersection values.

Intersection	Recharge probability %	Buffer distance (m)
Low (50) + low (50)	50	50
Low (50) + medium (70)	60	75
Low (50) + high (90)	70	100
Medium (70) + medium (70)	70	100
Medium (70) + High (90)	80	150
High (90) + high (90)	90	200

Land cover

For assessing the amount of precipitation interception and evapotranspiration the national land cover data set was used. The land cover types are based on mapping carried out by the Agricultural Research Council and the CSIR from 1:250 000 Landsat TM images. The land classes occurring within the study area and associated subjective recharge potential ratings are given in Table 6.18.

Table 6.18: Land cover types occurring within the study area and assigned recharge potential.

Land cover	Recharge probability (%)
Barren rock	100
Cultivated: temporary - commercial dryland	90
Cultivated: temporary - commercial irrigated	93
Mines & quarries	100
Shrubland and low Fynbos	95
Thicket & bushland (etc)	70
Unimproved grassland	97
Urban / built-up land: residential	85
Waterbodies	100
Wetlands	100

Topography and slope

The slope was calculated from the digital elevation model. The steeper the slope the greater the precipitation runoff and the smaller the groundwater infiltration. Table 6.19 shows the values used in association with slope.

Table 6.19: The relationship used between surface topography slope and percentage recharge potential.

Slope (degrees)	Recharge probability
0 – 5	100
5 - 10	95
10 – 20	75
20 – 50	50
50 – 90	25

Depth to water level

The thickness of the unsaturated zone is considered a relevant factor in calculating recharge potential. The deeper the groundwater the more likely the adsorption of infiltrating surface moisture within the unsaturated zone and the more effective groundwater recharge is reduced. The values used for the depth to groundwater parameter are given in Table 6.20.

Table 6.20: The relationship used between depth to water level and recharge probability.

Depth to water level (m)	Recharge probability
0 – 5	90
5 – 10	80
10 –15	70
15 – 20	60
20 – 26	50

The input data for the depth to groundwater level parameter needs to be carefully assessed before being used to generate groundwater level maps. An important issue is to determine whether the borehole water levels recorded are pumped or static values. The fractured dominated flow of the groundwater should be taken into account when generating a depth to water level contour map. In addition, input values also need to be assessed as to whether they are representing confined or unconfined aquifer conditions. An Inverse Distance Weighting (IDW) algorithm was used to generate the depth to water level map. This computer-based approach can be misleading and the results are particularly spurious some distance away from the data points.

6.5.1 Recharge map

All the input coverages were converted to 50 m grids with the same area of extent. Each grid was then reclassified according to the classification table (Table 6.21) and then weighted according to how significant the individual factor was considered to be in contributing to groundwater recharge potential.

Table 6.21: A listing of the data sets used.

Data set
1. Lineaments + flow potential (confirmed by NDVI / SAVI)
2. Lineament density
3. Lineament intersections
4. Drainage density
5. Land cover
6. Soil type (clay content)
7. Soil thickness
8. Soil texture (% rock vs % soil)
9. Slope (degrees)
10. Depth to groundwater
11. Lithology (geology)
12. Rainfall distribution

The recharge potential map gives an idea of direct vertical infiltration. Based on the hierarchy theory only a few variables are necessary to create a recharge map of the area. Several layers were removed by trial and error and by applying the conceptual understanding. The rainfall distribution was included to counterbalance the high weighting near the coastal area. For example, the slope increases the weighting near the coastal zone due to the low slopes (high rating). Recharge to the coastal zone is limited due to the low rainfall, high evapotranspiration and deep water tables. Overlaying a map with the rainfall distribution and amounts produces a map of recharge from direct rainfall (Figure 6.31).

The following layers were then used in producing a recharge potential map and by applying a recharge value to the map to produce the final recharge map of the area:

- Rainfall distribution;
- Soil thickness and texture;
- Slope; and
- Lineaments.

Due to the difficulties in upscaling the recharge rates calculated from the CRD and CMB methods a recharge rate of 0.6% -1% of MAP was applied over the whole of the area, respectively (Figure 6.32 and 6.33). The values for the alluvial aquifers were not included as the average recharge rate is unrealistically high for the whole area.

The GIS approach will overestimate recharge because a fixed percentage of recharge is applied over the area. The current approach also assumes a linear relationship between the recharge potential map and recharge as a percentage of rainfall. The approach needs more spatial recharge values that can be interpolated and incorporated in the GIS approach.

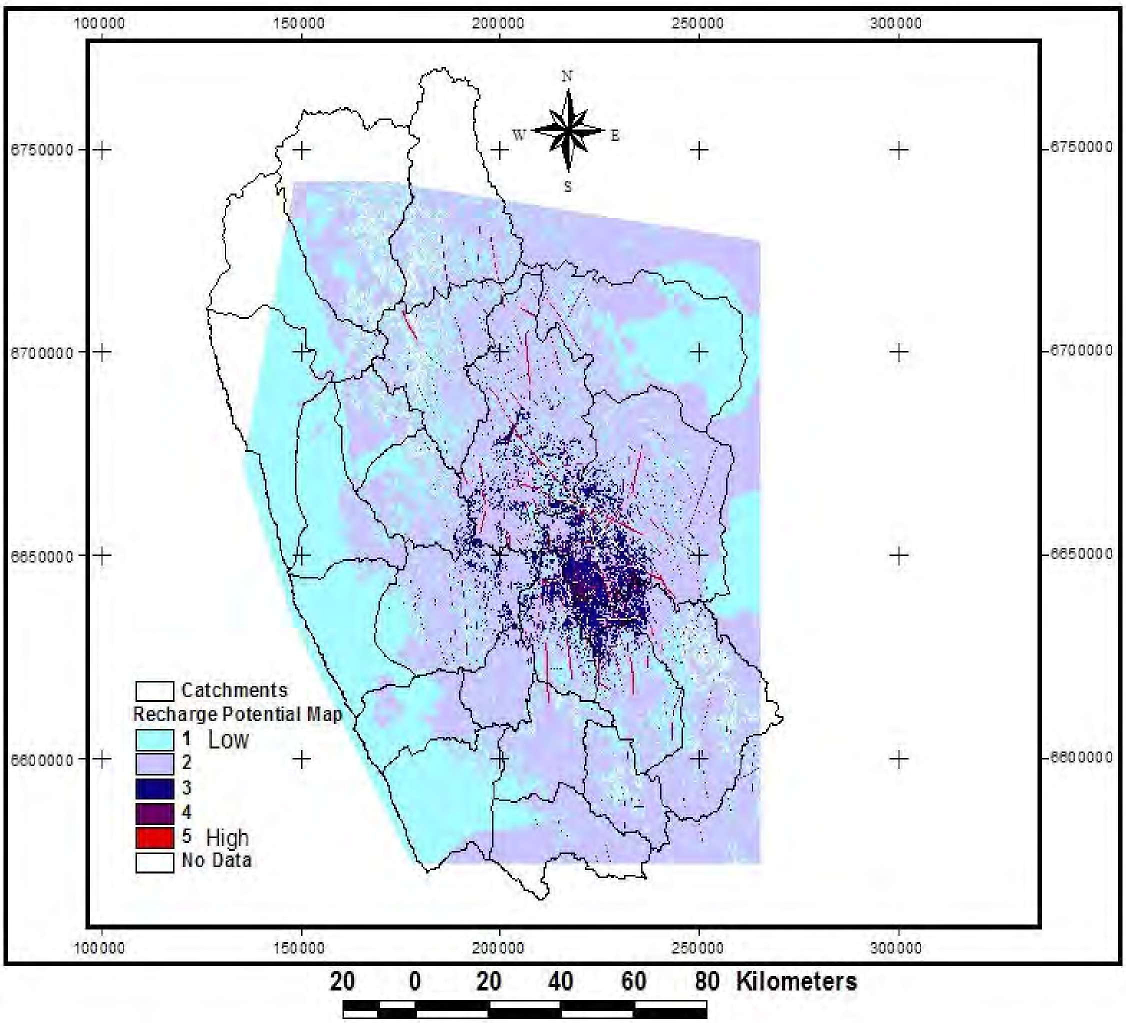


Figure 6.31: Recharge potential map for the Central Namaqualand region.

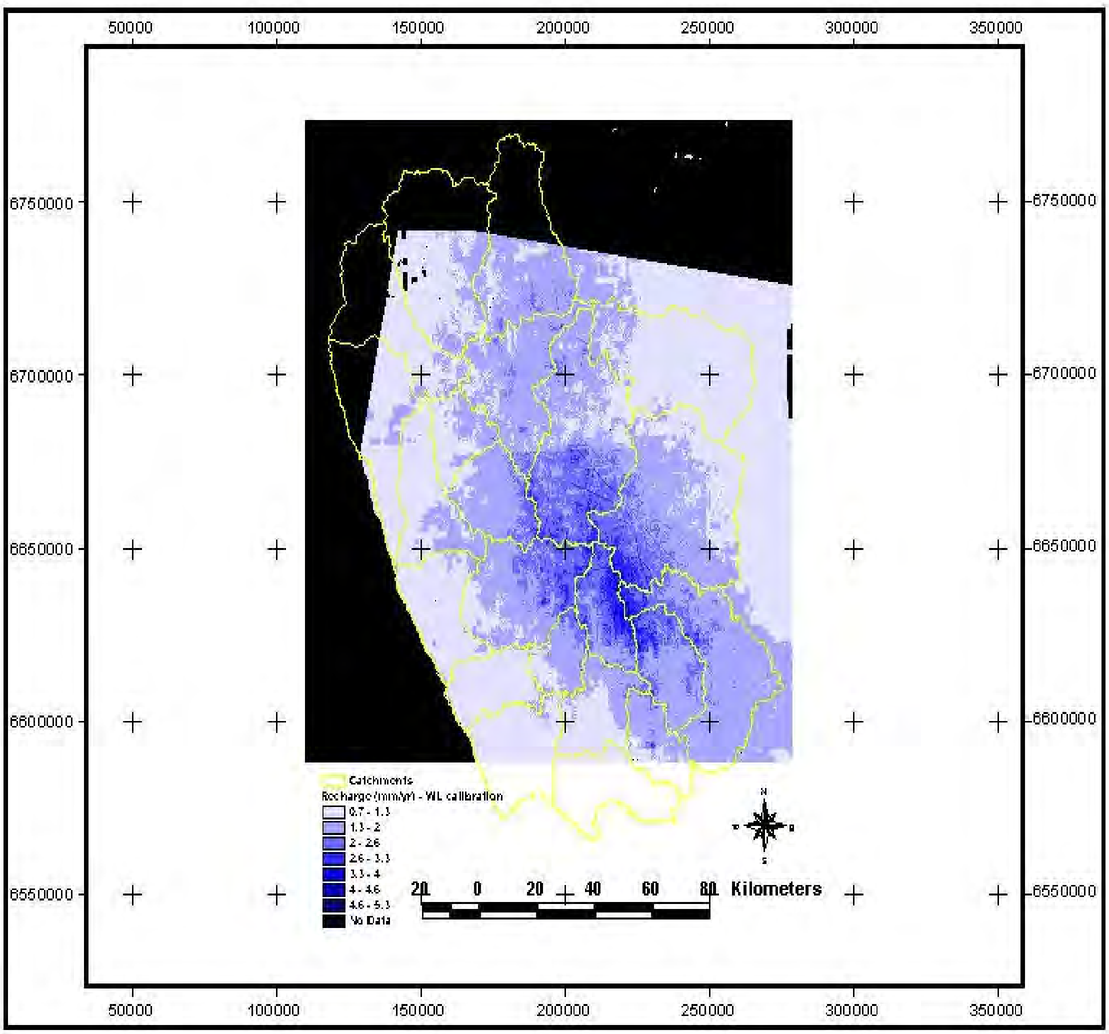


Figure 6.32: Recharge rate potential map with the average CRD recharge estimate for the Central Namaqualand region.

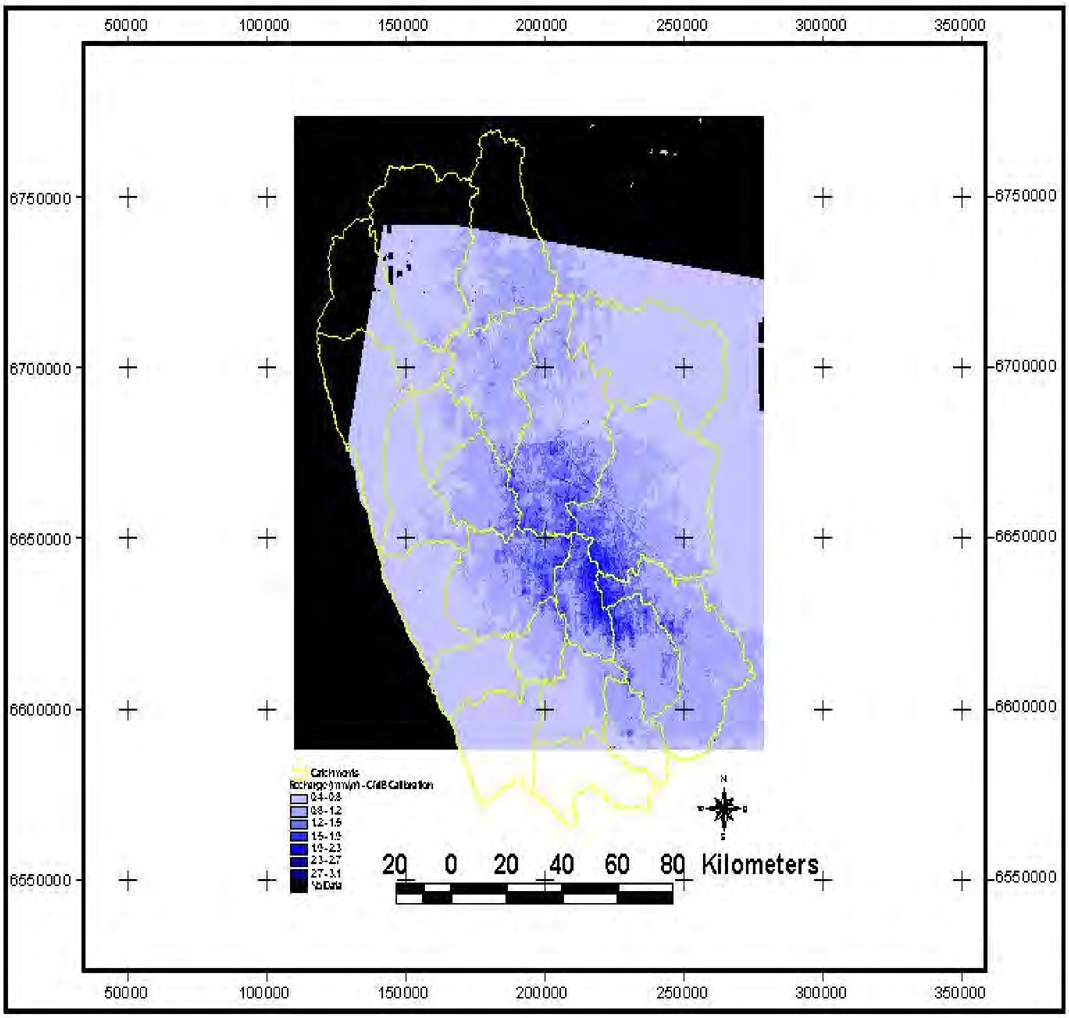


Figure 6.33: Recharge rate potential map with the average CMB recharge estimate for the Central Namaqualand region.

6.5.2 Summary

The GIS approach is an excellent tool for visualisation and spatial analysis. The method is more descriptive, less quantitative and more subjective. The main shortcoming of the approach is that it only assumes direct vertical infiltration. It has been demonstrated that recharge is predominantly indirect, away from the higher lying areas. The recharge potential map seems conceptually correct. The method is also combined with rainfall and the spatial average of recharge from the CMB and water level fluctuation methods. A constant value for recharge, expressed as a percentage of MAP, is applied over the entire site. It has been shown that this is not the case for the Namaqualand region. It is now well recognised that the rainfall to recharge relationships are not always linear in arid and semi-arid regions, especially at finer scales.

In the mountainous regions, where rainfall is extremely high for the area, the model assumes that most of the water is available for recharge; this may not be true. The rainfall in the higher lying areas is available for recharge further down the topographic profile where favourable conditions exist. The recharge for the downhill site is estimated using the rainfall of the area, which may be lower, by a factor of two than the rainfall of the higher lying areas. Recharge in the coastal areas is very low, but the model will assign high recharge values to the favourable conditions specified in the weighting and overlaying process. Data sets that may be collected that may refine the model are drainage density maps and distribution of the alluvial aquifers associated with rivers and paleochannels.

CHAPTER 7

Summary and Discussion

7.1 Evaluation of recharge assessment in Namaqualand

The main objective of this study was to estimate and characterise groundwater recharge to the basement and alluvial aquifers of Namaqualand. The conclusions are discussed in terms of the objectives as outlined in Chapter One.

7.1.1 Identifying methods suitable for recharge studies in the Central Namaqualand region

Five methods have been identified that can be applied in the study area, and they are:

- Chloride mass balance (CMB) method;
- Cumulative rainfall departures (CRD) method;
- Saturated volume fluctuation (SVF) method;
- Statistical approach; and
- GIS approach.

The methods were selected based on the availability of data and data that can be obtained easily and cost-effectively. An Excel spreadsheet program was developed to assist in selecting different methods, based on data availability and requirements.

7.1.2 Delineating recharge areas

Recharge areas were delineated on regional and local scales. Regionally, recharge areas correspond with the higher lying areas that receive most of the annual rainfall. Recharge areas were identified using factor analysis, employing the interrelationship between groundwater chemistry, isotopes and altitude to define recharge and discharge areas as well as intermediate areas. The results of the factor analysis also indicated recharge of polluted water into the aquifer. The GIS approach correlated various thematic layers to recharge probability. The layers were then integrated to generate a recharge potential map. Applying the rainfall distribution map over the area effectively shows the areas most likely to receive recharge. Although the approach gives a map that is conceptually correct, it can be further refined.

Localised recharge areas are related to the type of aquifer. It was found that the alluvial aquifers are easily recharged due to their hydraulic characteristics and their position within the landscape. The structural control on the ephemeral drainage systems is evident in their alignment along fracture systems that are associated with the underlying bedrock. The alluvial systems are major pathways for groundwater recharge to the weathered and bedrock zone aquifers.

7.1.3 Application and comparison of a number of independent approaches for recharge characterisation/estimation and selection of the best method(s) for recharge estimation

Assessing recharge to any aquifer depends on the type of area under investigation, the availability of data, the distribution of available data and the ability to obtain meaningful data. Groundwater resources assessment is inherently complex in semi-arid to arid crystalline terrain. Groundwater recharge rates over large areas are difficult to estimate due to problems associated with upscaling and data distribution. Two approaches have been followed in this study whereby recharge was qualitatively and quantitatively assessed. The qualitative assessment involved using existing data from the area and applying statistical and spatial techniques to assess recharge processes and patterns. Applying the CMB method and water level to rainfall relationships gave quantitative estimates of recharge.

The qualitative assessments of recharge, using statistical analysis (R and Q mode factor analysis) and the GIS assessment techniques, identify areas that are receiving recharge as well as being favourable for potential recharge. The statistical analysis is useful in that it also indicates areas of localised artificial recharge through agricultural and domestic activities. The isotope approach also provided some useful information in terms of recharge processes and the time since recharge. It was found that most of the recharged water was evaporated at the surface, as evidenced in the stable isotope data. Recharge is thus mainly indirect except for the higher-lying mountainous areas where recharge is mainly direct. The isotope samples of the higher-lying areas plot in a distinct pattern on the δ^2H- δ^{18}O plot. The radiogenic isotopes indicated the existence of very old water to recently recharged water.

The results of the quantitative analysis are shown in Table 7.1. Recharge was calculated as the average annual recharge. However, it is well recognized that only certain rainfall events during the wet winter season will contribute to meaningful recharge. It is evident from Table 7.1 that higher rates of recharge are experienced in areas where groundwater is exploited from a combination of the alluvial and basement aquifers. Basement aquifers are used here to describe both the weathered zone and fractured rock aquifers. The CMB method underestimates recharge to alluvial aquifers associated with the ephemeral rivers (i.e. Buffels River Town and Rooifontein). This may be explained by additional chloride input from run-on during periods of recharge. The current calculation of the CMB method lacks chloride data from run-on. The recharge rates also tend to correlate with the ^{14}C ages from individual boreholes, except that the Leliefontein sample does not fit the expected age and may be due to a sampling or analytical error. The scatter of estimates is probably due to the fact that the CMB, CRD and SVF methods measures recharge at different temporal scales. The CMB method estimates recharge over an extensive period, as opposed to the CRD and SVF methods that estimate recharge over a shorter period. The CMB method also depends on the degree of groundwater mixing within the borehole. It has been shown that the groundwater quality generally deteriorates with depth and ^{14}C evidence suggests stratification of groundwater of different ages. The uncertainties in the degree of mixing and rainfall chloride can have a considerable effect on the error associated with an estimate. The advantages and disadvantages of the methods are shown in Table 7.2.

Table 7.1: Comparison of results between the CMB, SVF and CRD methods.

Site	Ave. Rainfall (mm/yr)	CMB (mm/yr)	SVF (mm/yr)	CRD (mm/yr)	MRT (yrs)	Aquifer
Buffels River Town	188	0.71	5.3	6.4	Modern	Alluvial/Basement
Bulletrap	172	1.14	0.3	0.1		Basement
Klipfontein	196	0.23	0.3	0.1	>30 000	Basement
Komaggas	229	1.04	4.4	0.7	Modern	Alluvial/Basement
Rooifontein	138	0.39	2.6	3.06		Alluvial/Basement
Spoeg River	200	0.22	0.2	0.1	>2000	Basement

Table 7.2: Advantages and disadvantages of the methods used.

Methods	Advantages	Disadvantages
CMB (saturated zone)	- Quick and cheap. - Estimate total recharge. - Point to areal estimates.	- Other sources of chloride not known. - Method difficult to apply due to indirect nature of recharge. - Method not useful in alluvial aquifers. - Need long-term deposition rates. - Difficulty in rainwater sampling/analysis.
SVF	- Relies on easily obtainable data, except S-values and inflows/outflows. - Changes in water level may be from other causes.	- Need a good estimate of S- value. - In and outflow not always known. - Need several years of data. - Large contrasts in water level responses may be problematic.
CRD	- Relies on easily obtainable data, except S-values. - Changes in water level may be from other causes. - Relationship between rain and water level may decrease at great depth.	- Need a good estimate of S- value. - In and outflow not always known. - Need several years of data. - Large contrasts in water level responses may be problematic.
Stable isotopes	- Easily measured.	- Qualitative. - Give an indication of recharge processes.
Carbon-14	- Indicate time since recharge. - Relative ages are useful due to large variations.	- Qualitative. - Difficult to correct for dead carbon contribution. - Non-unique corrected ages. - Initial radionuclide activity not always known. - Aquifer depth and porosity difficult to determine in fractured aquifers (R = Hn/T). - Costly.
Statistical	- Use existing data. - Large amount of chemistry data available. - Delineate areas with different/similar chemical processes.	- Qualitative. - Depends on borehole distribution. - Data quality.
GIS	- Existing data can be used. - Easy to change and update information. - Delineate potential recharge/vulnerable sites.	- Scaling problems. - Calibration using point values may be costly. - Only potential recharge areas combined with an average recharge rate.

Comparison with available estimates

The regional estimates of Vegter (1995) indicate recharge ranges of 0.1, 3, 8, 12 mm/yr for the coastal to mountainous regions of the study area (Figure 7.1). Recharge is represented as occurring in a symmetrical manner around the higher-lying areas of the Kamies Mountains. The statistical and GIS assessment supports this recharge distribution pattern, which is mainly related to the rainfall distribution pattern. The results of this study support only the low values for the coastal areas not associated with the major ephemeral rivers and the high rates in the higher-lying mountainous regions of Vegters map.

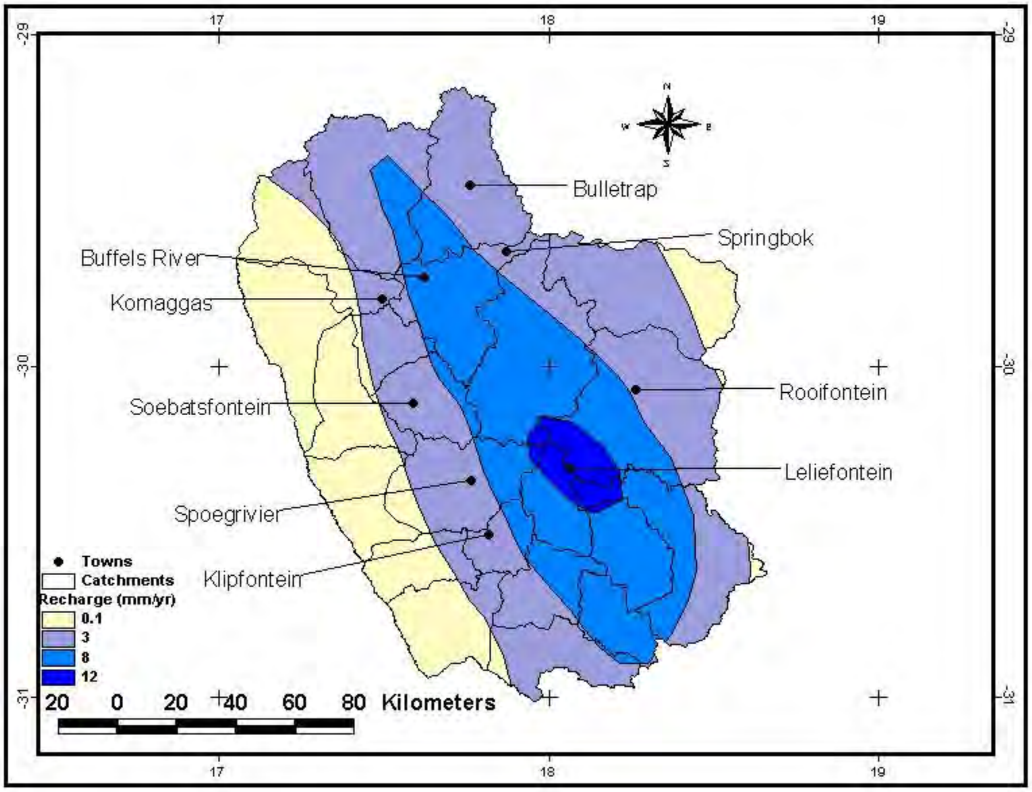


Figure 7.1: Distribution of recharge according to the national map of Vegter (1995).

7.1.4 A conceptual model for groundwater recharge

The conceptual model consists of a set of assumptions that verbally and or visually describe the aquifer systems composition, based on field observations and data interpretation. Groundwater recharge can be both direct and indirect during period of peak rainfall. Rainfall is highly variable in time, occurring mostly in the winter months when evapotranspiration is low. Rainfall mainly occurs in the winter months over the higher lying regions, which are mostly made up of exposed outcrops of crystalline basement rocks and valleys of weathered material. Geomorphic features favourable for recharge are indicated in Table 7.3. The alluvium (or soil cover) and weathered zones are important in that they store infiltrating water and may, under favourable conditions, transmit the stored water to the fractured aquifer. Thus, it is more likely for a borehole to be sustainable if it intersects the weathered zone and the fractured rock aquifers.

Table 7.3: Geomorphic features that influences recharge and discharge.

Terrain	Conditions	Recharge probability
Granitic domes	Fractured	Moderate
Open fractures	Little soil cover	Moderate
Foothills	Contact zones	High
Valleys	Fracture control	High
Rivers	Significant soil cover	High
Plains	Lowlands	Low

Potential evaporation exceeds rainfall for most of the year. However, the aquifers are being recharged to a very limited extent in some instances. The recharge is derived mainly from:

- Infiltration of runoff from episodic flash flood events originating in the escarpment zone.
- Rerouted runoff from the bornhardts/inselbergs. The runoff can then be either recharged at the foot (as mountain-front recharge) of the domes where it infiltrates, and are available for phreatophytes (Figure 7.2). Phreatophytes are a good indicator of the presence of shallow groundwater.
- Exposed fracture zones, which facilitate the transfer of the recharge into the basement aquifers infiltration, will be relatively higher on exposed outcrops with high-fracture densities and low-angle slopes.
- Runoff accumulated in streams where it infiltrates under favourable conditions (Figure 7.3). The runoff decreases rapidly downstream due to transmission losses and evaporation and is a function of the amount and duration of rainfall over the higher-lying areas as well as the prevailing temperature conditions.
- Infiltration from the runoff from the immediate hill slopes that are conducive for runoff generation during most rainfall events.
- The occasional snow occurring on the mountain peaks of the Kamies Mountains.

A conceptual model for recharge and groundwater flow in the three aquifer systems is presented in Figure 7.4.

Figure 7.2: Presence of groundwater at the foot of a granite dome.

Figure 7.3: Runoff after a rainfall event.

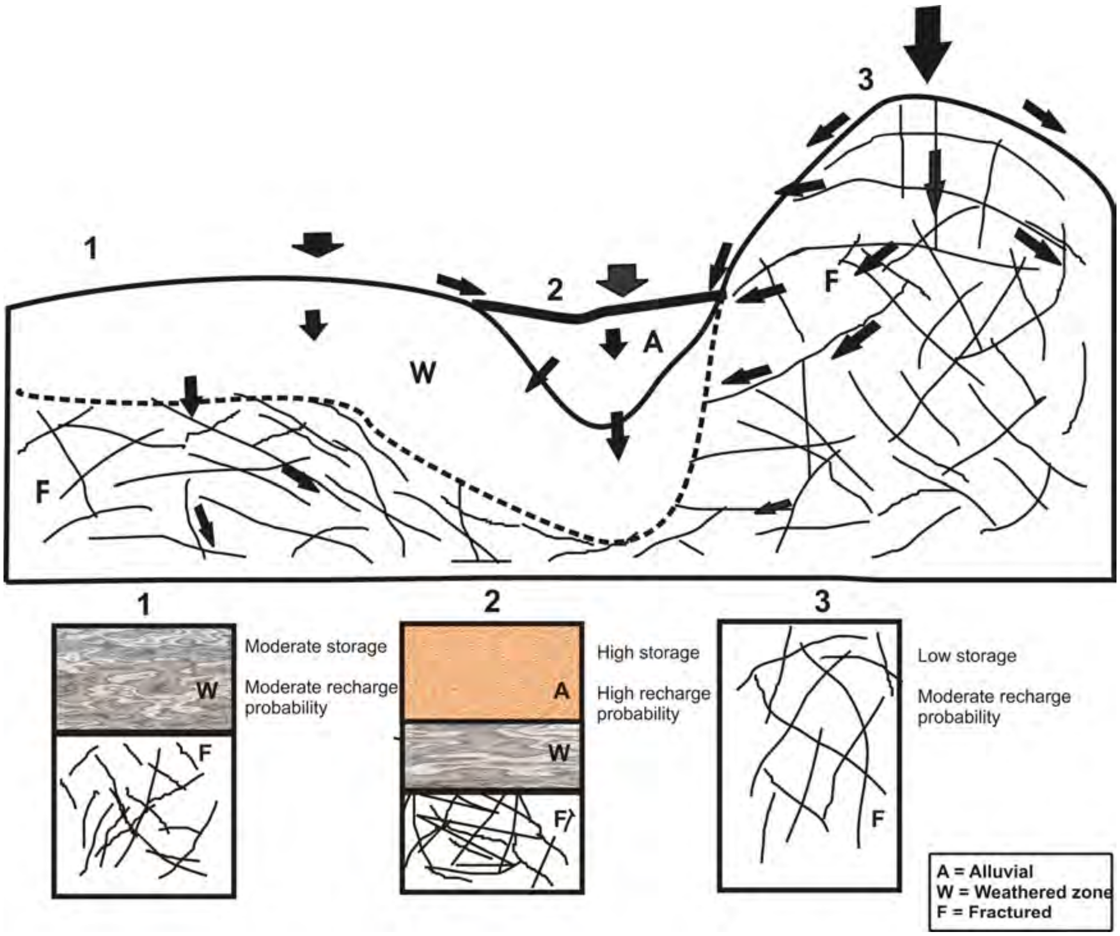


Figure 7.4: Conceptual model for recharge pathways and flow.

Recharge is primarily driven by the occurrence of periods of above-normal rainfall. Insignificant rainfall in arid areas evaporates from the ground surface and no recharge takes place. With significant rainfall over a few days in the cool winter months, it is likely that the water will infiltrate deeper and ultimately contribute to recharge. The climate of southern Africa is inherently variable in time and space and changes through seasonal, annual, decadal up to millennial and even further (Meadows, 2001). Recharge occurrence will also have this variability. Ragab and Prudomme (2002) believe that precipitation in semi-arid and arid regions will decrease. This is probably as a consequence of climatic change. A plot of mean annual precipitation versus mean annual maximum temperature reveals that the amount of annual rainfall decreased with increasing mean annual maximum temperature for the period 1960-2002 (Figure 7.5). If the climate change causes the temperature to rise the precipitation will decrease if the trend continues. This has a major bearing on the available water resources in Namaqualand. Most of the area receives little recharge and with a possible increase in the population due to the decommissioning of the mines, the region will experience a groundwater drought if there is a decrease in rainfall and an increase in water demand.

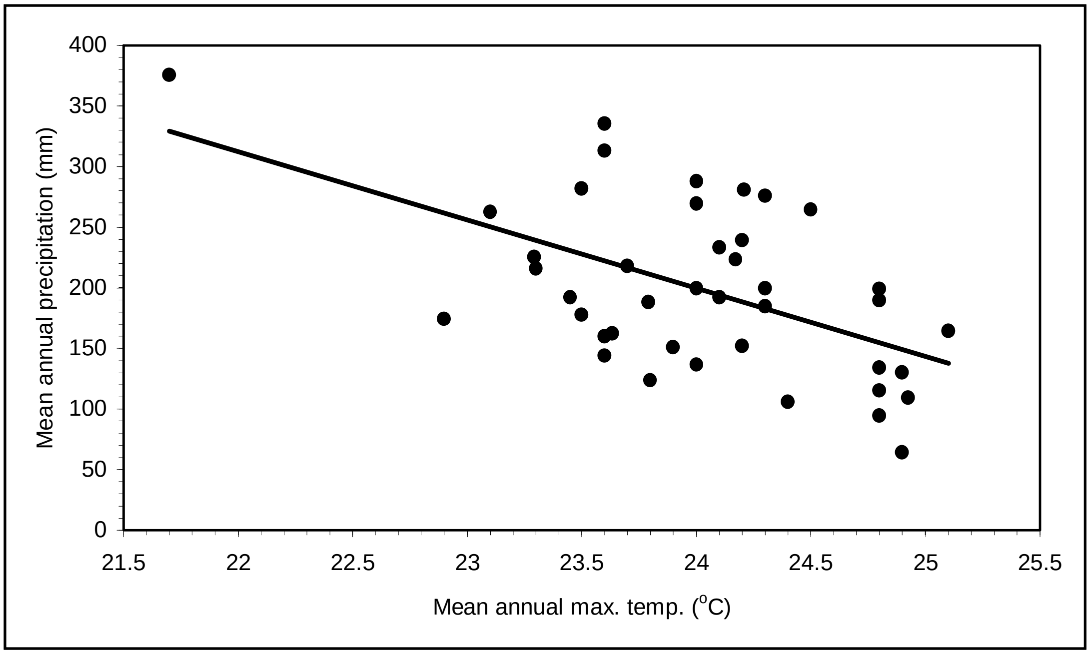


Figure 7.5: Mean annual rainfall vs. mean annual maximum temperature for the Springbok area (1960-2002).

The region experienced several periods of below-average rainfall and hence lower recharge to the basement aquifers. A few major recharge events have occurred over the last century, the most recent being the 1995-1997 seasons. Major recharge events are defined as periods with at least five or more years of above-average rainfall. Most of the aquifers with significant storage are recharged during these periods. Major recharge periods can be identified on a decadal level, available from rainfall records for the Springbok area (Figure 7.6). However, recharge can occur if the rainfall is of a significant duration on an annual scale. The shallow, high-porosity aquifers like the alluvial and weathered basement aquifers will be recharged during these periods. Extended periods of rainfall contribute to the long-term storage of groundwater. Water levels during the dry cycle recede to the deeper aquifer, which has a low storage capacity. During the wet cycle, the water levels rise to within the weathered zone. The weathered zone has a higher storage and feeds the deeper aquifers under favourable conditions over longer periods. The hydrographs shows a sharp increase in the water level until it reaches the weathered zone or alluvial aquifers where the water level gradually rises or declines, indicating increased storage capacity.

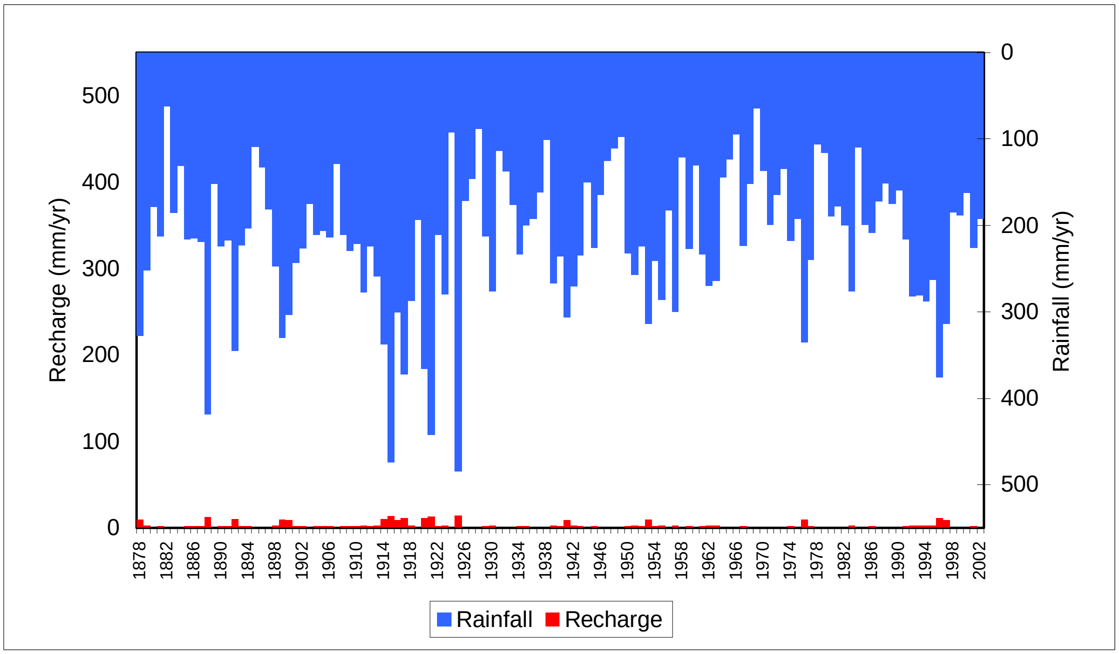


Figure 7.6: Periodicity of recharge in the Namaqualand region.

7.2 Regional Perspective

Beekman and Xu (2003) reviewed groundwater recharge estimation in arid and semi-arid Southern Africa. The CMB, CRD, EARTH, GM, SVF and WTF methods have been identified by them as methods with the most potential for application in arid and semi-arid Southern Africa.

Recharge estimation is an important aspect of groundwater development in most rural communities where groundwater is often the sole source of water supply. Groundwater management is reliant on the best estimate of groundwater sustainability, which is dependent, among other factors, on recharge estimates. Regional and national estimates of groundwater recharge are important for a first overview of recharge, but more detailed information on a local or sub-regional scale is necessary for best management practices. In Southern Africa, South Africa has the lowest recharge per capita (Figure 7.7). Groundwater is mainly used in rural South Africa where the population densities are low.

South Africa has a much larger population than all of the other countries, with the majority of people using surface water resources. As surface water resources become scarcer, due to the impact of climate change and population growth, groundwater resources will be an important buffer for periods of drought. In Namaqualand where most of the inhabitants depend on groundwater as a sole source of water supply, the recharge per capita is extremely low. A study conducted by Rush et al. (2000) indicated that water shortages in the central Namaqualand region are prevalent. They have defined water shortages as the availability of <25 liters per capita per day (l/c.d) in the short term, and <55 l/c.d in the medium term. Based on an inadequacy class (based on quality, quantity and access) they found that the Soebatsfontein and Klipfontein communities have an inadequacy class of –50 to –30.1 % and the town of Komaggas has a relatively better inadequacy class of –10 to –20 (Rush et al., 2000). Higher negative values indicate increased inadequacy. The inadequacy stems mainly from the lack of recharge; with higher recharge the quantity and quality of the water tends to become adequate. The recharge maps (factor analysis and GIS) can also be applied to determine the vulnerability and the state of the groundwater resources.

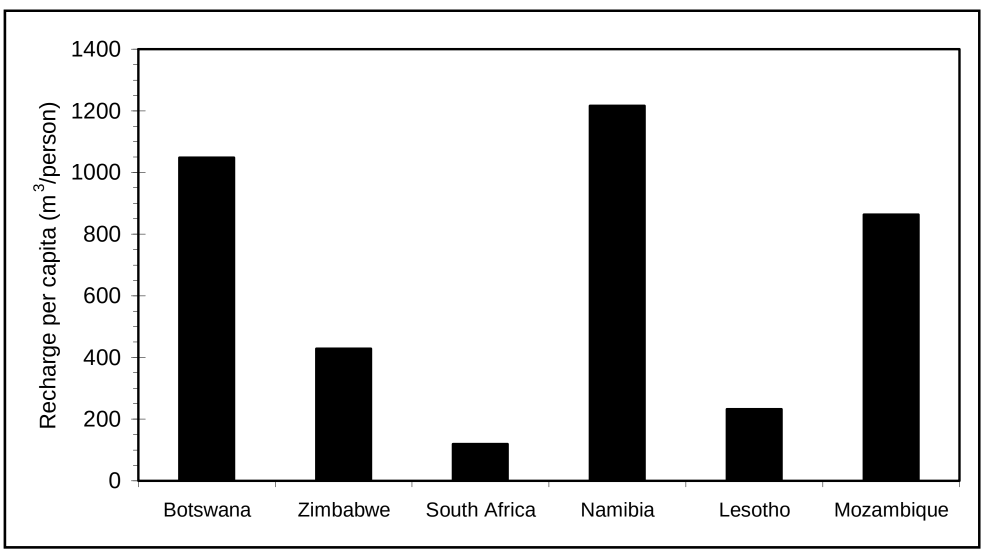
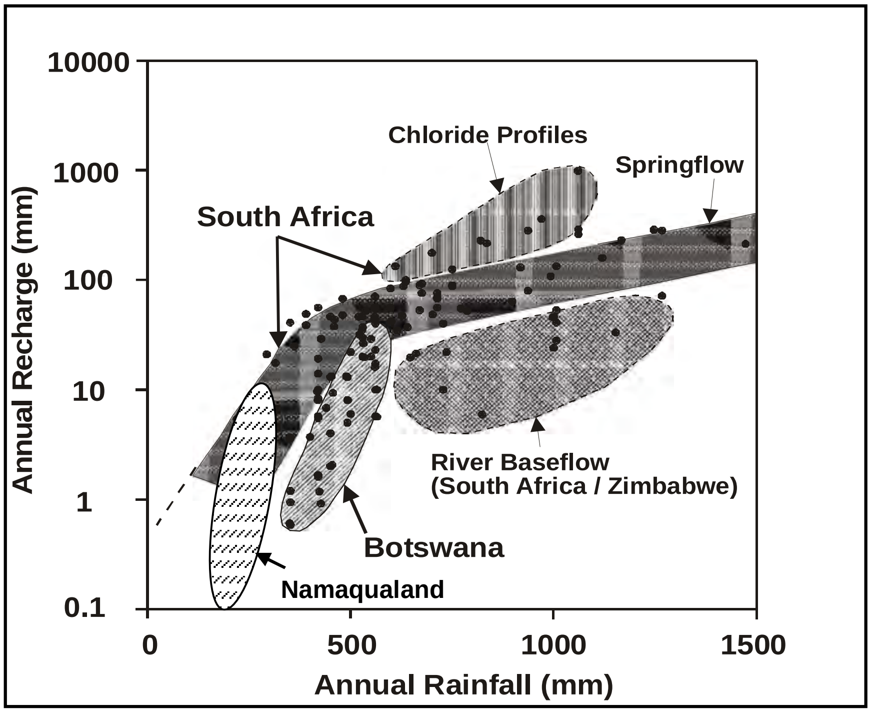


Figure 7.4: Recharge per capita for the Southern African region (data from World Resources Institute, 2002).

Recharge in the Southern African region is highly variable and is a function of the climate, geology, topography, and drainage. Beekman and Xu (2003) give an overview of major recharge assessments projects undertaken in the region. Regionally, recharge generally increases with the amount of rainfall. The Namaqualand estimates fits well into the recharge trends for Southern Africa, identified by Beekman et al. (1996) and Beekman and Xu (2003) (Figure 7.5).



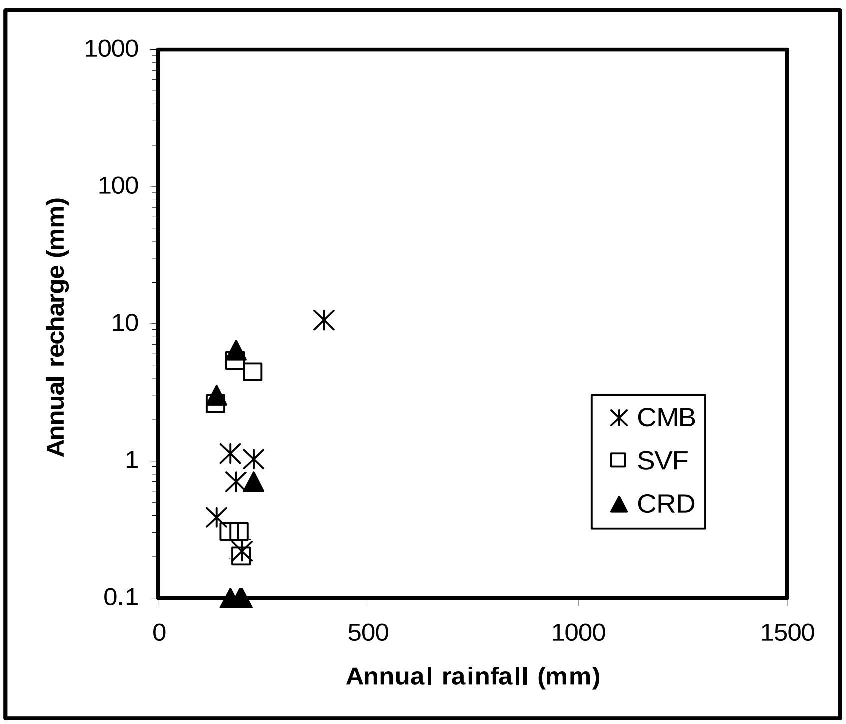


Figure 7.5: Recharge estimates for Southern Africa (after Beekman et al., 1996; Beekman and Xu, 2003) integrating the Namaqualand estimates from the CRD method.

7.3 Final remarks

This is the first systematic recharge study carried out in the central Namaqualand region. The results indicate that recharge is higher in the alluvial aquifers than in the hard rock basement aquifers. The results also indicate that recharge decreases from the escarpment zone to the coastal zone. Even under favourable rainfall conditions the areas around Klipfontein and Spoeg River receives minimal recharge. This phenomenon is probably related to the surface features in the areas.

- Groundwater recharge rates to the basement and alluvial aquifers are estimated to be within 0.1 and 10 mm/yr, with the higher values being mainly to the alluvial aquifers and high altitude sites, and the lower limits to the fractured rock aquifers.
- Groundwater level fluctuations and rainfall (CRD and SVF) was successfully used to estimate groundwater recharge. Water level data is usually available in most areas due to community water supply schemes. Uncertainties with regard to the determination of storage coefficients and contributing areas to recharge in fractured hard rock terrain are still of concern for most hydrogeologists. The estimates used in the calculations are ‘best estimates’.
- The CMB method is still a useful method for recharge estimations in most hydrogeological provinces as a first estimate of recharge. However, the method, if applied on its own, may not give an accurate account of recharge rates. The uncertainties and assumptions of the method need to be considered when interpreting the results. The recharge rates estimated for the alluvial aquifers are lower than expected. This is a result of the unaccounted chloride in the surface runoff flux.
- Isotope data indicate water ranging from very young to very old (<50 years - >30 000 years). Intermediate ages indicate active mixing of younger and old water.
- Recharge is related to the amount of rainfall and the position of the aquifers within the landscape, which is, in turn, related to altitude and topography. Recharge mainly occurs when rainfall is above normal. Above-normal rainfall produces more intense runoff that can travel further down the hydrological profile, recharging more of the alluvial aquifers.
- Recharge occurs as primary recharge in the mountainous areas where direct infiltration is more likely. Indirect recharge involves the infiltration of surface

runoff and discharges from springs and adjacent aquifers, dominating in most of the areas.

- Flood events will produce significant recharge, mainly to the alluvial aquifers.
- Recharge estimates that may seem to be within acceptable limits of error when interpreted, may be significantly high when applied to determine aquifer sustainability. Rainfall in semi-arid regions is episodic in nature, where most of the annual rainfall can occur within a very short period of time with a concomitant increase in recharge if favourable conditions exist, as opposed to distributing the rainfall over an entire year. The use of mean annual recharge rates can be misleading, as the simulated period only includes years of above-average rainfall and not the long-term cyclicity of rainfall.
- Recharge in arid to semi-arid crystalline basement aquifers is neither straightforward nor simple and needs both a qualitative (e.g. field observations and local knowledge) and a quantitative approach.

7.4 Future research

Topics or issues that must be considered for future research include:

- Results and techniques provided by this baseline study should be used to acquire additional data to optimise the estimated recharge rates.
- The utilisation of complementary water sources needs to be highlighted, such as rainwater harvesting, fog water collection, and artificial recharge using runoff, for example, from the bornhardts. Some of these schemes are operated on a limited scale in the area and can be expanded to other areas.
- Measurement campaigns for chloride deposition in precipitation.
- Application of the recharge estimates to management scenarios.
- Quantification of episodic recharge at various temporal scales.
- Scenario-based studies on the impact of climatic change on future groundwater resources.
- Expanding the GIS approach to distribute point estimates from a particular area to similar areas elsewhere. The spatial heterogeneity of recharge introduces difficulties in upscaling, and needs additional research aimed at improving the application of point data to larger areas.
- Hill slope processes and their impact on groundwater flow and recharge.

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Appendices

A1: Rainfall chloride chemistry data

Site	Distance (km)	Rain (mm)	Cl (mg/l)	Reference
Struis-M	13.000		25.00	Weaver and Talma (2002)
Struis-O	10.000		25.00	Weaver and Talma (2002)
Struis-P	8.000		26.00	Weaver and Talma (2002)
Lang-GB	3.000		22.00	Weaver and Talma (2002)
Lang-LWW	20.000		23.00	Weaver and Talma (2002)
Lang-Hop	25.000		14.00	Weaver and Talma (2002)
Lang-WH	45.000		13.00	Weaver and Talma (2002)
Ager-Wit	95.000	650	4.60	Weaver and Talma (2002)
SouthC-G	10.000		14.00	Weaver and Talma (2002)
SouthC-E	30.000		5.00	Weaver and Talma (2002)
SouthC-W	40.000		1.00	Weaver and Talma (2002)
SouthC-V	45.000		1.00	Weaver and Talma (2002)
SouthC-B	65.000		1.20	Weaver and Talma (2002)
SouthC-V	85.000		0.50	Weaver and Talma (2002)
Springbok	100.000	225	2.42	This study
Bedford Catchment	230.000	460	4.10	Sami and Hughes (1996)
St Lucia (min)		816	5.52	Bredenkamp et al. (1995)
Atlantis		390	2.50	Bredenkamp et al. (1995)
Zacharias		1063	4.23	Bredenkamp et al (1995)
Sodwana	0.500	1229	7.67	Meyer et al. (2001)
Mazingwenya	4.000	1061	7.03	Meyer et al. (2001)
Mbazwane	8.000	1124	5.45	Meyer et al. (2001)
Phelendaba	24.000	708	3.79	Meyer et al. (2001)
Makatini	44.000	683	2.65	Meyer et al. (2001)
Tembe	50.000	785	2.62	Meyer et al. (2001)

A2: Soil chemistry data

Site		Depth (cm)	EC (mS/m)	Na	Cl	Mg	HCO_3	NH_4	NO_3	Sr	S	Ca
Alluvium	After rain	0	34.8	46.7	43.4	15.5	210.4	0.6	3.9	0.2	41.5	53.3
Alluvium	After rain	20	16.6	34.5	43.4	4.6	28.1	0.7	1.6	0.1	26.1	12.4
Alluvium	After rain	40	10.3	19.6	34.8	2.9	42.1	0.4	1.8	0.0	9.7	9.1
Alluvium	After rain	60	21.2	40.9	52.1	15.7	98.2	0.9	1.9	0.1	21.2	23.4
Alluvium	After rain	80	37.5	108.3	174.0	7.9	70.1	0.8	0.4	0.3	129.2	36.4
Alluvium	Before rain	0	76.3	115.8	95.6	24.5	210.4	0.1	1.0	0.4	196.2	98.9
Alluvium	Before rain	20	13.9	28.2	26.1	4.1	42.1	0.2	1.3	0.0	12.2	8.6
Alluvium	Before rain	40	11.9	28.8	43.4	3.3	42.1	0.2	3.7	0.0	10.8	4.5
Alluvium	Before rain	60	11.9	27.4	52.1	2.9	70.1	0.2	1.4	0.0	16.0	5.0
Alluvium	Before rain	80	28.0	98.8	174.0	7.9	140.3	0.5	0.7	0.2	47.2	23.9
Escarpment	After rain	0	62.7	76.5	86.9	27.3	280.5	6.0	15.3	0.4	98.4	78.1
Escarpment	After rain	20	55.3	101.3	34.8	21.5	210.4	5.1	0.3	0.2	107.4	41.6
Escarpment	After rain	40	76.2	202.1	86.9	19.3	280.5	2.1	1.0	0.2	81.8	29.5
Escarpment	After rain	60	114.2	330.2	260.6	20.4	280.5	1.4	1.1	0.2	169.5	28.9
Escarpment	After rain	0	74.3	56.3	52.1	51.3	56.2	4.3	7.3	0.7	144.6	113.8
Escarpment	After rain	20	161.9	394.3	325.8	62.7	613.6	2.2	5.0	0.6	258.5	95.4
Escarpment	After rain	40	31.9	902.0	955.6	58.3	350.6	0.7	2.5	0.6	618.6	99.8
Escarpment	After rain	60	27.9	771.6	1042.5	32.3	252.5	0.3	1.3	0.3	381.4	49.1
Escarpment	Before rain	0	66.5	37.6	86.9	39.8	280.5	8.4	1.1	0.7	161.8	121.0
Escarpment	Before rain	20	60.6	104.9	69.6	29.6	175.3	1.3	3.8	0.4	92.2	64.5
Escarpment	Before rain	40	49.7	132.7	26.1	16.4	112.2	0.7	3.5	0.2	77.0	23.0
Escarpment	Before rain	60	134.1	376.7	347.5	34.1	350.7	1.3	4.1	0.3	162.7	42.8
Coastal low	Before rain	0	576.0	1714.9	1477.0	32.7	771.5	0.6	8.0	1.6	1547.0	186.1
Coastal low	Before rain	20	3216.0	9697.0	14769.0	131.1	490.9	2.6	10.8	9.5	2788.5	992.2
Coastal low	Before rain	40	2534.0	7633.8	11033.0	105.7	350.7	2.2	8.3	8.4	3789.0	1161.4
Coastal low	Before rain	60	2827.0	8702.4	12467.0	138.1	420.8	1.4	8.3	9.5	3503.0	1175.2
Coastal low	Before rain	0	327.0	1034.7	695.0	20.7	701.3	0.5	8.8	0.4	750.4	100.5
Coastal low	Before rain	20	3390.0	8772.6	15203.0	513.1	490.9	3.0	109.6	18.6	6326.0	2888.1
Coastal low	Before rain	40	3340.0	7786.2	15551.0	890.6	631.2	2.2	106.0	4.3	7544.0	4150.7
Coastal low	Before rain	60	3815.0	8788.2	**16941.0**	1004.7	350.6	1.8	138.0	5.6	7179.1	4094.7

All values in mg/l unless otherwise indicated

ANALYSIS OF SATURATED SOIL EXTRACTS

A. Preparation of saturated soil extracts

1. Place a known amount of soil in a plastic container and slowly add deionized water wile stirring continuously with a glass rod. The soil is saturated when the first signs of free water van be seen on the surface of the soil.
2. Determine the amount of water added. The saturation percentage is calculated as the percentage water needed to saturate the soil.

B. Determination of cations

1. The content of calcium, magnesium, sodium, potassium and strontium in the saturated extracts were determined with a Varion Vista ICP emmision spectrometer against suitable standards.

C. Determination of chloride

1. Pipet 20ml of the aquous extract into a 100ml erlenmeyer flask and add 5 drops phenolphthalien indicator. If the solution is pink, add 0,1 M H_2SO_4 untill colourless.
2. Add 1ml Potassium chromate indicator (dissolve 5 g potassium chromate in 100 ml deionized water).
3. Titrate with standardised 0,1 M silver nitrate to the end point (clour change from yellow to light brown).
4. Calculation:

   Chloride (mg/l) = 1771 X $AgNO_3$ molarity X Titration

D. Determination of Carbonate and Bicarbonate

1. Pipet 20 ml sample into a 100 ml erlenmeyer flask.
2. Add 5 drops phenilphthaleien indicator. If the colour is pink titrate with standardised 0,1 M HCl to the clourless end point. Note the titrtion figure (A).
3. Add 5 drops of a mixed indicator (methyl orange and xylene cyanol FF) and titrate with standardised 0,1 M HCl to the end point (colour change from green to purple-red). Note the titration figure (B).
4. Calculation:

   Carbonate (mg/l) = 3000 X HCl molarity X A

   Bicarbonate (mg/l) = 3050 X HCL molarity X (B – 2A)

A3: Groundwater chemistry data

NGDB data

Long	Lat	Site	pH	TAL	EC mS/m	N	NH4	F	Na	Mg	Si	P	SO4	Cl	K	Ca
17.504	-29.844	AGTERKRAAL IN LOPIE	7.6	23	76.7	0.5	0.13	0.5	68.7	38.9	5.16	0.01	8.3	215	5.13	13
17.504	-29.844	AGTERKRAAL IN LOPIE	7.6	24	78.2	1.3	0.09	0.4	72.4	41.5	5.96	0.01	12	232	4.71	14
18.017	-30.083	AMEGAS GED.NAKOIG	8.6	57	70.2	0.3	0.05	2.9	72.9	22.6	10.6	0.01	32	148	2.27	23
18.002	-30.082	ANEGAS GED.3	6.4	49	25.6	0.1	0.12	0.5	31.1	6.2	15.8	#	8.4	41.4	1.85	8.8
17.899	-30.074	ARAKOOP	8	250	252	4.4	0.05	3.3	272	83	14.1	#	156	554	4.29	118
17.918	-30.102	ARAKOOP GED.12	6.4	36	37.1	0.4	0.3	<0.1	41.1	8.1	9.84	#	15	76.8	3.24	15
17.902	-30.105	ARAKOOP GED.13	7.2	32	742	3.4	0.39	2.5	724	367	14.6	#	444	2569	9.68	416
17.907	-30.043	ARAKOOP GED.3	7.1	84	120	2.8	0.13	1.9	140	29.5	16.8	0.01	50	281	3.33	40
17.953	-30.045	ARAKOOP GED.4	7.2	128	333	34	0.35	0.6	286	142	20.2	#	226	852	6.34	178
17.833	-30.054	ARAKOOP GED.BRAKPUTS	7.7	90	996	5.7	0.08	2.3	1645	282	18.6	0.02	840	3331	35.3	282
17.958	-30.1	ARAKOOP GED.BRAKWATER	7.8	158	424	3.8	#	2.2	397	180	20.1	#	254	1247	5.54	209
17.95	-30.083	ARAKOOP GED.BRAKWATER	7.5	110	569	5.6	0.06	1.8	459	276	14.6	#	249	1784	7.13	330
17.459	-29.255	ARIROEP	8.4	127	310	2.6	0.07	2.1	422	77	15.5	#	166	850	16.2	98
17.942	-30.133	ARKOEP GED 12	7.4	76	200	5.9	0.04	1.4	221	65.4	16.9	#	105	533	3.53	83
17.772	-30.114	ARONEGAS GED.DE RUNEGAS	7.5	19	719	0.8	0.07	1.7	603	388	19.8	0.03	278	2303	14.3	304
17.448	-30.409	AVONTUUR	8.3	167	284	0.4	0.08	0.8	396	53.5	10.8	0.17	140	851	13.8	145
17.513	-30.391	AVONTUUR	7.7	142	894	#	#	1.3	1333	158	11.1	0.06	291	2902	34.3	380
17.392	-30.3	AVONTUUR	7.2	35	1040	0.1	#	2.1	1867	190	3.41	0.08	456	3297	43.4	177
17.346	-30.328	AVONTUUR	7.7	84	1620	0.3	0.06	2.4	2533	414	8.84	#	571	5709	98.2	646
17.461	-30.384	AVONTUUR GED DIK NEK	8.5	259	522	19	0.05	1.3	821	111	19.2	0.05	285	1662	11.6	257
17.427	-30.359	AVONTUUR GED DIK NEK	8	182	607	0.2	0.21	1.2	1237	77.1	9.69	0.03	323	2068	29.8	125
17.467	-30.383	AVONTUUR GED DIKNEK	7.6	64	484	0.2	0.09	2.3	750	67.1	5.99	0.02	202	1521	22.4	133
17.425	-30.352	AVONTUUR GED DIKNEK	7.4	117	576	0.2	0.06	0.9	988	44.8	6.5	0.02	245	1652	29.3	76
17.293	-30.333	AVONTUUR GED DIKNEK	6.4	42	843	0.4	#	2.4	1411	99.5	1.23	0.02	331	2417	49.9	166
17.934	-29.752	BIESJESFONTEIN	7.7	165	367	0.1	0.05	2.2	373	132	11.4	0.01	235	1081	9.2	237
17.888	-29.713	BIESJESFONTEIN	7.7	148	506	0.1	0.08	3.2	495	209	10.6	0.01	322	1633	9.27	297
18.23	-30.079	BITTERFONTEIN	7.5	193	888	0.4	0.08	1.8	1502	244	11.7	#	359	2910	42.3	165
18.23	-30.079	BITTERFONTEIN	7.3	193	920	#	0.06	2.7	1569	270	8.05	0.01	564	3023	39.1	190
18.45	-30.459	BLESKRANZ	7.7	246	121	20	0.04	2.2	51.7	43.1	14	0.01	132	114	5.72	146
18.333	-30.067	BOESMANPLAAT	8.1	220	680	0.1	#	4.1	1157	146	19.4	0.01	443	2076	111	146
17.935	-30.151	BOWENS DORP	7.7	109	60.7	0.4	#	1.2	79.6	12.8	15.4	0.01	31	114	2.77	22
17.771	-30.25	BRAKFONTEIN	7.4	115	252	#	0.04	2.5	304	68.3	15.1	0.01	73	654	7.61	78
17.242	-29.281	BREEKHOORN	8.3	146	780	10	0.05	2.5	1400	70.1	13.9	0.03	427	2255	39.4	114
17.765	-29.458	BULLETRAP	7.7	118	135	7.7	0.04	2.3	141	37.8	18.3	0.02	80	279	4.13	62
17.765	-29.458	BULLETRAP	7.5	122	125	7.5	#	2.2	139	38.7	17.9	0.02	81	284	4.27	63
17.506	-30.335	BYNESKRANS	8.1	173	995	2.6	#	3.3	1667	184	11.3	0.01	539	2955	71.8	218
17.748	-30.04	CANARIESFONTEIN	8	266	673	1.9	0.05	2.8	754	253	13.8	0.01	376	1995	25.7	265
17.85	-29.769	DANSEKRAAL	7.7	35	62.5	2.3	#	0.3	69	10.4	16.3	0.01	49	124	2.79	22
17.961	-29.95	DE DRAAY	7.8	86	59.7	1.5	#	3.1	53.9	19.2	18.9	0.01	32	115	2.78	35
18.024	-30.195	DE KUILEN	6.5	48	33.3	0.9	0.12	0.2	38.7	8.4	14.6	#	16	57.2	1.54	11
18.049	-30.186	DE KUILEN	6.5	54	66.6	3.2	0.12	0.6	73.4	16.8	11.6	#	41	133	2.3	26
18.049	-30.188	DE KUILEN	8.1	99	66	#	#	5.1	81.9	8.6	10.6	0.01	24	137	2.54	37
18.05	-30.176	DE KUILEN	6.6	43	85.6	2.8	0.14	0.3	90	24.8	13.9	#	43	193	0.79	33
18.049	-30.188	DE KUILEN	7.1	94	97.8	8	#	1.5	126	28.2	15	0.01	77	204	2.8	35
17.491	-29.716	DIE BRAND	7.4	42	268	6.1	0.07	1.2	363	57.4	21.8	0.04	92	699	4.59	45
17.491	-29.716	DIE BRAND	7.1	47	268	6.5	0.12	1.2	381	57.5	21.8	0.04	89	700	4.91	36

Long	Lat	Site	pH	TAL	EC mS/m	N	NH4	F	Na	Mg	Si	P	SO4	Cl	K	Ca
17.491	-29.716	DIE BRAND	7.4	62	281	2.8	0.04	1.2	395	63.2	16.2	0.03	94	728	7.62	49
17.456	-30.404	DIK NEK	8.3	112	1550	#	0.3	1.5	2482	284	2.22	0.02	649	5157	54.7	650
17.424	-30.353	DIK NEK	7.8	153	1500	0.1	0.08	2.1	2333	271	11.8	0.01	425	5725	113	887
17.243	-29.584	DIKGAT	7.4	81	648	4.3	0.08	1	885	170	22.6	0.02	184	2003	38.2	161
17.689	-30.15	DOORNFONTEIN	7.7	302	472	#	0.07	3.4	711	84	32.5	0.01	234	1240	24	120
17.251	-29.443	DROOGE KRAAL	8.3	115	429	0.3	0.05	2.5	801	45.4	10	0.28	245	1381	17	126
17.294	-29.421	DROOGE KRAAL	8.2	117	839	#	0.05	1.7	1279	179	15.1	0.06	434	2551	39.9	195
17.234	-29.494	DROOGE KRAAL	7.9	125	1069	0.7	0.05	1	1993	240	13.8	8.45	678	3889	92.5	273
17.917	-30.454	DROOGEKRAAL	8	127	1006	0.2	0.04	3.5	1274	358	<0.4	0.01	656	3281	30.1	422
17.246	-29.947	ELANDS KLIP	7.8	69	130	#	#	0.4	202	26.8	2.83	0.01	43	361	10.9	18
17.692	-29.699	EZELSFONTEIN	4.2	12	87.4	#	#	0.9	100	21.7	21.1	#	136	172	25.9	8.6
17.646	-29.698	EZELSFONTEIN	8	153	163	2.8	0.04	1.8	170	52.9	13.7	#	105	402	4.67	96
17.672	-29.698	EZELSFONTEIN	8	130	182	0.1	0.05	1.3	198	50.3	19.2	#	116	448	5.47	97
17.734	-29.691	EZELSFONTEIN	8.2	130	217	16	0.07	0.9	196	66.9	14.5	0.02	142	523	9.06	152
18.136	-30.39	EZELSFONTEIN	6.9	47	588	157	0.05	1.2	504	288	6.62	#	309	1892	8.73	347
17.169	-29.271	FARM	8	99	167	2.3	0.06	0.9	357	12.8	12.9	0.01	235	335	2.5	20
17.424	-30.473	FARM	7.6	322	775	22	0.04	1.5	1291	165	16.8	0.01	306	2323	42.1	167
17.626	-30.15	FARM	8	213	960	0.8	0.05	2.6	1234	251	11.8	0.01	380	2984	49.3	373
17.295	-29.244	FARQUARSON	8.2	29	1252	1.8	0.05	0.1	2112	239	4.88	0.04	790	4012	98.2	248
17.151	-29.321	GEMSBOK VLEI	8.2	84	1340	6.4	0.05	1.9	2245	261	13.9	0.03	689	4336	106	256
17.533	-30.471	GHAAMS	7.4	209	2030	3.7	0.05	1.6	3926	397	17	0.01	732	7349	152	257
18.238	-29.317	GOINAUP	7.6	156	188	14	0.05	3.4	231	39.4	12.2	0.01	145	386	7.81	90
17.116	-29.782	GORAAP	7.5	141	2030	0.1	0.58	0.9	3326	669	7.69	0.02	997	7949	128	842
17.417	-29.188	GRASVLAKTE	7.2	57	182	2.3	0.04	1.1	222	43.1	1.36	0.01	83	459	5.82	68
17.689	-30.226	GROOT BERG	7.9	304	888	11	0.05	1.9	1079	326	22.1	0.01	560	2752	27.5	377
17.807	-30.198	GROOT VALLEY	7.7	51	309	1.4	0.05	1.3	268	96.8	13.1	#	117	852	9.15	184
17.799	-30.208	GROOT VALLEY	7.4	92	395	38	#	2.4	441	138	21.6	#	228	1012	6.64	154
17.793	-30.233	GROOT VALLEY	7.5	43	880	15	0.06	2.8	811	372	15.8	#	246	2926	15.8	504
17.719	-30.303	GROOTBERG	6.8	10	132	27	#	0.8	203	20.9	28.3	#	106	250	2.45	22
17.713	-30.252	GROOTBERG	7.8	208	460	1.7	0.05	2.8	553	157	23	#	249	1257	15.4	152
17.199	-29.133	HARDEVLAKTE	7.3	155	700	4.7	0.05	2.5	1248	150	7.46	0.03	391	2251	27.2	139
17.203	-29.121	HARDEVLAKTE	7.8	138	804	10	0.06	2.7	1222	160	16.3	0.03	381	2258	28.8	163
17.199	-29.133	HARDEVLAKTE	7.3	191	710	0.6	0.06	2.6	1271	150	8.99	0.04	376	2262	29.3	143
17.204	-29.121	HARDEVLAKTE	7.8	137	813	11	0.06	2.7	1222	160	15.4	0.03	387	2285	28.6	167
17.199	-29.133	HARDEVLAKTE	7	137	700	0.1	0.05	2.2	1267	145	2.83	0.03	387	2318	26.2	132
17.238	-29.132	HARDEVLAKTE	7.9	196	940	#	0.05	4	1430	263	11	0.07	604	2932	46.9	317
17.199	-29.133	HARDEVLAKTE	7.2	131	900	4.9	0.07	1.5	959	335	10.4	0.04	566	3035	36.9	572
17.158	-29.146	HARDEVLAKTE	7.7	203	1728	3.3	0.06	3.3	3628	279	10.7	0.05	###	5914	115	293
17.163	-29.149	HARDEVLAKTE	7	108	4480	0.3	0.2	6.4	8765	1056	4.23	0.06	###	####	302	###
17.439	-29.326	HARRAS	8.1	146	267	1.1	0.05	4.2	401	69.3	10.6	#	149	695	7.93	50
17.418	-29.412	HARRAS	8.2	204	558	3.9	0.07	4.2	889	106	19.2	0.02	375	1608	24.2	168
17.275	-30.027	HEIDONS	8.3	333	290	39	0.05	1.4	496	42.2	11.9	0.09	112	615	17.8	82
17.292	-30.017	HEIDONS	7.1	58	286	0.2	#	2.1	505	11.3	12.4	0.01	106	766	9.78	30
17.211	-29.781	HONDE VLEI	7.8	109	547	0	0.04	0.6	935	109	13.6	0.01	119	1874	45.3	118
17.611	-30.314	HOREES	7.9	101	500	#	#	3.9	793	35.9	18.8	0.01	264	1468	31.1	185
17.633	-30.333	HOREES	7.1	57	731	0.8	0.06	###	1042	747	17.2	0.02	340	1971	288	224
17.817	-30	HUNBOOM GED.RONDEKOP	6.9	76	357	32	0.06	1.5	326	148	20.4	#	229	949	6.74	167
17.531	-29.69	KAMAGGAS	8	115	279	0.1	0.21	1.9	273	82.9	6.9	0.01	103	765	14.5	127
17.428	-29.786	KAMAGGAS	7.6	97	335	4.5	#	1.7	541	54.3	23.5	0.02	240	856	15.7	58
17.646	-30.442	KAMEELBOOM	7.5	205	1550	4.4	0.06	2.4	2483	447	17.3	0.02	945	5230	113	438
17.472	-29.995	KAMEELBOOM VLEY	7.8	160	939	1.4	0.05	2	1657	143	17.4	0.01	683	2640	91.5	175
17.952	-30.213	KAMIESKROON ALLOTMENT ARE	7.7	128	74	0.8	#	2.3	107	16.9	16.8	#	26	138	0.91	24
17.952	-30.214	KAMIESKROON ALLOTMENT ARE	7.9	122	72.7	0.6	#	2.1	107	16.6	15.1	0.01	33	142	1.3	23

Long	Lat	Site	pH	TAL	EC mS/m	N	NH4	F	Na	Mg	Si	P	SO4	Cl	K	Ca
17.952	-30.214	KAMIESKROON ALLOTMENT ARE	7.7	191	108	0.4	#	2.2	155	26.7	19.5	0.02	46	213	0.85	40
17.911	-30.217	KAMIESKROON ALLOTMENT ARE	7.5	157	390	2.2	#	1	395	138	16.3	0.01	199	1140	3.9	218
17.911	-30.221	KAMIESKROON ALLOTMENT ARE	7.4	151	420	1.7	#	0.9	385	173	15.2	#	220	1257	3.54	252
17.911	-30.22	KAMIESKROON TOEKENNINGS G	7.9	180	281	1.1	#	1.2	262	87.5	13.2	#	132	761	4.9	169
17.951	-30.214	KAMMIESKROON	7.9	141	366	1.1	0.04	1.3	361	129	13.1	0.01	152	1016	8.62	192
17.932	-30.228	KAMMIESKROON	8.1	188	704	44	0.05	3.4	991	215	16.5	0.03	506	2229	19.2	312
17.91	-30.216	KAMMIESKROON ALLOTMENT	8.3	165	63.7	0.5	0.04	1.4	108	11.5	8.72	0.02	28	99.1	3.56	23
17.91	-30.218	KAMMIESKROON ALLOTMENT	8.1	82	47.3	0.1	0.18	0.6	71.5	9.6	1.43	0.01	9.6	108	1.83	16
17.911	-30.219	KAMMIESKROON ALLOTMENT	7.8	30	65	0.1	0.27	0.4	105	8	0.71	0.01	13	195	2.29	13
17.91	-30.216	KAMMIESKROON ALLOTMENT	8	69	96.9	0.1	0.11	1.4	132	27.4	<0.4	0.01	38	266	4.81	30
17.91	-30.218	KAMMIESKROON ALLOTMENT	7.5	61	138	1.1	0.04	0.5	135	49.7	16.7	0.02	68	362	1.98	61
17.911	-30.219	KAMMIESKROON ALLOTMENT	7.8	165	263	1.6	#	1.2	294	93.9	13.9	0.01	127	779	4.34	149
17.928	-30.203	KAMMIESKROON DORPS WATER	7.7	121	155	0.8	#	2.2	176	44.6	14.6	0.01	78	385	3.42	66
17.928	-30.203	KAMMIESKROON DORPS WATER	8	122	151	1	#	2.2	172	43.4	14.7	0.01	72	388	3.13	69
17.558	-29.431	KAMNAP	8.1	141	164	13	0.04	2.6	219	42.7	22.8	0.01	102	340	4.36	49
17.558	-29.499	KAMNAP	8.1	201	270	4.9	0.06	2.5	281	112	11.9	#	232	744	14.8	145
17.218	-29.716	KANNABIEDUIN (TAAIBOSKNOP	7.8	77	257	2.1	#	0.5	364	47.4	24.9	0.02	49	670	15.6	45
17.15	-29.729	KANNABIEDUIN(STEENVLEI)	7.9	118	487	0.3	#	0.6	849	53.2	16.1	0.03	158	1386	42.5	47
17.013	-29.258	KANNIKWA	7.3	62	326	1.7	#	0.8	421	62.1	15.3	0.01	175	845	8.92	84
17.965	-29.708	KAREHOUTE KLOOF	7.9	86	116	2.6	#	2.7	105	32.2	12.2	0.01	61	287	3.15	81
17.638	-29.931	KEEROM	8.2	240	481	2.3	#	2.8	526	143	12.2	0.01	239	1334	14.1	217
17.683	-29.999	KEEROM	8	152	487	23	#	3.2	742	101	20.7	0.01	279	1427	14.9	163
17.971	-30.013	KERSBOSCH FONTEIN	7.2	109	320	0.5	0.04	3	274	121	12.8	0.01	193	809	5.69	173
18.057	-30.014	KERSBOSCH FONTEIN	7.4	107	716	63	0.3	0.7	459	344	17.5	#	524	2327	14.1	674
17.892	-30.033	KERSBOSCH FONTEIN GED.1	7.6	108	218	37	0.09	3.2	169	58.7	12.5	0.01	113	467	13.5	156
17.995	-30.008	KERSBOSCH FONTEIN GED.4	7.4	94	310	12	0.28	1.9	269	90.5	14.7	#	295	790	4.8	246
17.683	-30.204	KLIPBOKFONTEIN	7.1	124	385	0.1	0.04	2.4	323	143	14.6	0.03	176	1058	13	225
17.748	-29.805	KLIPFONTEIN	7.8	69	153	28	#	1.2	238	13.3	20.8	0.01	62	298	7.1	18
17.755	-29.835	KLIPFONTEIN	7.5	140	279	0.1	0.05	3.5	272	73.6	17.5	0.02	172	699	12.9	155
17.674	-29.845	KLIPFONTEIN	8.4	238	392	11	0.05	3.5	535	92.2	19.4	0.01	263	967	10.9	138
17.951	-30.214	KOETS	6.8	21	6	2.6	0.04	0.1	2.1	2.3	8.94	0.01	<4	3.2	1.5	5.2
17.571	-30.126	KOETS	8.4	116	73.4	1.1	#	2	98.2	15.6	15.6	0.03	29	136	2	20
17.493	-29.798	KOMAGGAS	7.4	212	49	2.5	0.04	0.2	10.6	31.7	12.6	0.01	4.6	11.3	0.95	44
17.488	-29.548	KOMAGGAS	7	23	88.4	1.9	0.08	0.5	96.4	27.9	16.4	0.02	42	194	6.19	14
17.488	-29.548	KOMAGGAS	6.7	29	87.8	2	#	0.6	95.7	27.7	17	0.02	47	197	6.08	16
17.488	-29.548	KOMAGGAS	6.7	28	88.3	1.7	0.05	0.4	97.2	27.7	16.7	0.02	45	198	6.42	15
17.493	-29.798	KOMAGGAS	6.1	36	88	1.8	0.06	0.4	95.2	28.3	16.4	0.03	38	201	6.3	17
17.493	-29.798	KOMAGGAS	6.3	38	90.8	1.6	0.17	0.3	98.3	29.3	16.4	0.02	39	206	6.3	17
17.493	-29.798	KOMAGGAS	6.2	36	92.3	1.5	0.07	0.4	99.1	30.3	15.8	0.01	39	219	6.08	16
17.502	-29.788	KOMAGGAS	8	244	255	2.5	#	0.7	346	91.7	14.7	0.01	141	608	14.1	50
17.502	-29.788	KOMAGGAS	7.7	158	262	4	0.04	0.7	368	84.4	15.3	0.02	147	648	13.1	47
17.484	-29.84	KOMAGGAS	7.1	155	452	3	1.19	2.4	687	159	17.3	0.04	297	1476	12.2	159
17.484	-29.84	KOMAGGAS	8	155	448	2.4	0.2	2.4	654	156	16.9	0.04	275	1481	11.7	163
17.495	-29.802	KOMAGGAS DORP	6.9	19	79.2	2.2	0.04	0.3	84.3	24.4	14.8	0.03	25	186	5.51	13
17.494	-29.799	KOMAGGAS DORP	6.6	19	84.2	2.2	0.05	0.4	94.3	26.9	16.5	0.03	37	197	5.99	14
17.494	-29.799	KOMAGGAS DORP	6.4	20	85.8	2.4	0.05	0.2	95	27.7	16.4	0.03	36	198	6.1	14
17.494	-29.799	KOMAGGAS DORP	6.5	23	85.7	2.2	0.05	0.3	93.5	27.7	16.2	0.02	37	200	5.98	14
17.494	-29.799	KOMAGGAS DORP	7	24	85.4	0.2	0.06	0.3	91.3	27.3	16.2	0.03	40	202	5.72	14
17.494	-29.799	KOMAGGAS DORP	6.9	19	86.1	1.2	0.06	0.4	92.7	27.8	16.4	0.03	42	205	5.83	14
17.494	-29.799	KOMAGGAS DORP	6.9	21	89.2	1	0.07	0.3	94.8	29.4	16.8	0.05	48	209	6.15	16
17.494	-29.799	KOMAGGAS DORP	6.9	19	91.3	1.5	0.07	0.5	96.6	29	16.5	0.03	43	209	5.99	15

Long	Lat	Site	pH	TAL	EC mS/m	N	NH4	F	Na	Mg	Si	P	SO4	Cl	K	Ca
17.494	-29.799	KOMAGGAS DORP	6.9	16	88.5	1.8	0.06	0.3	95.1	29.3	16.4	0.03	42	211	5.87	15
17.494	-29.799	KOMAGGAS DORP	6.9	19	102	2.6	0.12	0.3	108	36.4	18	0.03	85	223	6.97	20
17.497	-29.802	KOMAGGAS DORP	7.1	26	116	2.6	0.04	0.2	142	33.5	11.7	0.02	52	302	6.3	16
17.499	-29.803	KOMAGGAS DORP	7	34	142	2.5	0.04	0.5	187	40.8	10.8	0.02	69	361	8.75	20
17.499	-29.803	KOMAGGAS DORP	7.3	45	141	0.1	0.5	0.5	183	40.5	10.6	0.03	64	363	8.75	20
17.499	-29.803	KOMAGGAS DORP	6.6	37	148	2.1	0.05	0.6	194	42.7	10.4	0.02	69	374	9.41	21
17.499	-29.803	KOMAGGAS DORP	7.3	37	153	2.1	0.06	0.9	200	44.4	10.4	0.03	73	383	9.28	22
17.489	-29.795	KOMAGGAS DORP	6.7	63	256	4.3	#	3.6	347	25.6	10.8	0.03	151	659	6.36	136
17.499	-29.792	KOMAGGAS DORP	7.6	185	287	3.2	#	0.5	371	93.9	15.6	0.03	139	684	13.9	51
17.489	-29.795	KOMAGGAS DORP	7.3	34	271	2.8	0.05	4	343	21.6	10.3	0.03	133	684	5.34	133
17.499	-29.792	KOMAGGAS DORP	7.4	171	290	3.2	0.05	0.4	371	94	15.2	0.03	142	695	12.7	53
17.489	-29.795	KOMAGGAS DORP	7.4	37	273	2.7	0.06	4	333	21.5	10.8	0.02	127	701	3.58	137
17.489	-29.795	KOMAGGAS DORP	7.4	47	299	4	#	3.7	358	31	12.4	0.02	163	747	5.86	153
17.499	-29.792	KOMAGGAS DORP	7.3	120	303	4.7	0.04	0.3	398	95.4	15	0.03	149	763	13.3	51
17.489	-29.799	KOMAGGAS DORP	7.4	45	316	13	0.06	3.5	398	46.3	12.8	0.03	185	794	8.21	143
17.489	-29.795	KOMAGGAS DORP	7.4	55	303	3.9	#	3.8	370	33.9	13	0.03	137	848	7.07	166
17.663	-30.059	KOOKFONTEIN	8	341	727	1.3	#	3.4	1067	180	17.2	0.02	400	2041	34.5	209
17.776	-29.894	KOORNHUIS	7.6	130	212	3.5	0.04	2.9	204	60.9	14.3	0.01	118	502	4.39	94
17.674	-29.91	KOORNHUIS	7.9	174	291	#	#	2.2	356	74.5	15	0.01	152	814	12.2	138
17.734	-29.917	KOORNHUIS	8.3	258	313	0.8	#	3.5	412	81.5	14.9	0.01	174	836	11	131
17.82	-29.922	KOORNHUIS	8.1	230	529	0.3	0.08	3.8	637	157	16.7	0.01	339	1578	15.1	257
17.854	-29.971	KOORNHUIS	8.2	270	766	#	0.1	4.6	954	245	16.5	0.01	539	2400	23.3	423
17.775	-29.993	KOORNHUIS	8	213	949	4.4	0.1	4	1036	311	12.3	0.03	828	2834	40.9	617
17.393	-29.2	KOOTJIESVLEI	6.9	93	242	1.2	0.04	0.7	288	48.1	8.52	0.01	119	591	8.84	91
17.256	-29.066	KORRIDOR	7.3	118	466	2	#	2	668	81.8	15.3	0.02	307	1298	14.9	167
17.316	-29.086	KORRIDOR	7.4	121	511	1.3	#	1.1	686	112	15.3	0.05	327	1354	22.1	177
17.203	-29.132	KORRIDOR	7.9	134	690	2	1.02	2.6	1281	156	5.31	0.07	379	2358	27.4	118
17.24	-29.131	KORRIDOR	7.3	193	1017	3	0.05	4.2	1326	267	13.5	0.01	575	2797	32.1	353
17.24	-29.131	KORRIDOR	7.3	191	1032	3.1	0.08	4.3	1351	267	14	0.02	711	2821	37.1	307
17.24	-29.131	KORRIDOR	7.3	193	1039	3.3	0.07	4.4	1376	267	13.6	0.01	635	2850	36.9	338
17.144	-29.14	KORRIDOR	7.4	175	2656	7.7	0.04	2.2	5173	633	21.3	0.06	###	####	95.9	748
17.567	-29.098	KOSIES	7.4	132	187	2.3	0.05	1.8	198	58.8	15.2	0.02	88	473	1.99	94
18.4	-30.283	KOUGOEDVLAKTE	7.7	138	446	0.2	0.06	3.3	513	155	13.9	0.01	347	1260	9.78	192
17.505	-29.888	KOURKAM	7.9	141	911	12	0.08	2.9	1172	258	11.8	0.01	451	2609	43.7	243
17.346	-29.815	KOUROOTJE	7.7	71	431	7.2	0.05	0.7	617	109	11.5	0.01	169	1221	33.3	76
17.337	-29.791	KOUROOTJE	8	122	547	6.4	#	0.5	966	61.1	25.3	0.03	192	1526	34.1	45
17.551	-29.804	KOUTAS	8	95	423	3.1	0.05	3.5	517	137	18.6	0.03	195	1164	3.84	125
17.551	-29.804	KOUTAS	7.7	85	986	2	0.04	3	1160	398	17.2	0.04	338	3160	11.1	342
17.551	-29.804	KOUTAS	7.7	85	1066	1.7	0.08	2.8	1258	438	16.9	0.03	342	3439	16.2	388
17.485	-29.94	KRAAIFONTEIN	8.1	132	758	1.6	#	1.7	1177	181	18.4	0.01	349	2369	31.6	187
17.997	-30.478	KYSRIVIER	8	188	579	1.9	0.08	6.2	1064	73.1	24.8	0.02	336	1599	12.1	57
17.988	-30.433	KYSRIVIER	6.4	9.2	560	0.2	0.13	2.2	721	164	1.87	0.01	291	1707	17.6	161
18.337	-30.33	LANG DAM EXTENTION	7.7	256	882	0.1	0.25	1.9	1412	316	3.15	0.02	509	2813	28.9	201
17.357	-30.372	LANG KLIP	7.7	82	1258	0.3	0.09	0.4	1342	138	11.5	0.02	308	4106	110	922
17.308	-30.375	LANGKLIP	8.2	219	6728	#	0.16	1.5	####	2167	9.62	0.02	###	####	261	###
17.809	-30.295	LELIE FONTEIN	6.9	97	307	4.3	#	2.8	364	106	23.6	0.01	141	876	5.64	84
17.948	-30.48	LELIE FONTEIN	6.9	66	880	0.2	#	2.9	1126	308	22.1	0.01	348	2752	28.4	278
18.097	-30.349	LELIEFONTEIN	6.4	22	19.3	1.3	#	0.1	18	3.3	13.8	#	4.5	29.7	2.99	8.3
17.939	-30.328	LELIEFONTEIN	7.5	76	49.9	#	#	0.9	51.3	11.2	20.3	0.01	5.6	94.7	3.1	24
18.06	-30.28	LELIEFONTEIN	7	63	50	0.2	#	1.9	42.4	11.1	19.1	#	12	97.9	2.86	30
18.102	-30.222	LELIEFONTEIN	7	77	65	0.1	0.09	3.4	52.8	17.3	15.4	0.01	28	124	1.7	42
18.05	-30.249	LELIEFONTEIN	7.7	106	81.5	0.1	0.04	2.4	72.4	31.6	16.3	#	48	170	1.12	44
18.274	-30.334	LELIEFONTEIN	6.6	32	74	#	0.1	1.2	108	12.6	10.5	0.01	47	174	1.82	16
18.237	-30.073	LELIEFONTEIN	7.9	179	120	0.5	#	3.1	102	43.6	18	#	86	234	2.15	81
18.229	-30.102	LELIEFONTEIN	7.4	186	134	1.7	0.09	2.6	108	46.9	20.4	0.01	93	248	1.7	92

Long	Lat	Site	pH	TAL	EC mS/m	N	NH4	F	Na	Mg	Si	P	SO4	Cl	K	Ca
18.238	-30.279	LELIEFONTEIN	7.3	99	118	0.1	0.14	3.1	116	37.2	11.5	0.01	54	268	1.92	55
18.136	-30.302	LELIEFONTEIN	7.2	58	126	1.6	0.05	1.3	142	38.5	18.3	#	57	333	0.56	50
18.265	-30.271	LELIEFONTEIN	7.4	140	154	1.5	0.08	2.4	154	53	14.9	0.01	92	336	1.61	65
18.247	-30.065	LELIEFONTEIN	8.7	134	166	8	0.08	2.8	174	48	21.7	0.01	100	339	2.67	75
17.976	-30.354	LELIEFONTEIN	7.2	76	166	0.2	0.09	2.3	182	51.8	12	0.01	86	406	4.1	53
18.273	-30.03	LELIEFONTEIN	7.3	67	176	9.9	0.08	5	224	38.4	36.1	#	110	439	1.24	66
18.017	-30.336	LELIEFONTEIN	8.1	137	188	#	0.05	2.7	192	62.2	23.2	0.04	142	470	5.33	100
17.979	-30.344	LELIEFONTEIN	7.5	99	198	0.2	0.09	1.8	261	48.6	3.2	#	124	484	11.5	63
17.952	-30.358	LELIEFONTEIN	3.5	<4	199	0.1	0.43	0.3	297	26.8	1.22	0.01	51	545	3.58	22
18.2	-30.253	LELIEFONTEIN	7.7	106	245	0.6	0.04	2.9	243	63.4	11.1	0.01	200	623	1.75	162
17.935	-30.382	LELIEFONTEIN	7.4	98	278	0.1	0.16	2.9	271	71.5	5.3	#	193	691	12.7	182
18.308	-30.34	LELIEFONTEIN	7.4	142	278	0.1	0.23	2.7	295	90.2	8.75	0.01	150	712	8.07	115
17.992	-30.354	LELIEFONTEIN	7.7	119	285	2.3	#	3.6	326	87.1	16.1	#	170	759	6.91	119
18.021	-30.328	LELIEFONTEIN	8	143	282	0.3	0.07	2.8	335	91.4	19.4	0.04	213	776	5.66	127
18.268	-30.345	LELIEFONTEIN	7.2	67	304	3.6	0.04	1.7	297	122	11.9	0.03	193	859	4.14	150
18.268	-30.345	LELIEFONTEIN	6.9	127	323	2.6	0.12	3.5	316	128	8.34	0.01	186	882	13.1	157
18.265	-30.27	LELIEFONTEIN	7.1	101	389	0.1	0.22	2.5	375	158	5.71	0.01	161	1141	12.2	153
17.958	-30.343	LELIEFONTEIN	7.3	88	413	0.1	0.08	2.3	370	134	6.59	0.01	94	1252	24.8	235
17.989	-30.433	LELIEFONTEIN	8.8	148	536	0.2	0.07	3.5	653	155	14	0.01	270	1426	0.96	196
17.999	-30.478	LELIEFONTEIN	7.4	209	630	0.8	0.16	5.6	1140	80.3	20.7	0.01	350	1731	54.4	70
17.888	-30.366	LELIEFONTEIN	7.3	79	618	#	#	2.2	668	247	9.39	0.01	211	1967	13.7	181
17.992	-30.465	LELIEFONTEIN	7.6	299	676	0.3	0.09	2.5	1054	186	14.8	0.01	333	2059	73.9	218
17.887	-30.361	LELIEFONTEIN	7.5	98	669	#	#	3.5	660	282	13.6	#	274	2153	12.5	258
17.81	-30.295	LELIEFONTEIN	7.3	149	720	0.2	0.07	1.8	596	250	7.11	0.01	296	2359	57.4	611
18.261	-30.066	LELIEFONTEIN	7.6	290	740	0.1	0.16	3	1182	231	16	0.01	543	2466	4.62	318
17.731	-30.465	LELIEFONTEIN	7.6	145	858	0.6	0.1	3.1	1398	121	12.7	#	409	2669	60.6	341
17.709	-30.375	LELIEFONTEIN	7.9	94	930	2.2	0.35	1.9	1473	311	13.9	0.01	479	3201	37.9	253
17.727	-30.346	LELIEFONTEIN	8	70	1440	0.3	0.06	2.3	2059	568	20.8	0.02	581	5079	22.7	437
17.988	-30.449	LELIEFONTEIN	7.6	82	2918	3.1	0.08	3.3	4572	1016	9.66	0.02	###	####	112	###
17.931	-30.325	LELIEFONTEIN COM RE	6	57	185	#	0.09	1.4	200	51.2	7.4	#	78	486	5.4	75
17.931	-30.325	LELIEFONTEIN COM RE	7.8	87	238	0.1	0.04	2	226	78.3	12.7	0.02	206	657	10.4	152
17.936	-30.382	LELIEFONTEIN COM RE	7.4	80	300	3.2	0.17	3.1	308	85.6	5.31	0.02	283	789	29.2	156
17.888	-30.382	LELIEFONTEIN COM RE	7.8	98	419	0.1	0.06	2.7	443	153	12.7	0.01	190	1333	12	187
17.724	-30.377	LELIEFONTEIN GED BOOIGAL	7.1	104	1016	0.7	0.74	1.6	1474	335	13.9	0.01	581	3146	21.6	268
18.267	-30.278	LELIEFONTEIN GED EEN-WILG	7.2	117	134	0.5	0.04	2.2	139	46.9	11.9	0.02	80	280	1.13	48
17.889	-30.348	LELIEFONTEIN GED KARKAMS	5.7	17	20.8	1.3	0.09	1.8	33.5	2.2	14.9	0.03	27	31.7	1.36	2.7
17.893	-30.383	LELIEFONTEIN GED KARKAMS	6.3	20	35.5	1.5	0.1	0.7	46.8	5.2	14.9	0.03	19	72.3	2.29	6.8
17.89	-30.381	LELIEFONTEIN GED KARKAMS	6	11	47.9	9.6	0.17	1	62.8	7.6	13.5	0.01	20	89.7	2.3	10
17.93	-30.329	LELIEFONTEIN GED KARKAMS	6.5	64	52.6	#	#	0.7	63.4	14.7	10.2	#	37	103	4.89	25
17.931	-30.329	LELIEFONTEIN GED KARKAMS	6.9	81	159	#	#	1.9	135	52.8	7.61	#	74	444	8.36	126
17.929	-30.329	LELIEFONTEIN GED KARKAMS	6.8	78	183	#	#	2	177	57.9	17	#	107	545	12	150
17.89	-30.382	LELIEFONTEIN GED KARKAMS	7.3	111	339	0.1	#	2.5	350	129	37.4	#	130	1043	10	173
17.889	-30.348	LELIEFONTEIN GED KARKAMS	7.1	81	449	0.1	#	1.8	430	200	15.6	#	198	1345	11.4	223
17.899	-30.378	LELIEFONTEIN GED KARKAMS	7.5	132	506	0.1	0.22	3.1	600	153	12	0.01	131	1434	8.36	189
17.89	-30.381	LELIEFONTEIN GED KARKAMS	7.2	45	698	0.4	0.18	2	782	282	2.49	#	251	2318	51.6	292
17.905	-30.359	LELIEFONTEIN GED KARKAMS	6.7	20	1269	0.1	0.08	3.3	1456	836	35.5	#	569	5263	107	695
18.275	-30.329	LELIEFONTEIN GED MOEDVERL	6.9	65	227	0.1	0.04	3.5	274	62.2	10.4	0.02	136	573	2.37	70
17.713	-30.342	LELIEFONTEIN GED PATRYSVL	8	106	1460	0.1	0.05	2.3	2132	547	18.4	0.02	767	4929	28.4	462
17.713	-30.342	LELIEFONTEIN GED PATRYSVL	6.6	70	1540	#	0.11	1.8	2310	548	1.66	0.01	837	5288	23.6	433
18.307	-30.364	LELIEFONTEIN GED SLOOTJIE	7.4	134	282	0.1	0.05	2.6	297	96.9	10.1	0.01	171	719	5.1	110
17.812	-30.27	LELIEFONTEIN GED WITSAND	7	144	410	0.1	#	2	362	117	9.58	#	181	1113	17.2	277
18.196	-30.042	LELIEFONTEIN GED.KALBASKR	7	141	166	8	#	2.7	179	46.3	21.6	#	104	339	3.67	71
18.028	-30.302	LELIEFONTEIN WEST	7.8	132	119	0.1	#	3	108	43.5	18.6	0.02	47	282	3.76	66
18.028	-30.302	LELIEFONTEIN WEST	7.7	130	109	0.2	#	2.9	107	44.4	18.2	0.02	45	284	3.93	66
18.076	-30.334	LELIEFONTEIN WEST	8	169	210	#	0.08	3.5	249	67.8	17.5	0.03	151	535	6.55	107

Long	Lat	Site	pH	TAL	EC mS/m	N	NH4	F	Na	Mg	Si	P	SO4	Cl	K	Ca
18.018	-30.298	LELIEFONTEIN WEST	7.3	215	230	1.3	0.07	2.2	244	90.1	22.3	0.03	100	564	4.67	104
18.018	-30.298	LELIEFONTEIN WEST	8.5	232	225	1.4	0.12	2.1	239	91	22	0.05	100	566	4.52	111
18.018	-30.298	LELIEFONTEIN WEST	7.4	225	229	1.3	#	2.2	238	91.1	22	0.03	100	577	4.49	102
17.296	-29.767	LOUROOTJIE	8	74	205	1.5	0.05	0.9	323	24.2	16.8	0.02	55	552	13.4	21
17.964	-29.584	MELKBOSCHKUIL	8.1	121	359	4.7	0.11	3.3	304	130	11.7	0.01	287	1012	0.55	243
17.878	-29.888	MESKLIP	7.8	116	256	1.2	#	3.4	369	33.4	27	0.01	119	713	9.76	107
17.9	-29.953	MESKLIP	7.8	203	747	4.9	0.07	3.8	898	244	11.9	0.01	410	2421	16.4	421
17.99	-30.187	MODDERFONTEIN	7.1	80	49.3	0.1	0.12	2.7	43.5	14.8	5.76	#	20	85.5	1.55	28
18.013	-30.17	MODDERFONTEIN	7.7	98	97.2	3.9	#	1.3	111	31.9	16.2	0.01	50	231	2.69	38
17.777	-29.709	MODDERFONTEIN	7.8	130	428	0.1	0.07	2.5	377	125	15.1	0.01	234	1245	11.3	290
17.141	-29.404	NAKANAS	8.1	102	1133	2	0.04	2.6	1831	235	17.6	0.04	648	3562	100	231
17.911	-29.565	NARRAP	7.4	107	241	4.2	0.16	1.6	255	77.5	15.7	0.02	198	608	2.56	146
17.911	-29.565	NARRAP	7.4	110	242	4.4	#	1.6	240	77.8	15.4	0.02	195	621	2.48	140
17.227	-29.424	NEIDJES KARROO	8.3	98	674	2.4	0.05	3	1329	139	9.89	0.24	382	2359	59.5	115
17.199	-29.25	NIEUWE FONTEIN	8.2	100	220	2.1	0.04	0.8	311	10.2	15.3	0.01	212	317	2.4	17
17.913	-30.246	NIEUWE PLAATS	7.5	71	310	2.9	0.05	0.9	204	141	10.1	0.01	56	870	7.07	166
17.887	-30.24	NIEUWE PLAATS	7.6	197	654	20	0.07	1.5	409	361	22.3	#	189	2012	9.08	400
17.559	-29.58	NIGRAMOEP(OLIENHOUTBANK)	7.2	94	321	#	2.18	3.2	313	122	4.82	0.02	159	999	12.2	177
17.478	-29.476	NOMBIES	7.8	207	779	2.5	0.06	3	1129	175	14.8	0.02	615	2248	30.5	311
18.005	-30.23	OLYVENFONTEIN	7.3	70	45.1	2.8	#	1.1	46.1	8.2	12.5	0.01	15	80.7	2.42	26
17.096	-29.263	OOGRABIES	7.2	69	275	1.4	#	1	379	64.3	13.8	0.01	154	737	6.35	99
17.096	-29.263	OOGRABIES	7.1	68	286	1.7	#	0.8	366	58.8	15.9	0.01	157	748	8.11	75
17.094	-29.264	OOGRABIES	7.3	55	289	1.9	#	0.8	395	48.8	15.8	0.01	147	770	7.39	68
17.131	-29.233	OOGRABIES	7.9	96	688	1.5	#	3	1164	107	15.1	0.02	257	2074	63.3	161
17.051	-29.184	OOGRABIES WEST	8.2	168	927	2	0.06	1.3	1744	236	12.6	0.01	760	3381	102	281
17.976	-30.232	OOSLIESFONTEIN	7.8	91	90	#	0.07	1	63	29.5	10.5	0.09	27	203	2.23	68
18	-30.147	OSPLAAS	7.2	61	127	0.1	#	4.2	136	35.2	14.7	#	85	330	3.05	66
17.506	-30.074	OUBEES	7.9	144	509	1.8	0.14	2.7	826	66.1	19.2	0.01	232	1479	31.4	123
17.925	-29.83	OUHOEK	8.3	148	80.7	0.1	#	3.6	98.7	16.4	13.8	0.01	48	149	2.77	50
17.952	-30.214	OUSS	7.6	109	69.2	0.9	#	2.5	101	15.1	15.2	0.02	39	135	2.56	20
17.953	-30.231	OUSS	7.8	118	98.6	1.1	0.04	1.8	124	27.9	14.1	0.01	61	195	1.66	34
17.93	-30.179	OUSS	7.6	78	171	4	0.04	1	149	68.9	17.1	#	122	395	3.43	78
17.932	-30.177	OUSS	7.6	110	224	3.9	#	0.9	213	89	15.3	0.01	151	595	3.7	96
17.907	-30.17	OUSS	7.5	118	272	1	#	0.9	292	88.8	16.3	0.03	144	754	10.9	115
17.912	-30.202	OUSS	8.2	144	302	0.1	3.38	1.1	255	131	7.01	0.01	188	858	13.3	149
17.892	-30.154	OUSS	7.4	134	391	8.6	0.04	1.7	378	159	16.2	#	217	1055	7.81	170
17.936	-30.183	OUSS	7.7	131	346	0.3	0.07	1	298	185	13.7	0.03	356	1108	12.1	260
17.917	-30.221	OUSS	7.9	112	553	19	#	1.5	557	281	17.8	0.02	278	1835	6.42	280
17.951	-30.214	OUSS GED.KAMIESKROON	8	104	105	1.3	0.38	1.7	132	35.5	6.93	0.01	38	284	3.26	36
17.988	-29.917	PAARDEKRAAL	7.6	80	434	#	0.1	2.8	510	98.9	6.89	0.01	205	1322	9.42	224
17.394	-29.874	PAP VLEY	7.7	30	34.7	8	#	0.6	41.9	3.1	15.7	0.02	8.6	58.4	3.95	17
18.306	-30.153	PAPKUILSFONTEIN	7	146	129	0.5	#	3.8	159	29.1	17.9	0.01	86	252	4.85	49
18.106	-30.137	PEDROS KLOOF	7.5	218	130	4.5	0.12	0.7	124	49.7	19.4	#	70	226	1.23	64
18.062	-30.193	PEDROS KLOOF	6.9	80	148	0.4	0.12	2.7	145	48.4	6.71	0.01	78	369	1.4	64
18.087	-30.16	PEDROS KLOOF	7.3	102	192	5.1	0.09	1.1	157	73.4	17.5	#	126	465	3.64	107
18.258	-29.833	PERSEELA DABEEP	6.7	133	149	4.5	#	1.9	180	32.5	19.8	#	100	314	13.6	67
17.738	-30.464	PIET-SE-PUT	4.4	13	760	0.2	1.44	2.2	1254	93.4	0.77	0.01	420	2249	21.3	182
17.505	-29.173	PLAAS 15	7.4	134	210	0.3	#	1.1	261	60.9	22.2	0.03	112	552	4.49	91
17.505	-29.173	PLAAS 15	7.4	133	213	0.5	0.08	1.2	264	61.5	23	0.03	115	556	4.36	92
17.516	-29.105	PLAAS 29	7.6	117	219	3.7	#	1.4	277	61.5	18.8	0.02	128	577	4.6	91
17.516	-29.105	PLAAS 29	7.6	110	214	3.7	0.04	1.4	278	58.5	19.4	0.02	126	596	4.61	91
17.728	-29.513	PLAATJESFONTEIN	7.7	117	108	1.2	0.04	3.5	121	24	14.5	0.01	98	210	2.51	58
17.736	-29.543	PLAATJESFONTEIN	8.2	114	227	0	0.05	3.3	205	36.1	13.6	0.02	322	509	5.76	234
17.724	-29.537	PLAATJESFONTEIN	7.4	106	617	0.1	0.07	3.8	618	145	11.5	0.02	###	1491	13.5	618
17.386	-29.961	PLAT VLEY	7.6	34	219	2.6	#	0.7	305	41.4	26.3	#	6.4	649	17.1	25

Long	Lat	Site	pH	TAL	EC mS/m	N	NH4	F	Na	Mg	Si	P	SO4	Cl	K	Ca
17.555	-30.262	QUAGGAFONTEIN	7.1	109	689	141	#	2.2	941	223	28.3	0.02	339	1824	37.7	174
17.452	-30.253	QUAGGAFONTEIN	8.1	202	1195	4.4	0.05	2.4	2203	232	14.5	0.01	570	4112	107	204
17.575	-30.283	REST HOREES	7.6	174	579	5.8	#	2.6	787	156	6.46	0.01	537	1341	12.8	204
17.518	-29.274	RIET KLOOF	8.1	61	274	10	0.05	1.2	334	83.3	18.3	0.01	177	843	7.04	115
17.896	-30.299	RIETKLOOF	7.7	199	319	15	#	2.2	276	90.3	19.1	0.06	126	872	13.9	230
17.854	-30.269	RIETKLOOF	7.7	220	882	21	0.04	4.6	1039	419	14.3	0.01	497	3014	26.3	404
17.392	-30.059	RODEKLIPHEUVEL	8	169	584	2	0.91	0.8	1131	79.6	5.8	0.02	220	1878	40.8	66
17.409	-30.128	RODEKLIPHEUVEL	7.9	152	843	1.4	0.04	2.1	1341	226	16.1	0.02	418	2831	59.9	210
18.154	-30.496	RONDEFONTEIN	7.7	126	208	75	#	0.9	162	89.8	19.6	#	132	494	1.64	118
18.482	-30.23	RONDEGAT GED 2	8	95	157	29	#	3	205	39.8	19	0.01	102	384	4.93	60
18.083	-30.5	ROODEBERGSKLOOF	8.4	241	76.9	0.2	0.04	1.4	146	13	14.6	0.02	28	110	3.38	14
18.087	-30.499	ROODEBERGSKLOOF	7.4	164	89.2	0.7	#	2.9	137	20.7	9.81	0.03	42	156	11.7	28
18.087	-30.499	ROODEBERGSKLOOF	7.6	210	97.2	21	#	1.5	132	24.5	17.8	#	43	161	5.13	28
18.087	-30.499	ROODEBERGSKLOOF	7.4	182	178	4	#	2.1	246	42.7	17.5	0.02	87	384	20.3	53
17.359	-30.242	ROODELAAGTE	8.5	293	645	0.2	#	1.9	1282	63	9.09	0.01	287	1914	40.4	44
17.414	-30.184	ROODELAAGTE	7.7	103	805	5.2	0.04	0.8	1239	246	17.4	0.04	257	2751	60.9	177
17.163	-29.818	ROOIVLEI	8	231	642	0.1	0.04	0.8	1251	90.8	14.5	0.02	306	1952	42.6	79
17.155	-29.905	SAMSONS BAK	7.8	180	797	0.4	0.07	0.9	1188	238	13	0.01	364	2755	47.8	326
17.105	-29.673	SANDKOP	7.8	104	409	0.2	#	0.7	656	63.2	15.6	0.04	175	1123	28.4	65
17.142	-29.674	SANDKOP	7.7	109	428	0.1	#	0.7	706	58.7	14.5	0.02	175	1162	30	59
17.547	-30.112	SANDVLEI	7.9	83	853	#	#	3.3	1328	29.8	11.4	#	376	2696	39.5	439
17.635	-29.75	SANNASAS	7.1	135	162	1.6	0.05	1.3	188	39.8	11.9	0.03	102	348	7.97	69
17.604	-29.676	SCHAAPRIVIER	6.9	96	256	3.1	0.06	1.4	328	65.8	25	0.04	152	695	7.05	86
17.606	-29.671	SCHAAPRIVIER	6.7	111	509	2.8	0.06	2.4	626	153	22.7	0.04	335	1462	15.4	189
17.903	-30.495	SCHUINSKRAAL	7.5	200	1202	0.6	0.05	2.5	1582	499	26.4	0.01	532	4227	64.8	447
17.246	-30.081	SCHULP FONTEIN	8.2	227	150	22	#	0.6	274	16.3	11.8	0.15	57	258	6.78	32
17.401	-29.731	SESVLEI	7.7	179	730	#	0.06	2.3	1234	120	27.3	0.07	568	1817	31.7	105
17.401	-29.731	SESVLEI	7.6	166	775	18	0.06	2.1	1297	125	24.5	0.06	533	2058	35.3	93
17.401	-29.731	SESVLEI	7.6	160	774	9	#	2.1	1329	125	24	0.05	492	2102	36.5	89
17.382	-29.688	SESVLEI	7.6	52	1169	2.6	0.06	1.6	1897	109	12.9	0.03	466	3734	10.6	486
17.382	-29.688	SESVLEI	7.8	54	1170	2.6	0.17	1.6	1946	109	12.7	0.04	492	3930	19.5	486
17.382	-29.688	SESVLEI	7.4	31	1196	0.7	0.07	1.7	2045	98.7	9.78	0.03	517	4169	28.5	519
17.405	-29.725	SESVLEI	7.7	39	3148	0.4	0.07	1.1	4494	1162	20.1	0.06	###	####	96.1	###
17.405	-29.725	SESVLEI	7.5	14	3385	0.2	0.09	0.9	4732	1334	9.89	0.04	###	####	105	###
17.536	-29.758	SIEKKRAAL	7.8	116	239	3.2	0.05	3.3	227	61.6	12.2	0.02	97	562	2.62	125
17.536	-29.758	SIEKKRAAL	7.7	118	242	3	0.04	3.2	234	63.7	11.7	0.02	97	582	2.62	127
17.536	-29.758	SIEKKRAAL	7.6	97	251	2.5	0.07	3.2	233	70.2	8.64	0.02	103	633	2.01	126
18.1	-29.838	SILVERFONTEIN	7.1	88	109	2.2	#	3.6	125	23.2	14	0.02	66	242	2.3	55
18.075	-29.9	SILVERFONTEIN	6.7	40	108	3.2	0.04	2.4	117	25.6	16.5	0.02	87	257	1.88	54
18.058	-29.863	SILVERFONTEIN	6.2	53	117	0.5	0.05	2	134	28.8	14.2	0.03	87	282	4.21	59
18.05	-29.833	SILWERFONTEIN	6.8	32	128	2.2	#	2.9	137	31.3	11.5	0.02	94	305	2.78	67
17.594	-30.119	SOEBATSFONTEIN	8	87	607	0.1	#	3.3	889	25.2	20.6	0.04	170	2061	40.2	391
17.559	-30.217	SOEBATSFONTEIN	8.1	226	845	1.1	#	3.3	1334	183	13.3	0.01	432	2491	36.9	206
17.314	-30.113	SOMNAAS	8.3	144	302	0.1	#	1.5	545	42.7	7.7	0.02	118	913	27.1	36
17.566	-30.111	SOUBATTERS FONTEIN	8.2	130	2410	0.5	0.1	2.5	4305	283	17.5	0.03	846	9519	151	###
17.6	-30.154	SOUBATTERSFONTEIN GED.GOE	7.1	119	920	0.9	0.04	2.3	1699	229	15.1	0.01	739	3084	32.8	142
17.591	-29.658	SPEKTAKEL MYN	7.3	137	1040	5.9	0.12	4	1389	321	13.5	0.04	813	3312	22.6	466
17.283	-29.352	STEENBOK	7.9	67	334	4.3	0.04	0.9	570	75.1	12.2	0.01	187	1087	25.8	57
17.293	-29.323	STEENKOP	7.8	76	386	4.9	0.34	0.7	642	99.3	9.19	0.01	242	1248	27.7	76
17.951	-29.456	STEIKOPF	8.3	87	124	0.6	#	2.8	87.8	26.5	13.8	0.01	106	260	3.3	95
17.959	-29.242	STEINKOPF	9.4	94	44.1	5.7	#	1.3	35.6	7.9	2.23	0.1	34	26.1	3.07	30
17.88	-29.049	STEINKOPF	8.4	194	228	2	#	1.9	253	46.1	10.6	0.02	141	298	7.98	19
17.984	-29.289	STEINKOPF	8.3	183	209	7.2	0.05	1.9	222	45.7	12.1	0.01	113	298	5.38	17
17.738	-29.254	STEINKOPF	7.1	200	282	0.1	0.53	0.9	270	109	5.53	0.02	404	524	5.16	138

Long	Lat	Site	pH	TAL	EC mS/m	N	NH4	F	Na	Mg	Si	P	SO4	Cl	K	Ca
17.609	-29.5	STEINKOPF	8.1	71	211	2.6	0.04	0.6	327	51.5	30.9	0.06	98	582	7.86	44
17.926	-29.412	STEINKOPF	8	82	297	10	0.06	2.1	280	82.9	15.4	0.01	188	757	3.39	140
17.84	-29.444	STEINKOPF	8.3	133	363	2.3	#	4.5	477	63.7	12.7	0.02	272	917	9.69	142
17.866	-29.279	STEINKOPF	8.1	83	372	2.5	#	1.9	375	94.9	11.1	0.01	158	1030	11.7	169
18.158	-30.04	STOFKRAAL	7	64	184	0.7	0.16	2.3	256	33.2	21.2	#	111	466	1.1	58
18.183	-30.021	STOFKRAAL	7.6	100	499	2.4	0.05	2.2	612	124	15.7	0.01	373	1477	7.22	271
18.183	-30.021	STOFKRAAL	7.8	130	594	2.4	0.05	2.2	519	225	18.8	0.01	420	1886	10.1	442
17.262	-29.522	STRYD RIVIER	8	191	1360	#	0.69	2.3	2375	266	9.87	0.01	771	4433	102	311
17.293	-29.529	STRYD RIVIER	7	68	1510	0	3.7	1.9	2432	359	1.09	0.01	791	5116	127	470
17.501	-29.412	STYGER KRAAL	7.9	226	1047	1.2	0.19	3	1509	363	9.28	0.01	###	2898	30.7	488
17.425	-29.986	TAAIBOSCH VLAKTE	8	90	115	0.2	#	0.6	195	10.6	24.7	0.01	27	276	10	11
18.442	-29.433	TAAIBOSMOND	7.4	54	659	31	0.05	2.9	860	93.8	9.66	0.02	448	1798	45.2	312
18.486	-29.446	TAAIBOSMOND	7.2	<4	2035	50	0.08	1.8	2347	420	1.13	0.03	###	7126	94.9	###
18.486	-29.846	TAUSEEP	7.4	136	720	3.8	#	2.9	944	167	0.98	#	455	2055	56.1	322
17.917	-30.471	TEFFERDAM	7.1	67	731	0.1	#	2.3	964	249	8.65	0.02	302	2294	29.8	215
17.593	-29.671	TWADOUS	7.6	361	580	0.4	0.06	3.5	976	154	16.4	0.04	678	1515	19.2	219
17.806	-29.735	TWEEDAM	8.3	99	221	17	0.04	2.2	205	66.1	19.1	0.02	130	491	3.62	118
17.935	-30.25	TWEEFONTEIN	7.6	78	66.3	1.4	0.04	0.7	56.8	16.7	26.8	0.01	20	132	3.55	34
17.979	-30.256	TWEEFONTEIN	6.8	46	73	0.9	#	0.6	78.2	17.8	5.24	#	24	165	2.21	29
17.923	-30.286	TWEEFONTEIN	7.3	77	146	143	0.05	0.6	121	43.2	17.1	#	75	281	5.74	92
17.932	-30.26	TWEEFONTEIN	7.8	105	956	1.4	0.11	1.8	1101	406	16.7	0.02	529	3200	12.9	404
17.902	-30.418	UITKOMST	7.8	200	578	77	0.04	1.6	615	297	16.7	0.01	221	1880	17.2	247
17.923	-30.47	UITKOMST	7	127	1456	106	0.1	2.1	2658	421	25	1.92	910	5197	76.1	459
17.792	-30.3	VLEIE	6.3	30	235	56	0.06	0.5	335	54.4	27.7	#	180	499	4	37
17.783	-30.3	VLEIE	6.8	56	350	13	0.06	1.2	464	89.5	17	#	177	974	6.91	111
17.103	-29.129	VREDEFONTEIN	8	169	725	2	0.08	1.1	949	183	10.7	0.03	423	1969	32.4	213
17.026	-29.125	VREDEFONTEIN	7.8	137	889	1.4	0.06	1	1208	218	14.6	0.03	467	2543	33.2	268
17.027	-29.126	VREDEFONTEIN	7.5	197	771	1.8	0.06	0.9	1247	241	15.1	0.02	476	2566	35.5	269
17.027	-29.126	VREDEFONTEIN	7.5	198	769	2.1	#	0.9	1202	244	14.6	0.02	478	2573	33.8	273
17.026	-29.125	VREDEFONTEIN	8.1	134	893	1.7	0.05	1.1	1236	238	14.1	0.03	479	2575	32	258
17.026	-29.125	VREDEFONTEIN	8.1	113	890	1.8	#	1	1261	219	14.5	0.03	505	2682	33.1	251
18.13	-30.458	WELKOM	6	26	26.5	22	#	0.2	29.9	5.6	14.2	0.01	5.3	51.8	3.85	5.7
18.16	-30.428	WELKOM	7.7	53	205	4.7	#	0.6	157	94.1	19.8	#	61	586	1.07	94
17.601	-29.925	WILDE PAARDEHOEK	8.5	170	314	0.4	#	4	447	69	11.6	0.01	151	869	14	108
17.574	-29.971	WILDE PAARDEHOEK	7.8	149	426	2.2	#	1.6	604	113	19.7	0.01	216	1254	24.7	133
17.912	-29.344	WILDEHONDSPOORT	7.8	94	160	6.7	0.06	1.8	157	51.5	15.1	0.02	86	419	1.71	96
18.059	-30.47	WILGEHOUTFONTEIN	7.3	120	204	0.1	1.66	2.3	217	69.2	4.56	#	58	541	7.87	78
18.061	-30.492	WILGEHOUTFONTEIN	7.5	136	275	0.1	0.13	1.6	483	39	7.37	#	190	677	7.77	36
18.05	-30.5	WILGEHOUTFONTEIN GED MODD	6.8	38	39.7	#	#	0.8	49	7	8.97	0.01	11	74.8	2.3	9.9
17.497	-29.355	WIT KLIP HOOGTE	8.3	174	1023	3.3	0.27	4.7	1290	262	14.1	0.01	795	3015	42.5	542
17.505	-29.522	WITBERG'S KLOOF	8	185	375	5.7	0.07	3.5	482	93.6	14	0.01	287	1003	15	176
17.698	-29.639	WITWATER	8	126	60.3	0.1	#	1	74.1	20.1	10.6	#	86	88.9	6.24	28
17.659	-29.658	WITWATER	7.8	64	285	13	0.06	1.1	362	96.5	24.9	#	245	811	15.3	104
17.967	-29.883	WOLFBOOM	7.4	83	115	0.6	0.04	3.1	127	24.3	7.4	0.01	77	277	8.79	61
17.798	-30.166	WOLVEPOORT	7.3	54	359	22	0.06	2.7	389	126	23.3	0.01	182	937	3.94	136
17.878	-30.137	WOLVEPOORT	7.7	133	1033	23	0.08	2.6	1117	478	14.3	#	580	3290	16	504
18.233	-30.483	ZAKKIESBERG	7	79	557	9.4	0.05	2.4	675	173	11.8	0.01	373	1616	15.4	204
17.25	-29.855	ZONNEKWA	7.8	50	123	1.1	#	0.5	214	16.9	33.8	0.02	28	347	9.72	14
17.367	-30.17	ZOUTPAN	7.9	195	816	0.6	#	1.2	1403	199	18.7	0.01	287	2774	55.9	140
17.628	-29.736	BUFFELSRIVIER	7.6	115	164	0.4	#	1	188	41.7	13.7	0.03	102	383	9.45	71
17.628	-29.736	BUFFELSRIVIER	7	128	230	1.2	#	0.9	233	48.2	11.8	0.03	128	450	8.02	76
17.423	-30.353	DIKNEK	6.9	107	290	#	#	1.6	2290	206	11.2	0.01	383	5290	48.7	784
17.423	-30.353	DIKNEK	7.5	56	1650	0.1	0.05	2	2308	247	16.8	0.01	376	5440	54.1	871
17.946	-30.22	OUSS GED KAMIE	7.6	147	159	#	#	1.6	128	42.3	12.5	0.01	63	381	3.27	114

Long	Lat	Site	pH	TAL	EC mS/m	N	NH4	F	Na	Mg	Si	P	SO4	Cl	K	Ca
17.946	-30.22	OUSS GED KAMIE	7.1	137	250	#	#	1.7	184	43.8	11.8	0.01	89	502	3.68	137
17.983	-30.217	CLYVEN FONTEIN	7.1	135	78	0.5	#	2.1	116	18.9	18.6	0.02	25	158	0.79	25
17.244	-30.09	SCHULP FONTEIN	7.3	46	270	2.4	#	0.6	392	60.3	16.3	0.01	121	761	13.7	73
17.244	-30.09	SCHULP FONTEIN	6.8	47	310	2.7	#	0.5	375	58	14.6	0.02	139	768	12.8	71
17.244	-30.09	SCHULP FONTEIN	7.1	66	1520	2.7	#	0.4	397	59.9	13.9	0.03	106	773	13.7	78
17.688	-29.228	STEINKOPF - KA	6.9	63	98.2	1.5	#	0.5	90.5	30.2	19.8	0.01	34	240	2.2	44

All values inmg/l unless otherwise indicated

value below detection limit

Hydrocensus data

Lat	Long	Name	WL (m)	EC mS/m	Alk.	pH	HCO3	Na	Cl	Ca	K	Mg	SO4	N	F
-30.177	18.185	91LF88_well	ND	119.0	20	6.8	96.9	163.6	466.4	41.2	4.1	35.5	56.5	0.1	0.9
-30.240	18.031	AGTER1_well	2.5	21.4	40	6.8	27.7	28.7	43.9	5.3	0.3	5.2	5.7	2.1	0.4
-30.235	18.038	AGTER2_dam	3.5	67.7	117	7.8	69.2	72.7	149.6	20.4	0.1	12.5	10.8	4.7	0.4
-30.244	18.055	AGTER3	4.5	92.5	250	8.9	85.9	84.3	193.5	42.6	0.2	24.3	35.6	0.6	2.0
-30.354	17.687	Aigab	32.0	1141.0	145	8.1	205.0	1744.2	3167.9	314.6	20.9	371.3	832.0	34.4	3.7
-30.130	18.020	Anagas	ND	465.0	181	6.7	306.0	347.2	903.0	234.3	3.4	110.7	294.9	3.4	1.5
-30.041	17.985	ANE1_dam	8.1	346.0	585	8.1	124.6	414.4	809.5	152.6	3.0	129.1	244.3	1.4	4.0
-30.126	18.017	ANE2_dam	ND	329.0	854	6.9	166.2	308.1	818.3	210.9	2.8	183.9	219.9	20.0	1.5
-30.110	17.920	Arkoep	ND	179.2	79	7.2	104.0	137.0	318.0	73.6	4.3	58.2	73.6	0.7	2.0
-30.110	17.920	Arkoep	ND	220.0	42	7.3	114.0	171.6	473.0	94.8	4.8	67.9	87.2	0.1	2.6
-30.140	17.940	Arkoep	ND	276.0	95	6.8	141.0	354.2	464.0	52.3	0.7	53.1	157.8	8.8	2.0
-29.999	17.778	ARREGAS	ND	635.0	210	6.7	227.5	732.2	2628.0	483.5	21.8	317.6	567.8	13.1	2.1
-30.242	18.061	BAK1_well	2.2	52.3	125	7.0	39.3	56.0	85.1	11.6	0.9	17.6	24.3	4.0	1.0
-29.710	17.900	BeginWeer	ND	134.0	102	7.6	138.0	106.5	301.0	55.9	2.8	41.8	72.1	1.3	2.7
-30.384	17.836	Bethel	1.0	359.0	80	7.2	165.7	531.3	971.9	106.7	3.6	98.3	234.3	21.0	3.2
-29.740	17.930	Biesiesfontein	ND	167.5	62	7.4	111.0	178.6	370.0	70.4	1.5	42.9	104.2	2.0	3.3
-29.730	17.880	Biesiesfontein_Elec	ND	209.0	100	7.9	192.0	187.3	362.0	97.3	2.1	55.5	122.4	0.1	2.8
-29.720	17.890	Blouputs	ND	210.0	84	7.7	108.0	187.1	413.0	89.5	1.7	58.3	117.3	1.2	2.8
-29.740	17.880	Bloustasie	ND	201.0	75	6.8	81.0	153.4	318.0	89.3	0.9	55.9	112.8	9.3	1.2
-29.730	17.880	Bloustasie	ND	394.0	93	6.9	101.0	254.7	731.0	196.4	2.8	110.7	235.8	26.0	1.4
-29.710	17.910	Bloustasie	54.9	280.0	101	8.2	118.0	223.7	568.0	110.9	3.9	90.3	146.9	1.2	2.5
-29.720	17.890	Bloustasie	ND	250.0	50	7.8	151.0	217.0	429.0	103.5	1.6	73.2	167.3	9.4	2.5
-30.013	17.823	BLOUSYFER	13.3	457.0	192	8.9	210.6	758.5	1773.0	243.9	10.0	228.5	409.5	4.2	2.9
-30.191	18.154	BOB1_well	2.0	59.5	30	7.0	138.5	103.8	114.4	14.1	0.9	8.5	37.3	0.3	0.9
-29.802	17.560	BOKKRAAL	36.0	86.1	65	6.3	42.1	123.3	243.0	20.5	2.3	23.5	50.4	2.2	1.0
-29.793	17.563	BOKKRAAL	1.8	399.0	120	7.0	126.4	607.2	1476.0	189.9	3.9	182.5	321.3	7.8	3.5
-30.209	17.706	BOKSKRAAL	7.0	662.0	109	7.3	235.4	993.1	1795.1	274.1	10.1	248.2	417.4	4.8	3.1
-29.866	17.592	BOSLUISKRAAL	1.0	226.0	65	6.9	98.3	417.6	468.0	82.2	2.4	70.4	188.7	12.7	3.0
-30.200	18.050	Bovlei	10.0	87.4	42	6.8	108.0	85.7	138.0	32.9	1.8	32.7	67.4	10.8	1.1
-29.890	17.594	BRAKPITS	4.5	289.0	216	7.7	185.4	424.4	558.0	140.4	8.0	95.9	190.8	0.1	3.7
-30.246	17.710	Brakputs_No1	18.0	532.0	122	7.5	199.4	623.1	1812.7	238.8	11.5	198.9	312.5	10.4	2.9
-30.248	17.710	Brakputs_No2	20.0	319.5	56	7.7	176.9	366.4	1047.1	145.2	7.3	117.8	178.8	10.3	2.1
-30.001	17.691	BRANDBERG	ND	495.0	101	6.7	148.9	793.9	1647.0	229.9	8.5	162.3	395.0	21.8	2.6
ND	ND	Brandhoek(kraan)	11.2	764.0	ND	7.0	ND	1753.0	3813.0	502.0	35.5	254.0	656.0	0.1	2.0
-29.517	19.939	BRANDKLOOF	47.0	105.6	102	7.4	ND	105.6	175.0	68.6	1.3	24.9	215.2	ND	2.5
ND	ND	Buffelsfontein	ND	302.0	ND	6.4	ND	513.0	1167.0	159.0	13.1	114.0	206.0	6.9	0.8
-29.933	17.705	WILDEPERDEPAS	ND	216.0	ND	8.0	165.7	290.0	638.9	141.1	6.3	49.0	153.6	0.1	3.4
-29.736	17.637	BUFS1_Well	4.0	189.0	163	6.8	166.2	260.5	440.0	87.1	11.6	54.7	109.0	0.1	0.9
-29.770	17.660	BUFS3_Well	5.0	230.0	67	6.6	102.5	301.9	545.6	110.6	10.7	74.6	240.3	0.1	0.5
-29.772	17.660	BUFS5_well	5.0	317.0	145	7.4	166.2	525.8	747.9	137.3	17.0	78.2	289.4	16.0	1.2
-30.340	17.511	BYENESKRANS	13.7	1034.0	69	8.0	130.2	1876.9	2956.6	215.0	44.6	207.2	538.2	1.8	3.0
-29.583	17.792	CAROLUSBERG MINE	40.0	408.0	34	5.5	ND	129.0	158.0	350.5	3.6	404.3	6903.0	ND	125.0
-29.633	17.958	CAROLUSBERG MINE	ND	407.0	105	7.0	ND	448.3	544.0	356.2	3.5	119.2	3254.0	ND	2.6
-29.517	17.983	CONCORDIA	11.2	232.0	95	7.6	ND	238.5	579.0	119.1	1.7	66.7	324.9	ND	1.5
-30.181	18.273	COU1	ND	546.0	75	6.7	235.4	736.4	1452.0	363.7	16.4	214.4	451.7	21.0	1.9
-30.182	18.274	COU2_fontain	ND	2240.0	86	8.3	221.5	4521.0	9063.0	1014.1	71.1	992.1	878.6	0.3	1.6
-30.126	18.257	COU3	ND	209.0	88	7.2	294.9	261.8	585.9	98.9	2.4	71.2	177.0	3.9	4.5
-29.828	18.332	DAP1_dam	ND	358.0	113	7.3	157.9	514.5	915.1	202.1	18.0	107.0	247.8	13.0	1.9
-29.827	18.326	DAP2_dam	13.8	371.0	58	7.4	193.9	527.1	967.9	215.9	18.2	112.9	254.5	15.0	1.9
-30.323	18.390	DE_RIET_dam	2.0	780.0	1108	7.2	339.8	5827.1	1927.6	203.3	22.4	243.5	738.0	0.1	5.0
-29.959	17.975	DED1_Well	2.9	472.0	38	7.1	116.3	681.5	1372.7	220.3	7.1	139.9	181.7	0.1	0.9
-29.950	17.970	DeDraai	29.3	82.1	35	7.4	111.0	61.2	138.0	39.2	1.9	23.9	40.9	1.2	2.6
-29.960	17.970	DeDraai	36.6	805.0	108	7.6	252.0	935.8	2133.0	285.7	10.0	110.7	448.8	81.0	3.3
-29.770	17.940	Deurdrif	45.7	37.4	23	7.2	77.0	41.9	69.0	16.3	1.7	5.6	20.0	2.3	0.6
-29.770	17.940	Deurdrif	45.7	62.8	63	7.9	91.0	64.3	112.0	28.8	1.6	14.9	49.4	0.1	2.5
-29.780	17.960	Deurdrif	ND	647.0	112	6.9	161.0	900.8	877.0	192.2	2.7	110.8	546.2	0.1	4.6
-29.780	17.940	Deurdrif	ND	358.0	102	7.2	192.0	354.3	808.0	195.0	2.2	98.7	283.2	0.1	2.5
-29.780	17.950	Deurdrif	ND	344.0	112	7.6	279.0	347.7	705.0	170.4	4.1	105.8	243.6	0.6	3.0
-29.583	17.793	DOOIFONTEIN	6.2	267.0	175	6.9	ND	335.1	633.0	118.1	2.4	59.4	448.0	ND	2.5
ND	ND	Doring Draai(put)	ND	432.0	ND	6.8	ND	897.0	1797.0	193.0	18.6	158.0	318.0	0.1	1.0
ND	ND	Drieklip(put)	1.2	354.0	ND	6.8	ND	600.0	1333.0	137.0	27.3	143.0	254.0	9.9	0.6
ND	ND	Drieklip(windpomp)	ND	387.0	ND	7.1	ND	760.0	1348.0	117.0	19.6	120.0	311.0	4.0	2.7
-29.913	17.967	DRO1	ND	105.3	155	7.3	110.8	115.9	308.0	44.1	1.2	26.1	59.0	2.6	2.1
-29.683	17.840	DROEDAP	4.0	220.0	99	6.8	ND	177.7	569.3	155.8	2.3	66.9	155.3	ND	1.7
-30.374	17.717	Duikerkop_font	ND	771.5	105	8.0	137.6	1097.6	2446.2	229.2	21.6	265.2	469.0	0.8	1.5
-29.750	18.041	EENDOORN	ND	182.9	170	6.8	ND	204.1	367.9	86.2	0.7	48.8	157.7	ND	3.3
-30.393	18.097	EZEL1	ND	32.1	155	6.7	83.1	35.0	61.6	10.3	0.1	7.3	2.1	0.8	0.4
-29.811	17.501	F1_Fontain	0.0	84.7	61	7.4	55.4	112.7	211.2	14.1	5.6	28.7	30.5	1.7	0.3

Lat	Long	Name	WL (m)	EC mS/m	Alk.	pH	HCO3	Na	Cl	Ca	K	Mg	SO4	N	F
-29.781	17.503	F2_Fontain	0.0	82.1	56	6.1	49.8	114.4	211.2	13.7	5.7	29.2	31.0	2.2	0.5
-30.079	18.010	FIL1_Elec	9.0	150.5	248	7.0	96.9	170.0	343.2	75.8	2.9	47.1	99.3	0.1	4.3
-29.700	17.909	FONTEINTJIE	ND	89.1	64	7.0	ND	90.1	140.1	40.8	3.8	25.7	128.6	ND	0.5
-29.916	18.421	GAM1_dam	ND	213.0	80	7.7	193.9	294.0	484.0	93.1	10.8	74.4	155.8	3.4	2.7
ND	ND	Garagams	ND	179.0	ND	7.6	ND	239.0	522.0	104.0	7.5	61.0	150.0	0.6	3.7
-30.238	17.759	GBERG	6.9	1016.0	101	6.8	193.9	1598.1	3018.2	392.2	10.6	381.4	580.4	1.8	4.5
-29.417	17.751	GEMSBOK	ND	326.0	109	6.7	ND	281.5	983.0	191.1	4.4	122.6	241.6	ND	1.3
-29.767	17.991	GOEGAB	ND	98.1	47	6.9	ND	80.5	245.2	50.9	1.2	32.0	47.9	ND	1.4
-29.717	18.012	GOEGAB	ND	80.1	89	6.9	ND	113.3	219.0	39.8	1.0	23.7	53.0	ND	2.9
-29.740	17.940	GoeieHoop	ND	271.0	52	7.7	124.0	187.9	516.0	188.5	2.7	86.2	209.8	0.1	2.7
-29.740	17.940	Grashoek	ND	393.0	98	6.9	168.0	254.9	938.0	273.4	3.7	110.8	303.0	5.5	2.2
-29.740	17.940	Grashoek	ND	328.0	102	7.6	192.0	232.3	740.0	216.3	2.9	110.7	274.0	0.9	2.5
-29.633	18.204	GROOT KAU	ND	276.0	143	7.2	ND	331.6	753.2	125.6	21.6	67.5	157.6	ND	2.5
-29.700	17.971	GROOT KAU	ND	266.0	159	6.9	ND	349.5	735.7	147.2	6.0	59.9	203.1	ND	2.8
-29.633	18.255	GROOT KAU	ND	241.0	184	7.1	ND	340.0	718.2	145.0	6.0	8.7	175.1	ND	2.7
-30.234	17.692	Grootberg_No1	8.8	893.0	106	7.4	469.0	1054.4	2895.0	448.3	18.9	361.8	694.0	10.7	2.0
-30.274	17.712	Grootberg_No2	ND	247.5	68	7.3	190.9	277.3	1126.3	107.0	7.8	79.5	123.6	0.1	1.6
ND	ND	Grysklip	ND	244.0	ND	7.3	ND	381.0	817.0	97.0	12.9	86.0	143.0	2.0	0.7
-30.151	17.887	HAAS1	ND	84.9	146	7.6	135.7	94.7	149.6	41.9	4.7	27.5	35.4	0.1	1.0
-30.139	17.871	HAAS2	16.0	293.0	66	6.6	138.5	312.7	747.9	196.2	10.6	120.0	202.4	5.0	1.7
-29.617	17.837	HOMEB	ND	165.9	98	6.4	ND	162.0	360.0	96.2	1.0	48.8	294.0	ND	1.8
ND	ND	Hondeklipbaai(kraan)	ND	225.0	ND	7.1	ND	376.0	738.0	75.0	14.1	59.0	135.0	2.4	0.3
-30.323	17.618	Horees_No1	ND	650.0	73	7.4	154.5	1116.3	1844.9	256.7	285.5	99.7	395.1	0.5	3.3
-30.322	17.621	Horees_No2	ND	357.0	181	7.9	165.7	566.3	945.0	116.8	8.7	93.9	203.4	3.3	3.7
-30.307	17.635	Horeesfont	ND	479.0	159	7.7	132.0	821.0	864.0	195.9	22.4	40.0	313.8	0.1	3.5
-29.790	17.960	HoudeMond	ND	28.6	36	7.3	77.0	27.9	52.0	12.7	0.0	5.4	23.6	1.3	1.3
-29.800	17.970	HoudeMond	ND	385.0	53	7.5	104.0	387.9	1170.0	230.8	2.5	72.9	223.6	1.1	3.8
-29.800	17.960	HoudeMond	17.0	439.0	56	7.7	141.0	449.5	1487.0	276.6	2.4	87.7	255.0	1.3	3.8
-29.969	18.168	HYT1_dam	10.0	198.0	103	8.7	102.5	339.0	589.6	107.6	4.6	69.4	178.9	2.4	2.5
-29.854	17.789	JAK1	2.0	199.8	95	6.6	110.8	233.7	440.0	92.7	3.5	52.8	123.1	12.0	2.1
-29.855	17.789	JAK2_Elec	11.0	186.6	71	6.7	138.5	168.4	413.6	111.0	5.7	67.6	104.9	13.0	1.8
-30.359	17.742	Jakkalsfontein	ND	164.0	5	6.7	47.7	273.4	387.2	13.0	2.9	26.3	121.6	1.7	1.0
-29.600	18.217	KAIP	23.1	147.5	120	7.1	ND	186.6	315.3	66.0	2.2	35.1	108.9	ND	3.7
-30.036	18.276	KAM1_Well	2.8	316.0	25	7.3	69.2	379.7	774.3	144.8	8.3	95.6	181.8	7.7	1.5
-30.038	18.274	KAM2_windpump	5.1	131.0	30	7.3	96.9	178.6	246.4	32.4	1.5	19.4	80.9	8.6	5.5
ND	ND	Kamas(fontein)	ND	50.0	ND	8.5	ND	70.0	123.0	21.0	5.0	6.1	19.0	0.1	0.3
ND	ND	Kamas(windpomp)	ND	483.0	ND	6.7	ND	1000.0	2196.0	248.0	15.3	226.0	430.0	29.0	1.4
-30.036	18.277	Kamassies	ND	118.2	ND	6.9	146.7	164.3	278.7	44.5	6.1	30.2	63.6	0.1	1.0
-30.038	18.274	Kamassies	7.9	141.6	ND	7.3	152.9	220.6	270.0	41.4	1.5	26.6	100.9	8.7	5.7
-30.024	18.356	Kamassies	ND	213.0	ND	7.1	180.7	224.5	540.0	102.6	2.1	93.6	143.5	7.7	2.5
-30.022	18.356	Kamassies	6.1	206.0	ND	7.1	203.8	221.1	474.7	96.8	3.1	80.9	113.5	15.4	2.4
-30.053	18.202	Kamassies	ND	156.2	ND	7.5	208.5	194.2	348.4	72.0	2.4	50.1	107.9	20.0	2.2
-30.017	18.363	Kamassies	ND	205.0	ND	6.7	216.2	237.3	452.9	93.8	2.9	79.7	144.1	8.1	2.7
-30.053	18.206	Kamassies	2.5	298.0	ND	7.0	250.2	427.4	718.6	136.1	7.6	92.3	260.7	4.0	3.5
-30.041	18.274	Kamassies	5.3	134.8	ND	7.6	308.8	298.1	235.2	16.9	2.1	11.6	93.1	0.1	8.2
ND	ND	Kameelboom(windpomp)	6.0	572.0	ND	7.0	ND	1361.0	2686.0	262.0	30.6	206.0	488.0	1.5	3.5
-30.468	17.704	Kameelboom_No1	ND	825.0	83	7.6	303.0	1334.6	1682.7	223.6	26.6	210.5	505.0	1.4	3.5
-30.067	17.757	KANARIESFONTEIN	3.4	43.0	42	5.9	47.7	48.3	90.0	11.7	2.5	7.4	16.2	0.4	0.6
-30.045	17.758	KANARIESFONTEIN	ND	446.0	242	6.8	314.6	635.7	1521.0	215.4	12.9	207.3	321.0	4.0	2.4
ND	ND	Karkuip(kraan)	ND	415.0	ND	6.9	ND	771.0	1578.0	178.0	16.9	138.0	295.0	1.3	2.7
-30.064	18.014	KEER1_dam	ND	429.0	251	6.8	110.8	698.5	1232.0	207.8	1.5	222.0	274.6	8.5	1.0
-30.459	17.844	Kersboshoek	ND	803.0	123	7.4	278.0	1160.4	1827.0	256.9	16.9	258.4	481.6	0.1	3.3
-30.006	17.672	KEURBOS	ND	1144.0	139	6.6	269.6	2286.2	5093.9	488.5	11.2	403.9	1008.7	1.8	3.5
-30.040	17.734	KEURBOS	ND	631.0	305	7.0	382.0	850.0	2501.0	372.6	18.0	338.4	667.0	2.0	2.8
-29.804	17.507	KG93/106	26.0	133.6	37	6.9	58.2	175.1	316.8	22.6	7.7	46.2	63.4	2.3	0.3
-29.790	17.502	KG93/107	ND	208.0	128	6.6	191.1	293.9	439.7	43.1	13.0	77.8	96.5	3.6	0.6
-29.786	17.505	KG93/110_BuffelsR	6.0	188.5	154	7.3	235.4	298.0	369.6	38.0	8.6	59.4	62.8	0.1	0.8
-29.739	17.636	KG93/118_BuffelsR	4.0	195.7	116	7.1	110.8	285.1	457.6	86.1	9.2	57.0	135.0	0.9	1.0
ND	ND	Kheis put	1.5	176.0	ND	6.8	ND	321.0	490.0	62.0	13.6	39.0	152.0	0.1	2.0
-29.990	17.960	Kleinfontein	1.0	136.4	40	7.4	168.0	119.2	284.0	52.0	2.6	29.4	71.4	1.1	0.6
-29.970	17.970	Kleinfontein	ND	554.0	50	7.3	299.0	609.6	1513.0	164.6	6.5	110.8	402.9	2.3	3.0
-29.990	17.960	Kleinfontein	ND	1074.0	173	6.7	403.0	1093.0	2493.0	303.4	5.1	110.3	631.2	69.0	3.0
-29.844	17.770	KLI1	ND	100.2	86	7.2	119.1	97.6	202.4	77.0	4.2	22.4	85.1	0.1	2.4
-29.863	17.736	KLI2	7.3	256.0	155	6.8	185.5	304.0	624.8	132.0	4.9	78.3	138.5	3.7	2.5

Lat	Long	Name	WL (m)	EC mS/m	Alk.	pH	HCO3	Na	Cl	Ca	K	Mg	SO4	N	F
-29.863	17.737	KLI3	21.7	237.0	109	6.5	144.0	286.4	572.0	120.9	5.1	63.1	137.0	7.9	1.6
-30.504	17.839	KLIP1	ND	651.0	109	7.5	132.9	1049.2	1830.3	255.8	19.2	165.7	337.9	1.3	3.1
-29.417	17.774	KLIPDAM	1.0	54.8	70	6.6	ND	73.4	70.0	20.1	1.5	9.7	93.7	ND	0.4
-29.617	17.807	KLIPDAM	ND	85.9	74	8.5	ND	99.0	140.0	44.6	0.8	16.7	238.9	ND	1.0
-30.521	17.826	KLIPF_artesian	0.0	657.0	154	7.4	72.0	1093.2	1883.1	366.3	15.1	82.9	347.8	0.1	2.9
-30.490	17.870	Klipfontein	ND	44.8	10	7.0	24.0	66.6	86.0	1.6	1.6	1.9	12.4	0.3	0.1
-30.490	17.870	Klipfontein	ND	727.0	124	7.7	182.0	908.8	1393.0	216.0	17.8	110.8	348.4	1.4	2.8
ND	ND	Klipfontein	6.0	620.0	ND	7.3	ND	863.0	1797.0	211.0	17.4	130.0	337.0	0.6	3.0
ND	ND	Klipfontein(boorgat)	2.0	438.0	ND	7.0	ND	909.0	1859.0	310.0	14.7	65.0	347.0	0.1	2.9
-30.421	17.912	KLIPVLEI	6.0	1161.0	60	7.2	180.0	1812.4	3722.1	399.0	21.0	493.6	584.2	2.7	3.8
-29.450	17.724	KLOOF	0.0	135.4	112	7.2	ND	102.6	140.0	87.7	4.9	68.5	966.3	ND	0.6
-29.433	17.901	KOEGAS	20.0	633.0	146	7.0	ND	615.1	1966.0	343.9	2.3	199.7	617.8	ND	2.8
-30.060	17.910	Komri	ND	577.0	119	6.9	192.0	412.3	1350.0	286.2	7.6	110.6	278.9	22.0	1.3
-30.074	17.653	KOOFKF	ND	251.0	16	8.2	105.2	461.9	615.9	77.0	12.7	2.4	160.8	0.1	6.2
-30.066	17.670	KOOKFONT/BERG	ND	811.0	109	7.5	180.0	1298.0	2375.9	273.1	33.1	270.1	431.8	6.0	3.3
-30.073	17.654	KOOKFONTEIN_fontain	0.0	252.0	13	8.0	85.8	452.0	615.9	75.7	12.5	2.4	160.6	0.1	6.0
-29.683	17.925	KOPPERBERG	ND	180.9	0	8.0	ND	172.2	429.2	125.7	1.1	39.7	136.3	ND	2.8
-29.667	17.900	KOPPERBERG	0.0	497.0	139	7.0	ND	511.7	1445.0	324.9	4.2	140.1	487.3	ND	2.9
-29.700	17.905	KOPPERBERG	ND	565.0	210	7.2	ND	513.4	1725.0	410.7	6.5	194.5	441.4	ND	2.5
-29.909	17.784	KORINGHUIS	ND	190.1	80	6.4	84.3	212.2	504.0	68.0	7.5	73.1	124.1	14.7	0.5
-29.770	17.860	Krymekaar	0.0	92.7	26	6.4	77.0	98.1	206.0	35.1	1.8	19.0	70.9	2.2	0.4
-30.272	17.557	KWAGGANO1_dam	9.3	596.0	53	6.7	130.2	906.7	1539.9	153.6	29.0	205.6	322.3	59.0	2.0
-29.533	18.098	KWEEKFONTEIN	ND	128.3	50	7.1	ND	124.1	324.1	72.8	1.5	29.4	67.1	ND	1.5
-29.667	17.927	KWEEKFONTEIN	ND	81.8	54	7.2	ND	85.7	148.9	40.1	1.0	18.0	54.5	ND	1.2
-29.533	18.093	KWEEKFONTEIN	ND	90.5	86	8.1	ND	101.7	184.0	40.4	1.2	21.6	69.0	ND	1.1
-29.517	18.093	KWEEKFONTEIN	ND	208.0	91	7.0	ND	204.1	551.8	116.0	1.3	47.3	90.4	ND	2.1
29.730	17.870	Lammershoek	ND	245.0	69	7.3	121.0	217.3	438.0	89.3	1.7	71.7	155.2	4.6	1.7
-29.730	17.870	Lammershoek_Elec	ND	281.0	65	7.4	245.0	220.9	705.0	130.5	3.8	86.3	206.0	0.2	2.1
-30.327	18.069	Leliefontein	1.0	17.2	ND	6.2	30.9	15.2	17.4	2.2	0.7	2.0	2.6	0.1	0.2
-30.336	18.089	Leliefontein	1.5	16.7	ND	6.9	41.7	17.2	17.4	6.1	1.8	4.2	7.1	3.7	0.3
No_value	No_value	Leliefontein	ND	13.3	ND	6.1	41.9	14.5	13.1	3.4	0.4	3.1	6.7	0.5	0.2
-30.340	18.117	Leliefontein	ND	30.6	ND	6.1	57.1	32.7	43.6	8.0	1.8	7.3	26.1	1.4	0.2
0.000	0.000	Leliefontein	ND	64.3	ND	8.0	88.6	70.2	114.4	40.8	1.5	18.6	30.6	0.4	3.8
-30.331	18.089	Leliefontein	1.5	94.2	ND	7.6	97.3	97.7	209.0	41.6	3.3	32.6	77.3	1.5	0.2
-30.315	18.068	Leliefontein	1.0	49.8	ND	7.0	106.6	59.0	108.9	18.1	0.8	15.2	26.2	0.1	0.5
-30.342	18.086	Leliefontein	9.0	29.9	ND	6.8	114.3	25.4	34.8	21.4	1.7	7.1	10.8	0.1	1.3
0.000	0.000	Leliefontein	1.0	59.5	ND	7.0	138.5	103.8	114.4	14.1	0.9	8.5	37.3	0.3	0.9
-30.252	18.058	Leliefontein	1.0	76.8	ND	7.0	171.4	79.4	43.6	33.9	0.9	0.4	56.8	0.1	2.5
-30.349	18.093	Leliefontein	0.0	83.0	ND	7.0	200.7	56.6	174.2	86.6	2.5	13.9	48.5	0.1	1.1
-29.740	17.920	LittleCottage	15.0	305.0	70	7.2	101.0	238.9	533.0	197.2	3.2	93.4	229.5	9.4	1.7
ND	ND	Loerkop(windpomp)	ND	148.0	ND	7.4	ND	203.0	388.0	44.0	5.5	37.0	76.0	0.4	2.1
ND	ND	Loerkop2	ND	307.0	ND	8.1	ND	539.0	1083.0	123.0	12.3	111.0	200.0	0.1	2.5
-29.917	17.744	LUISKRAAL	12.5	352.0	210	7.1	264.0	481.6	1098.0	190.6	7.0	127.4	226.0	0.5	3.4
-29.483	17.723	MARAS	ND	95.3	95	7.8	ND	111.4	149.0	37.6	2.5	27.8	146.0	ND	0.7
-30.448	17.624	Melkbosheuwel	2.5	1085.0	50	7.2	146.0	1548.1	2194.5	383.4	20.3	331.9	400.5	0.2	1.3
-29.840	17.960	Mesklip	ND	159.3	101	7.2	111.0	131.0	293.0	86.4	2.2	36.5	92.3	2.8	2.5
-29.840	17.860	Mesklip	ND	123.8	46	7.4	114.0	102.4	138.0	68.4	1.6	22.2	66.2	0.1	2.7
-29.840	17.850	Mesklip	ND	588.0	95	6.9	124.0	534.7	1006.0	258.9	3.8	110.8	444.0	0.1	2.0
-29.840	17.860	Mesklip	ND	175.3	50	7.7	131.0	135.4	310.0	110.5	2.3	30.5	97.2	0.7	2.6
-29.820	17.850	Mesklip	ND	246.0	80	6.7	131.0	270.1	421.0	78.5	1.1	52.5	197.8	1.4	2.0
-29.550	19.004	MIDDELPOS	11.3	294.0	308	7.3	ND	305.2	588.0	188.7	0.7	88.5	563.1	ND	4.6
-29.879	17.574	MISKRAAL	ND	372.0	154	8.8	140.4	541.7	1062.0	191.6	6.4	163.8	290.9	6.2	2.4
-29.600	17.804	NABABEEP	3.0	205.0	196	7.2	ND	308.9	254.0	82.5	2.2	56.9	976.5	ND	2.5
-29.583	17.784	NABABEEP	0.5	287.0	218	7.0	ND	317.9	527.0	128.6	3.2	102.4	938.9	ND	1.6
-30.109	18.015	NAK1_Elec	14.0	110.1	558	7.2	152.3	150.5	300.5	39.8	1.3	37.5	72.8	8.8	2.4
-29.700	17.671	NARIES	ND	123.4	70	6.6	ND	131.3	289.1	59.2	3.0	30.8	73.9	ND	0.4
-30.053	17.954	NHO1_dam	3.2	230.0	1002	7.1	138.5	254.1	457.6	101.2	3.7	96.5	179.2	23.0	1.5
-29.650	17.588	NIGRAMOEP MINE	4.0	83.6	50	7.1	ND	88.8	210.2	35.8	2.5	22.5	69.5	ND	0.5
-29.567	17.588	NIGRAMOEP MINE	7.5	981.0	71	6.3	ND	1228.0	2952.0	770.1	65.0	84.9	1144.0	ND	0.5
-30.225	18.138	NOU1_well	2.9	176.9	146	6.6	77.5	241.8	439.9	56.6	5.4	53.5	70.2	0.6	0.4
-30.245	18.083	Nourivier	ND	34.5	ND	7.0	44.8	45.3	87.1	8.2	2.1	8.1	9.3	0.2	0.4
-30.243	18.143	Nourivier	ND	41.8	ND	8.0	64.9	50.8	95.8	11.2	2.1	10.2	12.9	0.1	0.3
-30.193	18.154	Nourivier	ND	84.7	ND	5.9	92.7	134.9	187.3	24.7	0.9	16.4	70.2	0.1	0.9
-30.226	18.137	Nourivier	ND	163.0	ND	6.0	100.4	263.7	448.6	45.1	5.4	48.0	99.7	1.7	0.4
-30.222	18.103	Nourivier	ND	55.2	ND	7.8	111.2	56.2	113.2	33.2	1.0	14.5	36.0	0.4	3.2
-30.174	18.195	Nourivier	6.2	358.0	ND	6.6	206.9	436.1	1058.3	200.5	8.3	133.4	214.5	1.6	2.6

Lat	Long	Name	WL (m)	EC mS/m	Alk.	pH	HCO3	Na	Cl	Ca	K	Mg	SO4	N	F
-30.222	18.103	Nourivier	ND	55.2	ND	7.8	111.2	56.2	113.2	33.2	1.0	14.5	36.0	0.4	3.2
-30.174	18.195	Nourivier	6.2	358.0	ND	6.6	206.9	436.1	1058.3	200.5	8.3	133.4	214.5	1.6	2.6
-30.260	18.203	Nourivier	ND	478.0	ND	6.2	227.0	481.5	1228.1	253.9	1.7	162.5	290.9	13.2	2.8
-30.198	18.198	Nourivier	ND	278.0	ND	7.1	231.6	306.2	714.2	150.2	5.9	112.1	183.3	0.1	1.4
-29.934	18.046	NUW12	ND	718.0	54	8.1	94.2	1106.2	2331.8	462.5	13.6	217.6	452.5	0.6	2.9
-29.965	18.064	NUW2_dam	ND	383.0	64	7.1	127.4	454.6	1047.1	227.9	10.6	165.0	237.8	11.0	1.3
-29.985	18.052	NUW3_dam	21.2	230.0	44	8.0	83.1	268.8	571.9	142.7	6.5	89.9	173.0	2.6	1.9
-29.819	17.790	NUWR1	ND	220.0	125	7.0	293.6	217.6	572.0	122.6	5.5	92.1	116.5	0.2	1.3
-30.228	18.001	OLIEN_dam	ND	27.2	108	6.7	69.2	29.3	61.6	9.7	2.6	4.5	6.5	0.9	0.2
-29.667	17.971	OLYNPUTS	33.0	48.7	27	6.1	ND	53.0	123.0	10.4	1.4	14.8	38.9	ND	0.6
-29.483	17.773	O'OKIEP COPPER MINE	ND	344.0	155	7.8	ND	365.8	588.0	265.6	10.3	111.6	2099.0	ND	2.2
-30.426	17.610	Ou_Plaas_No1	ND	1068.0	39	7.4	117.9	1629.0	3014.9	683.3	43.2	140.7	487.0	1.4	2.9
-30.427	17.603	Ou_Plaas_No2	ND	805.0	41	7.7	87.1	1277.1	2546.9	575.0	32.6	62.1	349.0	1.9	4.1
-23.896	17.632	OUBEEB	12.2	249.0	81	7.1	67.4	409.6	702.0	115.3	4.7	87.0	173.2	12.4	2.8
-29.893	17.633	OUBEEB	ND	265.0	94	7.2	95.5	459.1	828.0	115.6	4.9	89.2	185.0	8.4	3.4
-29.840	17.920	OuHoek	ND	301.0	95	6.9	87.0	195.8	722.0	200.6	2.7	87.6	201.9	4.0	2.3
-29.840	17.930	OuHoek	76.2	110.8	121	8.1	101.0	117.2	189.0	51.2	1.4	19.0	57.5	0.1	3.3
-30.190	18.012	OUT1_reservior	5.6	26.9	70	6.4	27.7	28.3	58.9	4.7	0.3	4.9	2.0	1.3	0.5
-30.186	18.011	OUT2_Fontain	0.0	57.6	76	6.4	55.4	54.2	96.8	11.9	1.5	9.5	8.1	1.2	0.3
ND	ND	Outiep	ND	576.0	ND	7.4	ND	1129.0	2627.0	273.0	14.2	260.0	455.0	2.0	1.9
-30.345	17.731	Partysvlei	1.8	950.5	108	8.1	221.9	1353.5	4258.9	327.3	16.6	357.8	710.8	0.1	1.4
-30.140	18.110	Pedroskloof	ND	153.4	57	7.2	121.0	95.6	292.0	87.7	2.0	60.5	62.1	24.0	0.4
-30.140	18.110	Pedroskloof	ND	202.0	141	6.7	397.0	183.6	241.0	93.3	1.0	77.4	60.4	4.0	1.1
-30.216	18.017	PEN1_dam	ND	82.8	209	9.3	59.0	80.5	122.9	27.9	1.7	26.8	39.0	0.1	0.9
-30.191	18.022	PEN2_reservior	ND	53.5	98	7.2	55.4	46.5	114.4	18.7	0.2	15.7	20.5	3.8	0.4
-30.284	18.484	PLAT1_dam	6.0	254.0	505	7.6	249.2	382.4	550.0	72.3	7.5	36.6	148.2	0.8	2.6
-30.318	18.486	PLAT2_well	2.5	1382.0	200	9.1	124.6	2367.1	4752.0	384.7	55.6	439.8	673.5	0.4	3.5
-30.321	18.489	PLAT3_reservior	5.4	246.0	455	7.6	213.2	299.3	585.2	115.2	10.8	63.0	121.9	10.0	2.2
-30.323	18.483	PLAT4_dam	ND	473.0	488	8.1	123.6	3039.7	933.6	185.2	19.8	129.3	289.9	0.5	4.5
-29.891	18.104	POT1	7.8	918.0	349	7.3	110.8	1413.0	2921.4	657.7	10.5	273.5	671.4	9.6	4.3
-30.149	17.850	RACHEL	ND	258.0	53	6.8	163.4	369.6	571.9	96.7	3.6	77.4	183.9	12.0	2.0
-30.448	17.652	Radyn	ND	1690.0	138	7.3	207.8	2691.2	4382.9	557.4	80.7	552.9	1479.1	3.9	2.2
-29.720	17.900	RanchoAmigo	ND	680.0	113	8.5	155.0	724.1	1315.0	220.2	17.6	110.7	841.2	20.0	0.0
-29.720	17.900	RanchoAmigo	ND	839.0	88	6.9	188.0	697.8	3087.0	390.0	2.2	110.5	649.5	1.8	1.9
-29.583	18.064	RATELKRAAL	ND	70.7	80	7.4	ND	82.4	183.9	72.7	4.4	19.8	77.2	ND	3.0
-29.567	18.121	RATELKRAAL	ND	389.0	93	6.7	ND	359.7	1261.0	409.5	2.5	147.9	354.4	ND	1.6
-29.600	18.156	RATELKRAAL	ND	71.4	94	6.6	ND	61.1	183.9	72.3	2.2	24.4	86.5	ND	2.0
-29.533	18.059	RATELKRAAL	20.2	514.0	115	6.6	ND	655.3	1594.0	296.1	2.3	122.3	361.6	ND	3.3
-29.533	18.093	RATELKRAAL	ND	104.5	116	7.4	ND	131.0	254.0	76.8	0.9	32.6	145.4	ND	3.4
-29.876	18.189	RIET4_dam	15.5	247.0	425	7.2	152.3	363.4	598.4	111.6	5.6	64.2	150.2	7.1	2.1
-29.800	18.139	RIETFONTEIN	ND	290.0	82	6.5	ND	263.9	858.3	184.9	1.4	89.1	147.1	ND	1.9
-29.902	18.157	RIETFONTEIN2_BuffelsR	5.0	543.0	38	7.2	132.9	892.0	1513.5	227.6	11.4	153.5	353.3	6.3	1.3
-29.925	18.150	RIETFONTEIN3	4.2	581.0	86	7.0	135.7	809.7	1680.7	333.6	19.7	203.9	346.1	12.0	1.1
-30.010	17.806	RIETMOND	ND	426.0	182	6.9	168.5	533.3	1206.0	294.1	10.9	208.8	290.6	22.8	1.4
ND	ND	Riviergat (Karkams)	0.1	535.0	ND	6.9	ND	936.0	2980.0	401.0	19.8	441.0	381.0	0.5	2.2
-29.820	17.950	Rockoptel	ND	234.0	63	7.7	108.0	214.0	439.0	104.6	2.7	46.3	114.8	0.7	2.7
0.000	0.000	ROODEPOORT/37227_dam	4.5	431.0	375	6.8	180.0	443.2	1214.0	191.9	3.9	176.9	271.5	5.2	2.7
-30.070	18.270	ROOI1_Well	1.0	205.0	56	7.3	124.6	265.3	475.2	84.0	7.5	57.6	84.5	0.1	1.2
-30.348	17.614	Rooiberg	ND	636.0	81	7.4	269.6	1023.1	2024.9	156.2	22.6	181.7	362.3	1.3	3.3
-30.093	18.194	Rooifontein	ND	74.9	ND	7.0	135.9	81.6	54.0	37.2	1.3	22.8	67.2	1.0	3.3
-30.066	18.269	Rooifontein	ND	136.5	ND	6.4	149.8	181.3	331.0	50.5	6.3	37.6	69.2	0.1	0.8
-30.080	18.236	Rooifontein	ND	208.0	ND	6.7	216.2	359.3	461.6	66.1	1.2	43.0	175.6	8.2	5.4
-30.154	18.241	Rooifontein	ND	203.0	ND	7.0	231.6	225.0	496.5	111.8	7.4	82.4	165.1	2.2	2.1
-30.141	18.234	Rooifontein	ND	267.0	ND	7.0	237.8	400.6	696.8	126.6	11.5	79.2	222.9	6.7	3.2
-30.104	18.236	Rooifontein	ND	160.1	ND	6.4	264.1	167.6	304.9	87.7	1.3	63.7	174.8	1.4	2.9
-30.076	18.267	Rooifontein	7.9	614.0	ND	6.6	463.3	1007.0	1907.5	218.2	4.1	193.6	463.7	0.1	6.1
-29.450	17.754	ROOIWATER	11.5	129.8	78	6.8	ND	115.2	325.0	64.2	2.1	42.7	89.0	ND	1.2
-30.030	17.890	Rotnoskop	ND	503.0	167	7.4	205.0	404.9	791.0	261.0	9.3	110.8	355.1	23.0	2.9
-29.333	17.919	SABIES	9.6	583.0	165	7.2	ND	659.9	1812.0	258.4	10.4	153.9	599.0	ND	2.0
-29.818	17.617	SANAGAS	12.0	235.0	190	8.1	64.6	262.5	522.0	95.3	7.1	62.8	94.5	0.0	2.2
-29.836	17.613	SANAGAS	ND	233.0	84	6.6	106.7	315.4	738.0	67.1	5.8	91.1	122.1	1.2	1.0
-29.854	17.623	SANAGAS	ND	444.0	110	7.1	269.6	550.3	1431.0	276.5	9.0	161.0	246.7	1.3	2.8
-30.225	18.110	SANDFONTEIN_monopump	11.4	64.3	35	8.0	88.6	70.2	114.4	40.8	1.5	18.6	30.6	0.4	3.8

Lat	Long	Name	WL (m)	EC mS/m	Alk.	pH	HCO3	Na	Cl	Ca	K	Mg	SO4	N	F
-30.502	17.071	Sandhoek	ND	425.0	54	7.4	244.3	569.9	1346.3	162.7	6.1	132.8	263.6	0.1	3.2
ND	ND	Sandkop(fontein)	ND	842.0	ND	8.8	ND	2140.0	3905.0	232.0	47.3	267.0	689.0	8.3	3.1
-29.903	17.783	SANDKRAAL	3.0	174.4	120	7.7	146.0	237.5	540.0	104.0	4.0	68.1	134.2	4.9	2.5
-29.717	18.053	SILVERFONTEIN	ND	85.8	115	7.5	ND	83.4	166.4	52.2	0.8	22.3	59.7	ND	3.4
-29.567	17.583	SILWERFONTEIN	ND	169.2	60	6.8	ND	160.4	438.0	107.4	3.1	50.6	157.9	ND	2.0
-29.681	17.626	SKA1_Artesian	0.0	550.0	44	6.9	180.0	714.4	1566.0	277.2	7.6	167.8	426.8	2.6	2.2
-29.677	17.602	SKA2_Well	3.2	229.0	146	7.5	238.2	4255.2	8183.0	1316.6	64.6	888.6	2568.5	0.2	2.0
-30.176	17.795	SKILPAD_fontain	0.0	109.6	63	8.6	166.2	197.6	439.9	22.0	4.3	17.8	84.2	0.3	4.0
ND	ND	Skuinskraal(windpomp)	22.3	388.0	ND	6.7	ND	646.0	1402.0	171.0	26.7	189.0	252.0	53.0	0.5
-30.118	17.600	SOEBATSF_Fontain	0.0	662.0	13	7.4	85.9	997.7	1979.9	423.9	35.8	36.5	219.3	0.1	3.1
-30.123	17.600	SOEBATSF	3.0	687.0	47	7.3	138.5	1138.4	1935.9	234.8	24.1	132.4	328.8	1.9	3.5
-30.218	17.564	SOUBATTERSFONTEIN_dam	ND	895.0	106	7.4	180.0	1524.7	2595.8	234.4	33.7	240.7	491.0	1.6	3.1
-29.852	17.719	SOUTKLOOF1	45.1	224.0	142	6.9	177.2	280.8	492.8	117.4	9.6	61.8	147.8	5.6	3.1
ND	ND	Speelmanshoek(gat)	ND	227.0	ND	6.5	ND	500.0	1167.0	146.0	13.1	120.0	206.0	1.4	1.0
ND	ND	Speelmanshoek(windpomp)	ND	321.0	ND	6.8	ND	363.0	756.0	65.0	13.2	72.0	141.0	0.1	0.4
-29.517	18.089	SPEKTAKEL MINE	ND	846.0	102	7.4	ND	1124.0	2575.0	384.1	11.4	213.2	794.4	ND	0.2
-30.350	17.771	Spoegrivier_LF90/20B	12.0	395.5	109	7.2	174.1	482.1	1575.1	165.5	5.9	142.2	224.6	3.4	2.9
-30.344	17.767	Spoegrivier_put	2.0	623.5	272	7.3	168.5	792.5	1970.8	248.1	13.1	221.5	350.5	0.9	1.3
-29.717	17.921	SPRINGBOK	ND	681.0	147	6.7	ND	662.5	2172.0	426.1	1.2	265.5	599.1	ND	2.0
-29.700	17.888	SPRINGBOK	ND	307.0	166	7.4	ND	302.6	814.6	177.5	1.6	104.1	251.2	ND	2.6
-29.683	17.901	SPRINGBOK CARAVAN PARK	ND	32.7	184	8.4	ND	21.3	43.8	29.6	8.6	12.0	36.9	ND	3.7
-29.700	17.888	SPRINGBOK GHOLF COURSE	ND	438.0	117	7.0	ND	447.5	1261.0	268.2	3.5	146.6	155.3	ND	1.7
ND	ND	Suidgat Karkams	ND	252.0	ND	7.1	ND	394.0	967.0	140.0	9.4	108.0	119.0	0.1	2.9
-29.433	17.956	SWARTPUTS	35.0	329.0	123	7.2	ND	294.8	904.0	157.8	4.0	123.7	396.6	ND	1.3
-30.024	17.984	THD1_Elec	ND	213.0	544	6.5	135.7	267.5	439.9	76.0	1.4	62.0	151.0	0.2	2.3
-29.700	17.670	TWEEDAM	ND	158.9	102	7.2	ND	165.6	376.6	115.7	3.1	33.8	181.5	ND	2.2
-29.947	18.264	TWEEFONTEIN1	ND	115.2	51	7.4	124.6	146.2	211.2	60.9	4.8	35.7	75.1	7.8	1.8
-30.336	18.003	TWEERIVIER1_dam	18.8	278.0	77	7.6	124.6	333.4	686.4	123.3	7.9	93.8	141.8	0.1	3.5
-30.314	18.000	TWEERIVIER2_dam	4.5	337.0	56	7.5	138.5	336.3	923.9	192.2	6.1	139.4	113.7	0.1	3.4
-30.323	18.014	TWEERIVIER3_Elec	18.1	245.0	58	7.7	138.5	331.3	580.8	85.3	6.7	74.3	110.4	0.1	4.5
-30.336	18.023	TWEERIVIER4_Elec	30.2	236.0	64	7.5	138.5	285.9	554.4	117.9	6.1	76.6	157.6	0.1	4.1
-30.336	18.022	TWEERIVIER5_Elec	14.0	285.0	38	7.3	99.7	340.1	695.2	135.1	5.1	102.5	202.6	0.1	2.6
-29.250	18.063	VAALDAM	ND	115.3	75	7.7	ND	122.6	306.6	62.7	1.5	29.7	83.6	ND	2.2
-30.446	17.801	Vaaldraai	ND	411.5	120	7.5	325.8	338.1	1062.7	137.7	8.6	89.7	230.4	0.1	4.1
-30.389	17.664	Vaalfontein	ND	860.0	132	7.9	227.5	1364.3	3446.9	248.7	23.0	224.5	541.7	0.7	3.1
-30.418	17.568	Varkwater	ND	3245.0	42	8.2	87.1	6154.7	19034.0	2148.9	127.9	455.8	2454.9	0.1	4.5
-29.909	18.076	VELS1	11.0	48.8	242	6.8	83.1	63.4	79.2	21.5	1.4	12.1	41.5	1.5	0.4
-30.307	17.722	Vleie_Naries	15.2	139.0	95	7.4	67.1	223.7	225.0	21.6	2.2	26.8	123.5	21.5	0.4
-30.261	17.614	Vlietjies	12.4	486.0	76	7.6	185.4	755.2	1251.0	167.4	10.9	159.4	288.2	4.8	2.9
-30.402	17.646	Vlugfontein	ND	537.5	23	7.6	137.6	890.2	1795.1	256.5	25.6	13.9	360.9	0.1	3.4
-29.760	17.890	Voelklip	ND	156.5	56	7.7	111.0	163.9	241.0	67.5	1.3	31.0	114.2	1.2	2.7
-29.750	17.870	Voelklip	ND	325.0	105	7.7	171.0	283.2	524.0	133.7	3.5	98.9	203.8	1.2	2.4
-29.750	17.870	Voelklip	15.0	326.0	58	7.5	188.0	258.9	464.0	158.0	3.1	98.5	206.9	1.0	2.3
ND	ND	Vonkelfontein(windpomp)	ND	557.0	ND	7.1	ND	1258.0	2549.0	270.0	13.6	250.0	580.0	6.1	2.0
-30.338	17.939	VYEMOND/G37152_Elec	ND	177.9	ND	7.1	124.6	290.2	527.9	91.5	6.5	69.6	120.7	0.1	2.5
-30.337	17.940	VYEMOND/G37153	6.5	111.7	53	6.9	134.8	118.6	200.6	62.6	4.8	30.5	56.5	0.1	2.2
-30.183	17.938	W/HOEK_well	1.8	73.7	25	6.6	27.7	105.6	219.9	18.4	2.2	17.6	35.1	1.9	0.3
-30.384	17.510	Wallekraal_No1	ND	1528.0	40	7.2	44.9	2622.8	4877.9	1056.5	37.7	149.3	673.0	0.1	2.0
-30.396	17.520	Wallekraal_No2	1.5	1835.0	61	7.4	196.6	3081.2	4652.9	910.2	44.0	349.2	667.2	0.1	1.1
-30.397	17.528	Wallekraal_No3_font	ND	1525.0	97	7.7	176.9	2451.2	3914.9	725.9	10.3	339.8	652.3	0.1	0.9
-29.924	17.644	Wildeperdehoek_Pass	ND	354.0	235	7.4	314.6	492.4	1179.0	183.4	8.1	118.9	248.0	0.0	3.0
-30.407	18.051	Wilgerhoutsrivier	10.0	67.0	16	7.5	84.3	72.5	158.4	19.7	11.2	20.5	18.1	9.1	0.1
-30.403	18.061	Wilgerhoutsrivier_font	ND	40.4	6	7.3	44.9	50.7	123.2	6.8	9.9	8.4	12.6	0.1	0.1
-30.377	17.688	Windheuwel	10.0	1059.0	106	7.8	199.4	1516.3	4616.9	365.7	35.5	378.0	657.2	7.0	1.6
-29.921	17.757	WITDAM	ND	180.3	100	6.5	106.7	233.0	468.0	58.5	9.2	47.2	112.4	3.8	0.7
-29.500	18.026	WITKOPPIES	0.0	250.0	110	7.4	ND	308.9	570.0	125.7	0.7	50.2	610.3	ND	1.7
0.000	0.000	YBE1_dam	3.3	409.0	89	8.3	166.2	586.8	1082.3	195.5	9.7	176.6	369.2	0.3	2.2
-29.990	17.990	Ybeep	ND	562.0	85	7.9	202.0	605.2	963.0	244.5	4.5	100.7	528.5	0.1	2.6
-29.958	18.013	YBEII_windpump	3.3	368.0	119	7.1	166.2	514.1	941.5	191.3	8.3	153.6	320.7	0.3	2.2

Lat	Long	Name	Si	Sr	Al	B	Ba	Zn	Mn	Fe	Ni	Cu	P	Pb
-30.177	18.185	91LF88_well	10.1	0.231	0.139	0.099	0.051	0.523	0.533	0.074	0.000	0.004	0.010	0.000
-30.240	18.031	AGTER1_well	11.7	0.033	0.024	0.028	0.014	0.079	0.000	0.007	0.000	0.000	0.000	0.019
-30.235	18.038	AGTER2_dam	14.6	0.143	0.086	0.026	0.000	0.204	0.002	0.006	0.000	0.000	0.005	0.039
-30.244	18.055	AGTER3	7.1	0.197	0.175	0.000	0.018	0.023	0.000	0.004	0.000	0.003	0.003	0.004
-30.354	17.687	Aigab	15.8	2.293	1.023	2.050	0.043	1.292	0.328	0.000	0.000	0.008	0.045	0.010
-30.130	18.020	Anagas	22.7	1.782	0.932	0.014	0.147	0.714	0.016	0.000	0.000	0.003	0.051	0.000
-30.041	17.985	ANE1_dam	14.1	0.632	0.527	0.256	0.015	0.086	0.035	0.007	0.000	0.005	0.000	0.032
-30.126	18.017	ANE2_dam	15.8	1.325	0.662	0.164	0.144	0.066	0.218	0.006	0.000	0.003	0.000	0.000
-30.110	17.920	Arkoep	13.6	0.474	0.316	0.000	0.004	1.892	0.027	0.004	0.002	0.020	0.105	0.009
-30.110	17.920	Arkoep	15.2	0.593	0.384	0.000	0.003	0.762	0.001	0.000	0.000	0.007	0.000	0.036
-30.140	17.940	Arkoep	18.5	0.367	0.384	0.000	0.003	0.762	0.001	0.000	0.000	0.007	0.016	0.036
-29.999	17.778	ARREGAS	19.4	3.026	1.393	0.674	0.118	0.043	0.061	0.000	0.000	0.028	0.069	0.027
-30.242	18.061	BAK1_well	15.2	0.095	0.621	0.039	0.025	0.072	0.001	0.367	0.000	0.002	0.006	0.008
-29.710	17.900	BeginWeer	14.9	0.429	0.202	0.000	0.004	0.131	0.001	0.000	0.000	0.000	0.071	0.031
-30.384	17.836	Bethel	20.4	0.674	0.385	0.480	0.024	0.029	0.000	0.000	0.000	0.000	0.047	0.024
-29.740	17.930	Biesiesfontein	16.6	0.437	0.285	0.000	0.043	1.467	0.007	0.000	0.000	0.001	0.000	0.002
-29.730	17.880	Biesiesfontein_Elec	13.3	0.660	0.404	0.000	0.011	0.280	0.000	0.000	0.000	0.000	0.000	0.000
-29.720	17.890	Blouputs	13.5	0.608	0.377	0.000	0.018	0.012	0.010	0.000	0.000	0.000	0.050	0.016
-29.740	17.880	Bloustasie	19.2	0.712	0.379	0.000	0.010	1.730	0.017	0.000	0.008	0.000	0.064	0.006
-29.730	17.880	Bloustasie	17.4	1.359	0.858	0.000	0.075	0.517	0.095	0.000	0.000	0.005	0.036	0.007
-29.710	17.910	Bloustasie	13.2	0.832	0.467	0.000	0.004	0.128	0.004	0.000	0.001	0.000	0.056	0.025
-29.720	17.890	Bloustasie	14.6	0.851	0.428	0.000	0.019	0.681	0.002	0.000	0.000	0.000	0.023	0.028
-30.013	17.823	BLOUSYFER	20.0	1.758	0.847	0.944	0.025	0.066	0.187	0.000	0.009	0.029	0.044	0.030
-30.191	18.154	BOB1_well	14.3	0.088	0.053	0.097	0.016	0.075	0.003	0.003	0.008	0.007	0.044	0.021
-29.802	17.560	BOKKRAAL	24.7	0.124	0.000	0.071	0.015	0.033	0.066	0.000	0.000	0.025	0.067	0.014
-29.793	17.563	BOKKRAAL	27.7	1.241	0.688	0.452	0.051	0.063	0.075	0.000	0.000	0.031	0.118	0.038
-30.209	17.706	BOKSKRAAL	21.6	1.649	0.855	1.107	0.064	0.065	0.013	0.000	0.006	0.013	0.008	0.030
-29.866	17.592	BOSLUISKRAAL	12.7	0.501	0.237	0.409	0.025	0.062	0.065	0.000	0.000	0.022	0.075	0.025
-30.200	18.050	Bovlei	12.3	0.217	0.133	0.000	0.017	0.843	0.010	0.000	0.004	0.004	0.054	0.008
-29.890	17.594	BRAKPITS	16.4	0.727	0.482	0.493	0.050	0.127	0.084	0.000	0.000	0.039	0.110	0.003
-30.246	17.710	Brakputs_No1	13.2	1.524	0.852	0.630	0.063	0.025	0.000	0.000	0.000	0.000	0.000	0.008
-30.248	17.710	Brakputs_No2	13.3	0.859	0.537	0.447	0.064	0.120	0.000	0.000	0.000	0.000	0.000	0.004
-30.001	17.691	BRANDBERG	22.1	1.213	0.841	0.975	0.064	0.049	0.061	0.000	0.000	0.021	0.065	0.022
ND	ND	Brandhoek(kraan)	12.8	7.700	ND	ND	ND	0.090	ND	ND	ND	ND	ND	ND
-29.517	19.939	BRANDKLOOF	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	Buffelsfontein	15.3	1.000	ND	ND	ND	0.080	ND	ND	ND	ND	ND	ND
-29.933	17.705	WILDEPERDEPAS	15.6	1.534	0.509	0.191	0.033	0.098	0.120	0.000	0.000	0.025	0.062	0.054
-29.736	17.637	BUFS1_Well	12.8	0.476	0.320	0.247	0.080	0.013	0.183	0.002	0.000	0.003	0.075	0.018
-29.770	17.660	BUFS3_Well	10.3	0.618	0.373	0.152	0.089	0.048	0.321	0.003	0.000	0.002	0.000	0.003
-29.772	17.660	BUFS5_well	14.6	0.775	0.427	0.486	0.080	0.010	0.001	0.004	0.000	0.000	0.181	0.017
-30.340	17.511	BYENESKRANS	9.4	2.060	0.731	2.654	0.017	0.177	0.060	0.000	0.001	0.002	0.000	0.059
-29.583	17.792	CAROLUSBERG MINE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.633	17.958	CAROLUSBERG MINE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.517	17.983	CONCORDIA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.181	18.273	COU1	15.8	1.594	1.077	0.350	0.065	0.120	0.014	0.000	0.004	0.010	0.015	0.010
-30.182	18.274	COU2_fontain	0.4	6.371	1.859	1.180	0.504	0.035	0.010	0.000	0.008	0.017	0.589	0.005
-30.126	18.257	COU3	20.7	0.444	0.372	0.313	0.026	0.093	0.119	0.000	0.002	0.004	0.000	0.000
-29.828	18.332	DAP1_dam	16.4	1.109	0.602	0.647	0.036	0.016	0.002	0.003	0.000	0.000	0.014	0.017
-29.827	18.326	DAP2_dam	16.3	1.182	0.618	0.649	0.037	0.023	0.000	0.002	0.000	0.001	0.006	0.025
-30.323	18.390	DE_RIET_dam	13.6	1.450	0.681	1.189	0.046	0.033	0.559	0.021	0.000	0.003	0.026	0.010
-29.959	17.975	DED1_Well	8.5	1.295	0.681	0.175	0.039	0.084	0.080	0.000	0.005	0.002	0.000	0.000
-29.950	17.970	DeDraai	20.4	0.238	0.150	0.000	0.003	0.141	0.007	0.000	0.000	0.002	0.031	0.000
-29.960	17.970	DeDraai	28.0	1.930	1.105	0.339	0.085	1.208	0.246	0.000	0.002	0.013	0.060	0.000
-29.770	17.940	Deurdrif	23.9	0.134	0.059	0.000	0.013	0.138	0.010	0.000	0.002	0.029	0.000	0.032
-29.770	17.940	Deurdrif	13.8	0.167	0.126	0.000	0.008	0.222	0.024	0.000	0.005	0.000	0.094	0.018
-29.780	17.960	Deurdrif	15.8	1.225	0.820	0.497	0.025	0.097	0.189	0.078	0.000	0.018	0.121	0.056
-29.780	17.940	Deurdrif	16.4	1.009	0.818	0.034	0.068	0.178	0.275	0.000	0.000	0.012	0.099	0.000
-29.780	17.950	Deurdrif	14.7	0.918	0.743	0.040	0.017	0.138	0.015	0.000	0.000	0.018	0.078	0.028
-29.583	17.793	DOOIFONTEIN	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	Doring Draai(put)	12.3	1.600	ND	ND	ND	0.050	ND	ND	ND	ND	ND	ND
ND	ND	Drieklip(put)	25.7	1.100	ND	ND	ND	0.060	ND	ND	ND	ND	ND	ND
ND	ND	Drieklip(windpomp)	18.6	0.900	ND	ND	ND	0.750	ND	ND	ND	ND	ND	ND
-29.913	17.967	DRO1	16.8	0.280	0.205	0.040	0.025	0.062	0.002	0.000	0.000	0.004	0.007	0.000
-29.683	17.840	DROEDAP	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.374	17.717	Duikerkop_font	8.9	1.931	0.850	1.409	0.050	0.000	0.000	0.000	0.000	0.000	0.000	0.042
-29.750	18.041	EENDOORN	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Lat	Long	Name	Si	Sr	Al	B	Ba	Zn	Mn	Fe	Ni	Cu	P	Pb
-30.393	18.097	EZEL1	17.2	0.139	0.418	0.000	0.030	0.028	0.000	0.160	0.000	0.005	0.173	0.007
-29.811	17.501	F1_Fontain	13.8	0.141	0.059	0.087	0.039	0.015	0.006	0.000	0.000	0.002	0.000	0.001
-29.781	17.503	F2_Fontain	7.8	0.122	0.052	0.096	0.029	0.020	0.001	0.000	0.011	0.001	0.000	0.000
-30.079	18.010	FIL1_Elec	10.1	0.293	0.268	0.050	0.028	0.116	0.628	0.019	0.000	0.000	0.000	0.012
-29.700	17.909	FONTEINTJIE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.916	18.421	GAM1_dam	14.9	0.540	0.372	0.375	0.007	0.038	0.001	0.000	0.008	0.001	0.024	0.004
ND	ND	Garagams	15.5	0.800	ND	ND	ND	1.530	ND	ND	ND	ND	ND	ND
-30.238	17.759	GBERG	15.5	2.091	1.004	1.073	0.062	0.043	0.245	0.003	0.003	0.004	0.000	0.016
-29.417	17.751	GEMSBOK	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.767	17.991	GOEGAB	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.717	18.012	GOEGAB	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.740	17.940	GoeieHoop	14.6	0.774	0.754	0.000	0.045	0.149	0.156	0.000	0.000	0.000	0.070	0.019
-29.740	17.940	Grashoek	16.0	1.360	1.053	0.097	0.062	0.528	0.281	0.000	0.001	0.048	0.064	0.045
-29.740	17.940	Grashoek	14.2	1.101	0.874	0.100	0.055	0.140	0.159	0.000	0.000	0.040	0.058	0.027
-29.633	18.204	GROOT KAU	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.700	17.971	GROOT KAU	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.633	18.255	GROOT KAU	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.234	17.692	Grootberg_No1	17.7	2.998	1.318	1.515	0.112	0.225	0.000	0.000	0.000	0.000	0.000	0.016
-30.274	17.712	Grootberg_No2	12.4	0.581	0.374	0.243	0.047	0.243	2.063	2.156	0.000	0.003	0.000	0.014
ND	ND	Grysklip	17.6	0.600	ND	ND	ND	0.130	ND	ND	ND	ND	ND	ND
-30.151	17.887	HAAS1	11.3	0.157	0.165	0.070	0.016	0.950	0.232	0.000	0.000	0.003	0.000	0.007
-30.139	17.871	HAAS2	13.9	0.909	0.696	0.195	0.046	0.116	0.014	0.000	0.002	0.003	0.000	0.000
-29.617	17.837	HOMEB	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	Hondeklipbaai(kraan)	13.9	0.700	ND	ND	ND	0.300	ND	ND	ND	ND	ND	ND
-30.323	17.618	Horees_No1	13.8	3.084	0.916	1.048	0.011	0.274	0.000	0.000	0.000	0.000	0.000	0.018
-30.322	17.621	Horees_No2	13.2	0.862	0.447	0.777	0.022	0.221	0.000	0.000	0.000	0.000	0.590	0.006
-30.307	17.635	Horeesfont	15.6	2.398	0.725	0.868	0.029	0.000	0.168	0.060	0.000	0.000	0.000	0.010
-29.790	17.960	HoudeMond	16.9	0.079	0.034	0.000	0.013	3.251	0.043	0.000	0.000	0.000	0.019	0.011
-29.800	17.970	HoudeMond	11.6	0.906	0.932	0.003	0.006	0.078	0.004	0.000	0.001	0.000	0.027	0.035
-29.800	17.960	HoudeMond	11.2	1.071	1.115	0.002	0.011	0.196	0.003	0.000	0.014	0.000	0.079	0.015
-29.969	18.168	HYT1_dam	22.2	0.608	0.414	0.312	0.062	0.014	0.000	0.000	0.009	0.013	0.000	0.010
-29.854	17.789	JAK1	12.8	0.423	0.343	0.143	0.013	0.018	0.007	0.002	0.000	0.000	0.000	0.021
-29.855	17.789	JAK2_Elec	12.0	0.476	0.381	0.080	0.012	0.034	0.060	0.015	0.000	0.001	0.000	0.011
-30.359	17.742	Jakkalsfontein	19.1	0.125	0.000	0.392	0.450	0.027	0.010	0.000	0.000	0.000	0.000	0.009
-29.600	18.217	KAIP	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.036	18.276	KAM1_Well	8.2	0.769	0.526	0.175	0.188	0.045	0.000	0.000	0.000	0.004	0.157	0.000
-30.038	18.274	KAM2_windpump	26.4	0.224	0.156	0.120	0.015	0.600	0.000	0.000	0.003	0.004	0.001	0.000
ND	ND	Kamas(fontein)	17.0	0.100	ND	ND	ND	0.090	ND	ND	ND	ND	ND	ND
ND	ND	Kamas(windpomp)	24.3	1.800	ND	ND	ND	0.210	ND	ND	ND	ND	ND	ND
-30.036	18.277	Kamassies	ND	0.341	0.000	0.119	0.060	0.011	0.000	0.000	0.019	0.000	0.049	ND
-30.038	18.274	Kamassies	ND	0.276	0.000	0.183	0.035	0.107	0.016	0.000	0.016	0.000	0.000	ND
-30.024	18.356	Kamassies	ND	0.607	0.000	0.315	0.080	0.000	0.021	0.000	0.009	0.000	0.000	ND
-30.022	18.356	Kamassies	ND	0.530	0.000	0.274	0.050	0.000	0.000	0.000	0.291	0.000	0.000	ND
-30.053	18.202	Kamassies	ND	0.319	0.000	0.244	0.015	0.020	0.000	0.000	0.208	0.000	0.000	ND
-30.017	18.363	Kamassies	ND	0.522	0.080	0.341	0.100	0.065	0.003	0.000	0.003	0.000	0.219	ND
-30.053	18.206	Kamassies	ND	0.767	0.012	0.477	0.032	0.000	0.000	0.000	0.000	0.000	0.092	ND
-30.041	18.274	Kamassies	ND	0.104	0.000	0.176	0.024	0.000	0.059	0.000	0.009	0.000	0.108	ND
ND	ND	Kameelboom(windpomp)	18.9	1.900	ND	ND	ND	0.870	ND	ND	ND	ND	ND	ND
-30.468	17.704	Kameelboom_No1	13.2	1.683	0.787	2.197	0.024	0.023	0.000	0.000	0.000	0.000	0.009	0.009
-30.067	17.757	KANARIESFONTEIN	22.1	0.065	0.000	0.011	0.009	0.060	0.064	0.000	0.000	0.030	0.137	0.017
-30.045	17.758	KANARIESFONTEIN	19.9	1.272	0.782	0.557	0.037	0.109	0.071	0.000	0.000	0.030	0.038	0.024
ND	ND	Karkuip(kraan)	16.9	1.400	ND	ND	ND	0.070	ND	ND	ND	ND	ND	ND
-30.064	18.014	KEER1_dam	16.0	1.390	0.748	0.110	0.025	0.214	0.009	0.000	0.009	0.014	0.000	0.002
-30.459	17.844	Kersboshoek	12.0	2.273	0.938	1.148	0.042	0.000	0.306	0.000	0.000	0.000	0.000	0.000
-30.006	17.672	KEURBOS	26.2	2.891	1.418	2.281	0.085	0.055	0.357	0.000	0.000	0.028	0.058	0.026
-30.040	17.734	KEURBOS	19.4	2.116	1.222	0.940	0.050	0.724	0.064	0.000	0.000	0.025	0.057	0.009
-29.804	17.507	KG93/106	8.7	0.207	0.073	0.156	0.061	0.028	0.017	0.025	0.000	0.000	0.000	0.020
-29.790	17.502	KG93/107	11.2	0.333	0.147	0.332	0.032	0.047	0.008	0.010	0.000	0.003	0.000	0.039
-29.786	17.505	KG93/110_BuffelsR	12.3	0.306	0.132	0.376	0.066	0.010	0.217	0.199	0.000	0.006	0.000	0.022
-29.739	17.636	KG93/118_BuffelsR	9.6	0.450	0.303	0.207	0.078	0.022	0.049	0.017	0.000	0.004	0.020	0.001
ND	ND	Kheis put	17.3	0.500	ND	ND	ND	0.350	ND	ND	ND	ND	ND	ND
-29.990	17.960	Kleinfontein	24.5	0.436	0.225	0.000	0.020	0.015	0.007	0.000	0.001	0.005	0.078	0.012
-29.970	17.970	Kleinfontein	14.8	1.170	0.736	0.512	0.021	0.293	0.081	0.229	0.000	0.015	0.000	0.006
-29.990	17.960	Kleinfontein	35.2	2.267	1.144	0.816	0.111	0.827	0.058	0.000	0.002	0.031	0.086	0.000
-29.844	17.770	KLI1	13.5	0.195	0.295	0.052	0.003	0.030	0.293	0.003	0.002	0.001	0.000	0.032

Lat	Long	Name	Si	Sr	Al	B	Ba	Zn	Mn	Fe	Ni	Cu	P	Pb
-29.863	17.736	KLI2	12.5	0.560	0.462	0.202	0.036	0.048	0.097	0.005	0.000	0.003	0.000	0.000
-29.863	17.737	KLI3	13.8	0.551	0.405	0.209	0.050	0.033	0.003	0.003	0.005	0.001	0.000	0.009
-30.504	17.839	KLIP1	10.7	4.786	0.825	0.897	0.021	0.016	0.001	0.000	0.008	0.003	0.641	0.001
-29.417	17.774	KLIPDAM	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.617	17.807	KLIPDAM	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.521	17.826	KLIPF_artesian	10.4	6.944	1.013	0.725	0.047	0.007	0.000	0.000	0.004	0.002	0.000	0.003
-30.490	17.870	Klipfontein	0.8	0.108	0.005	0.499	0.002	0.478	0.006	0.000	0.000	0.001	0.000	0.012
-30.490	17.870	Klipfontein	14.7	5.116	0.924	0.819	0.035	0.258	0.037	0.000	0.002	0.106	0.068	0.000
ND	ND	Klipfontein	13.0	4.500	ND	ND	ND	3.800	ND	ND	ND	ND	ND	ND
ND	ND	Klipfontein(boorgat)	12.9	6.400	ND	ND	ND	0.050	ND	ND	ND	ND	ND	ND
-30.421	17.912	KLIPVLEI	10.2	3.464	1.044	0.741	0.149	0.042	0.002	0.000	0.006	0.018	0.005	0.021
-29.450	17.724	KLOOF	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.433	17.901	KOEGAS	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.060	17.910	Komri	19.8	2.659	1.125	0.120	0.157	0.314	0.005	0.000	0.001	0.002	0.070	0.020
-30.074	17.653	KOOFKF	20.4	1.764	0.312	0.277	0.035	0.002	0.010	0.000	0.000	0.001	0.000	0.005
-30.066	17.670	KOOKFONT/BERG	20.1	2.134	0.862	1.470	0.038	4.940	0.008	0.000	0.000	0.004	0.037	0.010
-30.073	17.654	KOOKFONTEIN_fontain	20.6	1.755	0.305	0.275	0.036	0.001	0.022	0.000	0.002	0.005	0.000	0.008
-29.683	17.925	KOPPERBERG	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.667	17.900	KOPPERBERG	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.700	17.905	KOPPERBERG	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.909	17.784	KORINGHUIS	8.0	0.361	0.165	0.148	0.064	###	0.382	0.000	0.020	0.022	0.146	0.038
-29.770	17.860	Krymekaar	18.8	0.206	0.132	0.000	0.066	0.207	0.004	0.000	0.000	0.000	0.070	0.011
-30.272	17.557	KWAGGANO1_dam	23.1	1.201	0.554	1.087	0.031	0.156	1.482	0.000	0.007	0.028	0.003	0.014
-29.533	18.098	KWEEKFONTEIN	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.667	17.927	KWEEKFONTEIN	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.533	18.093	KWEEKFONTEIN	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.517	18.093	KWEEKFONTEIN	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
29.730	17.870	Lammershoek	16.5	0.731	0.382	0.000	0.011	0.302	0.008	0.000	0.000	0.000	0.091	0.019
-29.730	17.870	Lammershoek_Elec	14.1	0.898	0.544	0.000	0.008	0.077	0.119	0.000	0.000	0.000	0.047	0.027
-30.327	18.069	Leliefontein	ND	0.017	0.080	0.019	0.017	0.000	0.001	1.308	0.012	0.000	0.000	ND
-30.336	18.089	Leliefontein	ND	0.046	0.050	0.021	0.015	0.097	0.011	0.033	0.000	0.000	0.000	ND
No_value	No_value	Leliefontein	ND	0.021	0.075	0.011	0.000	0.000	0.012	0.116	0.000	0.005	0.064	ND
-30.340	18.117	Leliefontein	ND	0.118	0.070	0.015	0.080	0.000	0.041	0.120	0.002	0.000	0.134	ND
0.000	0.000	Leliefontein	ND	0.114	0.160	0.037	0.012	ND	0.062	0.000	0.000	0.004	0.000	ND
-30.331	18.089	Leliefontein	ND	0.358	0.000	0.015	0.070	0.064	0.151	0.000	0.007	0.003	0.000	ND
-30.315	18.068	Leliefontein	ND	0.133	0.000	0.027	0.030	0.026	0.114	0.100	0.002	0.006	0.024	ND
-30.342	18.086	Leliefontein	ND	0.067	0.015	0.019	0.005	0.000	0.066	0.000	0.006	0.000	0.530	ND
0.000	0.000	Leliefontein	ND	0.088	0.053	0.097	0.016	ND	0.003	0.003	0.008	0.007	0.044	ND
-30.252	18.058	Leliefontein	ND	0.149	0.000	0.036	0.013	0.056	0.000	0.000	0.000	0.004	0.000	ND
-30.349	18.093	Leliefontein	ND	0.485	0.000	0.014	0.030	0.196	0.023	0.000	0.012	0.000	0.000	ND
-29.740	17.920	LittleCottage	21.0	1.293	0.000	0.066	0.000	0.332	0.004	0.000	0.003	0.000	0.019	0.022
ND	ND	Loerkop(windpomp)	17.3	0.300	ND	ND	ND	0.600	ND	ND	ND	ND	ND	ND
ND	ND	Loerkop2	17.2	1.100	ND	ND	ND	0.270	ND	ND	ND	ND	ND	ND
-29.917	17.744	LUISKRAAL	15.6	0.958	0.673	0.444	0.036	0.822	0.077	0.000	0.000	0.027	0.051	0.019
-29.483	17.723	MARAS	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.448	17.624	Melkbosheuwel	13.8	2.947	1.246	0.641	0.179	0.029	0.109	0.000	0.000	0.000	0.037	0.015
-29.840	17.960	Mesklip	16.3	0.381	0.390	0.000	0.022	0.122	0.005	0.000	0.003	0.001	0.047	0.000
-29.840	17.860	Mesklip	16.2	0.245	0.296	0.000	0.011	0.040	0.143	0.000	0.000	0.000	0.064	0.023
-29.840	17.850	Mesklip	15.8	1.673	1.095	0.007	0.045	2.270	0.726	0.030	0.005	0.002	0.059	0.006
-29.840	17.860	Mesklip	14.8	0.423	0.484	0.000	0.019	0.094	0.004	0.000	0.000	0.000	0.060	0.000
-29.820	17.850	Mesklip	20.7	0.495	0.356	0.039	0.016	0.155	0.002	0.000	0.002	0.000	0.000	0.000
-29.550	19.004	MIDDELPOS	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.879	17.574	MISKRAAL	17.0	1.126	0.633	0.496	0.025	0.572	0.088	0.000	0.000	0.028	0.109	0.021
-29.600	17.804	NABABEEP	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.583	17.784	NABABEEP	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.109	18.015	NAK1_Elec	21.8	0.276	0.172	0.161	0.025	0.334	0.004	0.000	0.000	0.110	0.014	0.000
-29.700	17.671	NARIES	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.053	17.954	NHO1_dam	15.7	0.693	0.411	0.345	0.070	0.385	0.004	0.000	0.000	0.013	0.004	0.000
-29.650	17.588	NIGRAMOEP MINE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.567	17.588	NIGRAMOEP MINE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.225	18.138	NOU1_well	7.7	0.391	0.229	0.077	0.121	0.059	0.148	0.000	0.000	0.003	0.017	0.029
-30.245	18.083	Nourivier	ND	0.061	1.530	0.020	0.075	0.029	0.002	0.770	0.011	0.000	0.086	ND
-30.243	18.143	Nourivier	ND	0.080	0.000	0.045	0.022	0.016	0.010	0.000	0.003	0.000	0.238	ND
-30.193	18.154	Nourivier	ND	0.167	0.000	0.136	0.026	0.002	0.000	0.000	0.000	0.000	0.215	ND
-30.226	18.137	Nourivier	ND	0.352	0.014	0.058	0.150	0.016	0.163	0.000	0.004	0.005	0.253	ND

Lat	Long	Name	Si	Sr	Al	B	Ba	Zn	Mn	Fe	Ni	Cu	P	Pb
-30.222	18.103	Nourivier	ND	0.090	0.000	0.039	0.017	0.089	0.034	0.000	0.009	0.000	0.101	ND
-30.174	18.195	Nourivier	ND	1.235	0.000	0.342	0.100	0.014	3.699	0.000	0.015	0.000	0.000	ND
-30.260	18.203	Nourivier	ND	1.511	0.000	0.298	0.080	0.068	0.132	0.000	0.014	0.006	0.034	ND
-30.198	18.198	Nourivier	ND	0.613	0.000	0.173	0.080	0.000	0.008	0.000	0.034	0.000	0.000	ND
-29.934	18.046	NUW12	12.6	2.838	1.191	0.652	0.013	0.029	0.000	0.000	0.000	0.110	0.000	0.026
-29.965	18.064	NUW2_dam	14.9	1.294	0.737	0.435	0.081	0.311	0.021	0.000	0.000	0.002	0.000	0.017
-29.985	18.052	NUW3_dam	11.7	0.712	0.504	0.251	0.024	0.042	0.001	0.000	0.000	0.007	0.000	0.023
-29.819	17.790	NUWR1	7.8	0.628	0.412	0.102	0.053	0.084	1.661	0.066	0.000	0.007	0.002	0.006
-30.228	18.001	OLIEN_dam	14.7	0.074	0.038	0.000	0.017	0.153	0.008	0.011	0.000	0.003	0.000	0.022
-29.667	17.971	OLYNPUTS	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.483	17.773	O'OKIEP COPPER MINE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.426	17.610	Ou_Plaas_No1	13.4	7.970	1.772	1.542	0.041	0.138	0.292	0.000	0.005	0.000	0.000	0.031
-30.427	17.603	Ou_Plaas_No2	13.8	6.805	1.608	1.620	0.076	0.063	0.000	0.000	0.000	0.000	0.000	0.014
-23.896	17.632	OUBEEB	20.2	0.637	0.385	0.405	0.073	0.807	0.062	0.000	0.000	0.023	0.047	0.027
-29.893	17.633	OUBEEB	19.8	0.655	0.369	0.489	0.078	0.046	0.130	0.000	0.000	0.035	0.306	0.017
-29.840	17.920	OuHoek	14.0	0.808	0.790	0.000	0.033	0.273	0.024	0.000	0.007	0.017	0.000	0.017
-29.840	17.930	OuHoek	14.6	0.197	0.211	0.000	0.005	0.043	0.002	0.000	0.009	0.013	0.059	0.014
-30.190	18.012	OUT1_reservior	10.7	0.036	0.017	0.012	0.000	0.017	0.013	0.004	0.010	0.003	0.019	0.000
-30.186	18.011	OUT2_Fontain	14.2	0.108	0.038	0.000	0.031	0.039	0.002	0.011	0.000	0.003	0.010	0.022
ND	ND	Outiep	13.3	2.000	ND	ND	ND	0.690	ND	ND	ND	ND	ND	ND
-30.345	17.731	Partysvlei	4.0	2.389	1.116	1.482	0.069	1.710	0.125	0.000	0.000	0.000	0.002	0.019
-30.140	18.110	Pedroskloof	22.3	0.886	0.338	0.000	0.117	0.052	0.003	0.000	0.000	0.002	0.043	0.000
-30.140	18.110	Pedroskloof	21.5	0.710	0.390	0.106	0.098	0.057	0.002	0.000	0.007	0.000	0.068	0.018
-30.216	18.017	PEN1_dam	14.3	0.290	0.110	0.017	0.043	0.003	0.000	0.024	0.000	0.006	0.009	0.008
-30.191	18.022	PEN2_reservior	19.4	0.165	0.072	0.000	0.020	1.641	0.024	0.002	0.000	0.003	0.021	0.011
-30.284	18.484	PLAT1_dam	15.4	0.477	0.281	0.530	0.022	0.091	0.031	0.047	0.008	0.001	0.000	0.005
-30.318	18.486	PLAT2_well	4.0	3.545	0.998	1.970	0.101	0.017	0.000	0.002	0.000	0.004	0.015	0.016
-30.321	18.489	PLAT3_reservior	18.7	0.683	0.413	0.330	0.057	0.139	0.000	0.002	0.000	0.003	0.000	0.000
-30.323	18.483	PLAT4_dam	12.6	1.417	0.617	0.915	0.024	0.045	0.000	0.002	0.000	0.004	0.002	0.013
-29.891	18.104	POT1	23.5	3.921	1.452	1.110	0.090	1.135	0.006	0.000	0.004	0.004	0.012	0.008
-30.149	17.850	RACHEL	20.0	0.516	0.335	0.400	0.059	0.016	0.174	0.007	0.000	0.000	0.000	0.033
-30.448	17.652	Radyn	16.6	4.602	1.550	3.454	0.031	0.017	0.000	0.000	0.000	0.000	0.009	0.023
-29.720	17.900	RanchoAmigo	2.3	1.816	0.877	0.156	0.049	0.740	0.231	0.000	0.012	0.019	0.032	0.000
-29.720	17.900	RanchoAmigo	16.5	2.880	1.505	0.123	0.091	2.084	0.739	0.000	0.002	0.000	0.035	0.043
-29.583	18.064	RATELKRAAL	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.567	18.121	RATELKRAAL	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.600	18.156	RATELKRAAL	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.533	18.059	RATELKRAAL	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.533	18.093	RATELKRAAL	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.876	18.189	RIET4_dam	15.4	0.639	0.410	0.491	0.042	0.150	0.000	0.004	0.000	0.002	0.018	0.020
-29.800	18.139	RIETFONTEIN	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.902	18.157	RIETFONTEIN2_BuffelsR	17.6	1.259	0.654	0.568	0.086	0.361	0.002	0.004	0.000	0.000	0.022	0.006
-29.925	18.150	RIETFONTEIN3	16.4	2.201	0.927	0.437	0.097	0.068	0.000	0.004	0.000	0.009	0.005	0.008
-30.010	17.806	RIETMOND	12.8	1.514	0.970	0.399	0.086	0.066	0.841	0.000	0.007	0.027	0.051	0.022
ND	ND	Riviergat (Karkams)	12.0	3.600	ND	ND	ND	0.180	ND	ND	ND	ND	ND	ND
-29.820	17.950	Rockoptel	12.6	0.568	0.407	0.017	0.010	0.138	0.001	0.000	0.000	0.000	0.023	0.000
0.000	0.000	ROODEPOORT/37227_dam	12.2	1.107	0.686	0.260	0.018	1.094	0.121	0.003	0.000	0.000	0.000	0.000
-30.070	18.270	ROOI1_Well	10.7	0.432	0.287	0.156	0.072	0.009	0.000	0.004	0.000	0.000	0.124	0.009
-30.348	17.614	Rooiberg	16.9	1.132	0.602	1.618	0.020	0.036	0.181	0.000	0.000	0.000	0.000	0.012
-30.093	18.194	Rooifontein	ND	0.135	0.000	0.058	0.012	0.357	0.021	0.000	0.009	0.000	0.232	ND
-30.066	18.269	Rooifontein	ND	0.318	0.000	0.112	0.040	0.019	0.020	0.000	0.020	0.003	0.010	ND
-30.080	18.236	Rooifontein	ND	0.356	0.000	0.525	0.032	0.051	0.013	0.000	0.008	0.009	0.000	ND
-30.154	18.241	Rooifontein	ND	0.495	0.000	0.331	0.043	0.034	0.368	0.000	0.000	0.000	0.099	ND
-30.141	18.234	Rooifontein	ND	0.861	0.000	0.371	0.060	0.071	0.039	0.000	0.014	0.004	0.033	ND
-30.104	18.236	Rooifontein	ND	0.261	0.000	0.186	0.050	0.055	0.220	0.000	0.024	0.000	0.000	ND
-30.076	18.267	Rooifontein	ND	1.149	0.000	0.586	0.080	0.018	0.544	0.000	0.002	0.000	0.022	ND
-29.450	17.754	ROOIWATER	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.030	17.890	Rotnoskop	14.5	2.003	1.001	0.248	0.043	0.035	0.014	0.000	0.003	0.000	0.123	0.042
-29.333	17.919	SABIES	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.818	17.617	SANAGAS	6.3	0.672	0.291	0.192	0.038	0.050	0.171	0.000	0.000	0.024	0.032	0.032
-29.836	17.613	SANAGAS	9.7	0.410	0.144	0.233	0.059	0.132	0.063	0.000	0.000	0.022	0.052	0.041
-29.854	17.623	SANAGAS	13.3	1.147	0.928	0.546	0.056	0.028	0.090	0.000	0.000	0.027	0.027	0.040
-30.225	18.110	SANDFONTEIN_monopump	11.7	0.114	0.160	0.037	0.012	0.172	0.062	0.000	0.000	0.004	0.000	0.009

Lat	Long	Name	Si	Sr	Al	B	Ba	Zn	Mn	Fe	Ni	Cu	P	Pb
-30.502	17.071	Sandhoek	15.2	0.900	0.596	0.403	0.073	0.104	1.080	0.000	0.000	0.000	0.000	0.011
ND	ND	Sandkop(fontein)	14.2	2.300	ND	ND	ND	0.060	ND	ND	ND	ND	ND	ND
-29.903	17.783	SANDKRAAL	15.9	0.537	0.318	0.179	0.045	0.088	0.061	0.000	0.000	0.022	0.044	0.035
-29.717	18.053	SILVERFONTEIN	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.567	17.583	SILWERFONTEIN	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.681	17.626	SKA1_Artesian	15.7	2.522	0.884	0.310	0.079	0.055	0.570	0.000	0.000	0.001	0.000	0.010
-29.677	17.602	SKA2_Well	9.1	8.377	1.934	1.295	0.120	0.019	0.007	0.000	0.002	0.009	0.000	0.000
-30.176	17.795	SKILPAD_fontain	1.4	0.163	0.070	0.076	0.015	0.013	0.004	0.010	0.000	0.004	0.000	0.005
ND	ND	Skuinskraal(windpomp)	23.8	1.600	ND	ND	ND	1.690	ND	ND	ND	ND	ND	ND
-30.118	17.600	SOEBATSF_Fontain	17.7	6.339	1.170	0.637	0.067	0.001	0.060	0.000	0.011	0.007	0.003	0.005
-30.123	17.600	SOEBATSF	11.4	2.772	0.768	1.259	0.041	0.000	0.059	0.000	0.018	0.001	0.004	0.003
-30.218	17.564	SOUBATTERSFONTEIN_dam	11.4	2.208	0.789	2.073	0.025	0.038	0.192	0.000	0.000	0.005	0.000	0.004
-29.852	17.719	SOUTKLOOF1	9.4	0.353	0.411	0.189	0.017	0.252	0.213	0.004	0.000	0.003	0.007	0.018
ND	ND	Speelmanshoek(gat)	15.3	1.000	ND	ND	ND	0.250	ND	ND	ND	ND	ND	ND
ND	ND	Speelmanshoek(windpomp)	7.6	0.600	ND	ND	ND	0.650	ND	ND	ND	ND	ND	ND
-29.517	18.089	SPEKTAKEL MINE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.350	17.771	Spoegrivier_LF90/20B	16.1	0.920	0.651	0.446	0.069	0.294	0.000	0.000	0.000	0.000	0.000	0.003
-30.344	17.767	Spoegrivier_put	10.1	1.621	0.902	0.414	0.099	0.004	1.240	0.000	0.000	0.000	0.000	0.022
-29.717	17.921	SPRINGBOK	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.700	17.888	SPRINGBOK	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.683	17.901	SPRINGBOK CARAVAN PARK	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.700	17.888	SPRINGBOK GHOLF COURSE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	Suidgat Karkams	11.4	1.000	ND	ND	ND	0.160	ND	ND	ND	ND	ND	ND
-29.433	17.956	SWARTPUTS	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.024	17.984	THD1_Elec	14.4	0.361	0.306	0.149	0.029	1.033	0.082	0.000	0.000	0.021	0.000	0.000
-29.700	17.670	TWEEDAM	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-29.947	18.264	TWEEFONTEIN1	14.3	0.329	0.256	0.208	0.051	0.190	0.005	0.000	0.013	0.012	0.018	0.000
-30.336	18.003	TWEERIVIER1_dam	11.5	0.953	0.499	0.195	0.061	0.037	0.068	0.000	0.000	0.002	0.003	0.018
-30.314	18.000	TWEERIVIER2_dam	10.2	1.712	0.702	0.113	0.039	0.464	0.275	0.000	0.000	0.001	0.000	0.037
-30.323	18.014	TWEERIVIER3_Elec	12.5	0.754	0.355	0.115	0.063	0.241	0.302	0.000	0.001	0.002	0.000	0.008
-30.336	18.023	TWEERIVIER4_Elec	13.0	0.872	0.458	0.120	0.049	0.062	0.220	0.000	0.004	0.005	0.000	0.001
-30.336	18.022	TWEERIVIER5_Elec	10.7	0.974	0.521	0.156	0.057	1.676	0.465	0.016	0.002	0.006	0.013	0.000
-29.250	18.063	VAALDAM	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
-30.446	17.801	Vaaldraai	12.7	1.368	0.495	0.582	0.036	0.003	0.049	0.000	0.000	0.000	0.000	0.012
-30.389	17.664	Vaalfontein	13.6	1.820	0.827	1.777	0.017	0.009	0.011	0.000	0.000	0.000	0.000	0.020
-30.418	17.568	Varkwater	12.8	8.361	2.960	11.484	0.056	0.000	0.062	0.000	0.000	0.000	0.000	0.006
-29.909	18.076	VELS1	16.2	0.128	0.097	0.098	0.031	0.037	0.001	0.000	0.000	0.003	0.104	0.000
-30.307	17.722	Vleie_Naries	28.4	0.158	0.000	0.296	0.013	0.562	0.006	0.000	0.000	0.000	0.012	0.017
-30.261	17.614	Vlietjies	11.6	1.159	0.649	1.062	0.007	0.038	0.014	0.000	0.000	0.000	0.000	0.000
-30.402	17.646	Vlugfontein	20.2	3.210	0.924	0.829	0.032	0.008	0.083	0.000	0.000	0.000	0.016	0.014
-29.760	17.890	Voelklip	15.3	0.836	0.292	0.000	0.071	0.185	0.003	0.000	0.012	0.001	0.053	0.027
-29.750	17.870	Voelklip	10.1	0.851	0.529	0.000	0.010	0.952	0.241	0.000	0.000	0.001	0.068	0.001
-29.750	17.870	Voelklip	10.1	1.097	0.661	0.000	0.014	0.525	0.043	0.000	0.011	0.006	0.058	0.012
ND	ND	Vonkelfontein(windpomp)	13.9	2.200	ND	ND	ND	0.230	ND	ND	ND	ND	ND	ND
-30.338	17.939	VYEMOND/G37152_Elec	11.8	0.205	0.127	0.107	0.018	0.540	0.139	0.000	0.105	0.004	0.008	0.000
-30.337	17.940	VYEMOND/G37153	11.1	0.273	0.238	0.053	0.021	0.036	0.001	0.000	0.013	0.005	0.010	0.000
-30.183	17.938	W/HOEK_well	8.9	0.111	0.055	0.065	0.033	0.055	0.038	0.034	0.000	0.004	0.040	0.000
-30.384	17.510	Wallekraal_No1	7.6	8.383	2.197	1.950	0.040	2.416	0.366	0.000	0.000	0.000	0.000	0.002
-30.396	17.520	Wallekraal_No2	9.2	8.369	1.993	0.976	0.169	0.028	0.127	0.000	0.000	0.000	0.017	0.012
-30.397	17.528	Wallekraal_No3_font	6.3	6.848	1.859	1.051	0.123	0.000	0.000	0.000	0.002	0.000	0.012	0.010
-29.924	17.644	Wildeperdehoek_Pass	11.9	0.946	0.648	0.550	0.047	0.291	0.200	0.000	0.008	0.025	0.062	0.027
-30.407	18.051	Wilgerhoutsrivier	19.0	0.200	0.000	0.019	0.111	0.224	0.000	0.008	0.000	0.000	0.000	0.023
-30.403	18.061	Wilgerhoutsrivier_font	3.5	0.070	0.032	0.024	0.168	0.032	0.000	0.000	0.000	0.000	0.000	0.006
-30.377	17.688	Windheuwel	19.8	2.870	1.133	2.138	0.121	0.089	0.079	0.000	0.000	0.000	0.027	0.035
-29.921	17.757	WITDAM	24.8	0.403	0.111	0.214	0.033	0.100	0.098	0.000	0.000	0.029	0.041	0.062
-29.500	18.026	WITKOPPIES	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
0.000	0.000	YBE1_dam	9.3	1.094	0.579	0.770	0.035	0.043	0.000	0.002	0.007	0.002	0.000	0.043
-29.990	17.990	Ybeep	13.1	3.197	0.934	0.298	0.068	0.145	0.060	0.000	0.000	0.001	0.099	0.035
-29.958	18.013	YBEII_windpump	9.1	1.001	0.613	0.686	0.030	0.346	0.009	0.002	0.000	0.002	0.000	0.021

A4: Groundwater isotope data

Lat	Long	Site	$\delta^{18}O$ (‰)	δD (‰)	Catchment
-30.1769	18.1853	91LF88_well	-3.3900	-16.0000	F30
-30.2400	18.0311	AGTER1_well	-4.7400	-21.0000	F30
-30.2350	18.0383	AGTER2_dam	-4.0300	-19.0000	F30
-30.2436	18.0547	AGTER3_windmill	-4.9200	-24.0000	F30
-30.3539	17.6869	Aigab	-0.2400	-4.0000	F40
-30.0411	17.9853	ANE1_dam	-3.6300	-18.0000	F30
-30.1258	18.0169	ANE2_dam	-4.0400	-18.0000	F30
-29.9994	17.7778	ARREGAS	-3.5300	-17.4000	F30
-30.2419	18.0611	BAK1_well	-3.7400	-19.0000	F30
-30.3836	17.8364	Bethel	-2.9900	-14.6000	F40
-30.0133	17.8225	BLOUSYFER	0.1900	-1.4000	F30
-30.1906	18.1542	BOB1_well	-1.1500	-7.0000	F30
-29.7928	17.5633	BOKKRAAL	-3.2700	-15.6000	F30
-30.2089	17.7056	BOKSKRAAL_windmill	-3.5800	-19.0000	F30
-29.8664	17.5917	BOSLUISKRAAL	-2.5900	-14.7000	F30
-29.8900	17.5944	BRAKPITS	-2.2800	-11.0000	F30
-30.2458	17.7103	Brakputs_No1	-3.2800	-15.4000	F40
-30.2483	17.7103	Brakputs_No2	-2.9400	-11.6000	F40
-30.0014	17.6908	BRANDBERG	-3.6500	-17.4000	F30
-29.9325	17.7050	BUFFELSRIVER_WILDEPERDEPAS	-3.8700	-16.5000	F30
-29.7364	17.6372	BUFS1_Well	-4.0200	-19.0000	F30
-29.7703	17.6597	BUFS3_Well	-4.7600	-28.0000	F30
-29.7719	17.6600	BUFS5_well	-3.3500	-19.0000	F30
-30.3400	17.5106	BYENESKRANS_reservior	-2.3500	-15.0000	F40
-30.1811	18.2728	COU1_windmill	-3.3700	-22.0000	F30
-30.1822	18.2742	COU2_fontain	15.8100	51.0000	F30
-30.1261	18.2567	COU3_windmill	-4.9700	-31.0000	F30
-29.8283	18.3319	DAP1_dam	-4.3800	-29.0000	F30
-29.8272	18.3261	DAP2_dam	-4.2900	-29.0000	F30
-30.3225	18.3900	DE_RIET_dam	-4.5800	-27.0000	F30
-29.9592	17.9750	DED1_Well	-3.9700	-18.0000	F30
-29.9128	17.9672	DRO1_windmill	-4.9500	-26.0000	F30
-30.3742	17.7172	Duikerkop_font	-1.4800	-5.8000	F40
-30.3928	18.0967	EZEL1_windmill	-5.2500	-23.0000	F30
-29.8111	17.5011	F1_Fontain	-4.1300	-17.0000	F30
-29.7808	17.5033	F2_Fontain	-3.7900	-17.0000	F30
-30.0794	18.0103	FIL1_Elec_pump	-4.7700	-20.0000	F30
-29.9158	18.4214	GAM1_dam	-4.7700	-28.0000	F30
-30.2378	17.7586	GBERG_windmill	-2.5100	-12.0000	F30
-30.2336	17.6917	Grootberg_No1	-2.2800	-12.0000	F40
-30.2736	17.7117	Grootberg_No2	-3.4000	-14.5000	F40
-30.1506	17.8867	HAAS1_windmill	-4.3800	-20.0000	F30
-30.1389	17.8714	HAAS2_windmill	-3.8200	-19.0000	F30
-30.3233	17.6183	Horees_No1	-3.0600	-14.2000	F40
-30.3217	17.6206	Horees_No2	-1.0300	-6.6000	F40
-30.3072	17.6350	Horeesfont	-3.2000	-14.2000	F40
-29.9694	18.1683	HYT1_dam	-2.1200	-20.0000	F30
-29.8544	17.7892	JAK1_windmill	-3.8400	-17.0000	F30
-29.8547	17.7892	JAK2_Elec_pump	-4.1800	-20.0000	F30
-30.3586	17.7419	Jakkalsfontein	-3.2400	-13.5000	F40
-30.0358	18.2764	KAM1_Well	-2.8900	-17.0000	F30
-30.0375	18.2742	KAM2_windpump	-5.1500	-29.0000	F30
-30.0378	18.2744	Kamassies	-1.0300	-7.0000	F30

Lat	Long	Site	$\delta^{18}O$ (‰)	δD (‰)	Catchment
-30.0358	18.2767	Kamassies	-2.3800	-12.0000	F30
-30.0172	18.3628	Kamassies	-2.2400	-22.0000	F30
-30.0528	18.2058	Kamassies	-3.6000	-25.0000	F30
-30.0528	18.2019	Kamassies	-3.9000	-26.0000	F30
-30.0236	18.3556	Kamassies	-2.7900	-29.0000	F30
-30.0406	18.2744	Kamassies	-5.1200	-35.0000	F30
-30.0222	18.3561	Kamassies	-5.3000	-39.0000	F30
-30.4675	17.7044	Kameelboom_No1	-2.9700	-14.1000	F40
-30.0667	17.7569	KANARIESFONTEIN	-3.7000	-12.4000	F30
-30.0450	17.7583	KANARIESFONTEIN	-3.7400	-17.4000	F30
-30.0642	18.0136	KEER1_dam	-1.9400	-13.0000	F30
-30.4592	17.8439	Kersboshoek	-3.2600	-15.1000	F40
-30.0397	17.7342	KEURBOS	-2.0400	-7.5000	F30
-30.0056	17.6719	KEURBOS	-2.8700	-15.1000	F30
-29.8039	17.5067	KG93/106_windmill	-3.9600	-17.0000	F30
-29.7903	17.5022	KG93/107_windmill	-3.4200	-16.0000	F30
-29.7858	17.5053	KG93/110_BuffelsR_windmill	-3.6000	-17.0000	F30
-29.7386	17.6364	KG93/118_BuffelsR_dieselpump	-4.0000	-17.0000	F30
-29.8436	17.7703	KLI1_windmill	-4.7600	-21.0000	F30
-29.8633	17.7358	KLI2_windmill	-3.9800	-18.0000	F30
-29.8628	17.7367	KLI3_windmill	-2.9900	-15.0000	F30
-30.5044	17.8394	KLIP1_windmill	-3.3700	-17.0000	F40
-30.5214	17.8261	KLIPF_artesian	-3.7000	-21.0000	F40
-30.4214	17.9122	KLIPVLEI_windmill	-2.2923	-22.0000	F30
-30.0739	17.6531	KOOFKF_windmill	-4.2900	-20.0000	F40
-30.0664	17.6700	KOOKFONT/BERG_Windmill	-2.9900	-16.0000	F40
-30.0728	17.6539	KOOKFONTEIN_fontain	-4.3400	-20.0000	F40
-29.9086	17.7844	KORINGHUIS	-3.9400	-20.3000	F30
-30.2722	17.5572	KWAGGANO1_dam	-2.5800	-14.0000	F40
-30.3272	18.0686	Leliefontein	-4.7200	-21.0000	F30
-30.3150	18.0675	Leliefontein	-4.3800	-23.0000	F30
0.0000	0.0000	Leliefontein	-5.0300	-26.0000	F30
-30.2517	18.0578	Leliefontein	-4.9600	-27.0000	F30
-30.3306	18.0892	Leliefontein	-4.9200	-28.0000	F30
-30.3403	18.1172	Leliefontein	-4.9200	-29.0000	F30
-30.3489	18.0925	Leliefontein	-5.1200	-29.0000	F30
-30.3361	18.0894	Leliefontein	-5.2200	-30.0000	F30
		Leliefontein	-5.1700	-31.0000	F30
-30.3422	18.0861	Leliefontein	-5.0400	-31.0000	F30
-29.9172	17.7442	LUISKRAAL	-3.5800	-16.9000	F30
-30.4475	17.6239	Melkbosheuwel	-3.1700	-13.5000	F40
-30.1094	18.0150	NAK1_Elec_pump	-2.9700	-16.0000	F30
-30.0525	17.9544	NHO1_dam	-2.7700	-19.0000	F30
-30.2253	18.1381	NOU1_well	-1.4500	-8.0000	F30
-30.1928	18.1542	Nourivier	-1.3900	-7.0000	F30
-30.1981	18.1981	Nourivier	-1.5400	-12.0000	F30
-30.2264	18.1369	Nourivier	-2.0500	-13.0000	F30
-30.2431	18.1425	Nourivier	-2.5800	-16.0000	F30
-30.2600	18.2028	Nourivier	-4.1400	-24.0000	F30
-30.2219	18.1025	Nourivier	-4.4900	-26.0000	F30
-30.2453	18.0828	Nourivier	-4.9500	-26.0000	F30
-30.1739	18.1947	Nourivier	-4.4100	-29.0000	F30

Lat	Long	Site	$\delta^{18}O$ (‰)	δD (‰)	Catchment
-29.9344	18.0458	NUW12_windmill	-1.3700	-11.0000	F30
-29.9650	18.0639	NUW2_dam	-3.5200	-20.0000	F30
-29.9853	18.0519	NUW3_dam	-4.1300	-23.0000	F30
-29.8189	17.7900	NUWR1_windmill	-3.0600	-12.0000	F30
-30.2281	18.0006	OLIEN_dam	-5.0300	-22.0000	F30
-30.4261	17.6100	Ou_Plaas_No1	-3.1500	-15.1000	F40
-30.4269	17.6033	Ou_Plaas_No2	-2.3400	-10.6000	F40
-23.8958	17.6317	OUBEEB	-3.7900	-18.5000	F30
-29.8928	17.6328	OUBEEB	-3.5100	-18.6000	F30
-30.1903	18.0119	OUT1_reservior	-4.8300	-20.0000	F30
-30.1864	18.0106	OUT2_Fontain	-5.0200	-22.0000	F30
-30.3450	17.7306	Partysvlei	-2.9300	-13.0000	F40
-30.1908	18.0219	PEN2_reservior	-4.7000	-21.0000	F30
-30.2839	18.4839	PLAT1_dam	-5.2648	-31.0000	F30
-30.3208	18.4894	PLAT3_reservior	-5.1600	-30.0000	F30
-30.3231	18.4828	PLAT4_dam	-3.5200	-22.0000	F30
-29.8911	18.1044	POT1_windmill	-4.3200	-27.0000	F30
-30.1489	17.8500	RACHEL_windmill	-2.7800	-16.0000	F30
-30.4483	17.6522	Radyn	-2.0000	-11.0000	F40
-29.8758	18.1886	RIET4_dam	-5.2200	-34.0000	F30
-29.9019	18.1567	RIETFONTEIN2_BuffelsR_windmill	-5.0200	-30.0000	F30
-29.9250	18.1503	RIETFONTEIN3_windmill	-4.3200	-24.0000	F30
-30.0097	17.8058	RIETMOND	-3.6100	-18.7000	F30
0.0000	0.0000	ROODEPOORT/37227_dam	-5.4000	-29.0000	F30
-30.0700	18.2700	ROOI1_Well	-2.5200	-15.0000	F30
-30.3478	17.6142	Rooiberg	-3.4400	-15.9000	F40
-30.1039	18.2364	Rooifontein	-12.0000	-25.0000	F30
-30.1406	18.2339	Rooifontein	-4.1600	-27.0000	F30
-30.0931	18.1936	Rooifontein	-3.8400	-29.0000	F30
-30.1536	18.2408	Rooifontein	-4.1500	-30.0000	F30
-30.0664	18.2694	Rooifontein	-4.8300	-31.0000	F30
-30.0797	18.2364	Rooifontein	-4.6200	-32.0000	F30
-30.0764	18.2667	Rooifontein	-4.7800	-35.0000	F30
-29.8364	17.6128	SANAGAS	-3.7400	-16.4000	F30
-29.8175	17.6172	SANAGAS	-3.5400	-17.0000	F30
-30.2253	18.1097	SANDFONTEIN_monopump	-5.0300	-26.0000	F30
-30.5017	17.0711	Sandhoek	-4.1500	-20.1000	F40
-29.9028	17.7825	SANDKRAAL	-3.8100	-18.2000	F30
-29.6811	17.6264	SKA1_Artesian	-3.4700	-14.0000	F30
-29.6767	17.6022	SKA2_Well	-1.9300	-10.0000	F30
-30.1761	17.7953	SKILPAD_fontain	0.8800	0.2000	F30
-30.1181	17.5997	SOEBATSF_Fontain	-3.8300	-19.0000	F40
-30.1233	17.5997	SOEBATSF_windmill	-2.7000	-15.0000	F40
-30.2183	17.5644	SOUBATTERSFONTEIN_dam	-3.1300	-14.0000	F40
-29.8517	17.7189	SOUTKLOOF1_windmill	-2.8100	-12.0000	F30
-30.3500	17.7708	Spoegrivier_LF90/20B	-3.5000	-16.0000	F40
-30.3439	17.7667	Spoegrivier_put	-3.1800	-13.0000	F40
-30.0236	17.9839	THD1_Elec_pump	-3.7300	-18.0000	F30
-29.9467	18.2642	TWEEFONTEIN1_windmill	-6.7300	-42.0000	F30
-30.3364	18.0028	TWEERIVIER1_dam	-4.1400	-28.0000	F50
-30.3144	18.0000	TWEERIVIER2_dam	-4.3400	-30.0000	F50
-30.3231	18.0139	TWEERIVIER3_Elec_pump	-4.6700	-31.0000	F50

Lat	Long	Site	$\delta^{18}O$ (‰)	δD (‰)	Catchment
-30.3361	18.0233	TWEERIVIER4_Elec_pump	-4.9400	-30.0000	F50
-30.3361	18.0219	TWEERIVIER5_Elec_pump	-3.9600	-27.0000	F50
-30.4461	17.8014	Vaaldraai	-3.9700	-19.2000	F40
-30.3894	17.6644	Vaalfontein	-2.2100	-11.0000	F40
-29.9086	18.0761	VELS1_windmill	-4.2700	-21.0000	F30
-30.3069	17.7222	Vleie_Naries	-3.5700	-12.2000	F40
-30.2614	17.6139	Vlietjies	-2.6700	-13.0000	F40
-30.4019	17.6456	Vlugfontein	-3.5000	-17.0000	F40
-30.3375	17.9386	VYEMOND/G37152_Elec_pump	-4.5800	-23.0000	F50
-30.3369	17.9400	VYEMOND/G37153_windmill	-4.3800	-20.0000	F50
-30.1833	17.9383	W/HOEK_well	-2.7100	-12.0000	F30
-30.3839	17.5103	Wallekraal_No1	-2.5600	-11.0000	F40
-30.3958	17.5203	Wallekraal_No2	-2.6200	-11.3000	F40
-30.3967	17.5275	Wallekraal_No3_font	-0.8000	-3.6000	F40
-29.9244	17.6444	Wildeperdehoek_Pass	-3.7600	-14.2000	F30
-30.4069	18.0506	Wilgerhoutsrivier	-3.6800	-17.0000	F40
-30.4031	18.0606	Wilgerhoutsrivier_font	-0.4400	-3.3000	F40
-30.3772	17.6883	Windheuwel	-2.0100	-11.6000	F40
-29.9206	17.7572	WITDAM	-4.1300	-18.8000	F30
0.0000	0.0000	YBE1_dam	-1.5400	-13.0000	F30
-29.9583	18.0133	YBEII_windpump	-4.4000	-26.0000	F30

A5: Borehole monitoring data

Rain (mm); Abstraction (Q) (m^3); Water level (WL) (mbgl)

Buffels River

		216		217		218		
Month	Rain	Q	WL	Q	WL	Q	WL	Total Q
1	0	2729	-4.28	216	-4.00	50	-7.96	2995
2	0	2180	-4.38	504	-4.90	196	-7.25	2880
3	0	1820	-4.00	0	-3.70	136	-7.00	1956
4	0	1968	-4.00	0	-3.80	170	-7.00	2138
5	79	1568	-4.00	0	-3.60	144	-7.07	1712
6	16	1207	-4.00	0	-3.55	171	-7.00	1378
7	13	1174	-4.00	0	-3.55	167	-7.10	1341
8	30	1534	-4.00	0	-3.70	190	-7.01	1724
9	34	1739	-4.45	0	-3.70	243	-7.20	1982
10	42	1686	-4.00	0	-3.60	154	-7.25	1840
11	9	1984	-4.00	0	-3.56	317	-7.00	2301
12	8	2050	-6.50	0	-3.50	322	-7.10	2372
13	0	2002	-6.65	0	-3.83	380	-7.13	2382
14	11	1862	-6.90	0	-3.85	255	-7.12	2117
15	3	1145	-5.38	0	-3.77	255	-7.20	1400
16	0	1171	-3.10	0	-3.70	205	-7.39	1376
17	13	1118	-6.23	0	-3.70	272	-7.34	1390
18	21	281	-4.29	0	-3.75	230	-7.27	511
19	64	0	-3.42	0	-3.30	98	-6.90	98
20	63	0	-3.68	0	-3.45	133	-6.87	133
21	53	0	-1.00	0	-1.20	193	-1.77	193
22	14	0	-1.02	0	-1.10	179	-2.04	179
23	25	0		0		167	-2.18	167
24	21	0	-2.23	0	-2.16	283	-2.10	283
25	0	0	-1.27	0		263	-2.22	263
26	0	0	-2.17	0	-2.38	402	-2.24	402
27	21	0	-2.50	0	-2.55	224	-2.44	224
28	17	0	-2.73	0	-2.81	174	-2.51	174
29	74	0	-1.97	0	-1.57	203	-2.34	203
30	80	0		0		200		200
31	20	0		0		0		0
32	17	0		0		85	-1.60	85
33	0	0		0		530	-1.66	530
34	1	0		0		2,004	-1.79	2004
35	31	0		0		2,270	-1.89	2270
36	2	0		0		1,327	-1.97	1327
37	5	0		0		3,179	-2.25	3179
38	0	0		0		2,117	-2.30	2116.8
39	0	0		0		1,562	-2.42	1562.4
40	1	0		0		1,512	-2.89	1512
41	50	0		0		1,300	-3.39	1300
42	0	0		0		1,192	-3.40	1192
43	3	0		0		1,156	-2.70	1156
44	0	0		0		1,697	-3.11	1697
45	0	0		0		2,630	-3.46	2630
46	0	0		0		2,533	-3.47	2533
47	8	0		0		2,367	-3.44	2367
48	4	0		0		3,057	-3.63	3057
49	0	0		0		3,024	-3.65	3024
50	2	0		0		3,199	-3.80	3199
51	0	0		0		2,725	-3.37	2725
52	2	0		0		2,531	-3.89	2531
53	0	0		0		2,161	-3.94	2161
54	20	0		0		1,540	-3.98	1540
55	8	0		0		1,228	-4.10	1228
56	4	0		0		2,048	-4.60	2048
57	44	0		0		2,093	-4.80	2093
58	5	0		0		2,356	-4.64	2356
59	1	0		0		4,225	-3.77	4225
60	1	0		0		4,073	-3.73	4073

Bulletrap

			n104		oh		g38416		sk16		sk93/107	sk93/108	
Mont	**Rain**	**Q**	**WL**	**Q**	**WL**	**Q**	**WL**	**Q**	**WL**	**Q**	**WL**	**Q**	**WL**
1	0		-8.70	435	-		-	153	-				
2	0		-8.55	291	-		-		-				
3	0		-8.70	575	-		-	240	-				
4	0		-8.80	780	-		-	361	-				
5	42		-7.20	436	-		-	219	-				
6	14		-8.00	347	-		-	158	-9.80				
7	15		-8.00	663	-		-	240	-				
8	43		-8.00	561	-		-	151	-				
9	24		-8.00	797	-		-	209	-				
10	18		-7.60	581	-		-	146	-				
11	19		-8.80	748	-		-	218	-				
12	8		-8.60	1,184	-		-	412	-				
13	0		-8.80	576	-		-	198	-				
14	10		-9.00	884	-		-	304	-				
15	2		-	619	-		-	310	-				
16	0		-	423	-		-	168	-				
17	0		-	610	-		-	231	-				
18	16		-	507	-		-	192	-				
19	60		-	500	-		-	166	-6.10				
20	29		-7.50	500	-		-	194	-4.10				
21	96		-5.17	500	-		-9.02	126	-2.38				
22	15		-5.30	500	-		-9.60	321	-7.90				
23	28		-5.52	600	-		-8.10	330	-3.55				
24	8		-2.80	600	-		-	557	-				
25	0		-6.30	600	-		-6.70	318	-7.30				
26	0		-6.30	839	-		-8.80	410	-				
27	34		-6.00	608	-		-9.00	304	-				
28	20		-	533	-		-9.80	261	-				
29	40		-5.70	539	-		-7.90	298	-				
30	75		-4.90	415	-		-7.50	262	-3.70				
31	1		-1.72	391	-		-6.00	314	-4.50				
32	18		-2.80	792	-		-5.30	546	-4.20				
33	0		-2.82	608	-		-5.50	531	-4.40				
34	0		-3.00	1,212	-		-5.70	304	-4.50				
35	33		-2.67	893	-		-7.90	517	-6.20				
36	0		-3.00	1,094	-		-5.10	297	-6.10				
37	2		-2.68	710	-		-7.80	320	-7.90	-7.80	0	-2.20	0
38	0		-2.67	604	-7.20		-6.20	428	-	-7.90	0	-1.80	0
39	4		-2.70	700	-		-6.20	315	-	-7.80	0	-1.70	0
40	0		-2.70	0	-6.38		-6.80	320	-		0	-2.70	38
41	40		-2.80	475	-		-6.20	159	-6.70	-7.80	0	-1.90	0
42	4		-	473	-7.00		-6.00	179	-6.00	-8.30	0	-2.20	0
43	5		-3.40	411	-6.30		-6.40	99	-5.00	-8.10	104	-5.70	482
44	3		-2.10	358	-6.00		-3.50	0	-4.60	-	179	-5.00	630
45	0		-3.10	142	-6.30		-3.50	0	-5.30	-	357	-6.30	1,037
46	0		-	0	-7.60		-5.10	0	-5.10	-	372	-9.60	1,086
47	15		-5.60	0	-7.60		-9.10	0	-7.80	-9.90	433	-9.90	1,192
48	2		-9.10	0	-8.20		-8.90	0	-7.20	-	368	-	1,370
49	0		-9.50	0	-8.70		-7.90	0	-8.40	-	371	-	1,635
50	0		-	0	-8.90		-8.40	0	-9.60	-	222	-	1,385
51	2		-9.60	0	-		-8.20	0	-9.80	-	312	-	1,433
52	4		-6.30	0	-8.30		-9.60	0	-9.60	-	308	-	1,375
53	3		-	0	-8.40		-	0	-8.60	-	182	-	735
54	11		-7.70	0	-7.10		-3.10	0	-7.40	-	163	-	677
55	6		-8.40	0	-7.20		-3.40	0	-7.40	-	165	-	731
56	28		-6.80	0	-6.20		-1.40	0	-6.50	-	254	-	605
57	62		-7.80	0	-6.60		-3.10	0	-6.10	-	284	-	662
58	5		-7.40	0	-7.20		-5.60	0	-7.10	-	282	-	965
59	3		-8.40	0	-7.50		-7.10	0	-7.60	-	342	-	1,719
60	3		-8.60	0	-7.10		-5.90	0	-8.30	-	297	-	2,125
61	3		-6.40	0	-7.10		-9.40	0	-7.00	-	241	-	2,010

Klipfontein

		n138		LF90/207	
Month	Rain	Q	WL	Q	WL
1	0			161	-10.60
2	0		-10.01	291	
3	0		-10.01	293	
4	12		-9.12	156	-16.05
5	4		-9.10	243	-14.26
6	70		-8.87	139	-9.26
7	27		-8.71	138	-8.91
8	2		-6.25	197	-11.86
9	2		-10.85	273	-7.57
10	7		-7.01	208	-9.20
11	1		-7.22	128	-9.30
12	1		-15.08	412	-16.00
13	7		-9.10	60	-16.80
14	3		-9.30	106	-17.60
15	3		-9.40	147	-10.65
16	0		-8.12	247	-10.40
17	43		-12.67	100	-10.88
18	25		-13.11	111	-9.99
19	23		-11.50	229	-10.60
20	24		-7.80	173	-9.05
21	18		-9.00	211	-9.30
22	22		-8.34	169	-10.00
23	20		-12.51	180	-9.10
24	9		-10.81	489	-9.10
25	0		-9.80	368	-11.30
26	24		-10.90	64	-9.10
27	3		-10.65	249	-13.11
28	2		-11.52	712	-15.90
29	2		-13.12	360	-16.70
30	7		-7.80	153	-10.30
31	64		-12.50	331	-10.90
32	39		-9.00	161	-9.50
33	60		-8.00	206	-9.20
34	19		-6.80	131	-8.90
35	39		-6.90	198	-8.35
36	13		-7.84	228	-9.19
37	2		-8.99	165	-8.28
38	0		-14.20	218	-9.40
39	16			200	-9.00
40	16		-13.89	200	-11.97
41	126		-5.39	200	-7.50
42	150			100	-6.80
43	5		-4.20	0	-5.80
44	15		-5.02	281	-6.15
45	0		-9.41	102	-7.11
46	0		-4.52	113	-6.15
47	36		-4.60	395	-6.15
48	4		-13.89	588	-11.99
49	0		-5.00	0	-6.20
50	10		-3.82	287	-6.50
51	0		-5.60	250	-6.02
52	0		-8.04	0	-9.51
53	13			150	-9.50
54	9			300	-5.40
55	4			374.4	-5.10
56	4			288	-5.10
57	1		-3.20	300	-5.10
58	0			300	-5.20
59	10		-4.80	370	-5.10
60	0			266	-5.10
61	0		-4.30	334	-5.10
62	6			314	-5.10
63	16		-5.10	351	-5.60
64	22			244	-5.60
65	6			275	-5.60
66	10		-4.20	189	-5.60
67	6			357	-6.20
68	12			222	-6.20
69	20			275	-6.25
70	0			333	-6.24
71	0			93	-6.30
72	0			691	-6.30

Komaggas 1/3

		KG92/102		KG2		KG4		KG91/100		KG92/104	
Month	Rain	Q	WL	Q	WL	Q	WL	Q	WL	Q	WL
1	0	977	-33	1414	-10	968	-24.25	2185	-23.7	421	
2	0	629	-22.7	376	-7.35	570	-22.7	1592	-24.85	319	-54
3	0	1273	-21.61	1969	-6.5	1032	-20.2	1934	-25.2	421	-51.35
4	0	942	-19.9	1454	-6.9	741	-22.7	944	-23	431	-52
5	94	240	-18.8	0	-6.4	1941	-20.3	1614	-22	142	-49.56
6	9	362	-20.1	574	-7.6	1112	-23.1	1201	-23.7	258	-51.95
7	12	666	-20.3	2081	-7.4	1036	-23	1568	-23	215	-50
8	38	1020	-20.45	2253	-8.15	1026	-22.97	883	-21.8	320	-49.2
9	47	62	-20.5	1169	-9.85	125	-20.7	2348	-24.99	511	-48.7
10	42	1317	-24.2	1973	-7.21	1174	-20.99	1437	-23.11	238	-42.1
11	13	1705	-21.65	1357	-7.63	1268	-20.55	1976	-23.22	674	-43.23
12	12	1427	-25.16	1828	-10.44	1381	-22.24	1133	-23	381	-43.93
13	0	1450	-24	2994	-11.23	1399	-22.7	225	-23	504	-46.11
14	22	1529	-25.73	2764	-13.29	1291	-23.66	1892	-23.5	522	-50.9
15	3	1626	-24	910	-7.6	1764	-23.2	2375	-23.15	417	-52
16	0	2156	-22.3	95	-6.8	2719	-22.1	1589	-26.4	400	-52.1
17	13	1463	-22.27	2327	-7.8	1341	-21.4	1626	-24.67	220	-51.6
18	25	859	-22.46	1832	-8.41	718	-21.6	1156	-24.37	169	-51.5
19	54	933	-25.44	1249	-8	1094	-23	1131	-25.42	258	-51.32
20	56	1152	-25.2	1734	-8.9	986	-23.27	1286	-25.49	145	-39.88
21	63	1402	-21.95	1726	-7.28	1376	-23.7	1354	-25.8	0	-46
22	21	1275	-24	1980	-10	1380	-24	2231	-24	26	-47.6
23	46	1755	-22.5	2289	-8.9	261	-24	1764	-24.1	0	-46.24
24	21	1663	-22.55	3150	-9.7	0		2787	-23.89	0	-49.7
25	0	1295	-22.5	1761	-8	0		2837	-27.18	1	-47.8
26	0	1520	-24.99	2735	-10.9	407	-22.5	1989	-30.4	341	-42.63
27	21	1538	-25	1969	-8	1697	-23.78	1930	-27	249	-37.6
28	17	1247	-22.45	1907	-8.9	1406	-22.7	1884	-28.71	362	-49.26
29	94	1243	-20.9	2206	-7.54	1597	-22.24	1576	-29	50	-42.22
30	80	1674	-20.41	1320	-8.25	1314	-22.9	393	-28.43	123	-40
31	20	2216	-25.3	2498	-7.24	1484	-25.85	1779	-27.24	0	-34.2
32	8	1738	-20.15	1708	-7.1	1657	-24.22	1798	-27.65	340	-34
33	1	1523	-20.75	1833	-7.9	1288	-24.6	1642	-28.1	176	-39.84
34	1	2553	-20	3255	-8.51	2622	-24.28	3948	-28	532	-40.77
35	43	1440	-22.2	1571	-6.5	1554	-22.7	2580	-29.21	550	-49.99
36	2.5	1994	-22.8	1715	-7.05	1605	-26	2571	-29.72	287	-44.9
37	5	1548	-21.75	2152	-8	1736	-23.1	2187	-29.74	230	-40.4
38	0	1446	-23.38	1960	-8.3	1326	-24	2097	-29.14	385	-36
39	0	1454	-21.63	2490	-8	1097	-21	2476	-29	268	-36.42
40	1	1025	-21	2048	-8.3	867	-22.53	2574	-29	261	-49.12
41	48	1242	-20.4	913	-7.64	950	-20.9	1711	-32	165	-33.82
42	1	1258	-22.6	1757	-11.97	619	-24.22	1229	-29.99	218	-34.5
43	3	1584	-21.2	2106	-10.05	0	-18.3	1082	-33.1	111	-34.29
44	6	1010	-20.95	1293	-7.2	1447	-19.67	771	-30.8	109	-35.4
45	2	923	-20.4	2041	-7.54	343	-20.22	2337	-33.29	94	-36.82
46	1	827	-20.48	1390	-15.5	563	-21.6	1708	-29.37	75	-33.6
47	0	1,052	-22.2	1581	-9.32	826	-22.57	2041	-29.6	14	-40.5
48	5	1,386	-22.6	2109	-11.53	1120	-24.6	2299	-30.8	8	-35.2
49	0	1,312	-24.6	1532	-9.15	1015	-25	955	-31.4	266	-35.8
50	2	2,194	-24.24	3371	-12.15	2481	-27.56	274	-30.98	887	-34.5
51	2	1,200	-25	1608	-10	1382	-27.2	1660	-31	583	-36.17
52	2	11	-25	1855	-9.05	1953	-27.1	1700	-31.4	340	-35.2
53	0	0	-22.1	1230	-7.6	1677	-26	0		120	-35.21
54	17	6	-25.4	980	-8.48	1121	-26	0	-30.3	3	-57.18
55	14	496	-25.2	1035	-8	834	-25.28	354	-29.4	177	-38.16
56	4	403	-25.3	750	-8.39	756	-25.59	895	-30	517	-35.3
57	76	1,181	-25.1	1062	-7.2	1121	-25.3	1407	-30	636	-32.88
58	15	1,076	-25.3	1571	-7.2	1468	-26.58	1515	-29.4	149	-35.47
59	3	1,656	-25	1057	-7	1682	-26	2061	-29.3	192.05	-38.1
60	4	1,744	-29.5	0	-7	2491.8	-26.9	2229	-35.2	1033	-37.4
61	10	1,763	-25	0		2413.38	-26.3	2123	-30.3	794	-34.2

Komaggas 2/3

		KG93/106		KG93/107		KG93/108		KG93/109		KG93/110	
Month	**Rain**	**Q**	**WL**	**Q**	**WL**	**Q**	**WL**	**Q**	**WL**	**Q**	**WL**
1	0	1159	-23.45	2360	-12	2092	-13	1165	-12	111	-4.2
2	0	936	-17.4	1717	-12.7	1475	-10.25	1350	-11.5	325	-4.5
3	0	1255	-20.2	1769	-12.75	1547	-11.5	1436	-13.2	279	-5.6
4	0	1058	-18	1458	-12	2568	-11.88	2361	-11	215	-4.5
5	94	1273	-18.3	1525	-13.1	1233	-18	1814	-14.65	164	-3.9
6	9	1361	-22.25	618	-13	1466	-18	1335	-13.8	520	-4.7
7	12	1268	-21	205	-13	1376	-17	1217	-13.6	787	-5.1
8	38	1799	-22.05	173	-10.75	681	-15.65	636	-11.6	336	-5.2
9	47	2371	-22.5	1844	-13.5	2180	-17	2242	-13	1281	-5.4
10	42	1330	-22	1547	-13.9	936	-17.9	1446	-14.3	788	-6.94
11	13	1942	-20.2	2565	-14.93	2529	-17.77	2109	-18.59	1363	-9.68
12	12	1692	-19	2258	-15	2179	-17.55	2435	-17	1166	-8.15
13	0	2029	-20	3441	-16.9	3042	-19.4	2278	-18.2	1499	-9
14	22	1840	-24.34	2121	-14.3	2394	-21.65	1997	-12.83	969	-9
15	3	2680	-22.45	2148	-17.6	1613	-19	1590	-15.25	820	-10.74
16	0	3567	-24.9	3794	-21.8	3689	-24.7	3262	-21.6	0	-6.65
17	13	1771	-25.55	2003	-17.5	1711	-23	1727	-18.12	218	-8.55
18	25	1049	-23.55	1593	-20.05	1397	-23	1119	-19.8	656	-12.4
19	54	1389	-23.78	991	-19.55	885	-21.68	559	-19	363	-9.73
20	56	1766	-21.44	1344	-18	1138	-22	699	-18	265	-5.1
21	63	1689	-25.3	858	-18	714	-20	495	-15	363	-3.8
22	21	1699	-25	1953	-19.99	1610	-19.71	1385	-19	410	-10.8
23	46	2200	-20.49	1416	-19	2030	-18.66	918	-20.22	745	-5.6
24	21	2409	-23.1	2222	-19	2275	-22.6	1457	-17.45	1317	-5.8
25	0	2558	-24.27	3560	-22.99	2770	-23	1688	-18.75	1597	-7.84
26	0	2138	-24.2	2962	-27.9	2673	-23.57	79	-30.48	1307	-9.45
27	21	2337	-25.41	2298	-24.99	1927	-24.5	1013	-18.6	801	-8.37
28	17	1890	-24.8	1549	-24.15	1816	-25.25	1093	-18.4	777	-9.68
29	94	2174	-23	1338	-23.4	1483	-24.91	341	-16.8	357	-4.47
30	80	227	-21.11	1038	-21.9	614	-24.98	449	-14.5	632	-1.95
31	20	254	-17	1376	-19.4	1181	-20	427	-19.92	804	-4.9
32	8	708	-17.75	1696	-20.55	1502	-22.4	1119	-12.85	59	-5
33	1	434	-18.15	1683	-20.8	1597	-23.1	758	-13.65	0	-2.6
34	1	1335	-18	2687	-19.87	2898	-22.99	1950	-19.72	58	-4.5
35	43	962	-17.44	2448	-25.95	2379	-24.84	1434	-15.1	932	-5.13
36	2.5	500	-18	2502	-24.42	2423	-25.18	1398	-21.7	1176	-6.97
37	5	0	-17.82	2038	-24	2380	-25.3	1695	-17	1220	-4.6
38	0	0	-18.99	2087	-25	1567	-28.15	2068	-26	1276	-12.8
39	0	0	-22.4	2144	-24.39	478	-31.43	1917	-25	1304	-8.32
40	1	11	-17.35	2592	-25.87	1290	-27.34	1992	-26	574	-9.99
41	48	30	-22.33	1827	-25	1371	-26.05	1784	-22.1	629	-10
42	1	225	-22.5	1899	-25.36	420	-26.3	1728	-25.11	680	-12.33
43	3	1363	-23.1	2213	-28.7	267	-30.1	1938	-22.8	646	-13.6
44	6	2048	-27	1553	-25.45	883	-28	1028	-21.24	313	-17.6
45	2	2601	-21.8	2808	-24.27	1999	-25.42	1761	-22.67	590	-23.18
46	1	2248	-23.98	1977	-23.6	1679	-27.12	1512	-22.12	332	-25.44
47	0	2965	-20.17	2856	-25.32	1900	-27.9	1817	-21.34	0	
48	5	2140	-21.22	2676	-25.37	835	-23.12	1594	-22.33		-14.2
49	0	2088	-25.3	2396	-27.78	538	-27.16	1755	-26.03	76	-9.9
50	2	1494	-27.9	137	-27.5	403	-26.22	319	-27.85	98	-6.7
51	2	1511	-27.84	1787	-31.1	1726	-30	1337	-30.87	197	-9.6
52	2	960	-28.14	0	-27.15	1436	-27.9	1741	-30.2	199	-10
53	0	839	-27	1740	-27	1365	-29.6	1073	-30.1	111	-7.6
54	17	2579	-27.94	1838	-27.29	966	-28.4	384	-28.1	84	-9.1
55	14	1694	-29.7	1484	-26.27	974	-27	205	-27.4	54	-6.37
56	4	2015	-27.6	1666	-27	622	-25.46	343	-29.89	82	-7.9
57	76	1975	-27.55	1330.14	-26.4	986	-25.97	347	-25.17	1	-5.99
58	15	3965.8	-28.32	2085.66	-26.88	1607	-26	191	-26.63	3	-1.69
59	3	3373.3	-28.7	1883.64	-27.2	1971	-27.25	201	-24.7	0	-6.3
60	4	0	-27	2042.58	-27.56	2010	-30.2	973	-33.7	0	-7.1
61	10	0		1934	-29.6	2146	-27	899.7	-28.7	0	

Komaggas 3/3

		KG93/115		KG91/101		KG92/103		KG92/105		G37966	
Month	Rain	Q	WL	Q	WL	Q	WL	Q	WL	Q	WL
1	0	630	-16		-59.1		-9.68		-45.53		-18.73
2	0	0	-15.8		-60		-9.8		-44.78		-19.8
3	0	1093	-17		-64		-9.85		-44.53		-20.27
4	0	1170	-16.25		-61.2		-9.91		-43.6		-19.79
5	94	916	-25		-58.8		-9.96		-41.6		-19.33
6	9	882	-45.1		-58.4		-10.04		-42.5		-19.48
7	12	399	-39.2		-61.25		-10.1		-41.25		-19.47
8	38	249	-37.45		-56.8		-10.15		-41.65		-19.11
9	47	379	-39.9		-58.88		-10.2		-40.86		-19.89
10	42	255	-39.1		-58.6		-10.28		-42.13		-19.27
11	13	242	-39.55		-57.51		-10.32				-18.27
12	12	385	-34.6		-57.62		-10.42		-43.58		-18.89
13	0	382	-41.4		-57.51		-10.43		-43.58		-19.45
14	22	244	-39.78		-57.62		-10.49		-43.69		-18.25
15	3	141	-32.88		-61		-10.51		-41		-19.2
16	0	675	-45.8		-60		-10.51		-42.4		-19.2
17	13	142	-40.2		-62.49		-10.52				-19.7
18	25	308	-49.9		-65.28		-10.52		-41.88		-19.56
19	54	93	-39.48		-62.55		-10.54		-44		-19.68
20	56	12	-39.9		-63.2		-10.54		-41		-19.81
21	63	0	-37.2		-63.2		-10.57		-41		-19.75
22	21	17	-36.15		-63.73		-10.57		-41.22		-20.09
23	46	0	-33.2		-59				-41.55		-20.11
24	21	0	-31.65		-63		-10.58		-42		-21.17
25	0	0	-30.5		-60.33		-10.59		-41.6		-22.37
26	0	140	-32.8		-65.15		-10.59		-44		-21.73
27	21	0	-29.1		-65		-10.57		-43.44		-21.73
28	17	20	-27.6		-64.7		-10.58		-44.27		-21.06
29	94	0	-49.22		-62		-10.58		-43		-21.02
30	80	31	-26		-62.38		-10.56		-42		-22.98
31	20	5	-23.5		-63.92		-12.4		-41		-22.95
32	8	222	-26.85		-62.34		-12.52		-42.1		-22.81
33	1	17	-23.39		-64.11		-12.59		-42		-23.3
34	1	0	-20.42				-12.68				-22.88
35	43	0	-21.95		-65.13		-12.78		-42		-22.19
36	2.5	15	-21.8				-12.9		-41.94		
37	5	1	-21.6		-63.9		-12.99		-41.5		-27
38	0	0	-22.2				-13.11		-42		-27.45
39	0	0	-23.8		-64.9		-13.28		-42.78		-26.64
40	1	0			-64.26						
41	48	0	-20.6				-13.55		-43.28		-29.2
42	1	125	-22.34				-13.8		-43.28		-28.9
43	3	185	-21				-13.2		-44.17		-29.12
44	6	59	-20.6				-13.9		-44.22		-28.8
45	2	240.3542	-22.1				-13.76		-44.17		-30.8
46	1	344.8143	-21.9				-13.9		-44.12		-29.96
47	0	0					-13.6		-44.17		-32.12
48	5	0	-24.4				-14.3				
49	0	0	-23.8				-13.8		-44.1		-30.5
50	2	7	-23.8				-14.2		-44.6		-27.44
51	2	283	-23				-14.1		-45.76		-29.1
52	2	263	-24.9				-13.8		-45.2		-27.2
53	0	250	-25.23				-13.62		-44.6		-28.8
54	17	333	-23.47				-13.5		-44.2		
55	14	257	-24.5				-11.3		-44		
56	4	293	-23.17				-11.5		-44		-28.3
57	76	250	-23.2				-11.49		-44.69		-27.2
58	15	250	-24.2						-46		
59	3	250	-23.7						-46		
60	4	0	-23.8						-46.8		
61	10	0	-23.6						-46.15		

Rooifontein

		91/102		91/124	
	Rain	Q	WL	Q	WL
1	1	948	-2.5		-11.8
2	0	525	-2		-11.7
3	0	783	-1.8		-12.07
4	0	432	-1.5		-15.1
5	43	850	-1.4		-14.95
6	18	870	-1.3		-11.88
7	14	730	-1.2		-12
8	16	1,210	-1.55		-12.1
9	32	1,130	-1.44		-12.2
10	6	900	-1.57		-12.22
11	24	990	-1.33		-12.12
12	2	1,480	-1.27		-12.66
13	0	1,240	-1.34		-12.35
14	5	1,440	-1.86		-14.05
15	2	1,150	-1.73		-12.2
16	0	1,030	-1.83		-15.15
17	0	680	-1.66		-11.34
18	5	700	-0.6		-12.3
19	60	424	-1		-10
20	43	596	0		-8.8
21	9	460	0		-8.8
22	27	640	0		-8
23	24	1,080	-0.53		-6.89
24	10	1,000	-0.41		-7.95
25	2	1,380	-0.59		-7.05
26	0	1,160	-0.74		-7.81
27	22	790	-0.53		-7.9
28	20	580	-0.52		-7.82
29	70	660	-0.1		-7.22
30	32	300	0		-7.29
31	6	520	-0.76		-8.95
32	14	1,030	-0.49		-7.1
33	0	670	-0.43		-7.09
34	0	1,390	-1.19		-7.12
35	14	1,180	-1.65		-7.05
36	7	1,350	-1.21		-7.22
37	0	790	-1.03		-7.09
38	0	1,000	-2.02		-7.02
39	0	950	-2.52		-7.01
40	0	1,850	-1.1		-7.02
41	10	760	-2.08		-7.19
42	3	630	-1.36		-6.76
43	0	520	-1.42		-6.75
44	0	710	-1.1		-6.73
45	10	750	-1.1		-6.73
46	0	960	-1.1		-6.76
47	8	1,020	-1.1		-6.76
48	2	1,340	-1.7		-6.76
49	0	960	-1.55		-6.73
50	6	940	-1.2		-6.87
51	1	870	-1.1		-6.92
52	7	870	-1.1		-6.95
53	6	520	-1.1		-6.95
54	4	650	-1		-7
55	2	590	-1		-6.95
56	24	740	-1.09		-7
57	27	740	-0.65		-7.1
58	22	800	-0.65		-7.1
59	10	654	-0.79		-6.95
60	17	1,786	-0.75		-7.1
61	12	810	-1		-7.3

Spoeg River

		LF90/206		LF90/205		LF90/208		N096	
Month	Rain	Q	WL	Q	WL	Q	WL	Q	WL
1	5.5		-4.9	0		224	-9.62		-1.1
2	1.5		-5	0		224	-10.4		-2
3	5		-5.26	0		148	-9.6		-1.06
4	0		-5.4	0	-5.56	370	-11.28		-1.14
5	44		-5.43	1	-10.61	97	-10.1		-1.16
6	25		-5.39	1	-5.45	298	-14.96		-1.01
7	25		-5.5	1	-5.32	205	-9.82		-1.2
8	15		-5.8	1	-5.1	257	-13.1		-1
9	24		-4.9	1	-4.2	257	-9.1		-0.92
10	24		-5	1	-6	131	-12.5		-0.78
11	44		-5.07	1	-3.8	229	-15.41		-0.68
12	11		-5.09	1	-5.3	405	-11.53		-0.93
13	0		-5.09		-6.12	277	-11.85		-1.02
14	22		-5.09		-4.9	304	-15.72		-1.16
15	2		-5.02		-6.12	293	-17.1		-1.65
16	2		-5.48		-5.61	458	-11.7		-1.36
17	3		-5.02		-5.02	252	-12.05		-1.33
18	9		-5.8		-5.3	289	-11.9		-1.9
19	68		-5.1		-4.8	167	-15.1		-0.8
20	41		-4.8		-4.3	103	-10		0
21	55		-4.5		-4.3	120	-11.1		0
22	20		-5.3		-4.4	339	-4		-0.35
23	41		-4.5	0	-4.78	288	-13.15		-0.99
24	11		-4.61	0	-4.82	196	-9.37		-1.02
25	2		-4.89	0	-5.99	321	-13.89		-1.4
26	0		-4.8	0	-5.2	279	-9.1		-1.6
27	29		-5	0		303	-9.1		-1.15
28	27		-5.06	0	-5.2	335	-9.98		-1.71
29	99		-3.79	0	-4.52	29	-6.96		-0.26
30	150		-3.71	0	-4.49	0	-7.37		-0.1
31	4		-3.28	0	-4.52	323	-8.23		-0.83
32	13		-3.24	2	-4.94	241	-7.92		-0.67
33	0		-4.16	0	-6.36	247	-8.01		-0.49
34	0		-5.19	0	-6	356	-8.42		-0.72
35	48		-5	2	-5.15	428	-9.1		-0.77
36	4.5		-5.15	3	-5.68	410	-5.59		-1.57
37	0		-5.21	1	-5.15	235	-8.82		-1.91
38	6		-5.95	1	-6.11	115	-8.11		-0.98
39	0		-5.86	1	-6.11	320	-8.9		-1.99
40	0		-4.95	1	-5.49	246	-10.5		-1.4
41	15		-5.02	0	-5.1	236	-13.04		-1.5
42	10		-5	0	-5.2	282	-10.5		-1.15
43	4		-5.3	0	-5	556	-9.2		
44	7		-5.2	0		221	-9.3		
45	0		-5.8	0	-5.3	573	-7.4		
46	0		-5	0	-5.8	642	-12.3		
47	17		-5	0	-5.3	579	-10.5		
48	0		-5.2	0		526	-7.7		
49	0		-5.6	0	-6.7	589	-12.3		
50	20		-5.5	0		672	-9.8		-2
51	8		-5.7	0	-5	779	-12		-2.3
52	20		-5.5	0	-5.8	562	-10.8		-2
53	8		-5.8	0		859	-12.5		
54	6		-5	0	-5.8	424	-11.8		-2
55	3		-5	0	-5.8	644	-12.8		-2.8
56	12		-5.7	0	-5	446	-10.8		-2.8
57	16		-5.8	0	-5	457	-12		-2
58	8		-5.8	0	-5	403	-12.5		-2
59	5		-5.9	0	-5.1	1077	-12		-2
60	0		-5.8	0	-5	806	-12.8		-2
61	0		-5.8	0	-5	450	-12.5		-2